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High-spatial-resolution measurement of hotspot electron temperature distribution in inertial confinement fusion implosions

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ABSTRACT

High-resolution measurements of hotspot electron temperature profiles in inertial confinement fusion are critical for characterizing the ignition performance and understanding the physics of stagnation. The spatial resolution of current diagnostics for two-dimensional hotspot electron temperature distributions of (10-25 μm) requires improvements to meet the requirements of 30-60- μm -scale hotspot measurements. In this study, a 5- μm resolution two-dimensional hotspot time-integrated electron temperature detection technique is first developed using a high-space-resolving Kirkpatrick–Baez (KB) microscope and data extraction method based on the ratio of hotspot Bremsstrahlung intensity distributions. The hotspot electron temperatures are experimentally measured at the 100 kJ laser facility. The high-resolution electron temperature results exhibit several temperature peaks correlated to localized mix regions. The relatively high mix amounts in these finely resolved local regions are reasonably evaluated using the high-resolution diagnostic techniques adopted in this study. A one-dimensional model is established, which yields average electron temperatures and hotspot scale results that are consistent with the experimental results. The results demonstrate that spatially heterogeneous and localized mix features are embedded inside the hotspot. This study provides a robust foundation for precise measurements of the electron density and mix distributions and proposes an optimization method for improving data-extraction accuracy. Finally, this study is a pioneering work for diagnosing high-spatial-resolution hotspot electron temperature distributions and extending the KB imaging system to electron temperature measurements.

Introduction

Resolving two-dimensional (2D) hotspot electron temperature distributions with a high resolution is essential for characterizing the ignition performance and understanding the stagnation physics in inertial confinement fusion (ICF)^{1,2}. This is particularly critical when pursuing larger target gains and a higher ignition frequency, which are necessary for effectively utilizing fusion energy³. For example, a localized hotspot mix is on the atom-to-micron scale^{4,5} and one of the four main degradation mechanisms in ignition experiments^{6,7}. In an approximate isochoric model of a hotspot, spatial nonuniformity in the electron temperature leads to a nonuniform electron density. The resulting density nonuniformity is closely related to that of the hotspot mix. Therefore, a high-spatial-resolution electron temperature distribution is ideal for clarifying the detailed structure of the mix.

However, the spatial resolution of current diagnostics for 2D hotspot electron temperature distributions is only 10–25 μm when multi-pinhole imaging, penumbral imaging or KB microscope imaging is used^{8–10}. Therefore, spatial resolution improvements are necessary to meet the requirements of 30–60- μm -scale hotspot measurements^{11,12}. In this study, a hotspot electron temperature distribution with a spatial resolution of 5 μm was obtained for the first time using time-integrated imaging based on a high-space-resolving Kirkpatrick–Baez (KB) microscope^{13–20}. In addition, an electron temperature data extraction method was proposed using the ratio of hotspot Bremsstrahlung intensity distributions, which differed from the hotspot-emission-intensity counts fitting method proposed in Ref.¹⁰ that also used KB microscope imaging. The temperature peaks in the high-resolution results, which were closely related to the localized mixtures, were determined and thoroughly

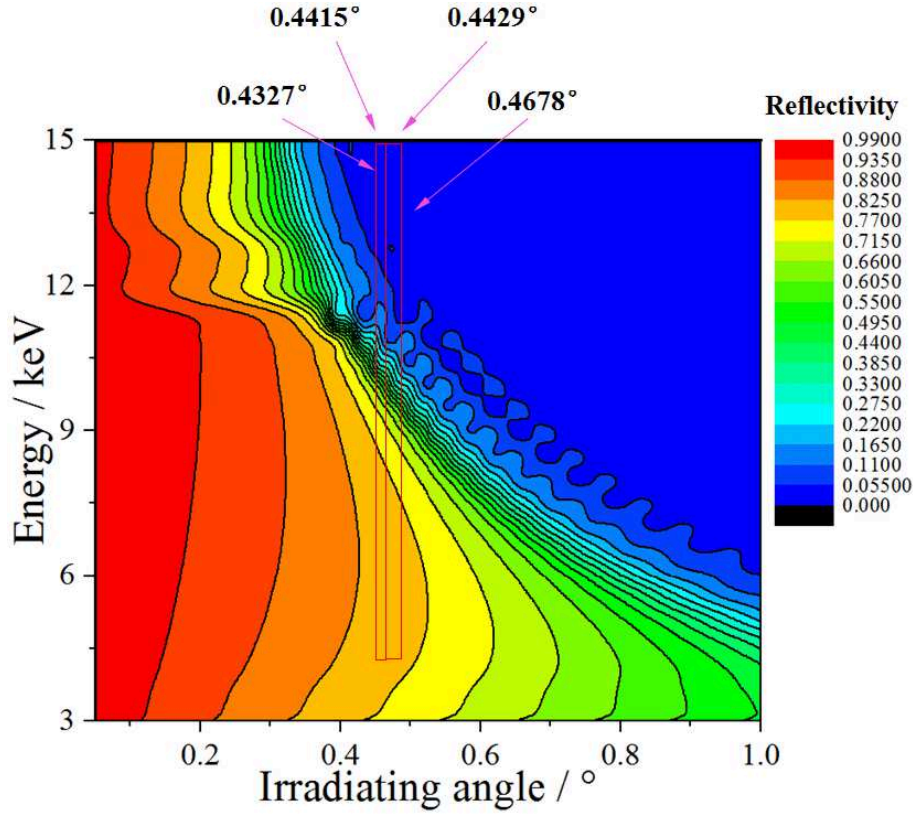


Figure 1. Reflectivity distribution of the Kirkpatrick–Baez (KB) microscope, which varies with the X-ray irradiating angle (corresponding to the field of view). The red rectangles indicate the glancing incidence angle ranges of the first and second spherical mirrors, with the range start and end angles.

analyzed. A reasonable evaluation method based on the high-spatial-resolution electron temperature distribution was proposed to extract the mix amount. In addition, a one-dimensional (1D) simulation was conducted using the average atomic mixing model for the hotspot, whose results were consistent with the experimental results.

The remainder of the paper is structured as follows. Section 2 describes the principles of the 5- μm -resolution hotspot electron temperature measurement, followed by the experimental setup in Section 3. The KB imaging results and data processing are described in Section 4, whereas the theoretical forward calculation is presented in Section 5. Sections 6 and 7 explain the simulation and analysis and discuss the results, respectively. The conclusions are included in Section 8.

Principles of the 5- μm -resolution hotspot electron temperature measurement

Enhanced diagnostic resolution requires high-spatial-resolution imaging equipment. Therefore, a high-resolution four-channel KB microscope, with a spatial resolution and magnification of $4 \pm 1 \mu\text{m}$ and 20 ± 1 ¹⁴, respectively, was used for hotspot electron temperature detection. In addition, an imaging plate (IP) with a spatial resolution of $62 \mu\text{m}$ ^{21–23} was used to capture X-ray images. Thus, 5- μm -spatial-resolution hotspot X-ray images in different energy bands (calculated as $\sqrt{4^2 + (62/20)^2} = 5 \pm 0.8 \mu\text{m}$, considering the field of view of the KB microscope) were obtained and used to extract the hotspot electron temperature at the same spatial resolution.

An extraction of the hotspot electron temperature requires a method that can easily avoid the influence of the reflectivity distributions of the KB channels. Therefore, a single-layer Pt-film-coated four-channel KB microscope¹⁴ was chosen for these measurements. The reflectivity distribution of the KB microscope varies smoothly within $\pm 40 \mu\text{m}$ of the center of the field of view (the position of the hotspot) in each channel. Considering that the hotspot in this study had a radius of approximately $20 \mu\text{m}$, the aiming error of the KB microscope was less than $\pm 20 \mu\text{m}$. The hotspot position corresponded to a glancing incidence angle range of 0.4327° – 0.4429° on the first spherical mirror of the KB microscope channel, considering different irradiating positions on the mirror. This glancing incidence angle range corresponded to an irradiating angle range of 0.4415° – 0.4678° on the second spherical mirror. The reflectivity distributions of the spherical mirrors at different incidence angles and energies

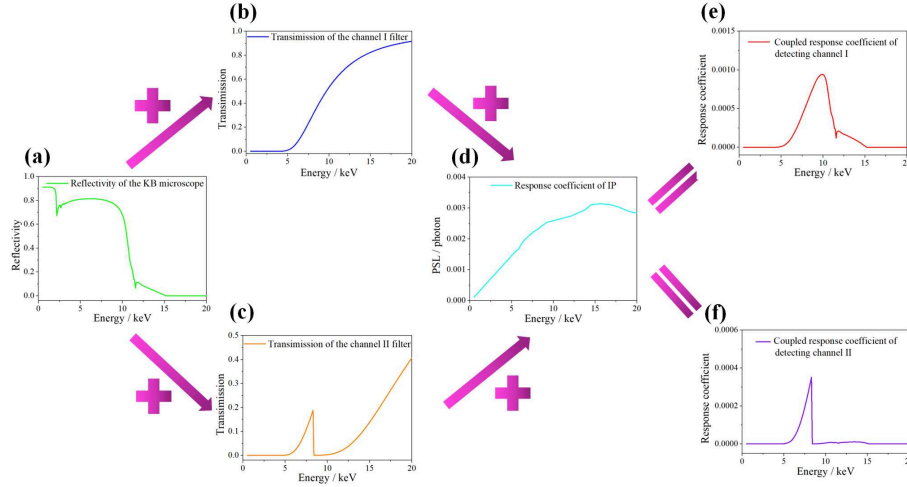


Figure 2. (a) One-dimensional (1D) reflectivity of the KB microscope, (b) transmittance of Channel I filter, (c) transmittance of Channel II filter, (d) IP response curve; total response curves for detecting Channels (e) I (R_1), and (f) II (R_2).

used for creating the hotspot X-ray images are illustrated in Figure 1. The reflectivity distribution varies slightly over the hotspot-position scale (that is, over the two aforementioned glancing incidence angle ranges), which is discussed and included in the final uncertainties. Hence, the 1D reflectivity of the KB microscope η_{KB} , which varies with the X-ray energy, transmittance of the filter T_{Filter} used for selecting the specified X-ray energy, and response coefficients of the IP P_{IP} used to record the hotspot images, can be combined to yield the total response $R = \eta_{KB} \times T_{Filter} \times P_{IP}$, as illustrated in Figure 2. Two types of filters, a 75 μm Al filter and 30 μm Ni filter overlapped with a 25 μm Al filter, were used in the four KB microscope channels. Correspondingly, the energy ranges of the total responses were 5.40–15.00 keV (named $a_1 - b_1$) for two channels and 5.80–8.30 keV (named $a_2 - b_2$) for the other two channels. The relatively high-energy bands were chosen to ignore the influence of carbon–hydrogen (CH) ablator emission. In addition, for each energy range, the X-ray image obtained from the channel with the higher signal-to-noise ratio was selected as the measured data.

Then, the spectrum of the hotspot Bremsstrahlung emission was integrated with the total responses²⁴. Following is Eq. (1):

$$f_1 = \int_{a_1 k_B/h}^{b_1 k_B/h} C \frac{n_e}{\sqrt{k_B T_e}} \exp\left(-\frac{h\nu}{k_B T_e}\right) R_1 d\nu. \quad (1)$$

Following is Eq. (2):

$$f_2 = \int_{a_2 k_B/h}^{b_2 k_B/h} C \frac{n_e}{\sqrt{k_B T_e}} \exp\left(-\frac{h\nu}{k_B T_e}\right) R_2 d\nu. \quad (2)$$

Here, the constant C encompasses the light velocity, proton mass, electron mass, elementary charge, mass number, and ionization degree, while n_e , k_B , T_e , h , and ν denote the electron density, Stefan–Boltzmann constant, electron temperature of the hotspot, Planck constant, and frequency of X-rays emitted by the hotspot, respectively. Thus, the following calculated ratio (Eq. (3)) is obtained:

$$K_t = \frac{f_1}{f_2} = \frac{\int_{a_1 k_B/h}^{b_1 k_B/h} \exp\left(-\frac{h\nu}{k_B T_e}\right) R_1 d\nu}{\int_{a_2 k_B/h}^{b_2 k_B/h} \exp\left(-\frac{h\nu}{k_B T_e}\right) R_2 d\nu}. \quad (3)$$

This expresses the relationship between the ratio K_t and hotspot electron temperature T_e , as illustrated in Figure 3.

In the next step, we obtained the experimental ratio distribution from the hotspot K_e , which is the ratio of the X-ray image intensity distribution in the 5.40–15.00 keV energy band to that in the 5.80–8.30 keV energy band. Then, the distribution of the hotspot electron temperature was obtained using the relationship between the ratio K_t and electron temperature T_e in Figure 3. The spatial resolution of the temperature distribution should be the same as that of the two hotspot X-ray images, namely, $5 \pm 0.8 \mu\text{m}$.

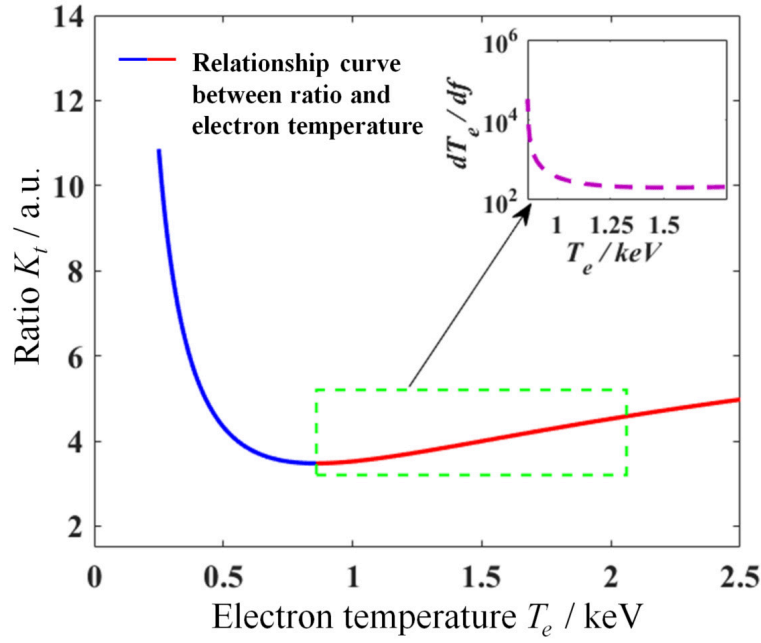


Figure 3. Relationship between the ratio K_t and hotspot electron temperature T_e .

Experimental setup

Figure 4 shows the experimental setup. The experiment was performed at the 100 kJ laser facility,^{25,26} which was designed for cylindrical hohlraums and comprised 48 frequency-tripled laser beams ($\lambda = 0.35 \mu\text{m}$). Considering the laser beam arrangement of the 100 kJ laser facility, 32 of the 48 laser beams (3280 J in 3.7 ns per square-wave beam) were selected to drive the octahedral spherical hohlraum through six laser entrance holes (LEHs). Four 55° and four 28.5° beams entered the hohlraum for the upper and lower LEHs, respectively. For the four LEHs in the equatorial plane, two 50° and two 35° beams entered the hohlraum. The incidence angles of the 50° and 35° beams were 47.9° and 61.5° , respectively. The diameters of the hohlraum and LEHs were 4.8 and 1.4 mm, respectively. The hohlraum wall was composed of $25\text{-}\mu\text{m}$ -thick Au and was filled with C_5H_{12} at 0.4 atm pressure. The laser beams were smoothed using continuous phase plates and had a focal spot with a diameter of $500 \mu\text{m}$ at the upper and lower LEH planes. The laser focal spots at the equatorial LEH plane were elliptical. The spherical hohlraum used in this experiment failed to produce high radiation symmetry because it was driven by only 32 of the 48 laser beams. The radiation symmetry was favorable during the mid-to-late stages, whereas it was less optimal in the early stages. This was primarily attributed to the inherent symmetry of the spherical hohlraum, particularly after spontaneous emission occurred outside the laser spot area. Consequently, the measured 20% contour asymmetry of the capsule at Bang Time was less than 1.5% with the same laser configuration²⁷.

An $802\text{-}\mu\text{m}$ -diameter deuterium–deuterium (DD) capsule (DD gas at 10.6 atm pressure filling a $750\text{-}\mu\text{m}$ -diameter area surrounded by a $26\text{-}\mu\text{m}$ -thick CH shell) was positioned at the center of the hohlraum. A relatively thin CH shell was designed to avoid the influence of ablation on the X-ray image intensity distribution of the hotspot in the subsequent measurements. The four-channel KB microscope, with a magnification of $20\times$, along with the filter and IP, was placed at the upper pole to measure the hotspot electron temperature (Figure 4). Flat-response X-ray detectors (F-XRDs) were placed at 64° relative to the hohlraum axis to measure the hohlraum radiation temperature. The plastic scintillator and neutron time-of-flight (nTOF) spectrometer were positioned on the equatorial plane to detect the neutron yield and ion temperature, respectively. A pinhole camera was used to monitor laser injection.

KB imaging results and data processing

The results for the radiation temperature, with a peak value of 187 eV measured by the 64° F-XRD, are shown in Figure 5. Additionally, the radiation temperature was simulated using the laser and radiation energy development (LARED) code²⁸ and was consistent with the measurement. LARED is a 1D multi-group radiation transfer hydrodynamic simulation that has been validated against various LASNEX models and experimental results. The capsule drive temperature calculated by LARED matched that measured by the 64° F-XRD (Figure 5). This differs from a traditional cylinder hohlraum, in which the capsule

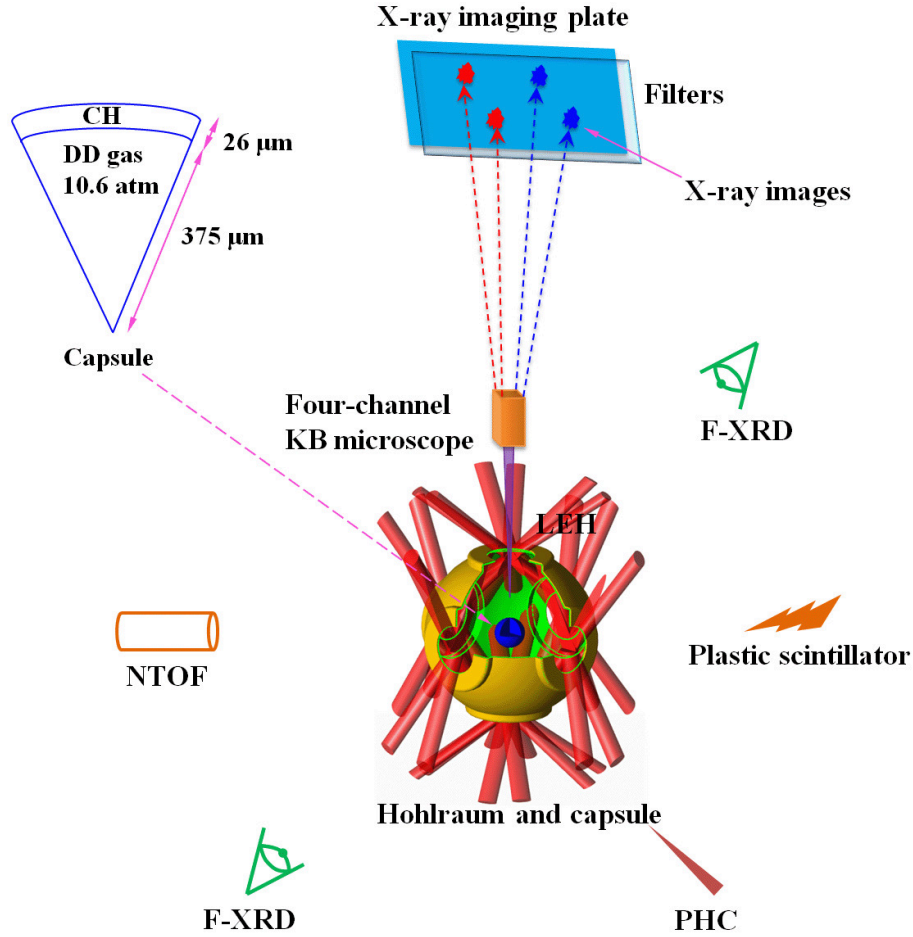


Figure 4. Experimental setup and arrangement of the main diagnostic devices used in the experiment.

drive temperature typically matches the temperature measured by the 42° F-XRD²⁹, owing to differences in the laser spot distributions and structural configuration of the hohlraum. The neutron yield, as measured using the plastic scintillator, was approximately 1.1×10^9 . The corresponding yield of clean was 32%. The ion temperature of the hotspot was approximately 1.60 keV, with a relative uncertainty of $\pm 10\%$ ³⁰, as measured by the nTOF spectrometer.

Figure 6 shows the KB imaging results recorded by the IP and procedure for extracting the experimental ratio K_e distribution. The X-ray IP quantitatively records X-ray images, with the following relationship between the grayscale and photo-stimulated luminescence (PSL) values^{22,23}:

$$PSL = \left(\frac{4000}{S}\right) \left(\frac{r}{100}\right)^2 10^{L[G/(2^B-1)-1/2]}. \quad (4)$$

Here, G denotes the image grayscale value, which ranges from 0 to 65535 and was obtained by scanning the X-ray IP; S is the sensitivity setting (in this study, 30000 was selected from 4000, 10000, and 30000); r indicates the reading step of the X-ray imaging plate (10 μm was selected from 10, 25, 50, 100, and 200 μm); L denotes the latitude (5 was selected from 4 and 5); and B indicates the dynamic range (16 was selected from 8 and 16). Quantitatively, PSL is proportional to the number of X-ray photons at a specified energy, based on the calibration of the X-ray IP sensitivity. Therefore, the ratio of the PSL distributions of the two X-ray images recorded by the IP is the experimental ratio K_e .

First, the PSL distributions of the two X-ray images (with $20\times$ magnification) were restored to the practicable hotspot scale with at least 5- μm spatial resolution, as shown in Figure 6(e) and (f). To obtain K_e , the coordinate interrelation between the two PSL distributions was required. Using Eqs. (1) and (2), the intensity of the PSL distribution can be expressed as Eq. (5):

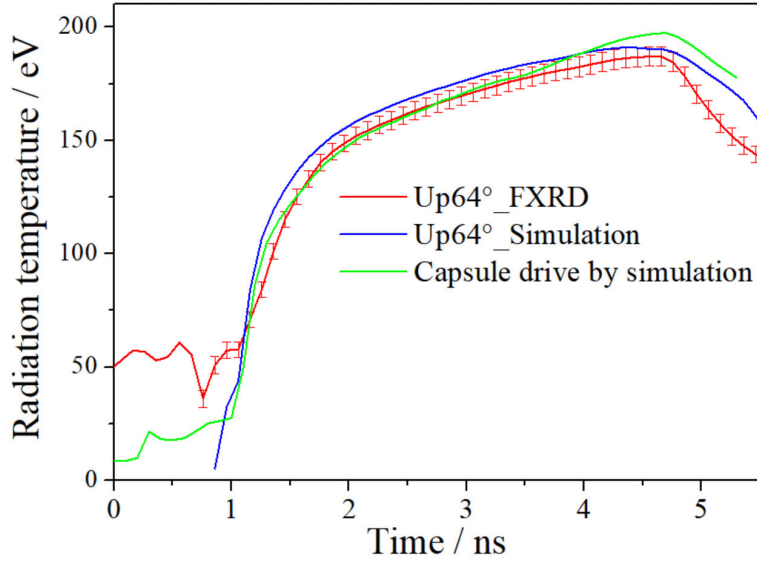


Figure 5. X-ray radiation temperature measured by the F-XRD placed at 64° relative to the hohlraum axis and simulated by our LARED code²⁸, which is additionally used to calculate the capsule drive temperature.

$$\begin{aligned}
 f &= \int_{\nu_1}^{\nu_2} C \frac{n_e}{\sqrt{k_B T_e}} \exp\left(-\frac{h\nu}{k_B T_e}\right) R d\nu \\
 &= \int_{\nu_1}^{\nu_2} C_1 \frac{n_e}{\sqrt{k_B T_e}} \exp\left(-\frac{h\nu}{k_B T_e}\right) d\nu \\
 &= \frac{C_1 n_e \sqrt{k_B T_e}}{h} \left[\exp\left(-\frac{h\nu_1}{k_B T_e}\right) - \exp\left(-\frac{h\nu_2}{k_B T_e}\right) \right],
 \end{aligned} \tag{5}$$

which is based on the integral mean value theorem. In this equation, C is a constant associated with the Bremsstrahlung emission of the hotspot, as defined in Eq. (1); C_1 represents an equivalent constant introduced via the integral mean value theorem; and R denotes the total response, including the reflectivity of the KB microscope, transmittance of the filter, and response coefficients of the IP, as described earlier. The range from $h\nu_1$ to $h\nu_2$ corresponds to the energy interval of the total response, as determined from Figure 2(e) and (f), and ν denotes the frequency. Thus, the gradient of the intensity of the *PSL* distribution is given by Eq.(6):

$$\frac{df}{f} = \frac{dn_e}{n_e} + \frac{dT_e}{T_e} \left[\frac{1}{2} + \frac{h}{k_B T_e} \frac{\exp(-\frac{h\nu_1}{k_B T_e})\nu_1 - \exp(-\frac{h\nu_2}{k_B T_e})\nu_2}{\exp(-\frac{h\nu_1}{k_B T_e}) - \exp(-\frac{h\nu_2}{k_B T_e})} \right]. \tag{6}$$

For an ideal gas, the following equation holds: $|\frac{dn_e}{n_e}| = |\frac{dT_e}{T_e}|$ in the hotspot, with the density increasing and temperature decreasing from the center to the edge. Considering the two different X-ray energy bands ($a_1 - b_1$) and $a_2 - b_2$) in Eq. (6) and assuming that the electron temperature ranged from 0.50 to 2.00 keV, we obtained $\frac{df}{f} < 0$. This indicates that f decreases with T_e from the center to the edge of the hotspot. Although the quantity $\frac{df}{f}$, with respect to $\frac{dT_e}{T_e}$ and $\frac{dn_e}{n_e}$, had no explicit r -dependence, the variations in the electron temperature T_e and density n_e were r -dependent. Therefore, the maximum f occurred at the same position for both energy bands. The maximum intensity of the *PSL* distribution was utilized to coordinate the interrelation between the two *PSL* distributions and obtain the ratio K_e distribution, as shown in Figure 6(g).

The relationship between the ratio K_t and electron temperature T_e in Figure 3 can be used to extract the experimental electron temperature distributions from the experimental K_e distribution in Figure 6(g). However, T_e has two solutions corresponding to a single value of K_t , as shown in the relationship curve of Figure 3. Therefore, two additional boundary conditions were introduced to determine the sole T_e distribution. The first condition assumed that the electron temperature $T_e \approx T_i = 1.60 \text{ keV}$ ³¹. Accordingly, we selected the right red curve in Figure 3 as the primary relationship between K_t and the electron temperature.

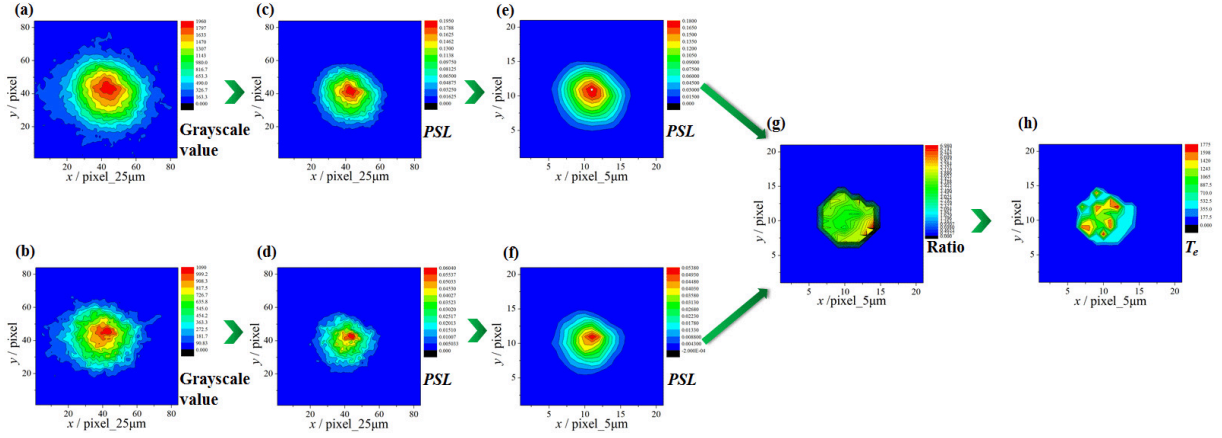


Figure 6. Observation results on the imaging plate for: raw images from (a) detecting Channel I and (b) detecting Channel II. Photo-stimulated luminescence (*PSL*) distributions of the observation results corresponding to (c) Channel I and (d) Channel II. 5- μm -spatial-resolving *PSL* distributions of (e) Channel I and (f) Channel II. (g) Ratio K_e of the two *PSL* distributions in the 17.8% contour profile, which is set as the hotspot region with a diameter of $35 \pm 2.5 \mu\text{m}$ ²⁹. (h) Extracted electron temperature distribution of the hotspot at a spatial resolution of 5 μm .

According to the second condition, the profile of the hotspot electron temperature distribution should be higher in the center and lower at the edge after repeated iterations to allow the maximum electron temperatures corresponding to the relatively large ratio $K_{I \rightarrow L}$ to be determined. First, the ratio $K_{I \rightarrow L}$ should be within the range of the ordinate values of the right red curve shown in Figure 3. Specifically, when the ratio in the hotspot region depicted in Figure 6(g) exceeded $K_{I \rightarrow L}$, the left blue curve in Figure 3 was used to extract the electron temperature. Then, the obtained electron temperature distribution was verified against the two boundary conditions. If these conditions were not satisfied, another value of $K_{I \rightarrow L}$ within the range was selected to repeat the extraction. After repeated iterations and extractions, the electron temperature distribution simultaneously satisfied both boundary conditions only when $K_{I \rightarrow L} = 4.30$ (corresponding to a maximum electron temperature $T_{e \max} = 1.80 \text{ keV}$). Thus, a 5- μm -resolution hotspot electron temperature distribution was obtained, as illustrated in Figure 6(h).

Theoretical forward calculation

To verify the data processing, the theoretical forward calculation was performed using MATLAB, with the preset electron temperature and density distributions of the hotspot cross-section based on the isobaric model³² (Figure 7(a) and (b)). Several mixtures were preset in the hotspot with 2.50% higher electron temperatures and a $\sim 1.40 \mu\text{m}$ scale. The equation governing the X-ray emission of the hotspot was obtained by considering Bremsstrahlung radiation applied to Eq. (5). The two-channel X-ray self-emission images of the hotspot were simulated using an ideal imaging system with a spatial resolution of 0 μm . Subsequently, the self-emission images were blurred because of the effect of spatial-resolving imaging of the KB microscope. The spatial resolution of 5 μm matched the full width at half maximum of the point spread function of the imaging system. The intensity distributions of the two blurred images were divided to obtain the intensity ratio distribution. Finally, the intensity ratio distribution was inverted using the simulated radio curve to obtain the 2D electron temperature distribution of the hotspot.

Figure 7(c) and (d) show the X-ray emission images of the hotspot in two different energy bands, with a theoretical spatial resolution of 0 μm . As shown in Figure 7(a)–(d), the X-ray emission intensity distribution and electron temperature distributions are aligned, which demonstrates that when $\frac{dT_e}{T_e} < 0$, $\frac{df}{f} < 0$, that is, f decreases with T_e from the center to the edge of the hotspot. Figure 7(e) and (f) show the images obtained by the KB microscope with a spatial resolution of 5 μm , which produces smoother results. The mixtures were smoothed to a $\sim 3.00 \mu\text{m}$ scale. In particular, considering the three-dimensional (3D) integration effects and observed image characteristics, the images obtained by the KB microscope, as shown in Figure 6(e) and (f), are expected to be smoother. Figure 7(g) shows the ratio distribution of Figure 7(e) to 7(f). The sensitivity $\frac{dT_e}{dK_I} > 200$ from 0.86 to 1.80 keV is shown in Figure 3. Consequently, the electron temperatures of the mixtures with more significant temperature divisions are inverted, as shown in Figure 7(h). Furthermore, the forward calculation results demonstrate that the positions of the temperature divisions are consistent with those of the mixtures. Therefore, the mixture positions can be precisely determined using hotspot electron temperature measurement with a resolution of 5 μm .

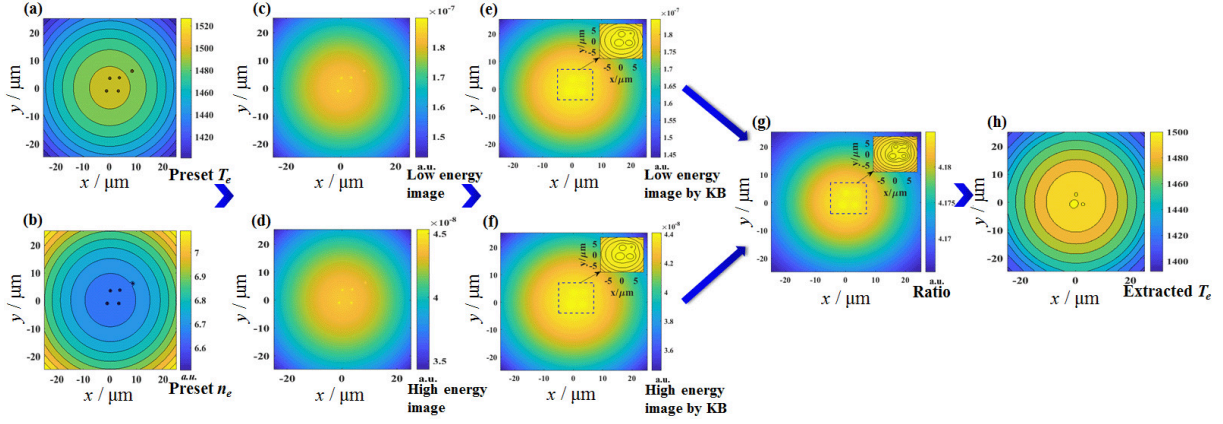


Figure 7. (a) Preset electron temperature and (b) density distributions of the hotspot cross-section in the theoretical forward calculation. Distributions of the X-ray intensity from (c) low and (d) high energy bands with a spatial resolution of $0 \mu\text{m}$, obtained via calculation. Distributions of the X-ray intensity from the (e) low and (f) high energy bands with a spatial resolution of $5 \mu\text{m}$, namely, the resolution of the KB microscope obtained via calculation. (g) Ratio of (e) to (f). (h) Extracted electron temperature distribution through the theoretical forward calculation.

Simulation and analysis

The LARED-S code²⁸ was used to conduct a 1D simulation of the implosion experiment for comparison with the experimental electron temperature results. LARED-S is a multi-material radiation hydrodynamic simulation that includes flux-limited electron and ion heat conduction, multi-group diffusion transport of charged particles, a second-order Godunov scheme with a material interface tracker based on the volume fraction method, and multi-group diffusion radiation transport. Additionally, the real equation of state and the tabular database of radiation parameters are used in this code. In the 1D simulation, the radiation temperature driving the capsule applies the temperature detected by the F-XRD set 64° relative to the hohlraum axis, as shown in Figure 5. Although the simulated radiation temperature does not match the measured value before 4.0 ns, the simulated peak radiation temperature remains within the experimental error bars. As the temperature simulation is based on a 2D model, it fails to fully simulate the 3D hohlraum model. In practice, if the simulated and experimental peak radiation temperatures are consistent, the simulation is considered reliable from the perspective of the total energy of the hohlraum. In addition, the relatively small deviations in the radiation temperature before 4.0 ns slightly affect the electron temperature simulation results. Using this, the electron temperature $T_e(r, t)$ that varies with space r and time t can be obtained using LARED-S.

Thus, we obtained the burn-weighted and time-averaged electron temperatures, as expressed by Eq.(7):

$$\langle T_e \rangle = \frac{\int \int T_e(r, t) e(r, t) d^3 r dt}{E}. \quad (7)$$

The total yield is expressed by Eq.(8):

$$E = \int \int e(r, t) d^3 r dt, \quad (8)$$

where $e(r, t)$ is the burn rate per unit volume. Thus, the 1D calculation yielded a hotspot electron temperature of 1.24 keV with a 1.70% atomic ratio mix. The radius of the hotspot, as obtained from the simulation, was $18.80 \mu\text{m}$. The 1.70% atomic mix was a pre-imposed ablator (CH material) mix added to the simulation, which was uniform throughout the gas volume. The amount of the mixture used was less than the detection limit of 2%. The mixture measurement is omitted in Figure 4 because of the small measurement result under the detection limit. Nonphysical oscillations were absent in the 1D calculation, as the LARED code used a high-precision monotonicity-preserving Eulerian scheme rather than a Lagrangian scheme. The mesh was convergent because the number of grid cells was sufficiently large, and the computational results were unaffected by increasing the number of grid cells. The simulated electron temperature, neutron yield, and hotspot radius were simultaneously closest to the experimental measurements only when the simulations incorporated the 1.70% atomic mix. The five temperature peaks were real. The impact on the electron temperature simulation from the small and uniform amount of mixture may be equivalent to

those from the localized nonuniform mixtures. The electron temperature, neutron yield, and hotspot radius considerably varied if the mixture was absent. Therefore, the five temperature peaks were most likely caused by local mixing. The differences between uniform and nonuniform mixing were difficult to resolve with the current data and required further investigation. In addition, considering the 3D effects and relatively small amount of mixing (1.70%), the mixture itself only slightly affected the accuracy of the X-ray luminescence measurement.

Discussion

The burn-weighted and averaged temperature of the hotspot, with an average radius of $17.50\ \mu\text{m}$, was approximately 1.43 keV with an average relative uncertainty of $\pm 24.10\%$ (Figure 6(h)). This value was consistent with the 1D simulation results. The electron temperature distribution (Figure 6(h)) was jagged and fluctuated by 28% in the center $\pm 15\text{-}\mu\text{m}$ region of the hotspot. Five temperature peaks, ranging from 1.40 to 1.80 keV, which occurred near the edge of this $\pm 15\text{-}\mu\text{m}$ hotspot region, may be associated with localized mixing induced by hydrodynamic instability³³. The characteristic scale of the peaks was approximately $5\ \mu\text{m}$; however, the peaks could actually be smaller than $5\ \mu\text{m}$ because the measurement system could not distinguish structures smaller than $5\ \mu\text{m}$ when its spatial resolution was $5\ \mu\text{m}$. A significant electron temperature gradient^{32,34} was observed from the center to the edge. The average temperature of the edge region of $5\text{--}10\ \mu\text{m}$ width was approximately 0.52 keV, which was approximately 41% of that at the center. This relatively low electron temperature edge region was also observed at the National Ignition Facility using the polar diagnostic instrument manipulator⁸. All electron temperature results were averaged along the line of sight. However, considering the 3D bowstring spatial integration, the self-emission of ablator remnants was expected to have the maximum influence on electron temperature measurements at the edge region of the hotspot in time-integrated X-ray images and could be primarily responsible for the relatively low electron temperature of the edge region.

Because temperature peaks could correlate with localized anomalous mixing amounts, a reasonable estimation method was proposed to extract the mix amount in the temperature peak regions of the hotspot based on the high-spatial-resolution electron temperature distribution depicted in Figure 6(h). According to Figure 6(h), the average electron temperature of the five temperature peaks can be extracted as T_{e_peaks} . The areas of all the peaks, pure DD regions, and entire hotspot can be extracted in Figure 6(h). Thus, the corresponding volumes V_1 , V_2 , and V_3 were obtained in the 3D-sphere approximate hotspot. Considering volume-weighted factors, Eq.(9), which expresses the obtained average electron temperature of the entire hotspot $T_{e_hotspot}$, was established:

$$T_{e_peaks} V_1 + T_{e_DD} V_2 = T_{e_hotspot} V_3, \quad (9)$$

where T_{e_DD} is the average electron temperature of the pure DD regions in the hotspot, excluding the peaks. The value of T_{e_DD} was then obtained. According to Eq. (1) and the energy band from 5.40 to 15.00 keV of the detecting channel, the spectral radiative power per unit volume was expressed by Eq.(10):

$$F \propto \frac{Z_i n_e^2}{\sqrt{T_e}} \exp\left(-\frac{h\nu}{k_B T_e}\right) \approx \frac{Z_i n_e^2}{T_e^{N_1}}, \quad (10)$$

where Z_i denotes the ionization degree and N_1 is a constant. In Eq. (10), $\exp(-\frac{h\nu}{k_B T_e})$ is fitted using an allometric model from $h\nu/k_B = 5.40\ \text{keV}$ to $h\nu/k_B = 15.00\ \text{keV}$, yielding $\exp(-\frac{h\nu}{k_B T_e}) \approx C_2 T_e^{N_1}$, where C_2 is a constant. Then, using the approximate isochoric model of the hotspot, we obtained $n_e \propto 1/T_e$. Thus,

$$F \propto \frac{Z_i}{T_e^{N_2}}, \quad (11)$$

where N_2 is a constant. As shown in Figure 6(e), the X-ray image is smooth over 5.40–15.00 keV, with no emission peaks corresponding to the measured electron temperature peaks. Thus, we obtained Eq. (12):

$$Z_i \propto T_e^{N_2}. \quad (12)$$

Hence, in the mix, Z_i is expected to change by $(T_{e_peaks}/T_{e_DD})^{N_2}$. Another expression related to the atomic ratio k of C, the ablator material in the mix region, is Eq.(13):

$$Z_{i_mix} = (1 - k)Z_{i_D} + kZ_{i_C}, \quad (13)$$

where Z_{i_mix} denotes the degree of ionization in the mix; $Z_{i_D} = 1$ is the degree of ionization of D (equal to that of H); and $Z_{i_C} = 6$ represents the degree of ionization of C when the average electron temperature is approximately 1.43 keV. Thus, $k = 19.20\%$ is obtained, indicating a relatively high mix amount in the temperature peak regions of the hotspot. The extraction

of the finely resolved local mix amount benefits from the high-resolution diagnostic techniques adopted in this work, compared with low-resolution techniques^{2,8,9}.

Finally, we discuss the uncertainties in the hotspot electron temperature measurement experiments that arise from three sources. The first stems from the influence of the KB microscope reflectivity η_{KB} fluctuation, with values approximately 0.77% and 5.08% for the two channels. The second originates from the response coefficient of the X-ray IP P_{IP} and is approximately 6.65%²². The third arises during the experimental calibration of the filter T_{Filter} and is approximately 0.5%. Consequently, the uncertainties of the PSL distributions $u_f/f = \sqrt{(u_{\eta_{KB}}/\eta_{KB})^2 + (u_{P_{IP}}/P_{IP})^2 + (u_{T_{Filter}}/T_{Filter})^2}$ in Figure 6(e) and (f) from the two channels are 6.71% and 8.38%, respectively. Thus, the uncertainty of the ratio K_e , $u_{K_e}/K_e = \sqrt{(u_{f_1}/f_1)^2 + (u_{f_2}/f_2)^2}$, as shown in Figure 6(g), is 10.74%. Hence, the total relative uncertainty in the hotspot electron temperature results (Figure 6(h)) was obtained by combining the uncertainty u_{K_e}/K_e with the numerical calculation derived from the relationship curve presented in Figure 3, which yields a range of 8.10% to 40.10%. The maximum and minimum uncertainties occur at 0.86 and 0.31 keV, respectively, which correspond to the lowest point of the relationship curve shown in Figure 3 and largest gradient of the curve, respectively. Hence, the optimization method for decreasing the uncertainty aimed to increase the gradient of the relationship curve and shift the position of the lowest point to the lower electron temperature by increasing the separation of the two energy bands for the two detection channels, decreasing the range of the high-energy band, and increasing the range of the low-energy band. In addition, the reflectance distribution of the KB microscope exhibited small variations; however, their effects were included in the uncertainty of the KB microscope reflectivity $u_{\eta_{KB}}/\eta_{KB}$. Finally, the electron temperature results agreed with the 1D simulation results.

Conclusion

A 5- μm -resolution 2D hotspot electron temperature detection technique was first developed in ICF research and currently exhibits the highest spatial resolution. A 1D model was constructed, and its calculation results were consistent with the experimental results. The results of the high-resolution and quantitative hotspot electron temperature distribution provided essential physical information about the temperature quantitative distribution and were used to benchmark the implosion simulation parameters. We identified several spatially nonuniform electron-temperature domains within the hotspot, with spatial and positional uncertainties constrained to $\pm 2.5\mu\text{m}$, which would be undetectable via low-resolution diagnostic techniques including pinhole imaging. Furthermore, the mixing fractions associated with these finely resolved peak-temperature regions were quantified using the high-spatial-resolution electron temperature distribution. These results directly demonstrate the presence of spatially heterogeneous, localized mix features embedded inside the hotspot. This study provides a robust foundation for the further precise measurements of the electron density and mix distributions, which is significant for characterizing the ignition performance. Furthermore, it proposes an optimization method to improve the data-extraction accuracy. Finally, it pioneers the diagnosis of high-spatial-resolution hotspot electron temperature distributions and expansion of the functionality of the KB imaging system^{15,17} to electron temperature measurements.

In the future, we aim to use three channels of the KB microscope, each with different filters, to detect the electron temperature. The filters will be optimized to transmit the appropriate X-ray energy ranges, thereby enabling the construction of three theoretical curves relating the intensity ratio to the electron temperature. Furthermore, the separation angle between the KB channels and target will be reduced to less than 1° to minimize the impact of the field-of-view geometry differences between the channels³⁵. In addition, we aim to extract three ratio distributions. Then, the sole electron temperature may be determined without repeated iterations. Furthermore, we aim to replace the X-ray IP with an X-ray framing camera with spectrum-response calibration, thereby obtaining high time-resolved and space-resolved electron temperature distributions. The high-spatial-resolution electron temperature distribution of the hotspot can facilitate the accurate determination of the electron density distribution and localized mix amount. As the hotspot pressure can be derived from the hotspot radius, ion temperature, and neutron yield, the electron density can be obtained based on the isochoric model and subsequently used to determine the precise global mix amount.

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Author contributions statement

Jianjun Dong, Kuan Ren, Junfeng Wu, Chuanshen Yin, and Yunsong Dong conceived the idea, analyzed the problems and the data, and wrote the main manuscript. Guoli Ren, Ke Lan, Zhiwei Lin, Longfei Jing, Longyu Kuang, Hang Li, Guibin Zhai, Huiyue Wei, Jianhua Zheng, Wei Jiang, Wei Liu, Wanli Shang, Zhenghua Yang, Yingjie Li, Pin Yang, Jin Li, Feng Wang, Lifeng Wang, Jiamin Yang, and Yongkun Ding helped in analyzing the problems and improving the manuscript. All authors presented here reviewed the final manuscript and agreed to the contents.

Additional information

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