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Letter

Non-equilibrium between ions and electrons inside hot spots from National Ignition Facility experiments

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Abstract

The non-equilibrium between ions and electrons in the hot spot can relax the ignition conditions in inertial confinement fusion [Fan et al., Phys. Plasmas 23, 010703 (2016)], and obvious ion-electron non-equilibrium could be observed by our simulations of high-foot implosions when the ion-electron relaxation is enlarged by a factor of 2. On the other hand, in many shots of high-foot implosions on the National Ignition Facility, the observed X-ray enhancement factors due to ablator mixing into the hot spot are less than unity assuming electrons and ions have the same temperature [Meezan et al., Phys. Plasmas 22, 062703 (2015)], which is not self-consistent because it can lead to negative ablator mixing into the hot spot. Actually, this non-consistency implies ion-electron non-equilibrium within the hot spot. From our study, we can infer that ion-electron non-equilibrium exists in high-foot implosions and the ion temperature could be ~9% larger than the equilibrium temperature in some NIF shots.

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Hot-spot physics is important for ignition target design in inertial confinement fusion (ICF). Fusion reactions of deuterium and tritium (DT) within the hot spot take place at several keV to overcome the Coulomb barrier between fusing nuclei, and the hot spot needs to have sufficient areal density to enter a self-heating regime. In the laser-driven central hot-spot ignition [1–3], a spherical shell of cryogenic D-T fuel, coated with a low-Z ablator, is imploded nearly isentropically either directly by lasers or indirectly by X-ray radiation converted from laser beams to a high velocity, so that the fuel is highly compressed under the spherical convergent effect, and an ignition hot spot with an areal density of ~0.3 g/cm^2 and a temperature of ~5–10 keV is formed in the center, triggering a burn of the main fuel and resulting in a significant thermonuclear energy gain. Within the hot spot, it is commonly assumed that ions and electrons are in equilibrium. This assumption restricts the target optimizations in design and may lead to non-consistency in the experimental diagnostics as well.

Fan et al. have proposed an ion-electron non-equilibrium model for relaxing the central hot-spot ignition conditions [4]. In this model, the ions and electrons are assumed to have separate temperatures, i.e. T_i and T_e, and T_i is higher than T_e. Within the hot spot, fusion reaction is proportional to T_i^α with $\alpha \approx 2-3$, therefore a higher ion temperature can obviously enhance the hot-spot nuclear reactions. On the other side, the hot-spot energy leaks due to electron thermal conduction and

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electron bremsstrahlung are proportional to $T_e^{7/2}$ and $T_e^{1/2}$, respectively. Therefore a lower electron temperature remarkably reduces the hot-spot energy leaks. The above two effects result in an enlarged ignition region in the hot-spot $\rho R-T$ space. According to the theory in Ref. [4], when the ion temperature becomes 10% higher than the equilibrium temperature, the required hot-spot ρR would reduce from ~0.32 g/cm^2 to ~0.17 g/cm^2 at a fixed equilibrium temperature of 5 keV. In this letter, we point out that obvious ion-electron non-equilibrium exits in ignition-scale capsule implosions and it can be observed in the National Ignition Facility (NIF) high-foot experiments. We will firstly discuss the thermal equilibration between ions and electrons, and then show the non-equilibrium phenomenon via simulation of an ignition-scale capsule implosion, and finally give an analysis of ion-electron non-equilibrium in the NIF high-foot experiments.

When ions and electrons have separate temperatures T_i and T_e, their thermal equilibration rate becomes important. For DT plasmas, the ion-electron energy inter-exchange via collisions is normally described by

$$\frac{dT_i}{dt} = -\frac{T_i - T_e}{\tau}, \quad (1)$$

$$\frac{dT_e}{dt} = \frac{T_i - T_e}{\tau}, \quad (2)$$

where τ is the relaxation time between ions and electrons. For a non-degenerate (ideal) plasma where the electrons have Maxwellian distribution [5],

$$\tau_{\text{ideal}} = 100\frac{T_e^{3/2}}{\rho \ln\Lambda}, \quad (3)$$

where τ_{ideal} and T_e are in units of ps and keV, respectively; the plasma density ρ is in the unit of g/cm^3; and $\ln\Lambda$ is the Coulomb logarithm. In ICF, the DT plasma is highly compressed and the electrons have Fermi–Dirac distribution which makes the ion-electron relaxation time longer than the non-degenerate case. In this case [5],

$$\tau = \tau_{\text{ideal}}\frac{2[1+\exp(-\mu/kT_e)]F_{1/2}(\mu/kT_e)}{\sqrt{\pi}}, \quad (4)$$

where μ is the chemical potential and $F_{1/2}(\mu/kT_e)$ is Fermi–Dirac integral. Fig. 1 shows the ion-electron relaxation time for densities ranging from 1 to 50 g/cm^3 and temperatures from 1 to 10 keV. We see that the ion-electron relaxation time is of tens of picoseconds when the temperature is >5 keV. In ICF, the deceleration phase of an ignition-scale capsule implosion lasts ~200–300 ps, and it lasts about ~100 ps since the capsule center has a density >10 g/cm^3. This implies that the ion-electron relaxation time within an ignition-scale hot spot is comparable to the deceleration phase, which creates preconditions for a non-equilibrium hot spot.

To study the non-equilibrium phenomenon, we considered a typical capsule used in the NIF [6] and its implosion dynamics was performed by our LARED-S code. The capsule cross-section is shown in Fig. 2(a). The CH ablator is 195 μm thick, and the DT ice is 69 μm thick. A high-foot radiation drive is shown in Fig. 2(b). A well tuned radiation temperature is plotted by red solid line, which has three steps, with an

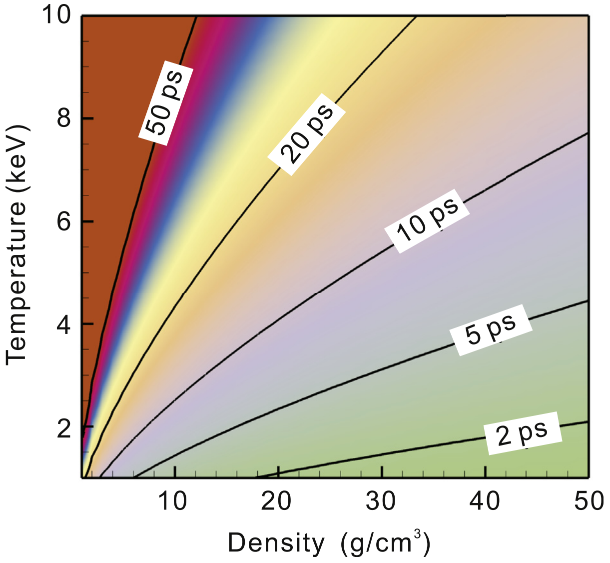

Fig. 1. Ion-electron relaxation time for different densities and temperatures.

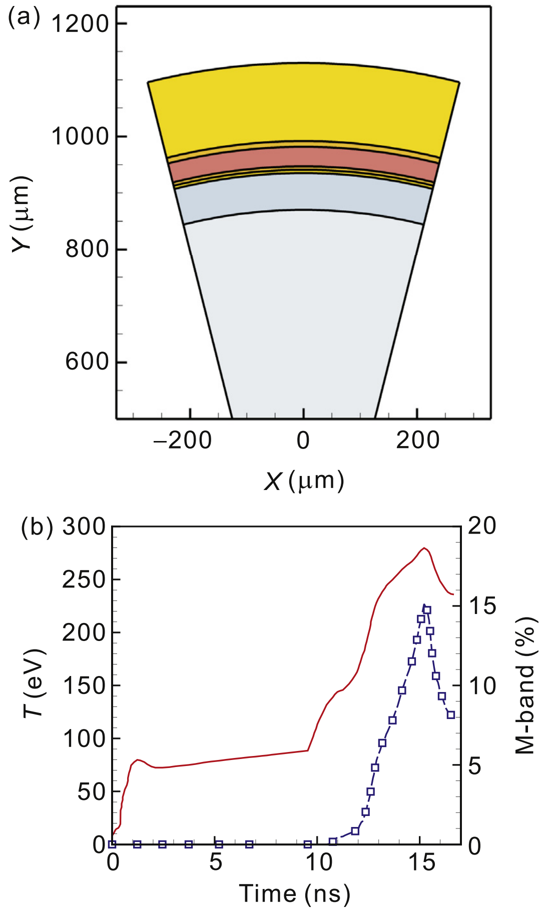

Fig. 2. (a) Sketch of the ignition capsule, (b) radiation drive pulse and M-band fraction.

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