Strategic plan to demonstrate heatwave-driven laser fusion with fast ignition scheme

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We had revealed an efficient heating mode "heatwave" that appears in laser fusion with the fast ignition (FI) scheme. The heatwave heating was experimentally confirmed at the Institute of Laser Engineering (ILE) using high-power lasers, nanosecond lasers for implosion (GEKKO-XII) and a petawatt kJ laser for heating (LFEX). The conditions for entering the heatwave mode and its characteristics (temperature, propagation velocity, etc.), were clarified for plasma and laser parameters. By employing the scaling, a high-efficient laser fusion for inertial fusion energy (IFE) was designed. ILE is currently refining GEKKO-XII and LFEX laser systems by introducing state-of-the-arts optical devices. In this talk, we overview our achievement last a few years and the strategic plan for the proof-of-principle experiment of heatwave-driven laser fusion toward IFE with the refined laser systems.

Laser fusion has entered a new phase of IFE research after achieving ignition at the National Ignition Facility (NIF) [1]. NIF is targeting gains as 20+ over the next decade by improving MJ laser/target performance and deepening burning physics. An IFE fusion reactor design that uses less laser energy and employs a simple and robust scheme is an urgent issue.

We study the FI scheme, which separates the implosion and heating processes, in a laser fusion research project, FIREX-NEO. The key to the success of FI as a fusion reactor lies in how efficiently the heating laser energy is coupled to the core plasma for ignition, and how the laser energy is minimized as IFE reactor. We had designed a reactor-scale laser fusion with total laser energies about a hundred kilojoules for direct laser implosion of a sold ball which contains DT fuel and for the core heating with PW lasers. Our design with "heatwave" mode which appears with the heating laser intensity much greater than 10^{19} W/cm^2 with duration over picosecond is a paradigm shift from the conventional FI. In the conventional design, the laser intensity must be fine-tuned to optimize fast electrons' energy around MeV for efficient drag heating, requiring relatively low laser intensity ($I \sim 10^{18}$ W/cm^2) which results inefficient coupling as the laser absorption location is farther from the core.

We have performed a series of basic experiments with GEKKO-XII and LFEX lasers and demonstrated the efficient heating by heatwave [2]. In this experiment, see Fig.1 (a) and (b), GEKKO-XII lasers imploded a solid ball attached on the top of Au cone to densities about 20 times of solid > 10g/cc, and the dense core plasma was heated to an electron temperature of over keV, confirmed by X-ray spectroscopy, by irradiating LFEX laser (1kJ/1ps) with intensity greater than 10^{19} W/cm^2. The total laser energies used in this experiment was only 5kJ for implosion and heating. To deepen the

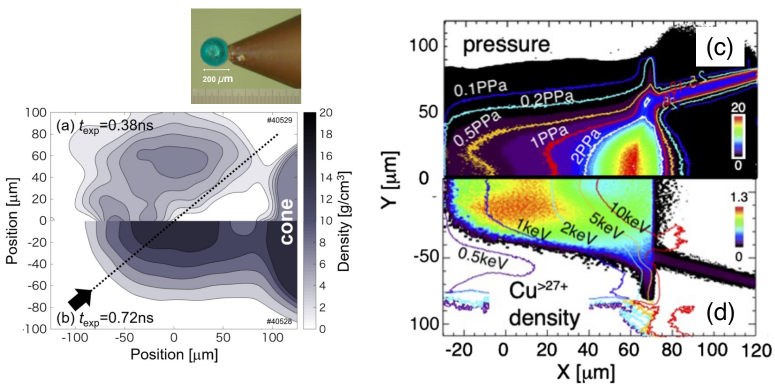

Fig. 1: A photo of FIREX target. GEKKO-XII laser implosion dynamics diagnosed by x-rays at t=0.38ns (a) and t=0.72ns (b). The simulated electron energy density [PPa] (c) and electron temperature [keV] [2].

understanding of "heatwave" FI physics and design a high-gain laser fusion, we have comprehensively studied the propagation, absorption, and energy transport processes of heating laser beams in imploding plasmas with a help of multi-dimensional plasma simulation code, PICLS [3], which cooperates with Coulomb collisions, ionizations, and radiations. PICLS simulations identified that the efficient heating with laser-core coupling efficiency ~10% was achieved by the heatwave driven from hot plasma interface established by the high laser photon pressure (> 2 Peta-Pascal) as shown in Fig.1(c) and (d).

With a governmental support, ILE is currently upgrading GEKKO-XII and LFEX lasers by introducing state-of-the-arts optical devices. GEKKO-XII lasers with higher energy of 6kJ will be converted to 3ω from 2 ω with an accurately tailored pulse profile over 4-order magnitude intensities, which will realize the ideal solid ball implosion to achieve a core density ≧100g/cc. LFEX laser beams will be refined by adapting a plasma electrode Pockels cell to reduce reflected light and double the energy. By realizing four-beam coherent overlapping, LFEX fluence is enhanced by a factor of 10 or more, which is strong enough to drive and sustain the heatwave for core heating and initiating fusions.

We show here the heatwave laser fusion designed by PICLS for the refined GEKKO-XII and LFEX lasers. Figure 2(left) shows the density profile of plasmas by imploding a simple solid ball target (no cone), computed by a radiation hydro-code PINOCO [4]. The plasma consists of deuterons, tritons, and electrons, and its core density is about 200g/cc, surrounded by dense plasma with exponential density profile. Figure 2(a) shows a snapshot (at 3.3ps, injecting ~3kJ heating laser) of plasma density profile (purple line), ion average energy (black), and bulk electron temperature (red) at the center. PW laser, a peak intensity 10^{21}W/cm^2 and a spot diameter 10μm, is irradiated continuously from the left boundary. The photon pressure reaches 10 Peta-Pascal and pushes the plasma surface. We saw clear transition of fast electron properties (not shown here) after forming the steep interface, namely, the electron energy drops significantly and thus the interface was heated efficiently via drag heating to the temperature above 10keV. The heatwave then starts to propagate at about the same temperature toward the core with a speed of 7% of light speed as shown in Fig. 2(a). After a few picoseconds later (injecting ~6.5kJ heating laser), the heatwave reached the core, causing the electron temperature in the core to rise and the ion temperature to increase thermally to the same level of the heatwave, see Fig. 2(b).

In this overview talk, our strategic plan for the proof-of-principle experiment of heatwave laser fusion for reactor scale is presented and the design of a compact IFE.

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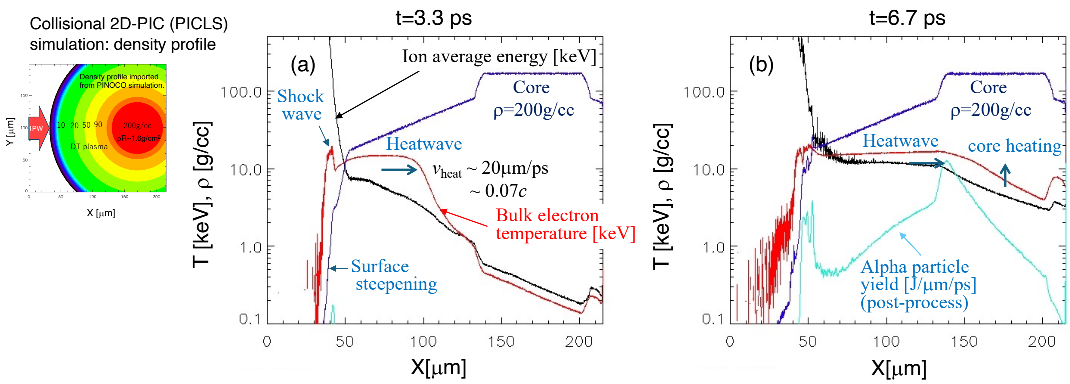

Fig. 2: Collisional PIC (PICLS) simulation of fast ignition. (a) Snapshot of plasma density [g/cc] (purple), ion average energy [keV] (black), bulk electron temperature [keV] (red), and alpha particle yield [J/μm/ps] (cyan) at 3.3 ps. (b) the same plot at 6.7 ps.