

CONFERENCE PRE-PRINT

STRATEGY TO DEMONSTRATE HEATWAVE-DRIVEN LASER FUSION WITH FAST IGNITION SCHEME

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Abstract

An efficient heating mode “heatwave” that appears in laser fusion with the fast ignition (FI) scheme had been revealed. The precursor of heatwave heating was experimentally detected at the Institute of Laser Engineering (ILE) using two high-power laser systems, namely, 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 refurbishing GEKKO-XII and LFEX laser systems by introducing state-of-the-arts optical devices. The paper overviews the achievement last a few years and the strategy for the proof-of-principle of heatwave-driven laser fusion toward IFE in the experiment applying the refined laser systems.

1. INTRODUCTION

Laser fusion has entered a new phase of IFE research after achieving ignition with a scientific gain > 2 (fusion energy is more than twice that of laser energy.) at the National Ignition Facility (NIF) [1]. NIF is the indirect drive, see Fig. 1 (left), 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 fast ignition (FI) scheme, which separates the implosion and heating processes, see Fig.1 (right), in a laser fusion research project, FIREX-NEO, at ILE. The FI scheme could be much more efficient than the indirect drive scheme. The key to the success of FI as a fusion reactor lies in how efficiently the heating laser energy is coupled to the fuel plasma to initiate the fusion burn and 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 solid ball which contains DT fuel and for the core heating with PW lasers with about 10% of the implosion laser energy. Our design with “heatwave” mode which appears with the heating laser intensity much greater than 10^{20} W/cm² with duration over picoseconds is a paradigm shift from the conventional electron driven 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 ($I < 10^{19}$ W/cm²) which results inefficient coupling as the laser absorption location is far from the core and inevitable large divergence (> 90 degrees) of fast electrons.

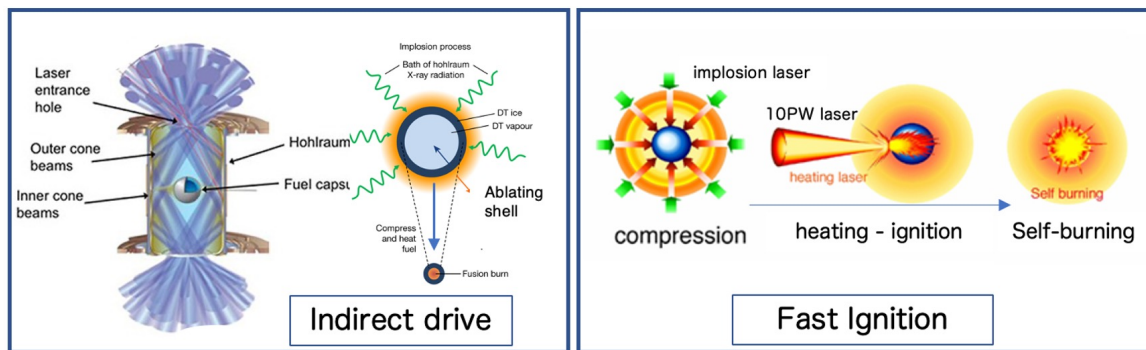


FIG. 1 (left) Indirect drive as central ignition. (right) Fast ignition.

2. FIRST EXPERIMENTAL DEMONSTRATION OF CORE PLASMA HEATING WITH HEATWAVE

We have performed a series of basic experiments with GEKKO-XII and LFEX lasers and demonstrated the efficient heating of imploded core plasma by drag heating and heatwave [2, 3]. In this experiment, see Fig. 2 (a) and (b), 6 beams of GEKKO-XII lasers (green) imploded a solid ball placed on the top of Au cone to densities about 20 times of solid $> 10\text{g/cc}$, 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 less than 5kJ as total for implosion and heating. The energy density of the core region was achieved to 2 Peta-Pascal (PPa). To deepen the understanding of “heatwave” FI physics, we have comprehensively studied the propagation, absorption, and energy transport processes of the heating phase in the imploding plasmas with a help of multi-dimensional plasma simulation code, PICLS [4], which cooperates with Coulomb collisions, ionizations, and radiations. PICLS simulations, which imported the plasma density profile measured in the experiment, Fig.2 (b) as the initial plasma, identified that the efficient heating with laser-core coupling efficiency $\sim 10\%$ was achieved by the fast diffusion (precursor of heatwave) driven from hot plasma interface [5] established by the high laser photon pressure ($\sim 1\text{ PPa}$) of the heating laser light as shown in Fig.2(c).

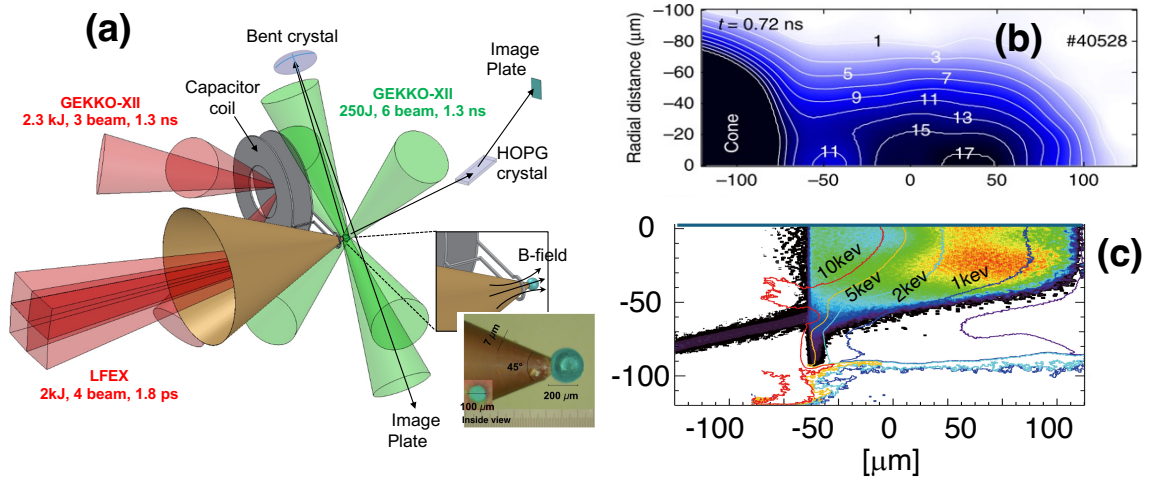


FIG. 2 (a) Experimental setup. Solid ball target attached to a Au cone. (b) Density profile measured at $t=0.72\text{ ns}$ at the maximum compression. (c) 2D-PICLS simulation: plasma density with bulk electron temperature (contour lines) at $t=4.8\text{ ps}$ after LFEX heating.

3. PHYSICS BEHIND THE HEATWAVE HEATING

In pursuing the fast ignition (FI) scheme for achieving ignition and high-gain IFE, several problems must be resolved in the conventional FI approaches. One is the restriction of the heating laser intensity. To make drag heating efficiently with fast electrons, their energy must be adjusted to around MeV levels for the core plasma heating. This inherently limits laser intensity to less than 10^{19} W/cm^2 . At the ignition scale, heating a fuel plasma compressed to about five hundreds of times the solid density to the ignition temperature $> 10\text{ keV}$ requires irradiation with a heating laser with tens of kilojoules. The heating time must be shorter than the core plasma expansion time scale $\sim$ a few tens of picoseconds. For example, with a laser energy of 30 kJ, a spot diameter of 30 microns, and a heating time of 20 picoseconds, the focusing intensity exceeds 10^{20} W/cm^2 , causing the fast electron energy to rise to nearly 10 MeV or higher. Thus, the heating efficiency by the drag heating becomes less efficient. Moreover, the critical density in imploded plasmas is located hundreds of microns from the core center, reducing heating efficiency critically. To avoid this, previous experiments used a gold cone attached to the target to secure the heating laser's propagation path reached the vicinity of the fuel plasma. However, for future IFE, such a gold cone-equipped target is impractical, necessitating a simple method to deliver the heating laser as close to the core as possible.

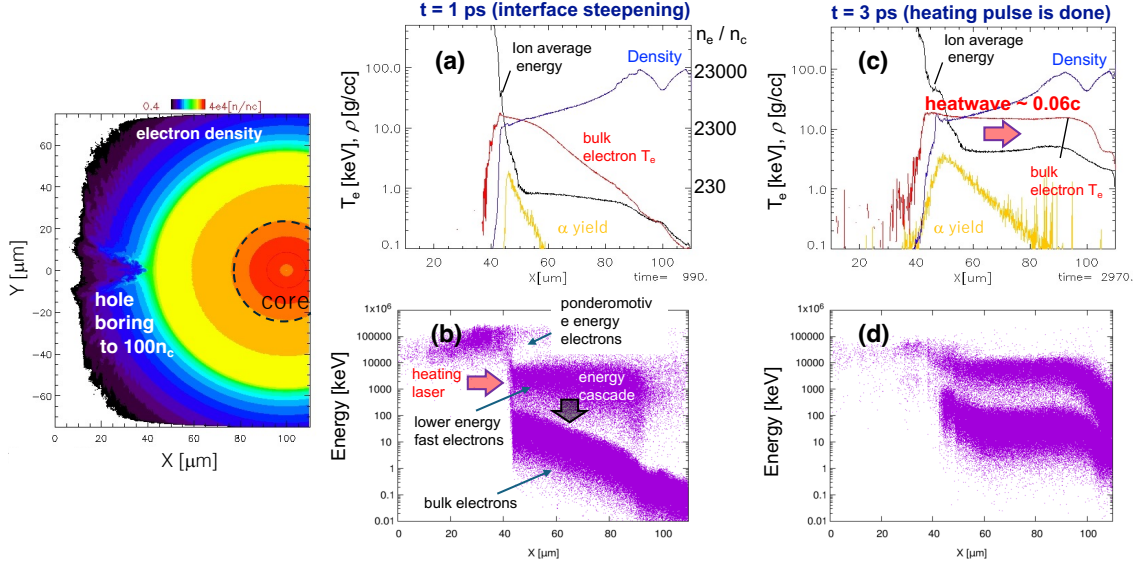


FIG.3 PICLS simulation: (left) Plasma density profile. (a, c) Ion average energy (black), ion mass density (blue), bulk electron temperature (red), and α particle energy density [PPa] at the center ($Y=0$) averaged in $10\ \mu\text{m}$ width. (b, d) Electron phase plot x - ϵ_c . (a, b) is observed at 1ps, during the heating pulse is on, (c, d) after the heating pulse (duration 3ps) is over.

We propose removing these limitations on the heating stage by increasing the laser intensity to extremely high intensities, $> 10^{20}\ \text{W}/\text{cm}^2$, to deliver the laser far beyond the critical density by the relativistic transparency and hole-boring processes. During the propagation of a relativistic intensity laser as it pushes the plasma with photon pressure, the plasma density at the leading edge of the laser pulse becomes extremely steep, causing the light to interact directly with the high-density plasma and be absorbed there. The energies of fast electrons then drop significantly from the energies at the critical density, the so-called ponderomotive scaling energy, by a factor of n_c/n_c , which is the ratio of the electron density at the steepened interface n_c and the critical density n_c . This can explain simply as follow; the relativistic intensity lasers penetrate far beyond critical density into the high-density region, interacting with large numbers of fast electrons. Namely, the number of electrons receiving the absorbed laser energy increases proportionally with density. It has been found that heat transport, i.e., a heatwave, is driven by the simultaneous occurrence of energy transport via these MeV electrons and thermal diffusion from the laser-plasma interface, thereby heating the electrons in the fuel plasma efficiently. The propagation speed of the heat wave depends on the heating laser intensity and plasma density, reaching a few percent of the speed of light. The heating temperature reaches tens of keV, which is optimal for driving DT fusion.

A simulation using a radiation hydro-code, PINOCO [6] and the PICLS code is performed to clarify the heatwave fast ignition. PINOCO simulated that nanosecond laser pulses with their total energy 6 kJ are irradiated uniformly on a solid DT fuel ball with $250\ \mu\text{m}$ radius form a core plasma with density $100\ \text{g}/\text{cc}$ as shown in Fig.3 (left). The core radius is about $10\ \mu\text{m}$ with average density about $90\ \text{g}/\text{cc}$ and ρR of fuel plasma with $50\ \mu\text{m}$ radius is $0.2\ \text{g}/\text{cm}^2$. The density profile was then introduced to the PICLS code and a heating laser pulse with $3\text{kJ}/3\text{ps}$ is irradiated from the left boundary with $10\ \mu\text{m}$ spot diameter and intensity $10^{21}\ \text{W}/\text{cm}^2$. Figs.3 (a-d) show the temporal evolution of ion average energy (black line), ion mass density (blue), bulk electron temperature (red), and α -particle energy density yielded from DT fusion reactions (yellow). Figs (a, b) observed at $t=1\text{ps}$, which is during the heating, show the plasma interface steepening and dense low energy fast electrons $\sim 1\text{MeV}$ flow into the core plasma. The low energy fast electrons cascade their energy to the bulk electrons resulting the bulk electrons temperature increases as diffusion (heatwave). The heatwave reaches to the core region with a speed of 6% of the speed of light with temperature $\sim 20\text{keV}$. The ion average energy also increases due to the energy relaxation with hot bulk electrons, close to 10keV , initiating DT reactions in the dense core region. The total yield, including neutrons, was achieved about 6kJ (gain ~ 0.6) at 6ps.

4. STRATEGY OF HIGH-POWER LASER SYSTEMS AT ILE

With a supplemental budget supported by the government, ILE is currently refurbishing 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 2ω with an accurately tailored pulse profile over 4-order magnitude intensities, which will realize the ideal solid ball implosion to achieve a core density $\geq 100\text{g/cc}$. 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. The refined laser systems meet the parameters simulated in the previous section to demonstrate the heatwave driven laser fusion with fast ignition scheme.

TABLE 1. Refinement of high-power laser systems at Institute of Laser Engineering (ILE)

System	GEKKO XII (12 beams)	LFEX (4 beams)
Energy	> 500 J/beam (> 6 kJ total)	> 500J/beam (> 2 kJ total)
Pulse duration	~ 20 nanoseconds	1.5 – 6 picoseconds
Wavelength	527 nm, 351nm	1053 nm
Pulse tailoring	Tailored pulse with 1:5000 contrast	Main and prepulse contrast > $1:10^{-11}$
Functional	Shot-rate increment, 3D SSD beam	Energy controllability, spatial flatness
Enhancements	smoothing beam, energy balance improvement.	of beam pattern, precise shot beam monitor, post compressor to boost intensity.

5. HIGH GAIN IFE DESING OF HEATWAVE DRIVEN FAST IGNITION SCHEME

This section introduces the design of future high-gain laser fusion system using heatwave driven fast ignition scheme. The imploded core plasma is computed by a radiation hydro-code, PINOCO, with the laser energy of 200 kJ as total. The target was a solid ball with a radius of 500 μm . The core radius is about 25 μm with average density about 400 g/cc and ρR of fuel plasma with 120 μm radius is 1.6 g/cm². The plasma density profile was introduced to the heating simulation PICLS, while the core plasma was modeled as a uniform density of 200 g/cc. A PW laser (kJ/ps) with intensity 10^{21}W/cm^2 and spot diameter 10 μm was irradiated from the left boundary. As discussed in Sec. 3, the heatwave propagated and reached to the core edge at about 10 ps, and the ion average

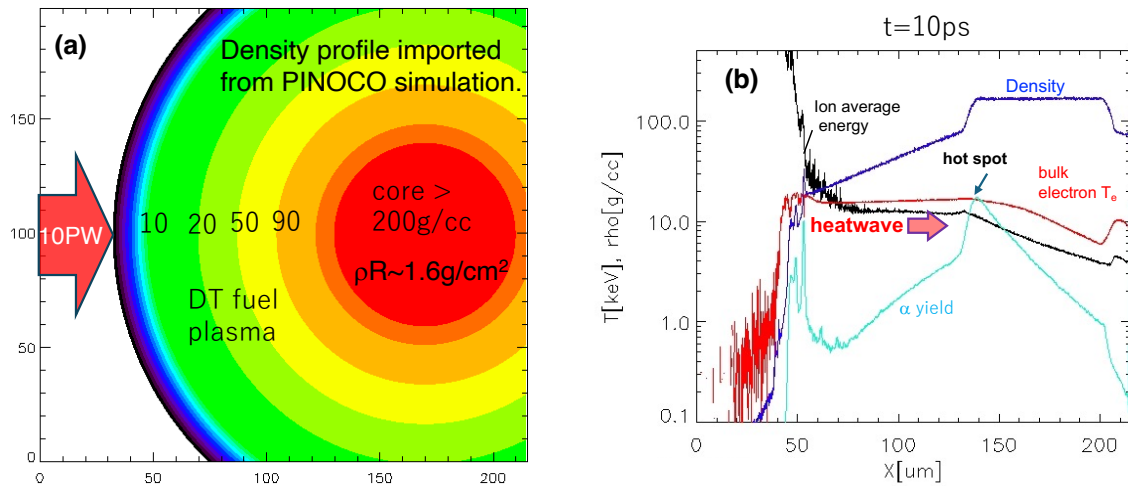


FIG.4 PICLS simulation: (a) Plasma density profile computed by a radiation hydro-code PINOCO with 200 kJ implosion lasers. The peak core density at the edge of the core is about 500 g/cc and the average core density is about 400 g/cc. In the PICLS simulation, the core is modeled as 200 g/cc uniform density. (b) Ion average energy (black), ion mass density (blue), bulk electron temperature (red), and α particle energy density (cyan) at the center ($Y=0$) averaged in 10 μm width at $t=10\text{ps}$. The heating laser pulse is a PW laser (kJ/ps) with intensity 10^{21}W/cm^2 and spot diameter 10 μm . The ion average energy at the core edge reaches 10keV and α yield has a sharp peak, namely, hot spot was formed.

energy increased to 10 keV, initiating DT fusion reactions and forming the hot spot there. We need the further calculation but if the burning wave could be driven in the core, then the gain could be greater than 50 with the total laser energy, including for both implosion and heating, less than 250 kJ.

6. SUMMARY

We present the heatwave-driven laser fusion with fast ignition scheme. The precursor of heatwave heating was experimentally detected at the Institute of Laser Engineering (ILE) using two high-power laser systems, namely, 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 refurbishing GEKKO-XII and LFEX laser systems by introducing state-of-the-arts optical devices. The paper overviews the achievement last a few years and the strategy for the proof-of-principle of heatwave-driven laser fusion toward IFE in the experiment applying the refined laser systems.

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