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Title: Research of laser fusion system based on fast ignition scheme in Japan

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Topics:
・General, including complete IFE concepts
・Target physics and design
・Targets (including manufacture, injection, and survivability)
・Drivers (including driver-specific technologies, e.g. final optics)
・Chamber, including first wall, materials, etc
・Diagnostics

Research of laser fusion system based on fast ignition scheme in Japan

Executive Summary:

We intend to appeal a plan of laser fusion energy research in Japan, based on the fast ignition scheme [1,2] enabling us to seek a high-gain laser fusion design in FIREX-NEO project. We also study its scalability in the ignition-scale laser system like NIF. Our tools to explore the laser-fusion physics such as fuel compression and core plasma heating are multi-kilo-joule lasers, i.e., GEKKO-XII for nanoseconds- and LFEX for picoseconds-interactions, and state-of-the-arts simulation codes: PINOCO (compression), PICLS (heating), and FIMBET (burning). We optimize the target compression with the GEKKO-XII laser for the fast ignition using a solid ball instead of a shell and demonstrate the imploded core plasma heating with the LFEX laser. Diagnostics for the implosion, core heating, and burning will also be developed to visualize the spatiotemporal evolution of the laser fusion dynamics. We utilize the experimental data to benchmark the simulation codes and improve accuracies of the physics models. The codes will be used to depict a high gain design and optimize the laser & target parameters. As an alternative approach for the laser fusion energy, we will develop a high-power & high-repetition (10 kJ/10-100 Hz) diode-pumped-Yb:YAG ceramic-based laser system, which will provide a platform to survey the laser-fusion physics experiment with much higher accuracy statistically improved by orders-of-magnitude more shots than the current glass-laser system. The accumulated data will also boost the benchmark of the codes. For the high-repetition laser fusion platform, we will develop an active laser system and a repetitive target-delivery system in the framework of the research.

1. Demonstration of advanced fast ignition (FI) scheme [3,4]

The FI scheme had been studied for a high-gain laser fusion over a decade. There have been following difficulties in the FI scheme as known in the community; (1) maintain a path of the heating laser in the imploded plasma, (2) implode stably a fuel in an asymmetric geometry due to having a cone, (3) deliver relativistic electron beam to the core, and (4) heat the core efficiently with a coupling efficiency > 20%.

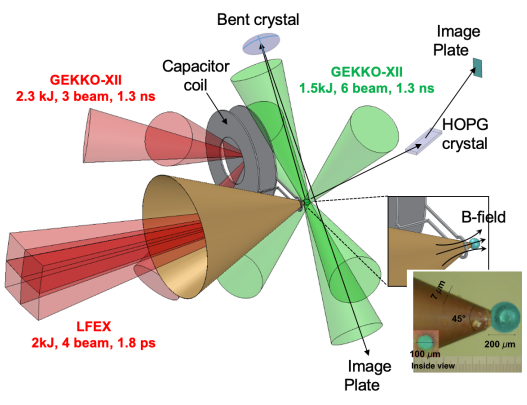

Fig.1 Experimental configuration of the advanced FI laser fusion. A target is a solid ball doped with Cu (2%) to diagnose the heating. 6 beams of GEKKO-XII (green) laser implode the ball. 3 beams of GEKKO-XII (red) laser drive a capacitor coil to induce a strong magnetic field. 4 beams of LFEX (red) laser heat the imploded plasma through the tip-free cone target.

We had solved these difficulties one by one and refined the FI scheme as following; (1) attach a tip-free cone to maintain the heating laser path, (2) use a sold ball instead of a shell to minimize the hydrodynamic instability, (3) apply an external kT-class magnetic field to guide the relativistic electrons, and (4) demonstrate the fast diffusion heating and achieve 20% coupling efficiency from kJ/ps heating pulse to the imploded core plasma.

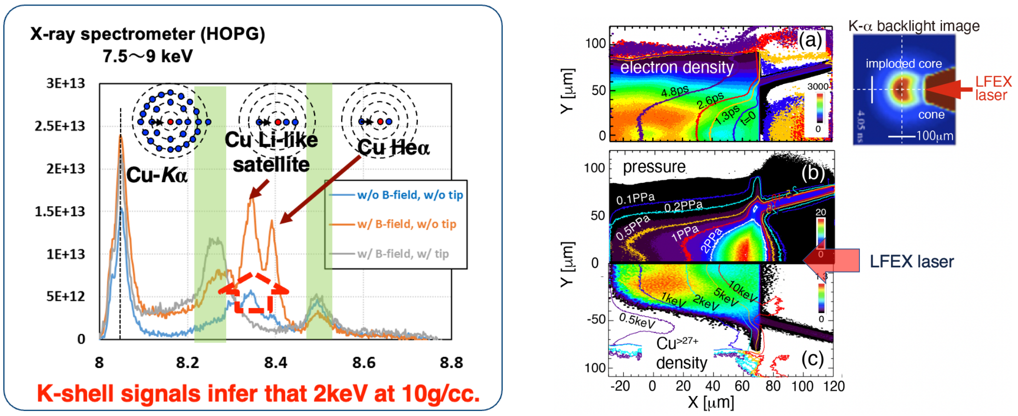

Fig.2 (Left) The K-shell signals from doped coppers. With the heating pulse the hot K-shell signals (Li-like and He-alpha) were increased, especially, with an external B-field. (Right panels) PICLS simulation shows that the imploded core (~10 g/cc) was heated up over keV which supports the experimental observation. The achieved energy density of the core plasma was estimated as 2.2 PPa. The energy coupling efficiency from the laser to the core plasma is ~20% in the simulation.

2. Laser fusion physics and design (Theories and simulation codes)

Laser fusion physics of FI; implosion, heating, and burning, are studied by numerical simulation codes developed by our group: PINOCO for implosion, PICLS for heating, and FIBMET for burning.

PINOCO is a 2-D radiation hydrodynamic simulation code for various laser plasmas, e.g., laser driven implosion for inertial fusion energy, laser ablation, pre-pulse of ultra-intense short-pulse laser, laser manufacturing etc.

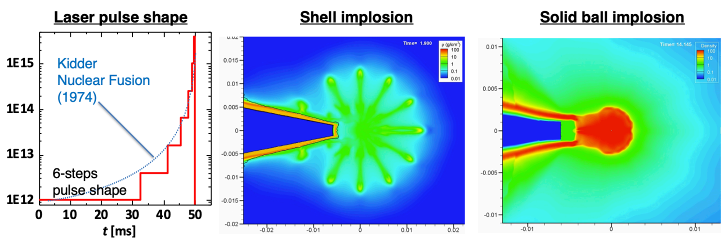

Fig. 3: PINOCO simulation: shell implosion and solid ball implosion. For the solid ball implosion, the pulse shape was 6 steps to be close to the ideal Kidder solution for isentropic compression. Both targets are imprinted same small perturbations to see the resistance of instabilities. It is clearly seen that the solid ball implosion is more stable than the shell implosion.

PICLS is a relativistic particle-in-cell (PIC) code for large density scale plasma produced by intense laser light. PICLS incorporates atomics physics and radiation transport physics. The code can simulate the relativistic laser-plasma interaction, e.g., fast electron generation, ion acceleration, x-ray and gamma-ray radiations, and fast isochoric heating for FI research as shown in Fig.2 (Right).

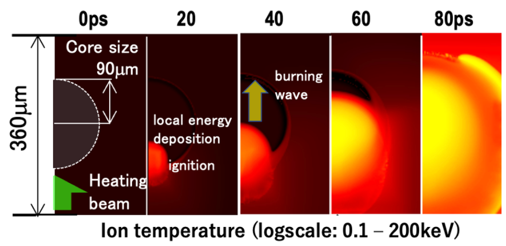

Fig. 4: High-gain design (x 130) by FIBMET. The required conditions for implosion and heating lasers are summarized in the following tables.

FIBMET is a hybrid code for fusion ignition and burning in dense plasmas with multiple energy transport such as relativistic electron and non-relativistic ion beams, fusion-produced charged particle and neutron, and radiation. FIBMET can model fusion ignition and burning in various ignition schemes of inertial fusion, e.g., conventional central ignition, volume ignition, fast ignition, and impact ignition. The following table is a high-gain (x 130) design by FIBMET.

Table1: High gain ignition design

Implosion laser 380kJ	Core radius 90μm	Core density 500g/cc	Areal density 2.4g/cm^2	Core internal energy 20kJ
Heating laser 200kJ/30ps	Laser intensity 3x10^{20}W/cm^2(2ω)	Coupling efficiency 20%	Gain x130	Yield 75MJ

We will benchmark these codes with experimental data and improve the speculation accuracy for the future design.

3. Experimental investigation of fast ignition on NIF for inertial fusion energy (IFE)

The scalability of the FI scheme to the ignition is essential for our IFE development, and we can investigate this on the NIF and ARC. Our strategy consists of “5 steps”: (1) characterization and optimization of relativistic electron beams generated by a multi-pico-second laser beam with energy more than 10 kJ, (2) guiding electron beam by a self-generated magnetic field and/or by externally applied magnetic field, (3) production of ignition-scale high-area-density (ρR > 0.5 g/cm^2) DT fuel core from a solid DT ball irradiated directly by NIF beams (laser-direct-drive may require beam port rearrangement), (4) evaluation of heating efficiency in the integrated experiment on NIF and ARC, and (5) investigation of off-central ignition and non-spherical burn wave propagation with ultra-fast fusion reaction detector.

Relativistic electron beams induced by high-intensity laser can be characterized with a vacuum electron analyzer, Bremsstrahlung x-ray spectrometer, x-ray spectrometer, etc. Heating dynamics can be visualized by using x-ray imaging system coupling with bent-crystal, Fresnel phase zone plate [4], multi-pinhole [5], curved x-ray mirrors, and others with imaging plates, x-ray streak camera, x-ray CCD camera, etc.

The off-central ignition and non-spherical burn wave propagation occur only in the FI scenario. The cutting-edge diagnostics of fusion reaction history will clarify this new physics of blast wave dynamics. We develop a killer tool for that, a neutron detector with a picosecond temporal resolution, which will also be beneficial to diagnose the NIF implosion, as described below.

• Detect a burning history with a ultrafast neutron detector

We propose a pico-second time resolution neutron or γ-ray detector. Figure 5 shows a schematic of the detector. An Electro Optical (EO) reaction is utilized; EO material makes an optical intensity modulation by neutron or γ-ray driven electric field to a chirped laser pulse, then spectrally resolved laser intensity provides neutron or γ-ray time history. In our design, an EO polymer [6] is attached to a small piece of silicon (less than 1 mm), which is attached to an optical fiber and is placed very close to the implosion (typically about 5 mm) center. The expected time resolution is 5 ps including an impulse response of the detector and a temporal broadening of the neutron. This detector can measure the time history of the neutron production in the burning plasma so that we will be able to approach dynamics of the nuclear burning wave physics. The prototype has been developed and tested at ILE [7] so that is ready to be tested at IFE facilities in USA.

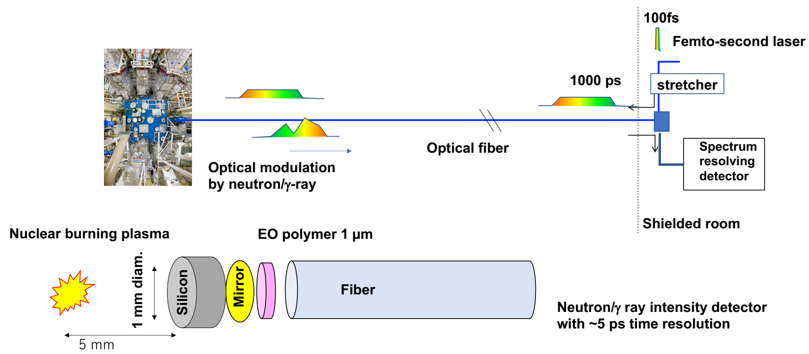

Fig. 5: Schematics of the ultrafast neutron detector.

3. Driver development: Multi-Kilojoule Repeatable Laser System

A promising repeatable laser system producing multi-kilojoule of pulse energy has been designed for realization of the FI-based IFE reactor. Two cultivated core key technologies ensure high reliability of the proposed design. First, an active-mirror amplifier enables 100 Hz repeatable operation at 100 J of pulse energy. Kilojoule energy can be easily obtained for the fuel compression by combining a number of amplifiers into a single beam. So far, all high-energy laser systems used for the IFE studies are a single shot laser, and there is no repeatable laser system in kilo-joule class over the world. Serious bottlenecks for repeatable laser operation are thermal effects caused by large heat loaded in the laser material of the energy amplifier, wave front distortion, induced birefringence, and material fracture. The first application of ceramic active mirror to high-energy fusion laser as a laser amplifier reduces these effects dramatically to enable repeatable operation.

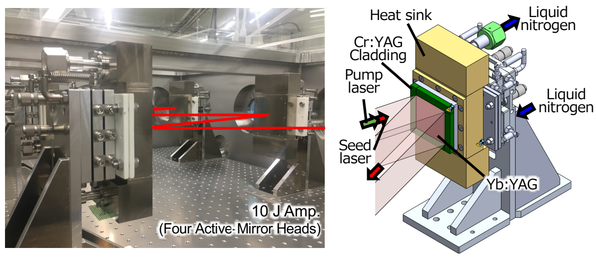

Fig.6: Active-mirror structure and 10 J amplifier.

The active mirror laser amplifier shows, in principle, two excellent capabilities of a high heat removal due to conductive cooling and a low wave front distortion due to the heat flow direction parallel to the laser propagation. The structure is shown in Fig. 6. In addition, a ytterbium-doped YAG (Yb:YAG) ceramic is used as a laser material instead of the conventional neodymium-doped laser glass (Nd:glass). The thermal conductivity of the YAG ceramic is about an order of magnitude higher than that of Nd:glass. Achieving a thermally strong bonding of the ceramic to a metal heat sink, however, is considerably difficult. By developing a novel bonding technology, which is under patent pending, to relax the stress, 7 cm x 7 cm active mirror has been successfully bonded, and 10 J pulse energy has been obtained at 10 Hz with the four diode-pumped cryogenic active mirrors. A higher repetition rate of 100 Hz will be demonstrated and a higher pulse energy of 100 J will be upgraded by enlarging the beam aperture size in the near future.

A promising repeatable laser system at multi-kilojoule has been basically designed for the FI-based IFE reactor development as shown in Fig.7, and roughly consists of two laser systems of a nano-seconds power laser and a pico-seconds petawatt laser. The power laser is a 16 kJ diode-pumped solid-state laser system with 160 beam lines. The 100 J/100 Hz active-mirror laser is the basic module and about half of all the beam lines are used as the implosion laser. The petawatts laser is a Titan-doped sapphire (Ti:sapphire) laser system and the residual half beamlines are used as a pump source of the Ti:sapphire laser after second harmonic generation. The laser system will accelerate both the core plasma research and reactor engineering technology.

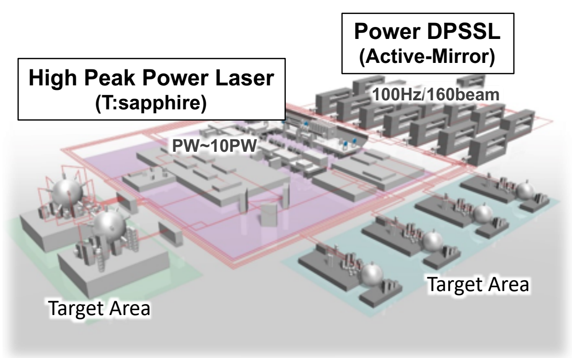

Fig.7: Repeatable multi-kJ multi-PW laser system.

References

[1] M. Tabak *et al.*, "*Ignition and high gain with ultrapowerful lasers*", Phys. Plasmas **1**, 1626 (1994).

[2] R. Kodama *et al*., "*Fast heating of ultrahigh-density plasma as a step towards laser fusion ignition*", Nature **412**, 798 (2001).

[3] S. Sakata *et al.*, "*Magnetized fast isochoric laser heating for efficient creation of ultra-high-energy-density states*", Nat. Commun. **9**, 3937 (2018).

[4] K. Matsuo, N. Higashi, N. Iwata et al., "*Petapascal pressure driven by fast isochoric heating with a multipicosecond intense laser pulse*", Phys. Rev. Lett. **124**, 035001 (2020).

[5] S. Fujioka *et al*., "*Laboratory spectroscopy of silicon plasmas photoionized by mimic astrophysical compact objects*", Plasma Phys. Control. Fusion **51**, 124032 (2009).

[6] A. Otomo et al., "*Organic Electro-Optic polymer devices for ultra-high speed optical communication*", J. Nat. Inst. Inform. & Commun. Tech. **60**, 1 (2013).

[7] Y. Arikawa et al., "*The conceptual design of 1-ps time resolution neutron detector for fusion reaction history measurement at OMEGA and the National Ignition Facility*", Rev. Sci. Instrum. **91**, 063304 (2020).