Progress toward a unified kJ-machine CANDY

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Abstract. To construct a unified experimental machine CANDY using a kJ DPSSL driver in the fast-ignition scheme, the Laser for Fast Ignition Experiment (LFEX) at Osaka is used, showing that the laser-driven ions heat the preimploded core of a deuterated polystyrene (CD) shell target from 0.8 keV to 2 keV, resulting in $5 \times 10^8$ DD neutrons best ever obtained in the scheme. 4-J/10-Hz DPSSL laser HAMA is for the first time applied to the CD shell implosion-core heating experiments in the fast ignition scheme to yield neutrons and also to a continuous target injection, which yields neutrons of $3 \times 10^5$ n/4\(\pi\)sr n/shot.

1. Introduction
To realize the Inertial Confinement Fusion (ICF) power plant, one key issue is a high-repetition-rate laser of kilojoules or greater. Others are the fuel fabrication and high-repetition injection, and ignition-high gain physics. Power plant technology, such as an innovative wall materials, will
need to be developed. We divide the roadmap for achieving a fusion plant into three phases. The zeroth phase involves developing kJ drivers. The first phase is to develop a breakeven machine that uses a 100-kJ driver. Here the fuel is compressed to 100× the solid density or more. The second phase is to demonstrate a commercial reactor. The fuel may be compressed to around 500×.

The zeroth goal is to construct an unified experimental machine CANDY. We have developed a laser-diode-(LD-)pumped laser system HAMA with a repetition rate of 10 Hz[1, 2]. We have done the fast ignition experiment at OSAKA to test this scheme. The Laser for Fast Ignition Experiment (LFEX), the most intense laser in the world, heated the preimploded core of a deuterated polystyrene (CD) shell target and increased the core temperature from 0.8 keV to 2 keV. We also present the target injection and engagement results for the first time[3, 4].

2. Direct Ion Heating of Laser-Imploded Core in a Fast-Ignition Scheme

Figure 1. (A) Neutron TOF signal from Scintillator 1. The sensitivity is 1 count/5.6 neutrons. The solid angle of the detector is $1.4 \times 10^{-4}$ sr. The small neutron peak at 2.45 MeV is thermal one. (b) Spectrum from Scintillator 2. (c) Neutron yields from Scintillator 1 as a function of LFEX + GXII lasers energy. Red dots are the total yields and blue squares are 2.45-MeV fraction of the yield. Vertical error is 16%. Blue line is the calculated implosion due to the thermal fusion effect. Red line is heated by LFEX using a beam fusion model. (d) STAR 1D: Beam fusion (Dotted line) and thermal fusion (solid line) yields versus LFEX intensity on target. Red circle and blue solid squares are the experiments from (b).

LFEX, faced to a core as close as possible, directly heated a preimploded core, enhancing $D(d, n)^3He$-reacted neutron (DD neutron) yields by a factor of 1000 ($5 \times 10^8 n/4\pi$ sr), the best ever obtained in fast-ignition scheme. A CD shell was polarily imploded by two counter beams (1.3 ns-515 J) of the GEKKO XII (GXII) green laser. Then, we focused the 600-J/1.5-ps LFEX laser onto the naked core from the side, vertical to the laser axis. The core temperature increased by a factor of two, i.e., from 0.8 keV to 2 keV. The laser-driven ions (deuteron and carbon+$^6$, too) heated the core. Beam-fusion neutrons and thermal neutrons are simultaneously observed. Figure 1 (a) shows neutron TOF spectrum from the gated Liquid Scintillator (Scintillator 1) at 13.35 m apart from the target in the direction of -69° (right-forward) to the LFEX incidence. The 4\pi sr yield is $5.1 \pm 0.8 \times 10^8$ neutrons against 613-J LFEX + 515-J GXII. The small neutron peak at 2.45 MeV is thermal one with a fraction of 13% or $6.4 \times 10^7 n/4\pi$ sr. The spectral width gives us the core temperature of 2 keV. (b) is the spectrum from Scintillator 2 at 2.5 m in 90° (bottom) to the LFEX axis: the same Shot. (c) is neutron yield from Scintillator 1 as a function of LFEX + GXII lasers energy. GXII 515-501 J. Red dots are the total yields and blue squares are 2.45-MeV fraction of the yield. Vertical error is 16%. Blue line is the calculated
implosion due to the thermal fusion effect. Red line is heated by LFEX using a beam fusion model.

STAR ID hydrocode predicts that deuterons are related to beam fusion and carbons to thermal fusion. (d) is STAR ID results. Dot lines and solid lines are beam-fusion originated and thermal fusion originated yields, respectively. Red circle and blue solid squares are the experiments from (b). This scheme is a potential path to fast-ignite the core at high gain fusion.

3. High-rep. rate fusion using fast heating of a compactly imploded CD core

A 4J/0.4-ns output of a laser-diode-pumped high-repetition laser HAMA is divided into four beams, two of which counter-illuminate double-deuterated polystyrene foils separated by 100 μm for implosion[5]. The remaining two beams, compressed to 110 fs for fast heating, illuminate the same paths. As shown in Figs. 2(c) and (d), we clearly found that the heating pulses heat the imploded core, emitting x-ray radiations >20 eV, and yielding some $10^3$ thermal neutrons. [PRL 108, 155001 (2012)]

4. Laser engagement of 1-Hz-injected pellets, channel borings, and neutrons[4]

Deuterated polystyrene (C₈D₈ or CD) bead pellets, after free-falling for a distance of 18 cm at 1 Hz, are successfully engaged in flight by two counter laser beams from a diode-pumped, ultra-intense laser HAMA[1]. The snapshot of a flying pellet at the instance of engagement by using a $2\omega$ harmonic laser probe is in Fig. 3. The laser energy on the pellet, pulse duration, and wavelength are 0.63 J per beam, 104 fs, and 811 nm, respectively, and the intensity is $4.7 \times 10^{18}$ W/cm². The irradiated pellets produce D(d,n)$^3$He-reacted neutrons (2.45 MeV DD neutrons) with a yield of $9.5 \times 10^4/4\pi$ sr/shot at maximum. The laser is found out to bore a straight channel through the 1-mm-diameter beads. A 10μm-diameter clear open channel is discovered inside the engaged pellet. It is not observed when the beads are attached to any metal support. The results of pellet injection, repetitive laser illumination, and hole boring indicate potentially useful technologies and findings for the next step in realizing inertial fusion energy.

Currently, the observed pellet placement accuracy is such that only 20% of the pellets are within 0.49 mm of the focal point on the laser perpendicular direction, leading to an average hit rate of less than 20%. To produce DD neutrons routinely, the laser intensity is required to be more than $10^{18}$ W/cm². Neutrons more than $1.0 \times 10^4/4\pi$ sr were observed for 2.5 % of these pellets. Improvements in the mechanical function are required to increase the placement accuracy. This result represents a step toward CANDY and the laser fusion.
Figure 3. Snapshot of a flying pellet engagement by laser probe. The probe is perpendicular to the counter beam axis. The two counter beams from HAMA simultaneously irradiate the surface of a falling pellet. CCD camera with an IF filter (394 nm), opened for 20 ns, captures both the probe shadow and self-emissions. The probe is synchronized with the two counter beams.

5. CANDY Concept
The zeroth goal is to construct an unified experimental machine CANDY. DT or DD cryogenic fuel pellet is injected at 10 Hz, to which the counter implosion beams are engaged, followed coaxially by the fast heating beams. Neutron Yield is $5 \times 10^{12}$/shot and energy gain is around 0.7%. A liquid Pb-Li blanket is to catch some mount of neutrons and radiations.

Figure 4. Conceptual Design of CANDY.

| Neutron yield | DT  | $5 \times 10^{12}$/shot |
|---------------|-----|------------------------|
| Implosion laser | Energy | 2 kJ/shot |
|               | Wavelength | 500 nm |
| Heating laser | Energy | 2 kJ/shot |
|               | Wavelength | 1000 nm |
| Gain          | DT   | 0.007 [90 W] |
|               | DD   | $1.5 \times 10^{-7}$ [0.3 W] |

6. Summary
To construct CANDY using a kJ DPSSL driver in the fast-ignition scheme, we pursue the fast ignition and the high repetition laser implosion. We succeed in the continuous target injection and engagement. LFEX results show us the ion contribution to the fast ignition.

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