# Counterbeam fast ignition experiments and the related studies

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## Introduction

The recent key physics of the laser fusion is how to make hot sparks for the alpha burning in the dense core. The fast ignition is expected to form a hot spark even with a non-uniform illumination configuration, such as with a counter-illumination one. A kJ-class mini reactor CANDY, as in Fig. 1(a), is proposed for an engineering feasibility study of the power plant in the counter beam fast ignition scheme fusion. To develop CANDY, we are performing fast ignition experiments and are developing a high-repetitive pellet injection using a high-repetition-rate laser-diode(LD)-pumped laser system HAMA with counter beam configuration[1]. Figure 1(b) shows a roadmap through CANDY to the Power plant.

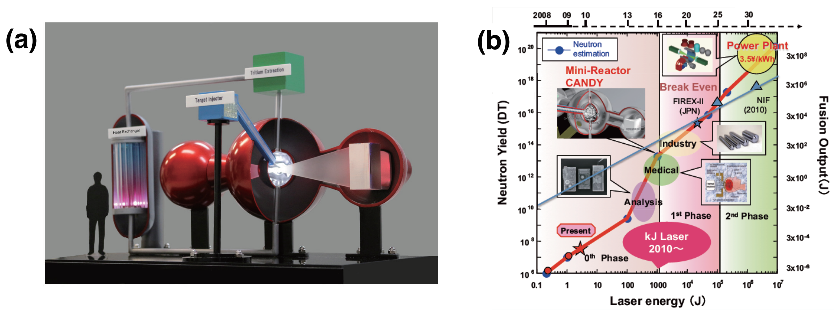


Figure 1: *(a) Image of Mini reactor CANDY. (b) Roadmap through CANDY to the Power plant.*

## Counter-heating of CD Double foils

First, using double-foil CD targets, we have proposed a compact fast ignition experiment to initiate a fusion reaction and clarify its dynamics[2]. A 4 J/0.4-ns output of an LD-pumped high-repetition laser HAMA is divided into four beams, two of which counter illuminate double foils separated by 100 $\mu$m for implosion, as shown in Figs. 2[1]. The remaining two beams, compressed to 110 fs for fast heating, illuminate the same paths. Hot electrons produced by the heating pulses heat the imploded core, emitting x-ray radiations >40 eV and yielding $10^3$ thermal neutrons. Simultaneously the driven shock waves seem to enhance the core emissions.

We discovered that the hot electrons reach the core plasma to emit x-ray radiations, and also that they deposit their energy to deuterons close to the ablation surface, driving a shock wave to heat the core. Once heated, the core plasma maintains a temperature of a few tens eV as long as the core stagnates. PIC simulations suggest that fast heating occurs due to the Weibel instability, as in Fig. 2(g) with on-side illumination and (h) with counter illumination.

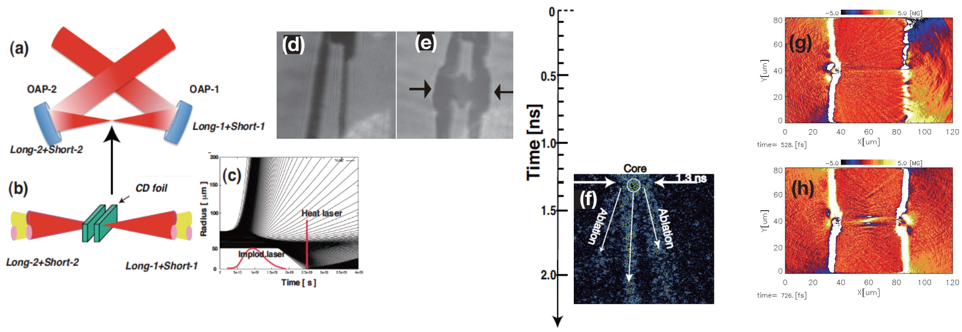


Figure 2: *(a) Counter-illumination scheme and (b) Double foil CD target. (c) STAR 1D hydrodynamic flowchart. Laser:* $5 \times 10^{13}$ *W/cm*$^2$. *2ω 100-fs probe captures the double foil image (d) before the shot and (e) when the imploded plasmas collide with each other and form the core. The gap separation is 100* $\mu$*m. (f) X-ray streak image of heating of the imploding foils at 1.3-ns delay. Three bright points are shown at the central core and at the peripheral (side) area. (g) 2D PIC of magnetic fields for left side(one-side) illumination, and (h) for counter(two-side) illumination.*

## Counter-heating of imploded CD shells

A tailored-pulse-imploded core with a diameter of 70 $\mu$m was flashed by counter irradiating 110 fs, 7 TW laser pulses[3]. Photon emission ( 40 eV) from the core exceeds the emission from the imploded core by six times, even though the heating pulses energies are only one-seventh of the implosion energy. The enhancement of photon emission shows the coupling from the heating laser to the core to be 14 %. Neutrons were produced by counter propagating fast deuterons accelerated by the photon pressure of the heating pulses. A collisional 2D PIC reveals that the two counter-propagating fast electron currents induce mega-Gauss magnetic filaments in the center of the core due to the Weibel instability. The counter-propagating fast electron currents are absolutely unstable and independent of the core density and resistivity. Fast electrons with energy below a few MeV are trapped by these filaments in the core region, inducing an additional coupling. This leads to the bright photon emissions.

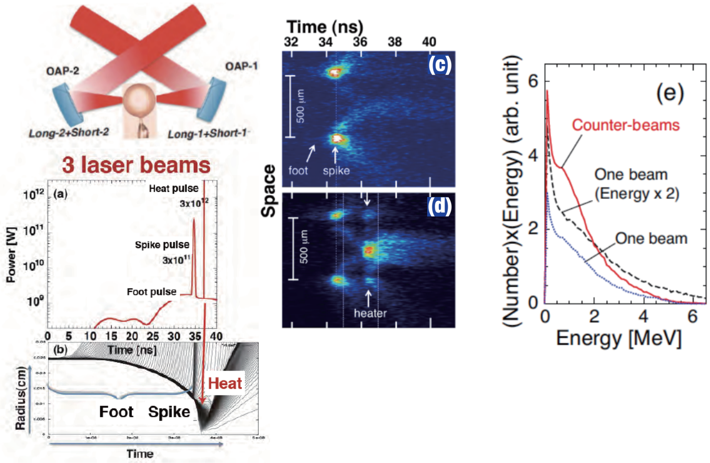


Figure 3: *(a) Tailored pulse chain, (b) Implosion diagram: radius of fluid elements versus time, (c) x-ray streak images without heating pulses and (d) with heating pulses. (e) Electron energy distribution in the core integrated in the region between* $X = 55\,\mu m$ *and* $65\,\mu m$ *at 500 fs. Solid(red), dotted(blue), and dashed(black) lines indicate the data for the cases of counter-propagating beams, one-beam, and one-beam with two times the intensity and the energy, respectively[3].*

## Counter-beam engagement of injected targets

The pellet injection, as well as the repetitive laser illumination, is a key technology for realizing the inertial fusion energy. By counter beam illumination, we have first demonstrated 600× repetitive pellets injection and neutron generation[4]. Figure 4(a) CD bead pellets, af-

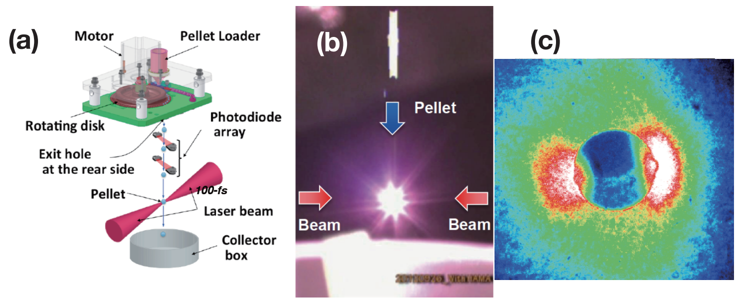


Figure 4: (a)Pellet injection system. Pellet loader stores more than 10,000 pellets. Rotating disk has holes to catch and feed pellets to the exit hole above a laser focal point. Collector box recollects the engaged pellets. (b) Visible emission from a engaged CD bead, and (c) snapshot of pellet at the instance of engagement by 2 $\omega$ harmonic laser probe[4].

ter free-fallen for a distance of 18 cm at 1 Hz, are engaged by the two counter laser beams from laser-diode-pumped ultra-intense laser HAMA[1]. The laser energy on target, pulse duration and wavelength are 0.63 J per beam, 104 fs and 800 nm, respectively. The intensity is $9.4 \times 10^{19}$ W/cm$^2$. They produced D(d,n)$^3$He reacted neutrons (2.45 MeV DD neutrons) with the yield of more than $5.0 \times 10^4/4\pi$ sr. The laser is first found to bore a straight channel throughout the 1 mm-diameter beads. The results of the pellet injection, the repetitive laser illumination and hole boring, are the useful technologies and findings for the next step to realize inertial fusion energy.

## Ion Fast-ignition Experiments using the LFEX at Osaka

By using a single-shot kJ laser with counter beam configuration, we have demonstrated a fast-ignition fusion[5]. Figure 5 shows that the counter (two side) blue beams from the GEKKO XII lasers implode a core, to which then the LFEX ( the red beam) is illuminated as close as possible. We found that the energetic ions heat the core rather than the hot electrons. LFEX illumination has enhanced DD neutron yields by a factor of 1000 ($5 \times 10^8$ n/4$\pi$ sr), the best ever obtained in fast-ignition scheme. $6 \times 10^7$ n/4$\pi$ sr thermal neutrons are observed at the same time, which is also the fast-ignition scheme record. STAR1D hydrocode predicts that deuterons are related to beam fusion. Hot electrons heat the entire core from 800 eV to 1 keV, whereas ions including carbon$^{+6}$ pre-dominantly heat the region 20 $\mu$m from the core surface from 1 to 1.8 keV. The scheme is a potential path to fast-ignite the core at high gain fusion.

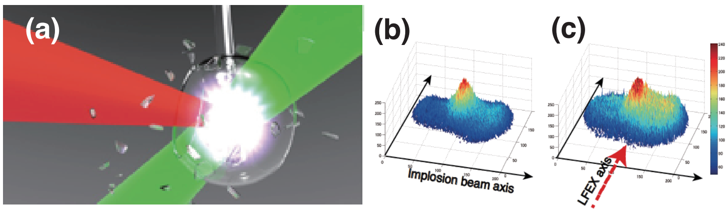


Figure 5: *(a) Two-side GXII beams (blue beams) preimplode a core and then LFEX (red beam) heats ions in the core. (b) X-ray pinhole image of the core before LFEX shot, (c) after shot[5].*

## Conclusion

We proposed two kinds of the core heating. The ultraintense laser driven hot electrons effectively heat the core with the counter beam configuration. The ultraintense laser driven ions heat the core, when the laser irradiates directly the core. The counterbeam configuration must make the fast ignition a potentially fruitful scheme for the inertial confinement fusion.

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