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H. S. Park

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Hye-Sook Park*

Lawrence Livermore National Laboratory, P. O. Box 808,
Livermore, California 94551, USA

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Thermonuclear fusion of hydrogen nuclei into helium is the basic principle under which the Sun generates energy. Duplicating this process in the laboratory will give a new physics regime in the laboratory and is of interest for fusion energy. Laser driven inertial confinement fusion is a possible method for achieving this goal. Recently, for the first time, the National Ignition Facility in Livermore, CA, USA, reported obtaining a higher energy output than the amount of energy input into the targets fusion fuel [1–4]. This was accomplished by a judicious tuning of the laser beam profile to dampen the hydrodynamic instabilities that cause unwanted mixing of the plastic capsule shell into the hydrogen fuel. While this energy output is only small fraction (∼1%) of the total laser input energy and thus far from what would be needed for energy applications, it signals a significant step forward in the understanding of the relevant physics phenomenon that occur under high pressure and high temperatures.

Nuclear fusion happens when the nuclei of two forms of hydrogen fuse together producing a single heavier nucleus of helium, while converting a small fraction of their mass into energy (Fig. 1). An enormous amount of heat and pressure, like that found in the core of the sun, is needed to overcome the Coulomb repulsion between the nuclei. Fusion "ignition" refers to the moment when a controlled fusion reactions outrun the rate of energy losses that cool the fusing region.

Since the 1950s, many scientists have been working to harness nuclear fusion in the laboratory. There are different approaches for achieving controllable nuclear fusion in the laboratory; most promising are magnetic confinement fusion[5, 6] and inertial confinement fusion(ICF) [7, 8]. This article focuses on the ICF approach.

The National Ignition Facility [9] is the most powerful laser system on the planet and is located at the Lawrence Livermore National Laboratory in Livermore, California, USA. It is comprised of 192 laser beams that provide up to 1.9 MJ of 351 nm laser light at 500 TW. The laser amplification system and target chamber span the width of three football fields and is 10 stories tall [Fig 2]. The target chamber is 10 m in diameter and studded with multiple laser and diagnostic ports [Fig 3]. Construction of the NIF began in 1997 and the first full-scale ignition experiments began in 2009. Since then, over 1000 target physics experiments including high energy density science , diagnostic calibration, and implosion experiments have been performed.

Inertial confinement fusion (ICF) attempts to generate nuclear fusion energy by heating and compressing a fuel target, typically in the form of a pellet that contains a mixture of deuterium and tritium. A required condition for ignition is that the deuterium-tritium (DT) fuel be compressed to 1000 g/cm^3 at a pressure of 350 Gbar, and that the central hot-spot be heated to ∼50 million

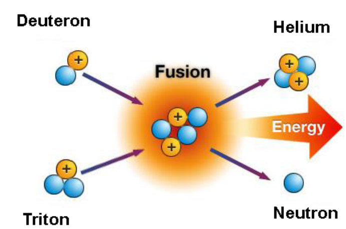

FIG. 1. Nuclear fusion reaction where deuterium and triton fuse into Helium atom and a neutron producing energy from the remaining mass amount.

degrees. The compression is achieved by an implosion, driven inward by pressure resulting from the high velocity outward ablation of the capsule surface material when it is heated either directly by the laser or indirectly by x-rays generated when the laser illuminates a surrounding gold container.

Currently, the ICF program at NIF is primarily focused on the indirect approach. Figure 4 (a) shows the schematic of the ignition experimental platform. Here the NIF laser beams enter a small (∼1 cm in length, 0.575 cm in diameter) hollow, high Z cylindrical can (called a hohlraum) through an opening in the cylinder endcaps. These laser entrance holes (LEHs) are roughly half the diameter of the cylinder. The 96 laser beams enter each LEH at different incident angles to uniformly illuminate the inside the hohlraum. To keep the gold plasma from the hohlraum wall from moving inward too fast the hohlraum is filled with 19 kelvin He gas at 1.6 mg/cm^3 pressure The capsule is held in the center of the hohlraum by a ∼45 nm thick membrane. The capsule is ∼2.2 mm in diameter and consists of CH ablator material ∼195 μm thick some of which (∼50 μm) is doped with 1-2% silicon to block soft x-ray Au M-band radiation. The DT fuel layer is a 69 μm thick single crystal

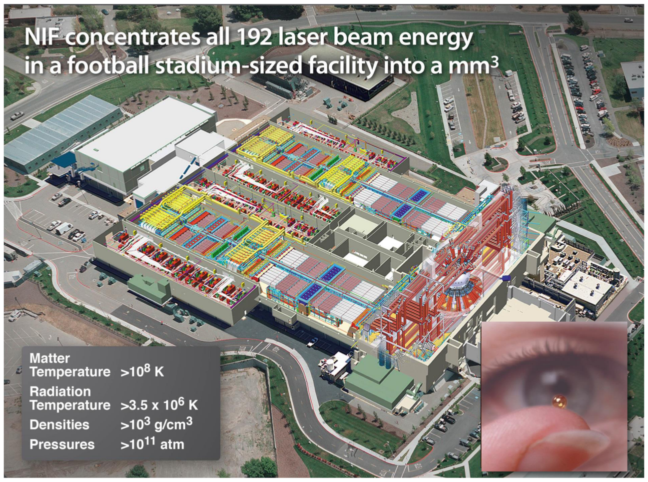

FIG. 2. National Ignition Facility in Livermore, California, USA. The 192 laser beams with up to 500 TW and 1.9 MJ energy can focus into a 2 mm diameter capsule to create high pressure and high temperature environment adequate for thermonuclear ignition environment.

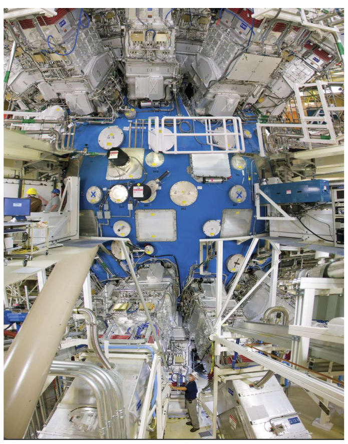

FIG. 3. Ten-meter NIF target chamber (blue section) and some beam ports and diagnostic ports.

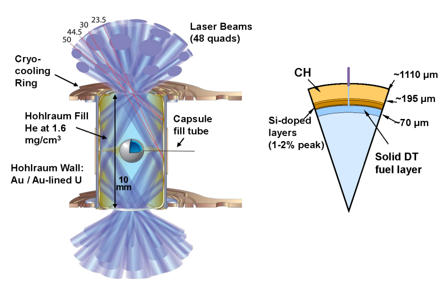

FIG. 4. The Deuterium-titium (DT) experimental platform. The 2 mm capsule is placed at the center of a gold hohlraum. The laser creates soft x-ray oven to ablate the capsule to compress the fuel layer of DT ice and to raise the temperatue of the hot spot at the center [10].

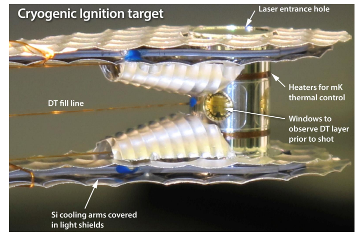

FIG. 5. An assembled DT target.

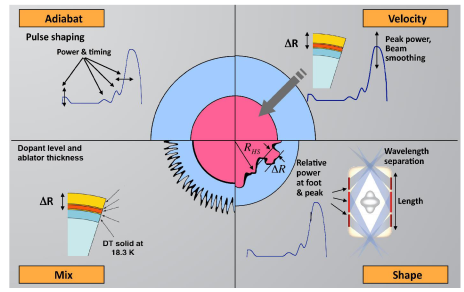

FIG. 6. A schemeatic view of required parameters for ignition. During the implosion, the capsule needs to maintain symmetric shape, high velocity, low adiabat and low mix to achieve ignition [11].

solid that is grown in situ at a cryogenic temperature of 18.3 kelvin. Figure 5 shows an example of the assembled target which includes windows to monitor the DT ice layer thickness and smoothness, thermal control lines and dimpled shields to protect against unconverted laser light.

In order to achieve ignition, four different factors affecting implosion performance need to be addressed: shape keeping the capsule symmetric as it compresses during the implosion; velocity maintaining a high velocity during the ablation process by controlling the peak laser power, controlling beam propagation, and laser energy coupling; mix suppressing cold ablator mix into the central hot spot due to hydrodynamic instabilities; adiabat keeping the entropy low during compression to convert the maximum amount of laser energy into fuel velocity. Each area requires sophisticated laser pulse shaping and an understanding of laser plasma interactions for proper beam propagation, target fabrication, and detailed physics modeling and simulations workable at these high temperature and pressure conditions. There are many review articles containing more details [12, 13].

Numerous DT layered shots have been performed in the past years that concentrated on ideal low adiabat pulse shapes that used a weak first laser pulse, called a low-foot, followed by three subsequent pulses whose timing and level were set to drive the fuel along a low-adiabat (α ~1.5). The adiabat (α) is defined to be the ratio of the fuel pressure at peak velocity to the Fermi degenerate pressure for DT [12]. These experiments achieved high

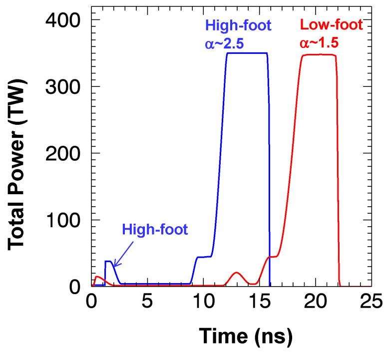

FIG. 7. Pulse shapes for low-foot and high-foot. The high-foot has high power initial starting push to mitigate the hydrodynamic instabilities.

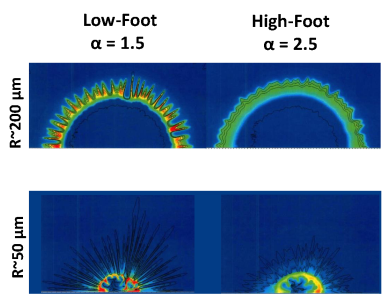

FIG. 8. Simulation results show that the high-foot high-adiabat implosion will reduce the ablation-front hydrodynamic instabilities [2].

implosion velocities and high DT fuel areal densities, ρR, but the measured yields did not compare favorably with the predictions of 1D clean simulations [10].

In order to improve implosion performance, a recent effort, the high-foot campaign, has been concentrating on ways to inhibit mixing[1]. The high-foot shots use higher power in the first pulse (picket) which simulations suggest significantly decrease the growth of hydrodynamic instabilities at the ablation front and fuel interface at the cost of an increase in adiabat. The difference in pulse shape between low-foot and high-foot is shown in Figure 7. Figure 8 shows simulations of the ablation front instability growth in high-foot and low-foot implosions 1) when the capsule has converged to a radius of 200 μm (top panel) and 2) near the bang time at radius of 50 μm (bottom panel). The high-foot is clearly predicted to have significant stabilization of the ablation front instabilities.

The implosion performance is measured by many diagnostics on NIF. The neutron yields and spectrum are measured by the neutron time-of-flight (NTOF) [15], the neutron activation detectors (NADs) [16], and the magnetic recoil spectrometer (MRS) detectors [17]; the hot spot and the fuel shapes are measured by the x-ray framing camera [18] and the neutron imagers [19]; the bang time is measured by an x-ray streak cameras and the

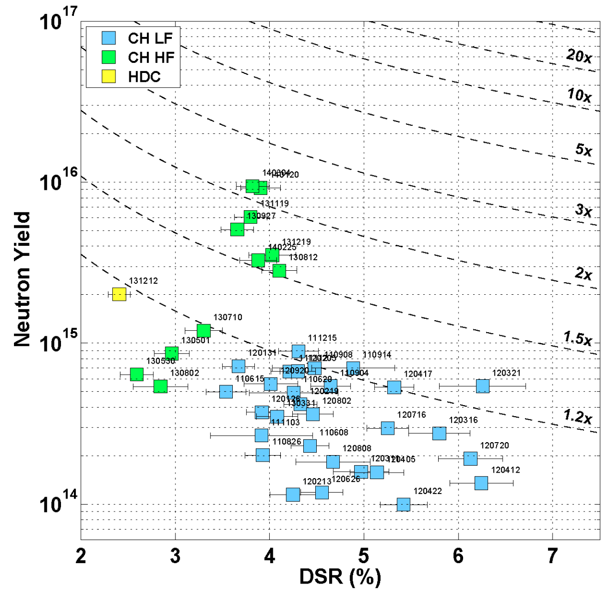

FIG. 9. Implosion perforamance of high-foot DT shots. Near 10^{16} neutron yields are achieved. The blue data points are from the low-foot; the yellow point is done with a diamond capsule and the high-foot data points are marked in green [14].

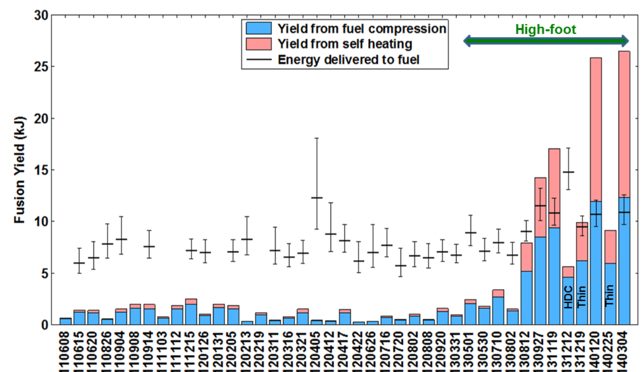

FIG. 10. Alpha heating yield vs. compressional yield of all the DT layered shots. N131212 (marked as HDC) was a diamond capsule shot and N131219 and N140225 used thinner capsule thickeness. The high-foot shots achieved the fuel gain (the energy output from the fuel over the energy input) greater than unity [14].

south-pole bangtime detector [20]. All the experimental measurements are assembled to derive the performance parameters for each shot.

The high-foot shots achieved a factor of 10 increase in performance compared to the low-foot shots. Figure 9 shows the progress in high-foot campaign DT shots where the neutron yield is steadily increasing while maintain moderate down-scattered-ratio (DSR). The DSR is the ratio of the number of neutrons with energies between 10 and 12 MeV over the number of neutrons with energies between 13 and 15 MeV. This DSR signifies the compression of the fuel. The mix of ablator material into was determined to be <100 billionths of a gram. The higher yields of the high-foot shots are mainly attributed to the lower mix achieved through suppression of the hydro instabilities.

Another significant observation is the large contribution to the neutron yield from alpha heating. When the fuel has a high enough ρR to range out alpha particles the energy deposited induces further fusion events creating even more neutrons. Alpha heating is a necessary condition for ignition where a fuel gain (the energy output over the energy input into the fuel) of unity is defined to be the point where the alpha heating yield is equal to the compression yield. In other words, the observed total yield is greater than 2 times the compressional yield (as marked with a dotted line in Figure 9.) As of March, 2014, the high-foot campaign achieved energy outputs from the fuel of up to ∼27 kJ in implosions where the energy input to the fuel was ∼12 kJ as shown in Figure 10.

This work represents a significan advance in our understanding of inertial fusion science; but much more needs to be done. The physics problems under these extreme conditions are very challenging. The project will continue working on improving the high-foot implosion performance and push it as far as possible.

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* park1@llnl.gov. Dr. Hye-Sook Park is a physicist at Lawrence Livermore National Laboratory. She received her Ph. D. from University of Michigan, Ann Arbor, MI. After a post-doctoral work at Univ. of California, Berkeley, CA, she has been working at LLNL since 1987. Her research includes many areas of high energy density physics. She is a Fellow of the American Physical Society since 2010.

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