LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-JRNL-410923

The Dawn of a New Era for High Energy Density Physics

E. Moses, R. McCrory, D. Meyerhofer, C. Keane

February 27, 2009

Optics & Photonics News

The Dawn of a New Era for High Energy Density Physics

E. I. Moses[1], R. L. McCrory[2], D.D. Meyerhofer[2], and C.J. Keane[1]

Lawrence Livermore National Laboratory, Livermore, CA 94550[1]
Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14627[2]

Abstract

The field of High Energy Density (HED) physics is on the verge of a revolutionary event – the achievement of fusion ignition in the laboratory. New laser facilities, the OMEGA Extended Performance (EP) laser at the University of Rochester and the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, greatly extend the range of high energy density (HED) plasma conditions (including ignition) accessible in the laboratory. These conditions are among the most extreme obtainable, with pressures in excess of ~1,000,000 atmospheres. Experiments at these facilities will elucidate fundamental new science in astrophysics, materials science, laser-matter interactions, and other areas. The demonstration of fusion ignition will be the culmination of decades of research, and for the first time, will open the burning plasma regime to laboratory exploration. Ignition will spur the development of advanced options for clean, environmentally sustainable energy.

High Energy Density Physics and Inertial Fusion Ignition

High Energy Density (HED) physics describes some of the most extreme conditions available in the laboratory. They are characterized by pressures ~1,000,000 atmospheres and higher. These conditions are ubiquitous in the natural universe, from supernovae explosions to astrophysical jets to planetary interiors. A new generation of laser facilities places laboratory HED physics on the verge of a revolution.

HED conditions were originally produced terrestrially in nuclear weapons tests. Since the development of high-power, high-energy lasers in the early 1970's, this research has also been conducted in the laboratory. The primary sponsor of this research has been the Department of Energy's National Nuclear Security Administration through its Stockpile Stewardship Program (SSP). Over the past decades, the experimental tools available to study these extreme conditions have expanded and improved, with increasingly energetic lasers and pulsed-power sources (drivers) becoming available. The ability to precisely control the driver interaction with the target is more important than total energy in creating and understanding of the HED plasma conditions.

The Nova laser at Lawrence Livermore National Laboratory (LLNL) (completed in 1984, decommissioned in 1999) and the 60-beam OMEGA laser system at the University of Rochester's Laboratory for Laser Energetics (LLE) (completed in 1995) developed the precision control and flexibility to generate a wide variety of HED conditions. Two new facilities, the OMEGA Extended Performance (OMEGA EP) laser system at LLE (completed April 2008) and the National Ignition Facility (NIF) at LLNL (to be completed March 2009) will significantly extend the range of HED plasma conditions that can be created and studied in the laboratory. The NIF will produce up to 1.8 MJ of 351-nm laser light, a factor of 60 more than any previous laser system. The OMEGA EP laser system includes two high-energy petawatt laser (HEPW) laser beams that will each produce 2.6 kJ of 1053-nm laser light in 10-ps pulses, a factor of ~5 more energy each than any previous short-pulse laser system.

The achievement of inertial confinement fusion (ICF) ignition, expected on the NIF in the next couple of years, will be the culmination of a decades-long quest to demonstrate controlled thermonuclear ignition in the laboratory. The ICF concept for thermonuclear ignition involves the radius compression of a spherical shell of deuterium-tritium (DT) ice by a factor of ~30 with an HED driver. This ice layer is enclosed within a spherical ablator (capsule). The ablator absorbs the driver energy, either directly (direct-drive), or through x-rays obtained by the driver interacting with a high atomic number (Z) material inside an x-ray radiation enclosure (x-ray oven or hohlraum) (indirect drive). As the ablator material is heated, it expands from the target surface. By conservation of momentum (rocket effect), the remaining target material is radially compressed to the extreme temperature and density conditions required to achieve ignition. A hot spot forms in the center of the compressed target with temperatures of ~50,000,000 degrees (C). The deuterium and tritium ions begin to undergo nuclear fusion, D+T → n (14.1 MeV) + He^{2+}(3.5 MeV), where n symbolizes a neutron. If the product of the density in and the radius of the hot spot are greater than 0.3 g/cm^2, the He^{2+}(alpha-particle) energy is deposited in the DT fuel, and a thermonuclear burn wave begins to propagate. The total neutron energy produced depends on the product of the density and thickness of the cold fuel region surrounding the hot spot formed by the compression of the solid DT shell. It is anticipated that in the initial NIF experiments, approximately 1/3 of the cold shell material will fuse, producing a total neutron energy output that is 10–20 times the laser energy required to drive the implosion. The initial ignition capsule will use a Be ablator that contains a ~100-micron-thick DT ice shell. The demonstration of ICF ignition on the NIF is the highest priority near-term HED goal, the “I” in the NIF!

The pursuit ignition on the NIF is a project managed through the National Ignition Campaign (NIC). The NIC is executed by a national team including LLNL, LLE, Los Alamos National Laboratory, General Atomics, and Sandia National Laboratories. It includes the ignition campaign on the NIF and supporting experiments, primarily carried out on the OMEGA laser facility. The goals of the NIC are to carry out the first “credible” ignition attempt in 2010 leading to the development of a robust ignition target for use in stockpile stewardship and other applications by 2012.

The NIF Laser System

The NIF and OMEGA EP laser systems will provide many HED physics opportunities beyond ignition, hither-to unavailable. The NIF (Figure 1) is the largest, most complex, and most expensive optical system ever built. It has 192 beamlines arrayed in 48 quads (4 neighboring beamlines) to irradiate the inside of a hohlraum target with cylindrical symmetry to achieve ICF ignition with indirect drive (the target is shown in Figure 2). The resulting x-ray irradiation will compress the capsule to ignition conditions. The NIF will deliver up to 1.8 MJ of ultraviolet energy in an approximately 20 nanosecond duration pulse, allowing the ignition hohlraum to reach a radiation temperature of ~3,300,000 degrees C (300 eV) driving the capsule to ignition conditions. The system requires exquisite pulse shaping, pointing, and beam-to-beam co-timing and co-pointing. To meet these stringent requirements, new technologies were developed, and the laser system architecture was completely rethought.

The NIF architecture uses a multipass laser system that extracts a much larger fraction of the energy stored in the amplifiers, a major advanced from previous high-energy inertial fusion lasers (See Figure 3). The NIF laser amplifies light from the master oscillator by a factor of 10^{15}. The NIF multipass design is enabled by a number of major technological advances, including development of large full beam aperture (40 cm square) plasma-based optical switches (Pockels cell) and deformable mirrors, 48 stable, high-gain preamplifiers (one for each of 4 beams) capable of high-precision spatial, temporal, and spectral pulseshaping, and a highly sophisticated computer control system capable of monitoring over 60,000 individual control points. The multipass design allows the laser beam to make four passes through the main amplifier while maintaining the laser beam spatial uniformity required for effective amplification and, ultimately, frequency conversion to 0.35-μm light at the target chamber. In common with all large inertial fusion laser systems worldwide, the entire NIF laser from master oscillator to just outside the target chamber operates at the fundamental laser wavelength of 1053 nm. The 351-nm ultraviolet light used in NIF experiments is produced by nonlinear optical frequency conversion of the 1053-nm fundamental harmonic. This conversion is performed by use of full aperture potassium dihydrogen phosphate (KDP) crystals located just outside of the 10-meter-diameter target chamber. This nonlinear frequency conversion scheme was first developed at LLE and is now in use at all major laser fusion facilities worldwide.

The NIF is now physically complete, with all optics installed. The Department of Energy will complete formal certification of project completion by the end of March 2009. The NIF has fired all 192 beams in the infrared and demonstrated an equivalent full system energy of more than 4 MJ of infrared laser energy. LLNL scientists are now in the process of ramping up the laser to full energy (1.8 MJ operation) in the ultraviolet. To date, a maximum total energy of 650 kJ has been demonstrated from 111 beams. A single bundle of 8 beams has been fired a number of times at energy of 78 kJ, equivalent to 1.8 MJ for the entire system. The first 192 ultraviolet target shot occurred on February 26, 2009, with over 80 kJ to target. NIF will commence 192-beam target experiments at 1-MJ energy later this year, with operation at 1.8 MJ expected by 2011. The system has met all of its performance requirements, including producing the high-contrast ignition pulse shape (see Figure 4).

High Energy Petawatt Capabilities at OMEGA and NIF

In the late 1980s Chirped Pulse Amplification (CPA) was developed at LLE. This revolutionary concept allowed the generation of the ultra-high peak power laser systems. By temporally stretching a short pulse before the amplification stages and then using a set of gratings to recompress the pulse to its original duration, orders of magnitude higher peak powers can be produced than would have been possible by directly amplifying the short pulse. The Nova Petawatt laser system used this technique to produce ~600 J pulses in a ~0.5-ps duration. This was the first high-energy petawatt (HEPW) laser system.

The OMEGA EP laser system was completed in April 2008 (Figure 5). It is a four-beamline system with a NIF-based architecture. Each of the four beamlines will deliver 6.5 kJ to target in the ultraviolet. Two of the beamlines can also be operated in an HEPW mode, each producing 2.6 kJ of infrared energy, making the system unique. The OMEGA EP significantly extends the flexibility of the OMEGA laser system (the combined system is referred to as the OMEGA Laser Facility). All four beamlines can be injected into the OMEGA EP target chamber in a variety of combinations of ultraviolet and HEPW beamlines. The two HEPW beams can also be injected into the OMEGA target chamber, significantly extending the flexibility of that system.

The capabilities of NIF will be extended via installation of a HEPW system known as the Advanced Radiographic Capability (ARC). ARC involves modification of one existing group of four beams (Quad) so that it may be operated as a short-pulse CPA laser system or in normal nanosecond-pulse mode. By splitting each beamline into two, up to eight individually controllable HEPW beamlines with separate timing and pointing will be available. Laser pulse widths from 0.75 psec-50 psec and energies of approximately 3 kJ will be available for each beamline. These beamlines can be individually focused onto high-Z targets adjacent to the main ignition target. Backlit images of the target produced using these x-rays are used to make multi-frame “movies” of the target during compression and are critical to diagnosing performance of the ignition target.

Ignition Progress and Future Plans

The achievement of ignition on the NIF will provide opportunities for a wide range of HED physics experiments. The production of ~10^{19} 14-MeV neutrons and extremely high x-ray fluxes from an igniting target will allow hitherto unexplored areas of astrophysical science to be studied. Among these are an understanding of the opacities and evolution of low-density, radiation-dominated photo-ionized plasmas relevant to the accretion disks of compact objects (neutron stars, black holes). The neutron yield will be used for nuclear astrophysics to study reactions rates associated with the C-N-O nuclear fusion cycle in massive stars and rare nuclear fusion reactions that may explain the production of high-Z materials in supernova explosions.

The demonstration of ignition will invigorate the development of ICF for fusion energy production. It is expected that target gains of 100 or more will be required for a viable inertial fusion power plant. The baseline indirect-drive ignition design is likely to have a gain of 15~20. There are several approaches for achieving higher fusion gain. These include alternative hot spot ignition schemes such as direct-drive, indirect-drive with frequency doubled (530-nm wavelength) light, and “fast ignition,” which involves coupling of an intense high-energy short-pulse laser emission to a compressed DT fuel core. These approaches couple more energy to an ignition target on the NIF than the initial ultraviolet laser design, allowing higher target mass and higher gain.

Alternative ignition schemes will be explored on the OMEGA laser facility and transferred to the NIF when they have achieved a sufficient level of maturity. An example of recent progress in the direct-drive concept on OMEGA is shown in Figure 6.

The target performance is plotted in neutron burn-averaged temperature – areal density space. The solid curve shows the locus of hydrodynamically equivalent targets (constant implosion velocity and cold fuel adiabat, α, a measure of the target compressibility). One-dimensional simulations suggest that target design used in the solid curve will marginally achieve ignition with 0.5 MJ of NIF drive energy, greatly increasing the probability of ignition with a 1.5-MJ NIF drive pulse. The various circles show the current and expected progress in direct-drive target performance, with the ultimate goal of achieving direct-drive ignition on the NIF with a 1.5-MJ laser pulse (solid blue circle). The orange point represents the highest cryogenic target performance in 2007, with the red point representing the improvements during 2008, with the goal of producing the conditions represented by the yellow point on OMEGA in the next year or two. This would give confidence in the ability to achieve direct-drive ignition on the NIF in the future. The HEPW capabilities at OMEGA and NIF will allow fast ignition feasibility experiments to be pursued.

Another possibility for energy production is the use of fission-fusion hybrid schemes, where a moderate gain ICF target has its output multiplied by passing through a fission blanket. Edward Teller, Hans Bethe, and Andrei Sakharov originally discussed such schemes. Rapid progress in the development of high-repetition rate lasers and the advent of advanced fusion concepts have made these schemes more attractive. In general, the achievement of ignition at NIF will spur study of inertial fusion and fusion/fission as clean, environmentally sustainable forms of energy.

While the achievement of ignition will be a major accomplishment, the flexibility of the NIF and OMEGA laser facilities, including HEPW beamlines, will allow an exploration of many unique HED states of matter. It will be possible, for example, to investigate the properties of high-Z materials at extremely high pressures (~100,000,000 atmospheres). The HEPW beamlines greatly extend the accessible range of parameters and diagnostics. High-energy ions, electrons, and photons are produced in prodigious quantities in HEPW laser-target interactions, and they can deposit their energy in secondary targets, isochorically heating them before or after they are compressed. The high laser-to- hard-x-ray conversion efficiency allows high-Z materials to be radiographed, enabling, for example, observation of the propagation of shock waves in metals.

Summary

The research opportunities in the fields of HED physics and ICF are poised to expand greatly in the next few years. The completion of the OMEGA EP system at LLE and the imminent completion of the NIF at LLNL will provide unparalleled experimental capabilities and open new scientific frontiers for exploration. In particular, achieving ignition on NIF will spur exploration of energy concepts that could provide limitless, carbon free energy for the future.

References and Resources

Frontiers in High Energy Density Physics: The X-Games of Contemporary Science, Washington, DC, National Academies Press, (2003).

"Frontiers for Discovery in High Energy Density Physics," prepared for the Office of Science and Technology Policy, National Science and Technology Council Interagency Working Group on the Physics of the Universe and prepared by the National Task Force on High Energy Density Physics (July 20, 2004).

Strickland, D. and G. Mourou (1985). "Compression of Amplified Chirped Optical Pulses," *Opt. Commun.* **56**(3): 219̃221.

C.A. Haynam et al., *Applied Optics*, **46**, 3276 (2007)

Lindl, J. D. (1998). *Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive*. New York, Springer-Verlag.

Zhou, C. D. and R. Betti (2008). "A Measurable Lawson Criterion and Hydro-Equivalent Curves for Inertial Confinement Fusion." *Phys. Plasmas* **15**(10): 102707.

E.I. Moses et al., Lawrence Livermore National Laboratory report, LLLNL-JRNL-4066521, "The National Ignition Facility: Ushering in a New Age for High Energy Density Science," Dec. 2008, to be published in *Phys. Plasmas*.

McCrory, R. L., D. D. Meyerhofer et al., (2008). "Progress in Direct-Drive Inertial Confinement Fusion Research," *Phys. Plasmas* **15**(5): 055503.

M. Tabak et al., (2005). "Review of Progress in Fast Ignition," *Phys. Plasmas* **12**(5): 057305.

Figures

Figure 1. NIF aerial view, showing the two laser bays containing 96 beams each, switchyard, target chamber area, diagnostics building, and optical assembly building.

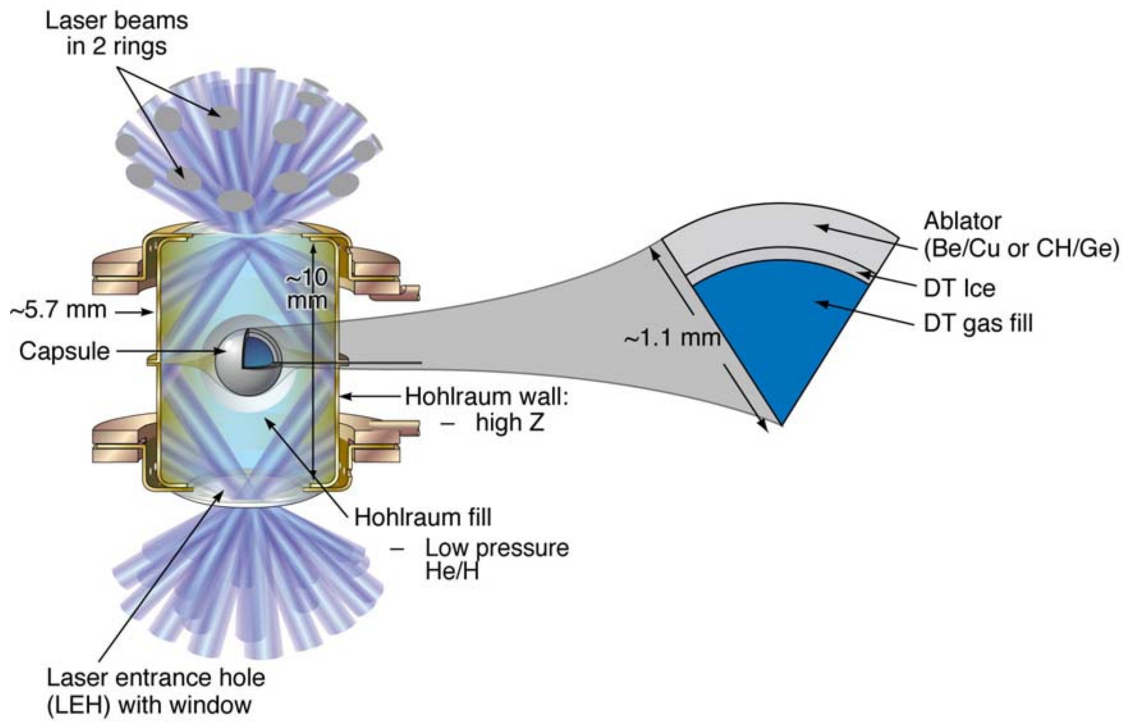

Figure 2. NIF indirect drive ignition target.

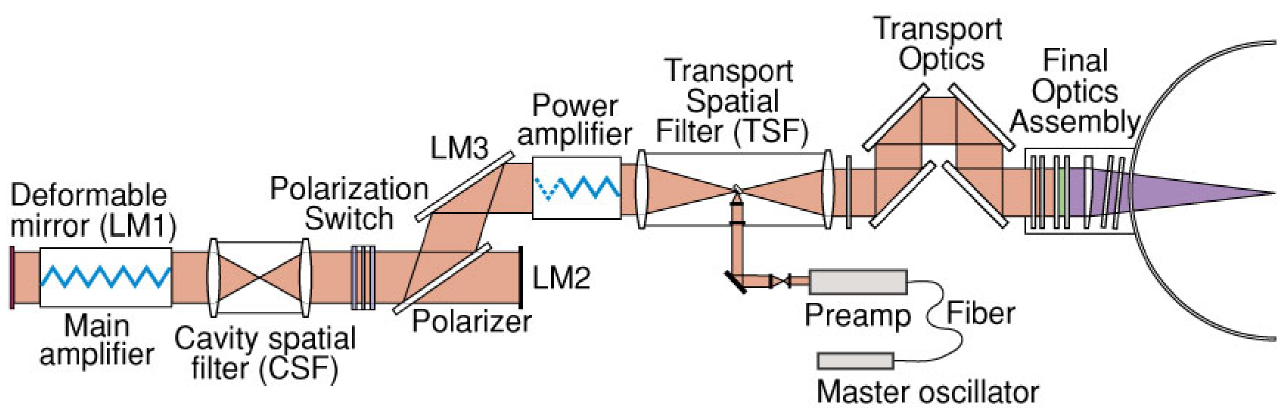

Figure 3. Schematic diagram of an individual NIF laser beamline (192 beamlines total).

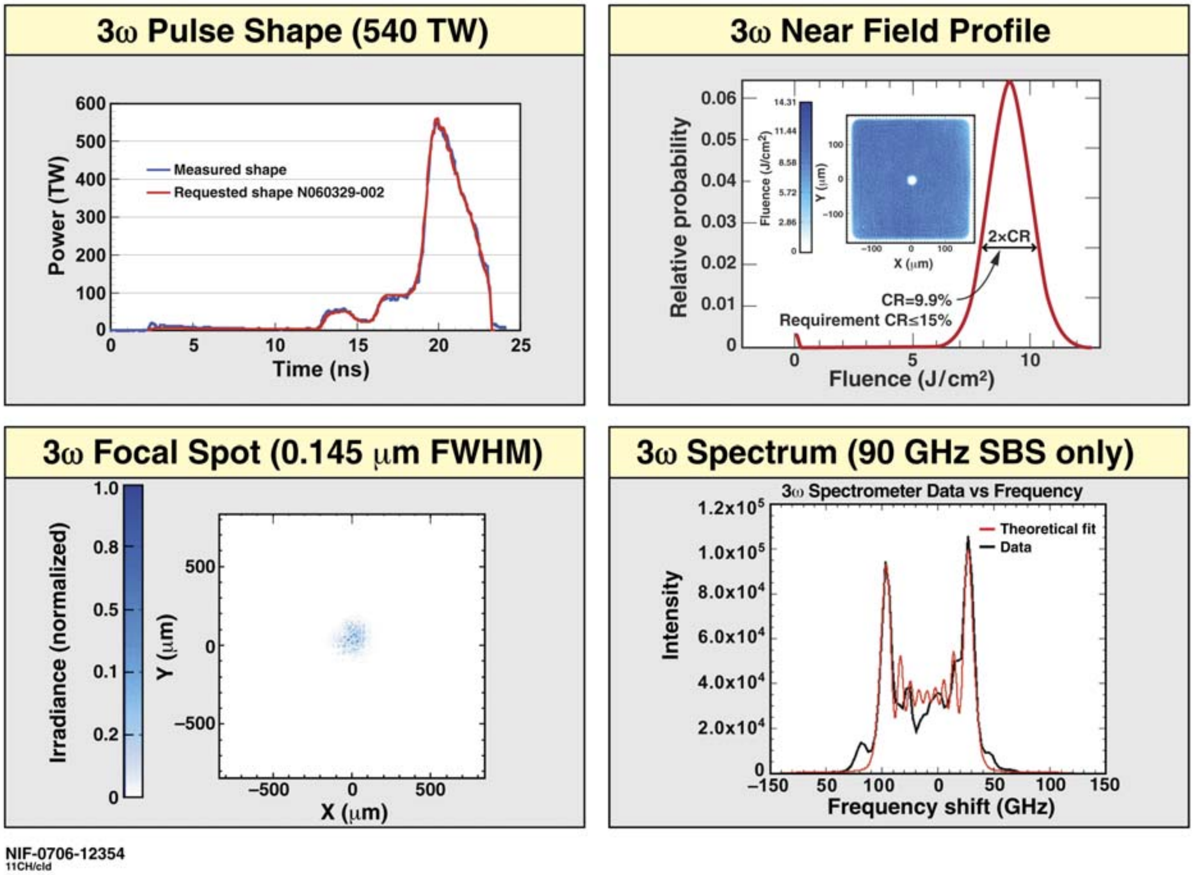

Figure 4. Performance of a NIF beamline in the ultraviolet (denoted as "3ω") in several areas essential for success of the ignition campaign. The NIF laser meets all specifications required for ignition experiments.

Figure 5. Picture of the OMEGA EP beamlines with the target chamber structure seen in the back. OMEGA EP was completed in April 2008.

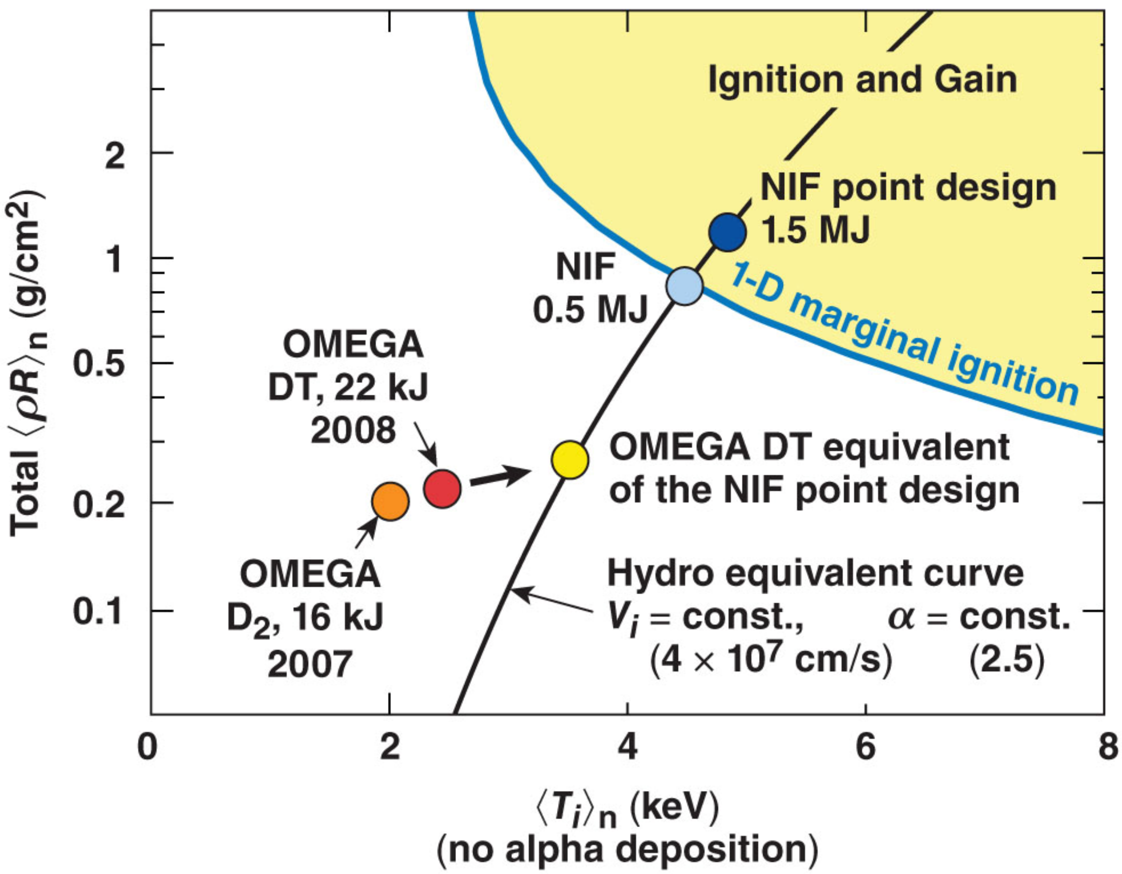

Figure 6. The progress in direct-drive ICF research at LLE. The various circles show the current and expected progress in direct-drive target performance, with the ultimate goal of achieving direct-drive ignition on the NIF with a 1.5-MJ laser pulse (solid blue circle). In 2007, areal densities of ~200 mg/cm^2 were measured with relatively low drive intensities (orange point) and recently with higher implosion velocities and ion temperatures (red point). Similar areal densities hydrodynamically equivalent to ignition implosions on the NIF with marginal ignition energy of ~0.5 MJ are soon expected to be achieved (yellow circle). These OMEGA experiments give confidence in the ability to achieve direct-drive ignition on the NIF in the future.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.