LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-CONF-484536

The National Ignition Facility: Status and Progress Towards Fusion Ignition

E. Moses

May 20, 2011

15th International Conference on Emerging Nuclear Energy Systems (ICENES)
San Francisco, CA, United States
May 15, 2011 through May 19, 2011

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

THE NATIONAL IGNITION FACILITY: STATUS AND PROGRESS TOWARDS FUSION IGNITION

E. I. Moses

Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94450; moses1@llnl.gov

The National Ignition Facility (NIF), the world's largest and most energetic laser system, built for studying inertial confinement fusion (ICF) and high-energy-density (HED) science, is operational at Lawrence Livermore National Laboratory (LLNL). A primary goal of the early experimental campaign on NIF is to create the conditions necessary to demonstrate laboratory-scale thermonuclear ignition and burn with gain. NIF experiments in support of indirect-drive ignition began late in FY2009 as part of the National Ignition Campaign (NIC) effort to achieve fusion ignition. NIC is a multi-institution partnership between LLNL, General Atomics, Los Alamos National Laboratory, Sandia National Laboratory, and the University of Rochester Laboratory for Energetics (LLE). NIC also includes a variety of collaborators from universities, national laboratories as well as international collaborators. To date, all of the capabilities to conduct implosion experiments are in place with the goal of demonstrating ignition in the laboratory and developing a predictable fusion experimental platform. The results from experiments completed so far are encouraging and show promise for the achievement of ignition. Capsule implosion experiments at energies up to 1.3 MJ have demonstrated laser energetics, radiation temperatures, and symmetry control that scale to ignition conditions. Of particular importance is the demonstration of peak hohlraum temperatures near 300 eV with overall backscatter less than 15%. Important national security and basic science experiments have also been conducted on NIF. Successful demonstration of ignition and net energy gain will be a major step towards demonstrating the feasibility of Inertial Fusion Energy (IFE) and will focus the world's attention on the possibility of IFE as a carbon-free, practically limitless energy option. This paper describes the unprecedented experimental capabilities of NIF and the results achieved so far on the path toward ignition, for stockpile stewardship, and the beginning of frontier science experiments. The paper will also address plans to transition NIF to a national user facility, providing access for researchers in the international high energy density science field.

I. Introduction

The National Ignition Facility (NIF) located at Lawrence Livermore National Laboratory (LLNL) is the world's largest laser facility for Inertial Confinement Fusion (ICF) research. NIF is the first laser system designed to obtain ignition and thermonuclear burn of deuterium-tritium filled ICF capsules.[1] High-powered, high-energy lasers such as NIF and other facilities around the world can compress and heat material producing unique states of matter and unique radiation environments in the laboratory. Such studies are of interest for High Energy Density Science (HEDS) supporting NIF missions in national security, energy security, and fundamental science.[2] Ignition on NIF will not only support the national security mission, but will be the next step in demonstrating the viability of fusion as a source of clean energy production.

NIF experiments on indirect-drive ignition began late in 2009 as part of the National Ignition Campaign (NIC). The approach to ignition uses indirect drive with a cryogenic-filled capsule inside of a hohlraum made of high atomic number materials.[3] Experiments have begun to study the four major control variables for ignition: symmetry, fuel adiabat, shell velocity, and mix. Initial results have demonstrated that newly developed techniques can observe and control the effects of the different variables individually and together. Symmetric implosions have been demonstrated in 1.3-MJ experiments with good absorption and low fast-electron preheat. Cryogenic layering of the DT fuel has been demonstrated, and the first experiments using these layers have been performed. In addition to the ignition campaign, HEDS experiments have begun as part of NIF's transition into a national user facility.

Successful demonstration of ignition on NIF will be an important achievement in realizing the potential of fusion as an energy source. A Laser Inertial Fusion Energy (LIFE) effort has begun for developing the science and technology needed to leverage ignition for fusion power. Its basis is a power plant conceptual design using available technologies. An aggressive development program has been identified that could potentially realize

a demonstration power plant within a twenty year horizon.

II. NIF Facility

The NIF is a stadium-sized facility housing a 192-beam Nd:glass laser for ignition experiments. The facility, shown in Fig. 1, consists of two laser bays, a control room and the target area, as well as two switchyards and four capacitors bays. The NIF Project started in 1995 and was successfully completed in March 2009. NIF has been operational for over two years, primarily performing physics experiments for ignition. NIF has also performed experiments for HEDS science, x-ray effects, and other national security missions as well as for fundamental science. So far, it has executed over 200 target experiments that have resulted in a number of peer-reviewed publications.

The laser is designed to deliver 1.8 MJ of frequency converted 0.35-μm light to a target with pulse lengths up to 33 ns. The beams irradiate the target in two cones from the top and bottom for indirect-drive implosions of ICF capsules. The beams pointing to the target have been demonstrated with 60 μm rms accuracy. Power balance, important for symmetric implosions, has been demonstrated to be 3% at peak powers. Both pointing and beam balance meet specification requirements for ignition experiments. Ignition physics experiments have been completed with up to 1.3 MJ of laser energy on target. Laser experiments have demonstrated beam line performance for operating at 1.8 MJ.[4] The plan is to increase laser energy during the next year to perform 192-beam experiments with 1.8 MJ of 0.35-μm light.[5]

A number of new diagnostics have been added for ignition and HED experiments. Over 40 diagnostics have been commissioned and fielded in the facility. Diagnostics measure scattered optical light, X rays, and nuclear products from the fusion reactions. These diagnostics can have spatial resolution of 10 μm with sub-hundred-picosecond time resolution for measuring the dynamics of the implosion. An example of a new diagnostic is the South Pole Bang Time (SPBT), shown in Fig. 2, which measures the x-ray flash from the stagnation of the implosion, viewing from the bottom of the target chamber, to 30-ps resolution. This diagnostic was designed and built by LLE and is an example of a multi-laboratory national effort toward obtaining ignition. On the right of the figure are light scattering plates for the Near Backscatter Imager (NBI) that measures the scattered light from outside of the beam solid angle.

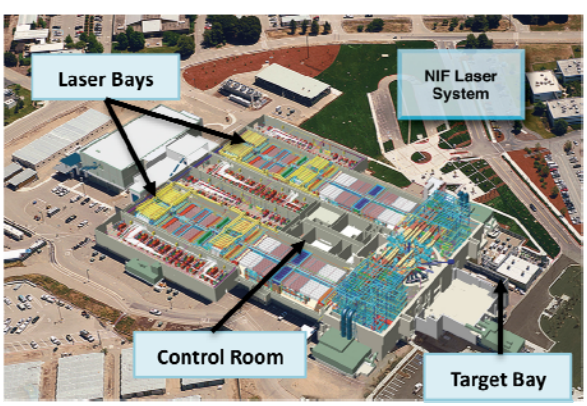


Fig. 1. The NIF facility showing the major areas of the facility with a cut-away drawing of the beam path.

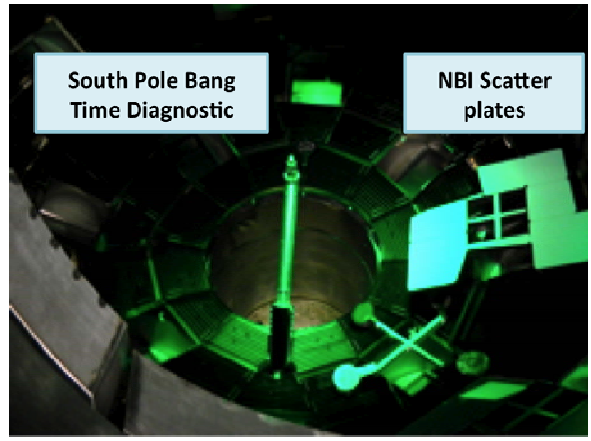


Fig. 2. The South Pole Bang Time Diagnostic measures x-ray bang time of the capsule, viewing from the bottom of the target chamber. The Near Backscatter Imager (NBI) plates are on the right.

During the past year additional hardware has been added to manage the unique conditions produced by ignition experiments, which can contain beryllium (Be) and uranium. Equipment and procedures have been developed to safely handle these hazardous materials. Tritium processing and handling equipment has also been installed to manage the tritium from ignition targets. An ignition shot at full yield of 20 MJ of fusion energy produces nearly 10^{19} neutrons. Shielding and monitors have been installed to ensure safe operation. The facility is now qualified for full yield ignition experiments with hazardous materials.

II. National Ignition Campaign (NIC) - Ignition Progress

The NIC was formed in 2005 as a comprehensive program to provide all of the capabilities for performing ignition experiments, to develop the physics basis for ignition, and to conduct the initial ignition experimental campaign. The goal of the NIC program is to demonstrate a reliable and repeatable ignition platform and develop NIF as a user facility for its multiple missions. NIC is a national partnership between General Atomics (GA),

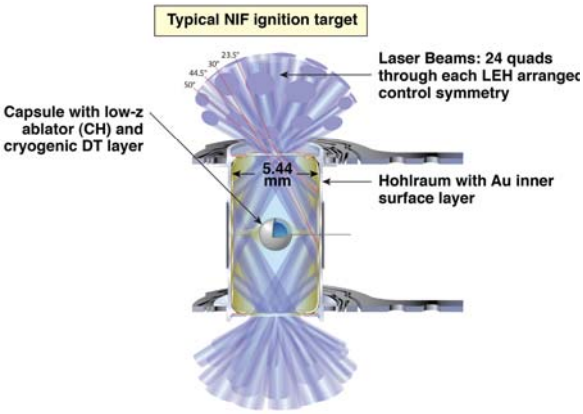


Fig. 3. Schematic of the ignition target design.

LLNL, Los Alamos National Laboratory (LANL) and Sandia National Laboratories (SNL), the University of Rochester Laboratory for Laser Energetics (LLE), and a number of other collaborators including Lawrence Berkeley National Laboratory, the Massachusetts Institute of Technology, the U.K. Atomic Weapons Establishment (AWE), England, and the French Atomic Energy Commission (CEA) in France. The capabilities for performing ignition experiments include development of the diagnostics, targets, target cryogenic system, phase plates and other optics, and personnel and environmental protection equipment. Experiments on OMEGA, NIF and other facilities provide the technical basis for ignition experiments. The initial ignition campaign began in 2010 with the first cryogenic implosion experiments.

Indirect-drive ignition designs use a ~ 2-mm capsule inside of a high Z hohlraum shown schematically in Fig. 3.[3] Initial experiments use a CH capsule, but ignition designs have also been developed for be and high-density carbon capsules. Capsules are filled with the deuterium-tritium fuel (DT) in the form of a cryogenic layer on the inside of the capsule. Present experiments use Au hohlraum, but experiments using U hohlraums for higher efficiency are planned. The beams irradiate the target from top and bottom hitting the high Z wall producing X rays for driving the capsule implosion. The hohlraums are three to six times larger, and the laser energy is over forty times more energetic than those used on previous experiments at Nova and OMEGA.

Experiments on NIF have demonstrated good performance for these ignition-scale targets. Drive temperatures of over 300 eV have been obtained with backscatter of less than 13%. The data is shown in Fig. 4 for the scaling of drive with laser energy showing a T_r of 300 eV for 1.3 MJ of laser energy in an ignition-scale hohlraum.[6] Control of radiation symmetry has been demonstrated both by varying the inner and outer cone beam energy and by varying the wavelength difference to obtain symmetric implosions.[7,8]

NIF experiments have brought new understanding to hohlraum performance. In these larger hohlraums, beam propagation in underdense plasma is more important than for previous experiments on Nova and OMEGA. Energy transfer between crossing beams has been shown to be an important effect, as well as that the transfer can be controlled by tuning the wavelength difference of the two beam cones.[9,10] Underdense plasma production from hohlraum blow off is also a larger part of the energy balance in NIF hohlraums. New models have been developed using a high flux model for the radiating plasma to model NIF results.[11] Agreement with the high flux model and the data is shown in Fig. 4. Both of these phenomena are now included in the ignition target design models.

The first integrated ignition experiment on NIF was executed on September 29, 2010. Fig. 5 shows the cryogenic-layered target as it was being prepared for the experiment. This is the first layered target experiment in a series leading to full-yield ignition experiments. This first experiment used a capsule filled with a mixture of tritium/hydrogen/deuterium (THD). The experiment successfully integrated all of the facility capabilities including the laser, the cryogenic target system, the array of diagnostics and the infrastructure required for ignition demonstration. All 192-laser beams fired, delivering over 1 MJ of laser energy into the hohlraum. All systems operated successfully with 26 target diagnostics acquiring data. The radiation drive was consistent with earlier shots

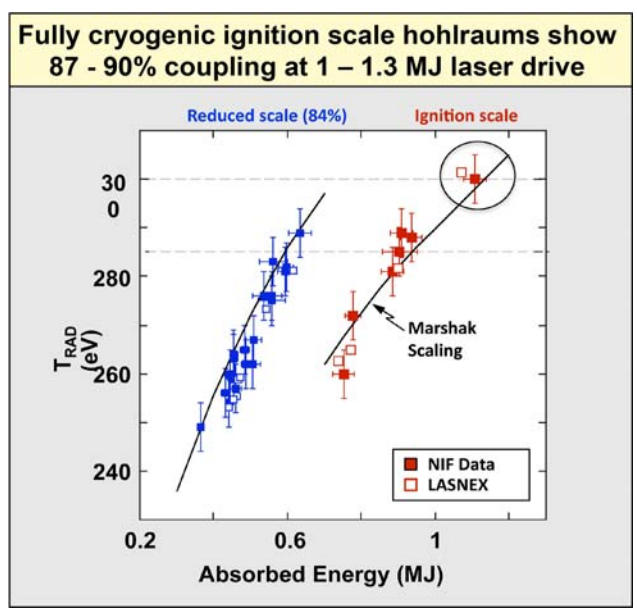


Fig.4. Hohlraum drive scaling shows 300-eV drive from an ignition-scale target with 1.3 MJ of laser energy.

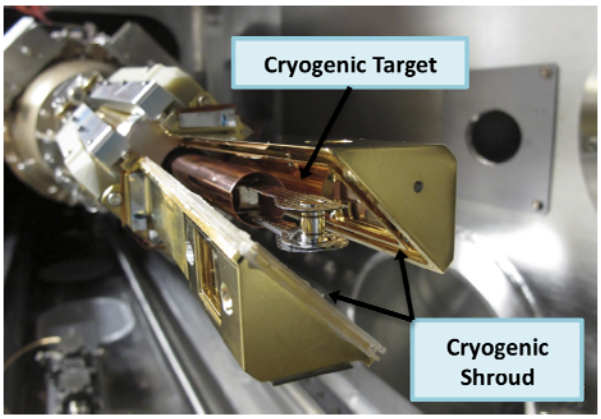


Fig. 5. Cryogenic layered target shot on September 29, 2010 before being shot in the NIF target chamber. The target is the cylinder in the center of the picture. The two triangular structures are the cold shield shrouds that are closed to provide the required thermal environment. The shrouds are open immediately before the shot.

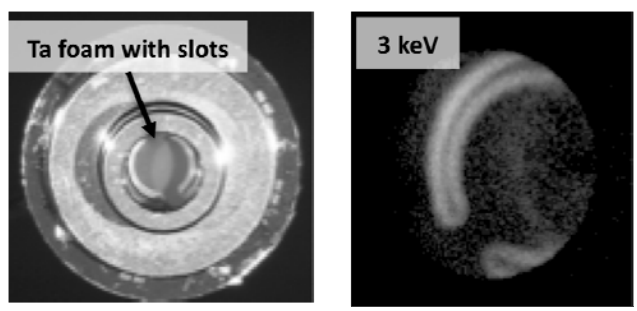
at this energy and the yield was 10^{13} neutrons. Three additional cryogenic layered experiments have been successfully executed with increased laser energy and larger deuterium fraction with the last experiment attaining a yield of 2×10^{14} n.

Recently, NIF set the record for neutron yield. The experiment used 121 kJ of 3ω light to irradiate a deuterium/tritium gas-filled direct-drive capsule for calibrating neutron diagnostics. The capsule was driven using polar-drive illumination.[12] The shot produced a neutron yield of ~ 3×10^{14}, the highest neutron yield ever accomplished by a laser facility. These experiments are used to qualify implosion diagnostics for ignition shots. Presently, over twenty diagnostics have been commissioned for measuring the x rays, particles, and neutrons produced in ignition implosions.

Experiments are planned to continue through this year with the initial ignition campaign. A series of experiments will study shock timing, ablator velocity, and mix as well as continuing implosions to optimize symmetry, fuel adiabat, shell velocity, and mix. Additional THD shots are planned to demonstrate improved performance due to this optimization. The THD composition will be changed, increasing the amount of deuterium to increase the yield to ~10^{16} neutrons. These yields should be sufficient to observe the effects of fuel heating by alpha particle energy deposition, the next step in demonstrating ignition.

NIF has also performed HED experiments supporting its missions for national security and basic sciences. Experiments have measured transport of thermal radiation through voids in high Z, low-density materials. Slots in Ta foams are placed on the end of a half-hohlraum irradiated by the lower hemisphere NIF beams. The Ta foam with slots is shown in Fig. 6(a). Radiation streams through the void heating it and causing the material to blow in, changing the radiation transport through the void. A 3-keV time integrated x-ray image shows the foam with its slot edges heated by the radiation flowing through the slot (Fig. 6(b)). Material studies have also begun that are similar to the ignition shock timing experiments. Shock heating and isentropic compression experiments have begun as well on low Z materials for understanding material properties of giant planets and on Ta for studying high Z material at high density. NIF can produce high brightness x-ray pulses that have been used to understand material response to high fluxes for radiation effects studies.

The initial review of peer-reviewed science proposals has recently been completed at NIF. Forty proposals for experimental time were submitted and eight proposals have been accepted. The proposals are in fields as diverse as planetary science, supernova hydrodynamics, pair production plasmas, and nucleosynthesis. Initial experiments have already begun in some of the proposals. An HED campus is being established to facilitate NIF becoming the premier center for HED science.



(a) (b)

Fig. 6. Ta foam with slots used for radiation transport experiments with (a) view of Ta foam on the end of a half hohlraum and (b) time-integrated image of 3-keV x rays.

III. Laser Inertial Fusion Energy (LIFE)

Energy production from a burning ICF target has been a long-term goal of ICF research since its inception. Successful demonstration of ignition and net energy gain on NIF will be a major step towards demonstrating the feasibility of Inertial Fusion Energy (IFE) and will focus the world's attention on the possibility of IFE as a carbon-free, energy option. Significant technology development is required beyond the successful demonstration of ignition and burn of an ICF target to realize the goal of IFE. To meet the growing demand for an environmentally friendly energy source, the LIFE activities are focused on

developing the technology in parallel with the target physics research in order to exploit a successful ICF demonstration as soon as possible.

A laser-based IFE power plant requires significant advances in performance compared to a target physics research facility like NIF. The laser requires a repetition rate of 10–20 Hz and approximately 10% electrical efficiency with high availability. Mass-production of targets is required to meet a rate of 400 million per year. The LIFE engine is designed to deliver targets to chamber center at the high repetition rate, provide laser irradiation of the target with the required accuracy, and manage the thermal and radiation environment of the repetitive target implosion.

LIFE is the result of a systems engineering approach to defining and developing the technology program for an IFE power plant. A conceptual design of the system has been developed that identifies and prioritizes the technology development for a power system. The LIFE engine includes the reactor vessel with target and laser delivery systems, energy extraction and tritium breeding. The lasers are conceived as line replaceable units that can be exchanged during hot operations. The reactor vessel is designed for easy replacement to ensure high facility availability. The turbine building houses a conventional electrical power plant driven by the thermal production from the LIFE engine.

Fusion energy holds the promise of an energy source with no greenhouse gas emissions and a virtually inexhaustible, widely available fuel supply. It would remove the need for actinide enrichment and reprocessing and high-level waste storage required by fission power plants. While these and other features of fusion energy are attractive, scientific and technological challenges remain. Successful demonstration of ignition by the NIC coupled with a robust LIFE technology development effort could lead to the delivery of this plant in a 10- to 15-year time frame.

IV. Summary

In summary, NIF has been completed and has demonstrated performance at its design goals. The Facility is being prepared for full yield experiments. A full set of diagnostics has been commissioned for initial ignition experiments, and the next phase of radiation-hardened diagnostics are being installed. The NIF is now qualified for full yield experiments with hazardous materials.

The NIC has begun its ignition campaign. First results on ignition-scale targets show excellent performance with good energy coupling and good radiation symmetry control. Experiments are continuing to optimize the ignition target design for the four major control variables for ignition: symmetry, fuel adiabat, shell velocity, and mix. Cryogenic layered experiments with THD have shown that the facility can successfully field ignition experiments. Further ignition experiments are planned to improve performance and demonstrate alpha heating of the fuel, the next step in ignition demonstration. NIF has also begun experiments supporting national security and fundamental science as a start to becoming a national user facility.

Plans have begun for developing IFE beyond ignition. The LIFE activities are developing the technology along with the ignition target physics research to fully exploit inertial fusion as a viable source of clean energy production. LIFE is using a systems engineering approach to develop the technology for exploiting IFE in parallel with the ignition physics program. This aggressive parallel effort can expedite the realization of IFE to meet the growing demands for a source of abundant clean energy.

ACKNOWLEDGMENTS

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

REFERENCES

1. G. H MILLER, E. I. MOSES, and C. R. WUEST, “The National Ignition Facility: enabling fusion ignition for the 21st century,” *Nucl. Fusion*, **44** S228 (2004).
2. R. DAVIDSON et al., “*Frontiers in High Energy Density Physics: The X-Games of Contemporary Science*,” The National Academies, Washington, DC (2003).
3. J.D. LINDL, “Inertial confinement fusion: the quest for ignition and energy gain using indirect drive,” American Institute of Physics Press, New York (1998).
4. G. A. HAYNAM, P.J. WEGNER, J. M. AERBACH, M. W. BOWERS, S. N. DIXIT, G. V. ERBERT, G. M. HEESTAND, M. A. HENESIAN, M. R. HERMANN, K. S. JANCAITIS, K. R. MANES, C. D. MARSHALL, N. C. MEHTA, J. MENAPACE, E. MOSES, J. R. MURRAY, M. C. NOSTRAND, C. D. ORTH, R. PATTERSON, R. A. SACKS, M. J. SHAW, M. SPAETH, S. B. SUTTON, W. H. WILLIAMS, C. C. WIDMAYER, R. K. WHITE, S. T. YANG, and B. M. VAN WONTERGHEM, “National Ignition Facility laser performance status,” *Appl. Opt.* **46**, 3276 (2007).

5. T. I. SURATWALA, P. E. MILLER, J. D. BUDE, W. A. STEELE, N. SHEN, M. V. MONTICELLI, M. D. FEIT, T. A. LAURENCE, M. A. NORTON, C. W. CARR, and L. L. WONG, "HF-Based Etching Processes for Improving Laser Damage Resistance of Fused Silica Optical Surfaces," *J. Am. Ceram. Soc.* **94**, 416-28 (2011).
6. S. H. GLENZER et al., "Demonstration of Ignition Radiation Temperatures in Indirect-Drive Inertial Confinement Fusion Hohlraums," *Phys. Rev. Lett*., **106**, 085004 (2011)..
7. N.B. MEEZAN, L.J. ATHERTON, D.A. CALLAHAN, E.L.DEWALD, S. DIXIT, E.G. DZENITIS, M.J. EDWARDS, C.A. HAYNAM, D.E. HINKEL, O.S. JONES, O. LANDEN, R.A. LONDON, P.A. MICHEL, J.D. MOODY, J.L. MILOVICH, M.B. SCHNEIDER, C.A. THOMAS, R.P.J. TOWN, A.L. WARRICK, S.V. WEBER, K. WIDMANN, S.H. GLENZER, L.J. SUTER, B.J. MACGOWAN, J.L. KLINE, G.A. KYRALA, and A. NIKROO, "National Ignition Campaign Hohlraum Energetics," *Phys. Plasmas* **17**, 056304 (2010).
8. S. H. GLENZER et al., "Symmetric Inertial Confinement Fusion Implosions at Ultra-High Laser Energies," *Science* **327**, 1228 (2010).
9. P. MICHEL, L. DIVOL, E. A. WILLIAMS, S. WEBER, C. A. THOMAS, D. A. CALLAHAN, S. W. HAAN, J. D. SALMONSON, S. DIXIT, D. E. HINKEL, M. J. EDWARDS, B. J. MACGOWAN, J. D. LINDL, S. H. GLENZER, and L. J. SUTER, "Tuning the Implosion Symmetry of ICF Targets via Controlled Crossed-Beam Energy Transfer," *Phys. Rev. Letters* **102**, 025004 (2009).
10. G. A. KYRALA, J. L. KLINE, S. DIXIT, S. GLENZER, D. KALANTAR, D. BRADLEY, N. IZUMI, N. MEEZAN, O. LANDEN, D. CALLAHAN, S. V. WEBER, J. P. HOLDER, S. GLENN, M. J. EDWARDS, J. KOCH, L. J. SUTER, S. W. HAAN, R. P. J. TOWN, P. MICHEL, O. JONES, S. LANGER, J. D. MOODY, E. L. DEWALD, T. MA, J. RALPH, A. HAMZA, E. DZENITIS, and J. KILKENNY, "Symmetry tuning for ignition capsules via the symcap technique," *Phys. Plasmas* **18**, 056307 (2011).
11. R. P. J. TOWN, M. SD. ROSEN, P. A. MICHEL, L. DIVOL, J. D. MOODY, G. A. KYRALA, M. B. SCHNEIDER, J. L. KLINE, C. A. THOMAS, J. L. MILOVICH, D. A. CALLAHAN, N. B. MEEZAN, D. E. HINEL, E. A. WILLIAMS, R. L. BERGER, M. J. EDWARDS, L. J. SUTER, S. W. HAAN, J. D. LINDL, E. L. DEWALD, S. DIXIT, S. H. GLENZER, O. L. LANDEN, E. I. MOSES, H. A. SCOTT, J. A. HARTE, and G. B. ZIMMERMAN, "Analysis of the National Ignition Facility ignition hohlraum energetics experiments," *Phys. Plasmas* **18**, 056302 (2011).
12. P. W. McKENTY, R. S. CRAXTON, F. J. MARSHALL, T. C. SANGSTER, J. A. MAROZAS, A. M. COK, M. J. BONINO, D. R. HARDING, D. D. MEYERHOFER, R. L. McCRORY, J. D. KILKINNEY, A. NIKROO, J. FOOKS, M. L. HOPPE, J. M. EDWARDS, A. J. MacKINNON, D. H. MUNRO, and R. J. WALLACE, "Design of High-Neutron-Yield, Polar-Drive Targets for Diagnostic Activation Experiments on the NIF," *Journal of Physics Conference Series* 244, 032054 (2010).