Precision Diagnostics Tell All

Robust, high-resolution instruments at the National Ignition Facility reveal the physics behind creating fusion in a laboratory.

Technicians install a static x-ray imager in the target chamber at the National Ignition Facility (NIF). This device helps scientists determine the positioning of NIF beamlines within the hohlraum.

THE ability to capture data from high-energy-density experiments has always been of great importance to the Laboratory and its missions. During the years of underground nuclear testing, Livermore scientists developed advanced diagnostics such as specialized oscilloscopes, streak cameras, and detectors to measure key physical properties of nuclear blasts, including reaction time histories and the overall yield of an explosion. In the absence of underground testing, these sophisticated instruments are still crucial for national security research, especially for the novel experiments conducted at the National Ignition Facility (NIF).

Built to generate up to 1.8 megajoules of ultraviolet light at a peak power of 500 terawatts, NIF is the world's largest, most energetic laser. With its one-of-a-kind capabilities, NIF enables researchers to explore new frontiers in high-energy-density science, from understanding the intricacies of astrophysics, hydrodynamics, and radiation transport to ensuring the continued safety and reliability of the nation's nuclear weapons stockpile. In September 2010, NIF completed its first integrated ignition experiment, demonstrating that all of the facility's complex systems function together as designed. (See the news brief on p. 2.) This experiment was a key milestone in the National Ignition Campaign (NIC), a multi-institutional effort focused on achieving fusion ignition and energy gain.

In an ignition experiment, all of NIF's 192 laser beams will be fired into a cylindrical case called a hohlraum, which contains a BB-sized capsule filled with deuterium–tritium (DT) fuel. Gathering data from ignition experiments requires an extensive suite of reliable, robust diagnostics that can image an experiment faster and in more detail than ever before. These devices detect and measure visible light, x rays, gamma rays, and nuclear products such as neutrons generated during an experiment. By studying the collected data, scientists and engineers can evaluate the performance characteristics of the laser, hohlraum, and target capsule. With this better understanding of the system's performance, they can determine how to manipulate the laser and the target design to produce the precise conditions for initiating fusion burn that produces more energy than was used to create it.

NIF diagnostics are designed to withstand the harsh environment of the target chamber—conditions that would destroy traditional electronics—and to record micrometer-scale details within tens of picoseconds (trillionths of a second). Since 2005, an international team of scientists and engineers has been working to improve established diagnostic systems and build new devices that can meet these stringent requirements. (See the box on p. 16.) Says Livermore scientist Bob Kauffman, "As a result of this collaboration, we have designed and built over 30 diagnostics specifically for NIF, and the number keeps growing."

Each diagnostic is being installed, calibrated, and tested in one of three stages. The first stage, completed in fall 2009, focused on instruments designed to measure the laser's operational capabilities. (See *S&TR*, April/May 2010, pp. 4–11.) Diagnostics tested in the second stage analyzed hohlraum energetics and how well the laser energy coupled to surrogate targets. (See *S&TR*, June 2010, pp. 17–19.) In 2011, the remaining diagnostics needed to evaluate the capsule implosion and neutron yield will be integrated into the target chamber.

Shock to the Heart

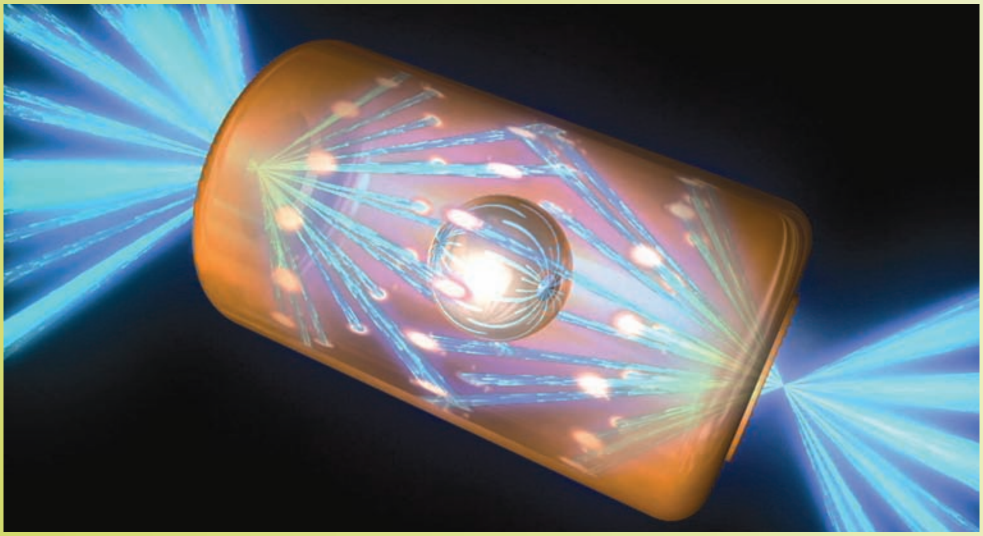
Inertial confinement fusion is the process by which a laser imparts enough energy into a capsule filled with hydrogen isotopes to heat and compress the fuel, creating fusion reactions. During an ignition experiment, 192 beams enter the hohlraum via holes at either end of the target. When these beams hit the hohlraum's interior walls, they generate x rays that heat and vaporize the fuel capsule's surface. The vaporizing outer (ablator) surface produces an inward force that compresses the fuel. This compression generates a series of shock waves that heat the capsule's inner core. The ignition "hot spot" created in the core starts the fusion burn. The velocity of the implosion, x-ray temperature of the hohlraum, shape and size of the hot spot, and neutron yield are all factors that determine whether ignition will be achieved.

Optical diagnostics designed to detect visible light help determine the energy balance of an experiment as well as the implosion velocity of the fuel capsule, laser–plasma interactions, and instabilities that affect the target performance. In a perfect world, the amount of energy fired into the hohlraum would be transferred to the target with minimal loss. However, two types of optical effects—Raman and Brillouin scattering—can cause the light to scatter out of the hohlraum. Because scattered light can adversely affect the drive of an implosion, researchers have designed optical devices to measure the light's power, spectrum, and angular distribution.

One such instrument is the full-aperture backscatter station. When light bounces off the hohlraum, some of it is reflected back through the laser's final focusing lens and into the beamline. There, a turning mirror diverts it into the backscatter station, which combines time-resolved imaging, spectrometry, and calorimetry to accurately characterize the reflected light.

A near backscatter imager, on the other hand, uses specially coated plates inside the target chamber to measure light scattered outside the aperture of the focusing lens. Says Kauffman, "We need these data to calculate the total energy absorbed from the incident beam, which is important for determining energy balance." A gated, intensified charge-coupled-device camera within the near backscatter imager provides time-resolved images recorded inside the hohlraum for analysis.

Another optical diagnostic is VISAR, the Velocity Interferometer for Any Reflector, which measures the speed of shock waves compressing the DT fuel. NIF can deliver pulses in a variety of shapes and lengths depending on the demands of a given experiment. For ignition, the laser produces four shocks that are timed to collapse the capsule in a specific sequence. If the shocks are too close together, they will coalesce in the ice layer that surrounds



During an ignition experiment, NIF's 192 beamlines will be fired into a hohlraum containing a deuterium–tritium fuel capsule. Within 20-billionths of a second, the capsule will be compressed and heated to create an energy-producing fusion reaction.

the DT gas. If they are too far apart, the ice will decompress between shocks.

VISAR is a time-resolved Doppler velocity camera that detects and images light reflected from the fuel capsule's ablator surface. Two interferometers combine the reflected beam with a reference beam to create an interference pattern. When a shock hits the fuel capsule, the interference pattern changes, indicating a phase difference between the beams that is proportional to the shock velocity. A streak camera records the pattern, providing the information needed to optimize the target design and its overall performance.

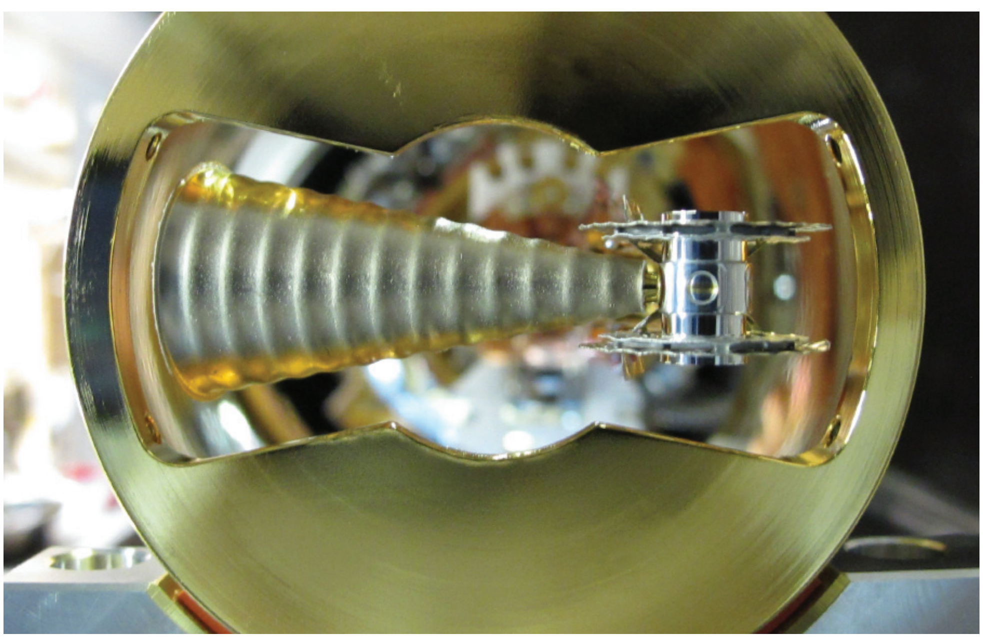
Feeling Hot, Hot, Hot

Diagnostic techniques that can detect hard and soft x-ray emissions also help researchers evaluate laser, hohlraum, and target performance. Among their many capabilities, these instruments measure beam alignment, hohlraum temperature, and implosion symmetry. Static x-ray imagers located near the laser entrance holes of the hohlraum, for example, reveal whether all 192 beamlines are hitting the hohlraum's interior walls at the designated points for generating a uniform x-ray bath.

Beamlines that miss the entrance holes produce an x-ray emission spot outside the hohlraum. A static x-ray imager is a filtered pinhole camera designed to record such emissions. These cameras typically measure x rays in the 2- to 3-kiloelectronvolt range. However, filters made from different materials can be placed in the imager to broaden the detection range. Time-integrated images show the x-ray emission from each laser beam as it irradiates the target, allowing shot controllers to verify beam positioning.

X-ray diagnostics also help measure the radiation temperature within the hohlraum, providing details on the time history and symmetry of the x-ray drive needed to implode the fuel capsule. A broadband, time-resolved x-ray spectrometer called Dante measures the x-ray flux emitted by the target throughout an experiment. "Dante is the workhorse diagnostic for measuring hohlraum temperature," says Joe Kilkenny, diagnostic chief scientist and the NIC program leader at General Atomics. "Using data from Dante, we can determine the radiation temperature from the distribution of x-ray energies as a function of time." Dante includes an array of filters and diodes for measuring radiation flux. Depending on the requirements for an experiment, filters made from various materials can be placed within the 18-channel instrument to detect a broad range of x-ray spectra emitted at the foot and peak of the laser pulse.

Without x-ray diagnostics, obtaining a clear picture of the physical processes occurring inside the hohlraum would be nearly impossible. Additional devices such as gated x-ray cameras capture details on the shape and velocity of the implosion. Streak x-ray cameras continually record a target as it evolves over trillionths of a second, producing time-resolved images that show the x-ray emissions of beams focused on the target. And an x-ray fluorescer characterizes broadband high-energy x rays that can preheat the capsule and degrade the quality of the implosion.

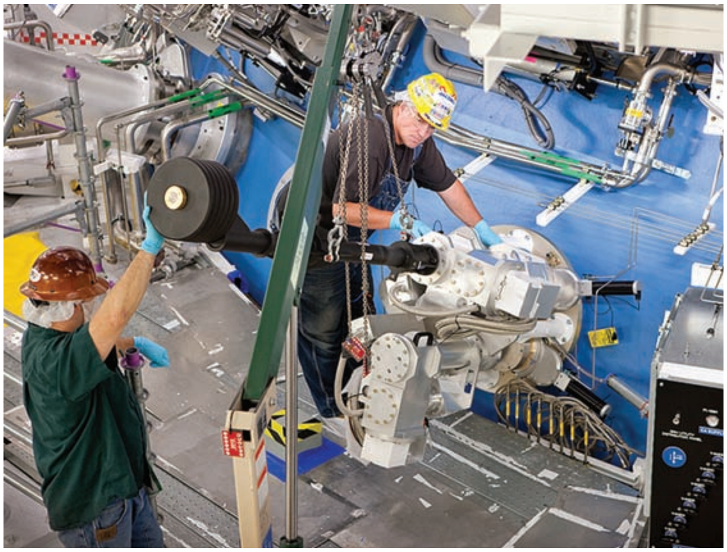


This target is used with the Velocity Interferometer for Any Reflector (VISAR) diagnostic. VISAR data help optimize the laser pulse and NIF target design.

Are We There Yet?

The ultimate signature for ignition will be the presence of high-energy neutrons, which are generated along with alpha particles during DT fusion. The positively charged alpha particles extend the fusion burn as they deposit their energy in the compressed fuel layers, one layer at a time. However, neutrons, which carry no electric charge, escape the fuel, retaining their energy. As the burn wave propagates outward, the fuel becomes hotter and burns more rapidly, releasing more alpha particles and neutrons. The process continues until the pressure is so high that the fuel is no longer inertially confined and fusion ceases.

"NIF experiments will produce about 10^{19} neutrons in a few tens of picoseconds," says Trish Baisden, the deputy director for NIC Operations. "Nuclear diagnostics will allow us to measure physical properties

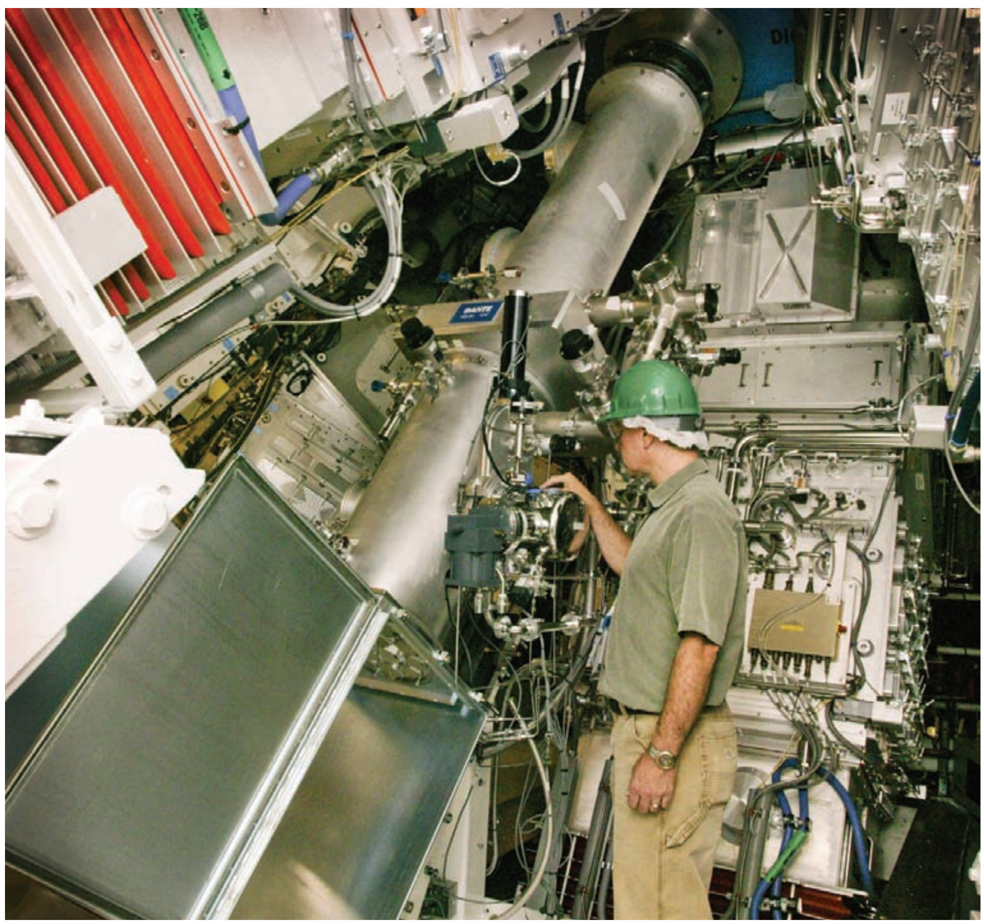


More than 30 diagnostic instruments have been installed at NIF, such as the gamma reaction history device (left) and the gated x-ray imager (above).

such as neutron yield, ion temperature, bang time, core temperature, and reaction history to understand how well the experiment performed and how much energy was produced."

One such diagnostic device is the neutron time-of-flight detector. Made with plastic scintillator and photomultiplier tubes or diamond photoconductors, this detector measures the total neutron yield and the energy broadening of the neutron signal from the time neutrons originate in the target to when they arrive at the detector. The signal's travel time depends on the kinetic energy spread, which is a function of ion temperature. "Ion temperature is directly related to how fast the core implodes," says David Meyerhofer, the director of the Experiment Division at the University of Rochester's Laboratory for Laser Energetics. "Without the right temperature, ignition will not occur."

The number of neutrons generated in an experiment depends on the combined thickness and density of the fuel shell. Known as the areal density, this characteristic is a function of how much energy is absorbed by the material, the accuracy of target conditions during implosion, and the attenuation of particles through the material. By detecting the



A technician inspects a Dante diagnostic device, which measures the x-ray flux emitted by the target—data that are used to determine hohlraum temperature.

It Takes a Team to Achieve Ignition

Developing diagnostics that can meet the stringent requirements for the National Ignition Facility (NIF) is an international endeavor. Since 2005, a multidisciplinary team of scientists and engineers from institutions in the U.S. and abroad has been hard at work designing, building, and calibrating more than 30 diagnostics for the National Ignition Campaign (NIC)—the program dedicated to achieving thermonuclear burn and energy gain through inertial confinement fusion. Collectively, team members offer a wealth of expertise in areas such as optics, electronics, imaging, and data acquisition and analysis, to name a few.

The advanced instruments created by this collaboration allow researchers to gather key physics data from experiments under the most extreme conditions. "What one has to realize is that the NIF environment is uncharted territory," says Trish Baisden, deputy director for NIC Operations. Inside the target chamber, the high radiation, intense electromagnetic pulses, and considerable debris from experiments are too much for traditional equipment and electronics to survive. "To build diagnostics that can handle this harsh environment, we need as much brainpower as possible solving the difficult challenges associated with the task."

Work on the diagnostics suite involves researchers from Lawrence Livermore, Lawrence Berkeley, Los Alamos, Brookhaven, and Sandia national laboratories; National Security Technologies, LLC; the Laboratory for Laser Energetics (LLE) at the University of Rochester; Massachusetts Institute of Technology (MIT); Duke University; Atomic Weapons Establishment in the United Kingdom; and Commissariat à L'Énergie Atomique in France. Several sites are dedicated to the entire diagnostic development cycle, from drawing up the initial specifications to testing prototypes. Others such as Lawrence Berkeley, National Security Technologies, and Duke University are also responsible for calibrating devices. Each site's assignment is based on its expertise in a given area. As an example, MIT has a history of research and development in new types of nuclear diagnostics. That knowledge was valuable for building the magnetic recoil spectrometer to detect neutron time of flight.

Before a device is installed at NIF, it is tested on the OMEGA laser at LLE. "LLE is a key partner in our diagnostic effort," says Baisden. Although the OMEGA laser operates at lower energy than NIF, it provides a valuable test bed for each diagnostic. "At LLE, we cannot achieve the neutron flux that NIF will produce," says David Meyerhofer, director of LLE's Experiment Division. "Instead, we increase the number of neutrons that diagnostics are exposed to by moving the diagnostics closer to the target." In what Meyerhofer and colleagues whimsically refer to as "neutron derbies," LLE hosts Diagnostic Development Days where they invite scientists from across the country to conduct experiments on the OMEGA laser, with the goal of achieving the highest neutron yields possible. These events are useful not only for testing diagnostics but also for stimulating new ideas to measure data from high-energy-density experiments.

In the past two years, Livermore has hosted several workshops geared toward expanding the diagnostic effort. "Through these workshops, we engage with the broader scientific community to overcome the complex physics challenges posed by NIF," says Doug Larson, lead engineer for NIC Diagnostics. Thanks to the help of a dedicated multidisciplinary team, an array of advanced diagnostics will provide a wealth of information about laser, hohlraum, and capsule performance. "From the beginning, it has been a team effort to make ignition happen at NIF," says Meyerhofer. "All of us want to see the facility succeed. It's essential to the future of fusion research."

In May 2010, Livermore hosted the fourth diagnostic workshop for the National Ignition Facility, with participants from the U.S. and abroad.

dispersion and spread of neutrons, scientists can calculate a target's areal density, which is essential for determining whether the capsule has enough mass to sustain the fusion reaction. "The temperature and shape of the implosion at peak compression and the areal density of the material are the most critical components for ensuring that we are on track to ignition," says Meyerhofer.

The neutron time-of-flight detectors work in conjunction with neutron-based reaction history diagnostics to determine the burn time of the imploding capsule. Neutron imaging and spectroscopy devices further detail the compressed capsule's shape and size.

To test these diagnostics, researchers are conducting experiments with dudded targets, in which hydrogen is added to the DT fuel mix. "The dudded targets allow us to study all the necessary experimental parameters for ignition in an environment with very low neutron yield," says Baisden.

A Balanced View

NIF diagnostics are designed to be redundant and complementary. For example, NIF has two Dante devices, one in the upper half of the target chamber and the other in the lower half. From these two locations, the "Dantes" can measure the soft x-ray emission from either side of the hohlraum, increasing the fidelity of the captured data. During an experiment, multiple diagnostics work in concert to gather sets of data that together help scientists compare and verify experimental results. "No diagnostic makes a perfect measurement," says Kilkenny. "We need complementary and redundant devices to truly understand what is going on."

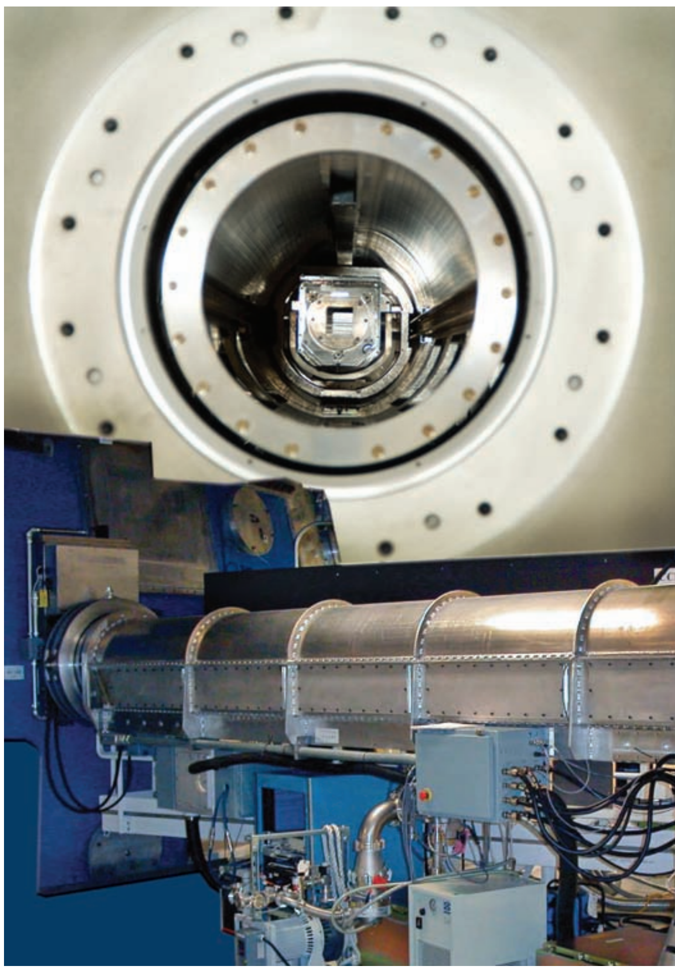
The variety of diagnostic techniques provides a more complete picture of what is happening with the laser, hohlraum, and target. "During hohlraum energetics experiments, we simultaneously measured laser light entering the target, light backscattered from the target, and hohlraum temperature," says Alex Hamza, a target fabrication manager at NIF. "We evaluated all three pieces of recorded data together. If the results had not matched, we would have needed to investigate the discrepancies."

More than 20 devices can be installed for an experiment using diagnostic instrument manipulators. These vacuum-sealed tubes are attached to the target chamber and house specialized carts that can accommodate up to five diagnostics at a time. "The manipulators are like the Swiss Army knives of NIF," says the facility's operations manager Bruno Van Wonterghem. "With this equipment, we can tailor diagnostics to fit the requirements of a particular experiment."

Diagnostic instrument manipulators allow the same diagnostic to view an experiment from different lines of sight, improving the operational availability and reliability of the detectors. In addition, they provide flexibility to quickly reconfigure and relocate instruments between shots.

Going beyond the Standard

Many NIF diagnostics are variations of time-tested technologies used in high-energy-density research. Dante and the two backscatter devices, for example, have all been fielded on other lasers, such as Nova, the predecessor laser to NIF, and the University of Rochester's OMEGA laser. "We know how well certain diagnostics work based on past experience," says Kauffman. "Our primary objective has been to adapt technologies so they can survive the harsh, often destructive conditions of the NIF target chamber." Diagnostic development teams have designed special shielding to protect instruments from electromagnetic pulses,



A diagnostic instrument manipulator (top) has a specialized cart that can house multiple devices. Shown from the outside (below), attached to the target chamber, the manipulator allows several diagnostics to simultaneously record data during an experiment.

The magnetic recoil spectrometer provides a novel approach to measuring neutron time of flight by converting neutrons to protons, which have a higher interaction probability within the detector.

high-energy neutrons, and debris. In addition, devices are modified to function at greater distances from the target than they do at other laser facilities.

Radiochemical techniques are also being adapted for NIF research. During an underground nuclear test, tracer elements incorporated into materials were activated by neutrons generated in the explosion, as one material transmuted into another. Researchers analyzed the resulting isotopes to determine whether the experiment achieved the desired conditions.

Using the same principles for NIF, scientists are adding tracer elements to target materials. "A big difference between applying these techniques for laser research as opposed to underground testing is that we can collect a signal within hours instead of weeks," says Hamza. Future diagnostics may collect solid elements from an experiment by using a device that acts like a catcher's mitt.

Some NIF diagnostics are new additions to inertial fusion research. For example, the magnetic recoil spectrometer, developed at the Massachusetts Institute of Technology, is a novel approach for measuring the neutron energy spectrum. Because neutrons cannot be dispersed according to energy by a magnet, they are first converted to protons. A diagnostic instrument manipulator places a plastic foil about 1 meter from the target. Neutrons from the experiment collide with atoms in the foil, causing protons to recoil. This process converts the neutron energy to protons, which are dispersed by a magnet onto a detector that measures the proton energy spectrum. The probability of detecting a proton is much higher than it is for detecting a neutron, allowing the magnetic recoil spectrometer to capture more information. When fielded on the OMEGA laser during DT experiments, the device proved to be extremely successful.

The most highly anticipated NIF diagnostic is the advanced radiographic capability. This high-energy, short-pulse x-ray backlighter uses one of the NIF beamlines to x ray a target during an experiment. Each pulse of x-ray energy lasts just a few picoseconds. Coupled with a backlighter, the device provides high-resolution images of the capsule as it implodes.

A Future Filled with Possibilities

Over the next decade, scientists will use NIF to delve into unexplored areas of high-energy-density science. "At Livermore, we already have some of the world's fastest supercomputers providing us with unprecedented predictive capabilities," says Livermore physicist Richard Fortner, one of the pioneers in developing NIF diagnostics. "With NIF, we'll be able to perform the most complex high-energy-density experiments ever attempted and compare those results to our simulations. The data provided by the two methods won't always agree, but that's what helps us to learn. Science on NIF is going to be very exciting."

The full suite of NIF diagnostics will be essential to making ignition a success. "Because of the hard work and ingenuity of scientists and engineers all over the country and abroad designing and building instruments that can help us characterize the laser, hohlraum, and capsule, we are closer to achieving ignition than ever before," says Ed Moses, principal associate director for NIF and Photon Science. As anticipation builds for the first ignition shot, scientists look forward to analyzing the impressive data these precision diagnostics will reveal.

—Caryn Meissner

Key Words: advanced radiographic capability, Dante spectrometer, diagnostic instrument manipulator, full aperture backscatter station, high-energy-density science, hohlraum, ignition, inertial confinement fusion, laser, magnetic recoil spectrometer, National Ignition Campaign (NIC), National Ignition Facility (NIF), near backscatter imager, neutron, OMEGA laser, target, Velocity Interferometer for Any Reflector (VISAR).

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