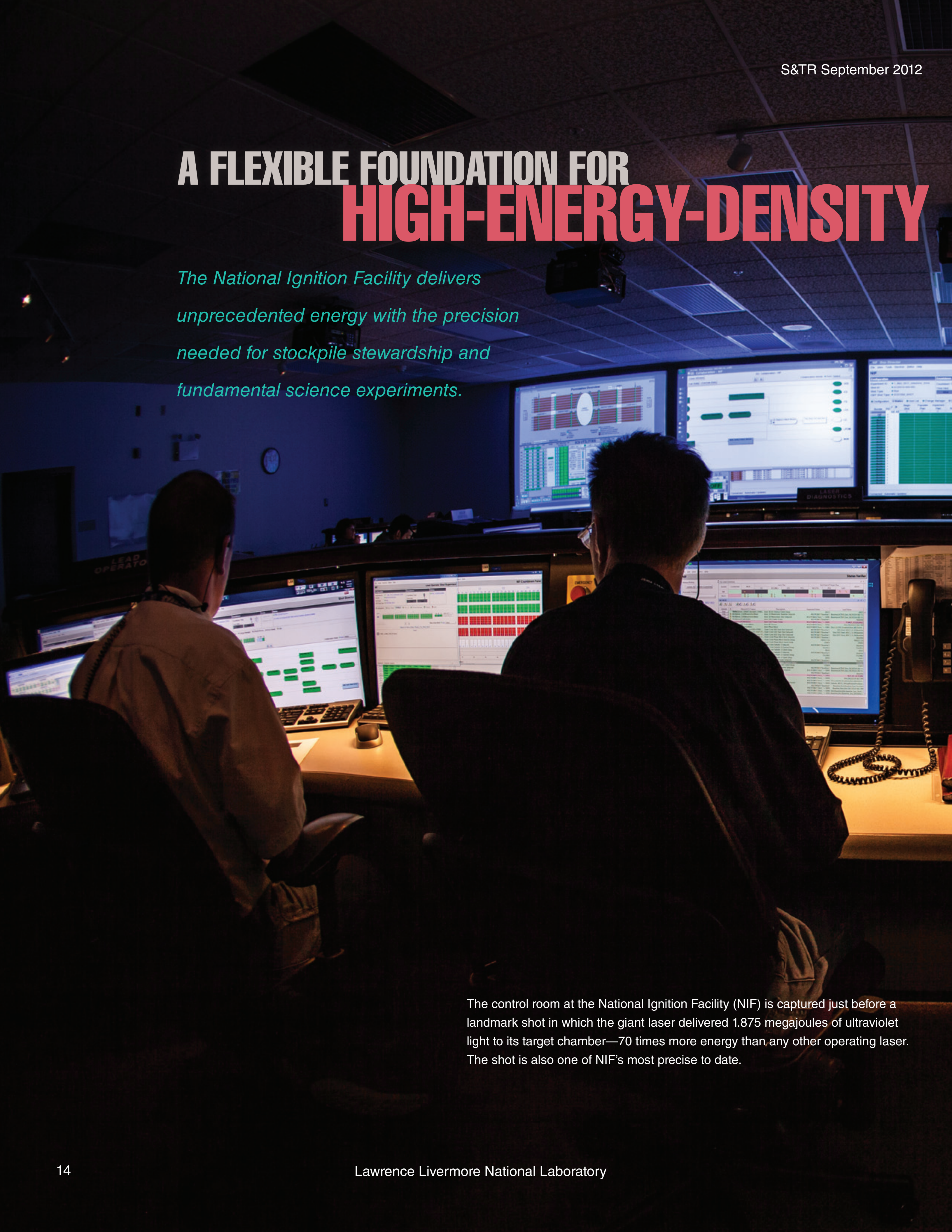
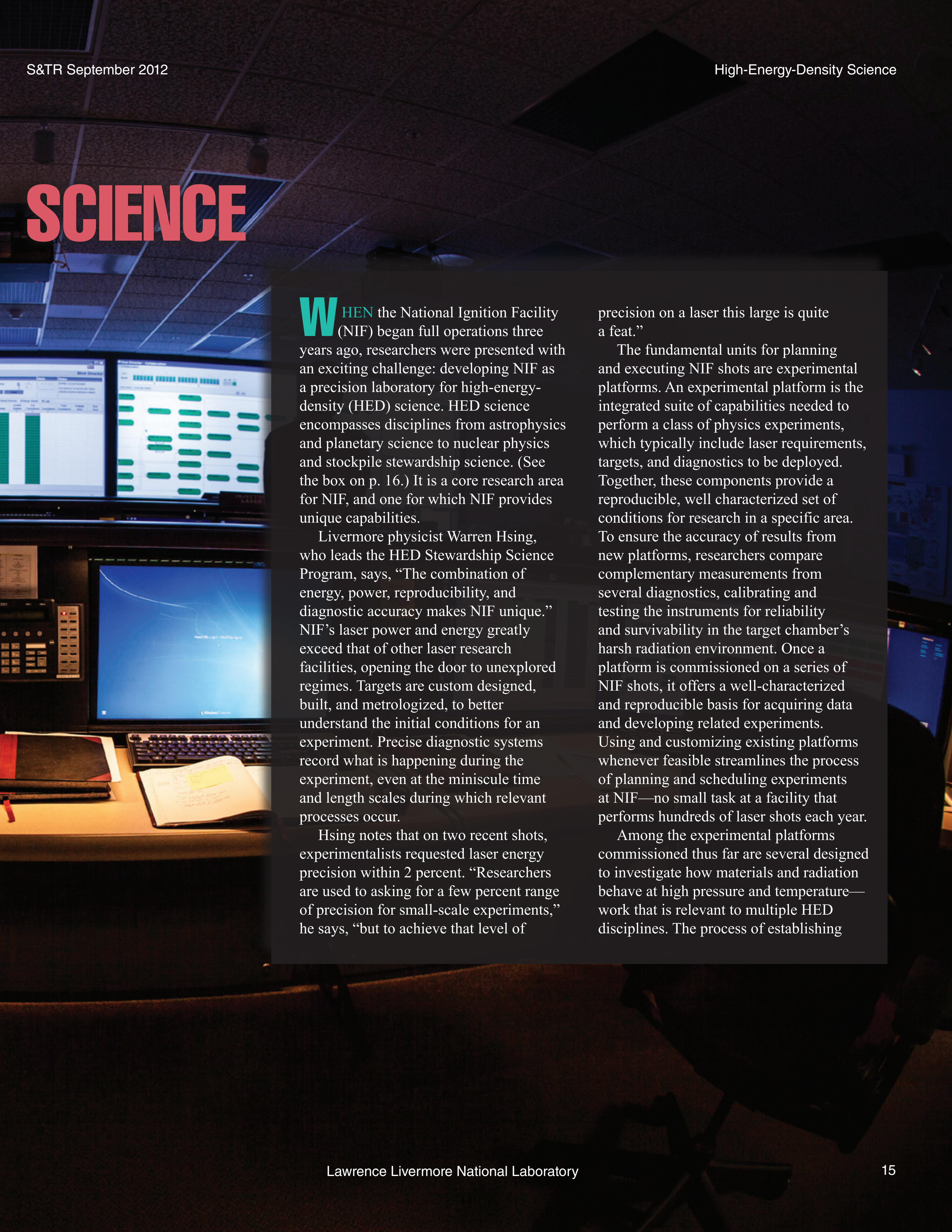
A FLEXIBLE FOUNDATION FOR HIGH-ENERGY-DENSITY

The National Ignition Facility delivers unprecedented energy with the precision needed for stockpile stewardship and fundamental science experiments.



The control room at the National Ignition Facility (NIF) is captured just before a landmark shot in which the giant laser delivered 1.875 megajoules of ultraviolet light to its target chamber—70 times more energy than any other operating laser. The shot is also one of NIF’s most precise to date.



SCIENCE

WHEN the National Ignition Facility (NIF) began full operations three years ago, researchers were presented with an exciting challenge: developing NIF as a precision laboratory for high-energy-density (HED) science. HED science encompasses disciplines from astrophysics and planetary science to nuclear physics and stockpile stewardship science. (See the box on p. 16.) It is a core research area for NIF, and one for which NIF provides unique capabilities.

Livermore physicist Warren Hsing, who leads the HED Stewardship Science Program, says, "The combination of energy, power, reproducibility, and diagnostic accuracy makes NIF unique." NIF's laser power and energy greatly exceed that of other laser research facilities, opening the door to unexplored regimes. Targets are custom designed, built, and metrologized, to better understand the initial conditions for an experiment. Precise diagnostic systems record what is happening during the experiment, even at the miniscule time and length scales during which relevant processes occur.

Hsing notes that on two recent shots, experimentalists requested laser energy precision within 2 percent. "Researchers are used to asking for a few percent range of precision for small-scale experiments," he says, "but to achieve that level of precision on a laser this large is quite a feat."

The fundamental units for planning and executing NIF shots are experimental platforms. An experimental platform is the integrated suite of capabilities needed to perform a class of physics experiments, which typically include laser requirements, targets, and diagnostics to be deployed. Together, these components provide a reproducible, well characterized set of conditions for research in a specific area. To ensure the accuracy of results from new platforms, researchers compare complementary measurements from several diagnostics, calibrating and testing the instruments for reliability and survivability in the target chamber's harsh radiation environment. Once a platform is commissioned on a series of NIF shots, it offers a well-characterized and reproducible basis for acquiring data and developing related experiments. Using and customizing existing platforms whenever feasible streamlines the process of planning and scheduling experiments at NIF—no small task at a facility that performs hundreds of laser shots each year.

Among the experimental platforms commissioned thus far are several designed to investigate how materials and radiation behave at high pressure and temperature—work that is relevant to multiple HED disciplines. The process of establishing

60 Years of National Service

Validating Computer Models through NIF Experiments

To maintain and verify the performance of the nation's aging nuclear weapons stockpile without performing underground nuclear experiments, scientists rely heavily on integrated computer modeling and experimental validation of the physical behavior of individual weapons components. The National Ignition Facility (NIF), in only three years of operation, has become a cornerstone of the experimental element of stockpile stewardship.

Bruce Goodwin, the principal associate director for Weapons and Complex Integration and a veteran of many underground tests, began his career as an astrophysicist studying supernovae—rare events that occur in our galaxy about once every 400 years. Even when a supernova does occur, researchers cannot prepare for it or control the experimental conditions. Once they observe a supernova, they attempt to gather what data they can.

Goodwin notes that this approach is quite similar to past weapons experiments. "During an underground test, we could not directly measure the crucial parameters of a nuclear detonation," he says. At best, researchers could infer physical phenomena from the data acquired. An ongoing challenge was finding reliable methods to separate various weapons effects, since researchers could not simply turn off one part of an explosion.

"NIF changes the whole game," says Goodwin. "It allows us to perform experiments in a controlled environment and at a much higher rate than we ever could with underground testing. We can pick a problem apart and study individual physics pieces, which is immensely valuable. No longer do we have to wait and hope for a supernova event or attempt to parse information from an underground test with limited diagnostics. We can actually do experiments at NIF that benefit both stockpile stewardship and astrophysics research, with an array of state-of-the-art diagnostics to measure and record the results."

NIF can generate extreme pressures, temperatures, and densities—the three axes of the equation of state. For example, scientists have squeezed carbon to 100 million times Earth's atmospheric pressure using a special ramp-compression technique. "Ramped compression is truly a tour de force," says Goodwin. "The experiments on carbon helped confirm that we can do all of the pressure experiments we need for stockpile stewardship with NIF." Radiation transport is also central to the operation of nuclear weapons. With NIF, researchers can, for the first time, perform detailed radiation-hydrodynamic experiments.

In the two decades since underground testing ended, stockpile scientists have made great strides in improving computer models to simulate the complex interactions that occur in a nuclear detonation. But, adds Goodwin, "For experimental validation, we needed NIF." Integrating experimental results into these computational models provides confidence that the codes are reflecting nature. "The accuracy of our weapons models could mean the difference between a weapon working as designed and not," says Goodwin. "By eliminating luck and replacing it with rigorous testing and accuracy, NIF is meeting a need that no other research facility can." NIF will allow the Laboratory to maintain a preeminent role in the nation's stockpile stewardship efforts for many years to come.

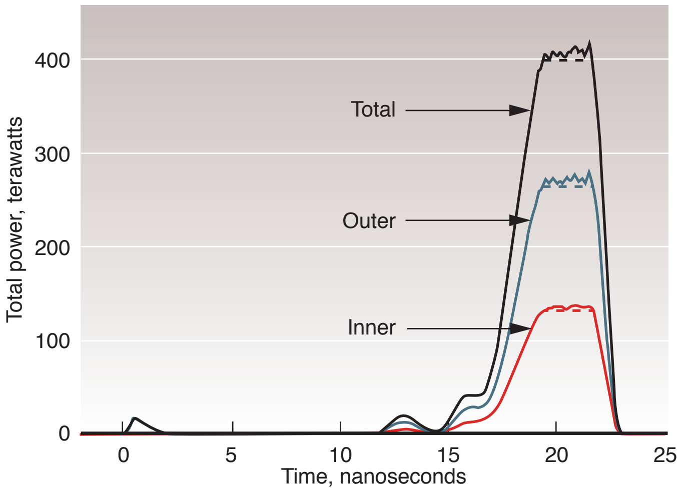
these platforms has laid the groundwork for future experiments and has already produced noteworthy results.

Radiation Transport

Within the dense clouds of gas and dust where stars are born, regions of interstellar gas will vary in density. As a star begins to form, it bathes the nonuniform cloud in radiation, producing shock waves and other radiation-driven hydrodynamic effects. Scientists are developing several NIF platforms for studying the interaction of radiation with matter. These platforms will allow researchers to examine the ionization of molecular clouds, star formation, and radiation transport through lower and higher density materials, phenomena relevant to astrophysics and stockpile science.

The Pleiades campaign is an HED science effort focused on developing a high-temperature NIF platform to study how radiation in the form of x rays interacts with matter. This effort, which is led by Los Alamos National Laboratory in collaboration with the Atomic Weapons Establishment (AWE) in the United Kingdom, is focused on better understanding the physics of stellar environments such as the bright blue star cluster for which the campaign is named. The Pleiades platform will help researchers evaluate how low-density matter behaves when it is driven by radiation at extremely high temperatures.

In the Pleiades experiments, 80 of NIF's 192 laser beams are directed upward at a half-hohlraum target. A half-hohlraum, or halfraum, is a metal cylinder with a laser entrance hole at only one end, whereas a hohlraum has entrance holes at both ends. Inside the halfraum, above and opposite the laser entrance hole is a tube made of substances with extremely low density, such as silicon dioxide or carbon foam. Laser beams hit the inside walls of the halfraum and generate x-ray photons, which illuminate the foam. The photons are absorbed by the foam, reemitted, and reabsorbed, producing a radiation wave



This graph displays the close agreement between the laser power requested (dashed) and delivered (solid) to the target chamber for inner and outer groups of beams and NIF's full 192 beams.

that travels the length of the tube. Because the radiation moves faster than the shock wave it produces, the foam is not displaced or heated by the shock.

Photons must reach extremely high temperatures for the radiative wave to exceed the shock speed. Thus, a crucial element in the Pleiades campaign was ensuring that the platform could consistently generate temperatures over 3 million degrees. To confirm this performance, researchers characterized x-ray emissions from the target at different angles using two x-ray power diagnostic devices known as Dante spectrometers.

The Los Alamos–AWE team then tested whether the target generated a supersonic wave. A time-integrated camera, the Dante instruments, and a spectral and time-resolved camera commissioned for Pleiades precisely measured when radiation exits the foam tube. Together, these diagnostics generate data regarding the temperature, velocity, and quantity of radiation transported through the foam.

Pleiades platform development produced at least one surprise. When the researchers noticed a mismatch between simulations and early experimental results, they realized that the experiments required more extensive target characterization. NIF's laser energy precision actually demanded greater accuracy for other experimental inputs, such as foam density, than researchers had anticipated. Says AWE physicist Alastair Moore, "We are now trying to assess all aspects of the foam for future shots so we'll know that the results we're measuring are due to the physics being studied, not to the material properties of the foam."

The new spectrally resolved camera also allowed the team to examine the spectral content of radiation entering and exiting the foam tube. This information helps constrain the foam's material properties, including its opacity and equation of state—how it responds to changes in temperature, density, and pressure. Information on material properties also enhances the fidelity of radiation transport models and codes that use the Pleiades experimental data.

NIF's high energy and precision are key assets for the Pleiades experiments. "Because of the laser energy available, we can heat enough material to have absorption events down the full length of the tube," says Moore. "We can't do that with other lasers." Los Alamos physicist John Kline adds, "NIF allows us to test larger samples with higher densities, resulting in more accurate measurements."

Shaping Plasma Evolution

A second experimental platform is designed to study the interaction of radiation with higher density material. In contrast to the Pleiades experiments, the radiation wave produced with this platform is closely coupled to the shock wave it creates in the medium. The team designing and commissioning the platform includes participants from Lawrence Livermore, Los Alamos, AWE, National Security Technologies, and General Atomics.

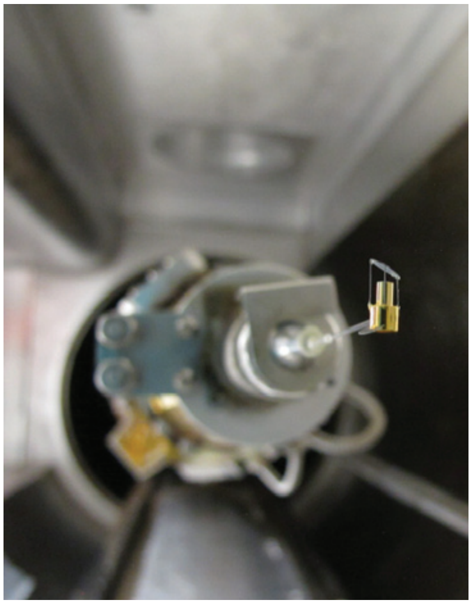
To examine how radiation travels through evolving density gradients, the researchers again use a gold halfraum to generate x rays. By precisely changing the shape of the laser pulse in time, they can control the temperature of the halfraum. Eighty laser beams illuminate one end of the halfraum and generate an x-ray temperature of 2.1 million kelvins—hot enough to strip electrons from neutral atoms and form a plasma. Affixed to the upper end of the halfraum is a thin piece of tantalum oxide foam with slots cut into it. Except for the slot openings, the foam is opaque to the x-ray photons. The radiation heats the foam and generates a plasma. As plasma is generated on the inner edges of the slots, it begins to fill in the openings, modifying the material's density profile and thus the radiation transport through the slots. As part of the commissioning work on this platform, a VISAR (Velocity Interferometer System for Any Reflector) diagnostic recorded the speed of a shock generated in an aluminum disk loaded in place of the foam target. The VISAR data provide a measure of the energy delivered to the target package and the angle at which beams hit the package. The shock velocity and angle were within an impressive 2 percent of predictions.

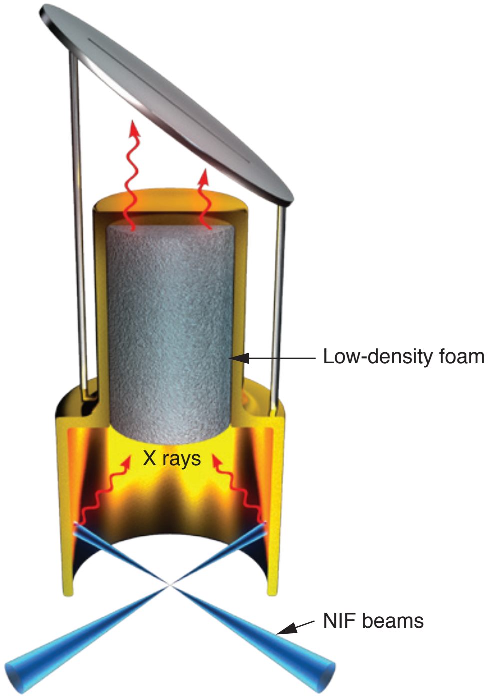
For some of these experiments, a gold calorimeter captures the energy passing through the slots. The two Dante devices measure x-ray emissions from within the hohlraum and the calorimeter. By comparing these measurements, scientists can determine how much radiation has been transported over time.

An alternate platform was developed to record the hydrodynamic evolution of radiation within the slot. Measuring the changes in a material's motion and density as well as the radiation transported provides a more complete data set for validating computer models. An x-ray source for radiography, similar to a dental x ray, is created by illuminating a target with eight NIF laser beams. X rays from the target pass though the plasma in the slot and are recorded with a time-resolved camera. The x-ray radiography source, or backlighter, developed specifically for this platform, enables precise measurements of a material's evolution over time.

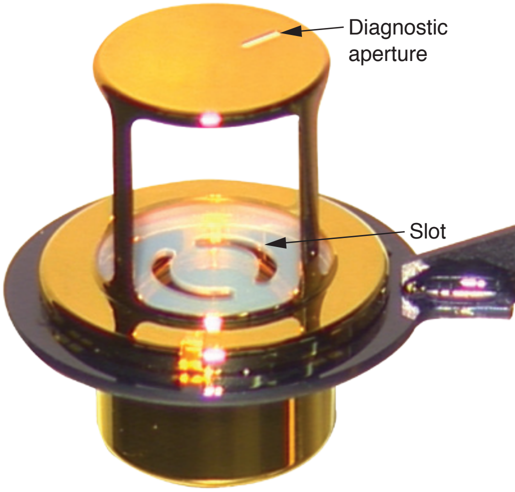
A series of calorimetry and radiography experiments collected physics data using the newly commissioned platforms. Scientists fielded a succession of slot patterns to test how radiation transport is affected by variables such as slot width and angle (straight or slanted), proximity of adjacent slots, and the effect of intersecting slots. Again, the experimental measurements aligned well with predictions. "NIF really delivered on shot-after-shot reproducibility," says Livermore physicist Stephan MacLaren, who worked on the experiments. "The laser's reproducibility was even better than expected."

MacLaren notes that the experiments have already provided enough high-quality data for scientists to evaluate and fine-tune relevant radiation-hydrodynamics models. Future endeavors will also benefit from this platform, which can produce the hot, precise stream of x-ray energy needed to





For the Pleiades experiments, 80 laser beams focus through a hole in the bottom of a hollow gold cylinder, causing x rays to illuminate a foam-filled tube. The "lid" positioned above the tube has a small opening for radiation to pass through for diagnostic measurements. (Rendering by Kwei-Yu Chu.)



study radiation flow. In fact, an upcoming effort will study the radiatively driven molecular clouds of the Eagle Nebula, a region of active star formation about 6,500 light-years from Earth.

The Pressure Builds

Another important area of HED research is examining solids under extremely high pressures and densities—conditions that exist at Earth's core, inside giant planets such as Jupiter and Saturn, or those relevant to stockpile science. At high pressures and densities, materials can behave in complex and sometimes unpredictable ways. Subjected to sufficient pressure, a material may even form a previously unknown molecular arrangement with new properties.

To accurately map this behavior, researchers perform experiments to find a material's equation of state. Livermore physicist Jon Eggert says, "NIF is the only facility where we can study solids at pressures above a few million times Earth's atmospheric pressure." This information is then incorporated into weapon simulations and astrophysics codes to better understand a material's characteristics under such extreme conditions.

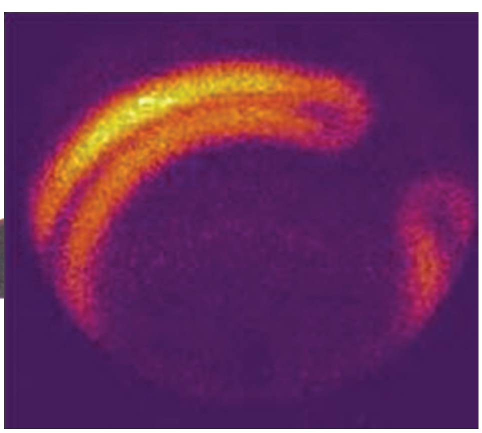
Livermore scientists often use tantalum, a dense and very hard metal, as a substitute for fissile materials in hydrodynamics research. NIF experiments on tantalum are allowing researchers to examine the strength, compressibility, and phase transitions (in this instance, from one solid crystalline state to another) of materials at high pressures. For these experiments, 176 laser beams are directed at a gas-filled hohlraum, which converts the laser power to x-ray power. Mounted on the side of the hohlraum is a target with a high-density carbon layer topped by a stepped sample made from tantalum (or other material). Each layer has a different thickness.

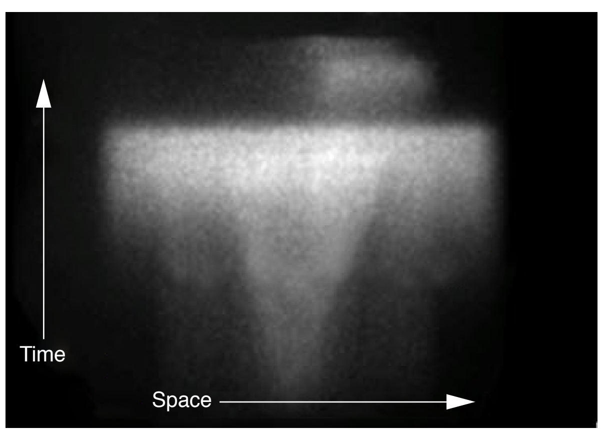
X rays heat and ablate the high-density carbon, driving a pressure pulse into the tantalum. The laser energy directed into the hohlraum is tailored so that the x-ray power on the high-density carbon layer increases in a controlled, ramped fashion, gradually compressing the tantalum samples to high pressure while keeping the tantalum below its melt temperature. Instantaneous shock compression tests cannot detect phase transitions, but ramped compression over a period of about 25 nanoseconds can. (See *S&TR*, June 2009, pp. 22–23; July/August 2007, pp. 20–21.)

Characterizing the high-density carbon properties is important for platform development because the carbon serves as both a pressure-inducing layer and a "window" for the equation-of-state experiments. A window is a layer applied to the exterior of the stepped tantalum sample. It is typically made of a strong yet transparent material that preserves the sample's surface at high pressure yet allows light to pass through to diagnostic detectors. Knowing the window's compressibility and opacity with great accuracy helps scientists interpret diagnostic measurements correctly.

A smooth, shock-free compression produces the most accurate thermodynamic analysis. To prevent the laser pulse from generating a shock and possibly melting the sample, researchers must customize the pulse shape precisely to match the material being compressed. Accurate knowledge of the sample material's compressibility is necessary to optimize the laser pulse shape, which requires several iterations of data gathering and pulse adjustment. Because of the precision and repeatability of NIF and its diagnostics, this process can be performed rapidly and efficiently, sometimes with only one or two shots.

VISAR records the velocity of each layer. By comparing data from the different thicknesses, scientists can deduce the sample's equation of state. The streak cameras are carefully calibrated to acquire data with spatial and temporal accuracies within a few percent. A calibration system built specifically for these experiments generates a series of precisely timed optical impulses at 10 locations across the input slit of the streak camera, right before and immediately after each shot. The resulting calibration information is used in the VISAR data analysis.





Scientists use two primary diagnostic techniques to study radiation as it passes through a feature, such as the slot cut in the lightweight foam (left) mounted on top of a target. Time-integrated x-ray emission (middle) or streaked radiography (right) measurements document the evolution of radiation as it moves through the feature.

NIF experiments using the ramped-compression platform have acquired data on tantalum more than 10 million times Earth's atmospheric pressure and have reached nearly 10 times that amount of pressure on high-density carbon. Although experiments on high-density carbon have achieved spectacular pressures, experiments on the much denser tantalum samples have produced more intriguing results. The first tantalum experiment unexpectedly produced a shock at around 3.5 million atmospheres (roughly the pressure at Earth's core). Even after adjusting the pulse shape and laser drive energy for subsequent experiments, shocks still occurred at around the same pressure.

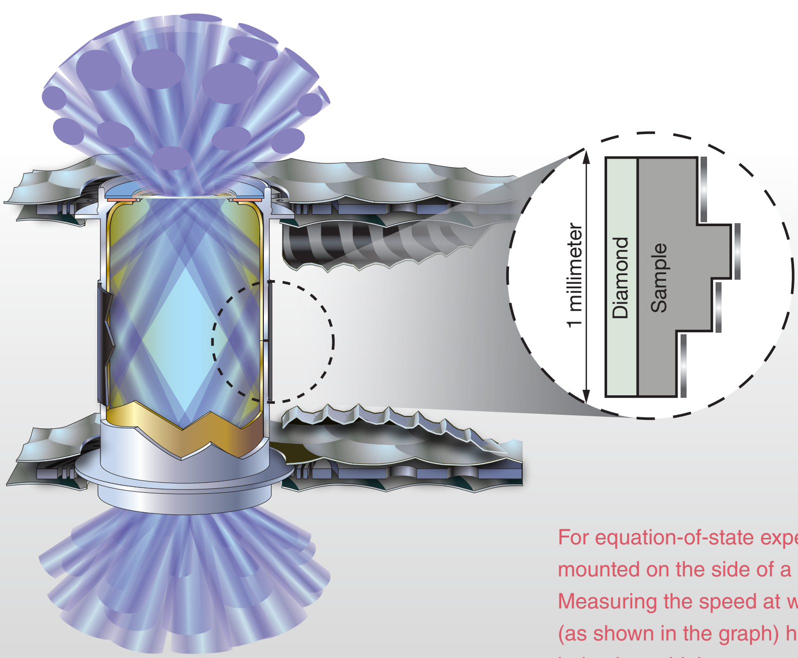
The team suspects that the tantalum behavior is signaling a previously unrecorded phase transition. "Unexpected events such as this are at the heart of scientific discovery," says Edward Moses, principal associate director for NIF and Photon Science. Results from gas-gun and diamond-anvil-cell experiments indicated a possible phase transition in tantalum, but confirming the discovery will require further study. Meanwhile, the researchers have modified the target design and laser pulse shape so they can collect the high-pressure data required for platform development.

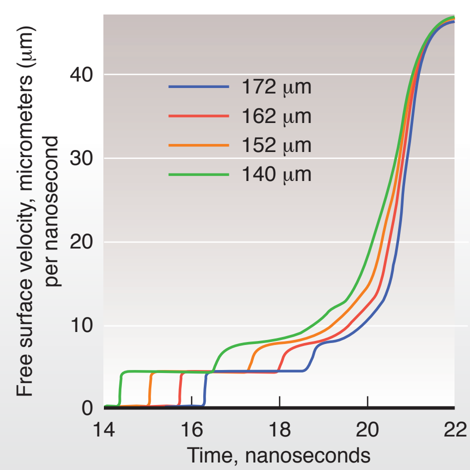
Inducing Instability

Livermore scientists are commissioning a separate platform to investigate the strength of materials at extreme pressures. This experimental arrangement has been used to demonstrate ramped compression up to 4.5 million atmospheres in molybdenum and nearly 10 million atmospheres in tantalum. As commissioning experiments continue, scientists will increase the laser energy to compress rippled samples and measure the ripple growth over time to understand how the material responds to stress.

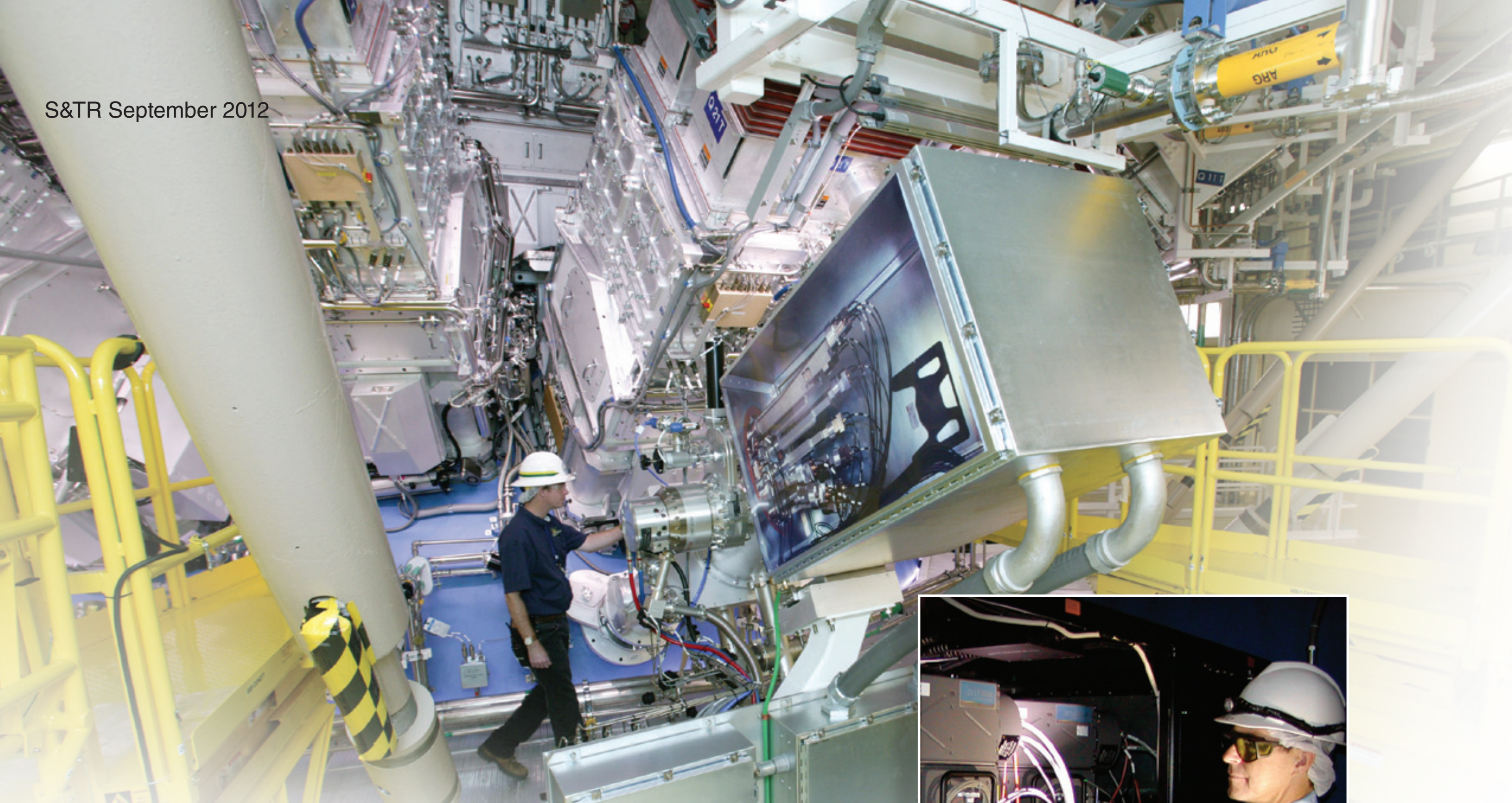
These experiments are designed to produce a hydrodynamic phenomenon called Rayleigh–Taylor instability at the interface between two materials, one heavier than the other. The target package consists of a multilayered structure known as a reservoir, a 50-micrometer-thick sample of rippled tantalum, and a layer of carbon foam that is less dense than the tantalum. Laser energy heats the hohlraum and produces x rays. The x-ray energy generates plasma, which heats and expands the reservoir and compresses the tantalum sample. The ripple machined into the front surface of the sample grows via Rayleigh–Taylor instability, and an x-ray backlighter records the changes. "By examining the ripple growth, we can test various strength models," says Livermore physicist Brad Wallin. "A material that resists deformation will inhibit instability growth. In a weaker material, instability increases quickly."

In these experiments, researchers are fielding the largest hohlraums ever fired





For equation-of-state experiments, four sample thicknesses of a material mounted on the side of a metal cylinder undergo ramped compression. Measuring the speed at which each sample moves during the experiment (as shown in the graph) helps researchers better understand material behavior at high pressure.



Diagnostics that excel at precision measurements over short timescales and distances are essential to high-energy-density science experiments. Key diagnostics include (above) Dante, a broadband, time-resolved x-ray spectrometer, and (right) VISAR, a time-resolved Doppler velocity camera, which in this photo is being aligned by Livermore scientist Gene Frieders.

at NIF: 16-millimeter-long gold cylinders large enough to hold a standard NIF ignition hohlraum. (See *S&TR*, June 2012, pp. 16–19.) Experiments tested both gas-filled and vacuum hohlraums, but only the gas-filled ones produced the continuous pressure increase necessary for shock-free compression. The laser pulse, diagnosed using VISAR and corroborated by Dante, was very repeatable and in agreement with simulations in terms of pressure ramp timing and peak pressure.

Scientists are testing other high-density materials for use as reservoir layers to determine how those properties influence the timing of the pressure pulse on the tantalum. Experiments performed in June 2012 characterized tantalum and compared copper and palladium as candidate materials for the reservoir.

Recent enhancements have boosted NIF's power and energy to its full design specifications, which benefits many experimental configurations, including those to push material strength and equation-of-state experiments to even higher pressures. Some new platforms, such as one to study high-temperature material opacity, have become possible for the first time with the boost in capabilities.

Hsing notes that the goal is to develop two to three new HED platforms a year. Each new platform extends the scope of scientific inquiry available at NIF. Those already commissioned have demonstrated the laser's ability to perform precise experiments that are relevant to both stockpile stewardship and basic science research and provide a reliable and flexible foundation for future exploration of HED phenomena. As Wallin says, "Scientifically, NIF is taking us into regimes no one has been to before."

—*Rose Hansen*

Key Words: backlighter, Dante spectrometer, equation of state, halfraum, hohlraum, National Ignition Facility (NIF), Pleiades campaign, ramp compression, Rayleigh–Taylor instability, Velocity Interferometer System for Any Reflector (VISAR) diagnostic.

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