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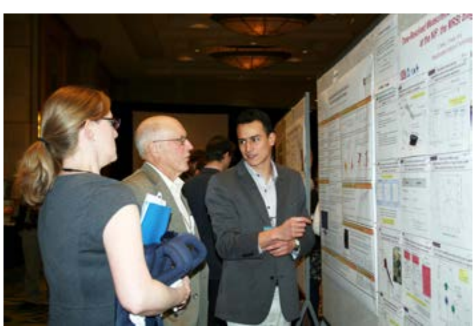
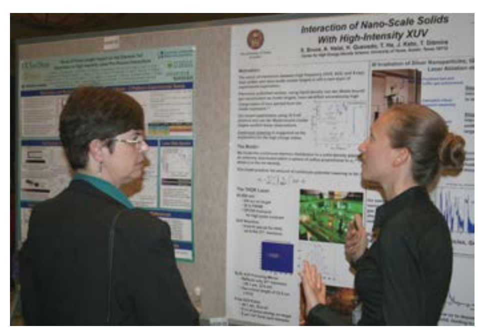
Message from the Assistant Deputy Administrator for Research, Development, Test, and Evaluation, Dr. Kathleen Alexander

Showcasing examples of the capabilities that National Nuclear Security Administration national laboratories and sites bring to the Stockpile Stewardship Program (SSP) is one of the key intents of the *Stockpile Stewardship Quarterly* (SSQ). SSQ articles celebrate representative successes of our programs that are made possible by the incredibly talented staff that contributes to these efforts. This issue of SSQ highlights some major diagnostics which enable important SSP experiments and also discusses the role and impact of Laboratory Directed Research and Development (LDRD) on SSP.

The first article in this issue summarizes a major diagnostic on the National Ignition Facility (NIF), the Advanced Radiographic Capability (ARC). ARC is able to produce a bright source of penetrating high energy x-rays for target backlighting that is not possible with current NIF x-ray sources and sources at other high energy density experimental facilities. The second article describes a next-generation diagnostic for experiments at the Nevada National Security Site. It diagnoses the behavior of materials under highly explosive dynamic shock conditions and has been transformative for U1a Complex experiments. The next article highlights representative University of Rochester Laboratory for Laser Energetics diagnostics from the 160 diagnostics on OMEGA. It will focus on diagnosing the burn averaged hot spot pressure and other key performance metrics for layered deuterium-tritium implosions on OMEGA. These diagnostics have served as a basis for NIF diagnostics. The final article in this issue highlights select LDRD projects from the program's more than 25-year history, which have had a significant effect on the SSP and, in general, have had a significant scientific impact within the high technology industries.

Inside





This year's SSAP Annual Review Symposium, held February 17-18 at the Bethesda North Marriott in Bethesda, Maryland, hosted more than 300 academic partners, NNSA national laboratories staff, and NNSA staff. Geared toward NNSA-supported researchers with grants and cooperative agreements, the work of students and postdoctoral researchers, and university faculty was highlighted in the more than 120 posters on display during the poster reception.

Comments
The *Stockpile Stewardship Quarterly* is produced by the U.S. Department of Energy/National Nuclear Security Administration (DOE/NNSA) Office of Research, Development, Test, and Evaluation. Questions and comments regarding this publication should be directed to Terri Stone at terri.stone@nnsa.doe.gov.
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Recent Progress on the National Ignition Facility Advanced Radiographic Capability *by P. Wegner, M. Bowers, H. Chen, J. Heebner, M. Hermann, D. Kalantar, and D. Martinez (Lawrence Livermore National Laboratory)*

The National Ignition Facility (NIF) is a megajoule (million joule)-class laser and experimental facility built for stockpile stewardship and high energy density (HED) science research.[1] Up to several times a day, 192 laser pulses from NIF's 192 laser beamlines converge on a millimeter-scale target located at the center of the facility's 10-meter-diameter target chamber. The carefully synchronized pulses, typically a few nanoseconds (billionths of a second) in duration and co-timed to better than 20 picoseconds (trillionths of a second), deliver a combined energy of up to 1.8 megajoules and a peak power of 500 terawatts (trillion watts). This drives temperatures inside the target to tens of millions of degrees and pressures to many billion times greater than Earth's atmosphere.

The need to better understand the physical processes occurring in NIF experiments over time scales measured in picoseconds has required researchers to develop a new generation of ultrafast, ultrahigh-resolution diagnostic capabilities.[2] One such capability, the Advanced Radiographic Capability (ARC), enhances the suite of detectors, spectrometers, interferometers, streak cameras, and other instruments deployed on NIF. ARC is a kilojoule petawatt-class laser—that is, it can deliver more than 1,000 joules of energy at peak powers exceeding a quadrillion (10^{15}) watts. Following in the footsteps and building on the capabilities of successful petawatt systems built at other HED experimental facilities,[3-9] ARC is able to produce a brighter source of penetrating, high-energy x rays for target backlighting than is possible with current NIF x-ray sources.[10] With ARC, scientists can record a series of snapshots revealing the dynamics of NIF target materials under extreme conditions of density, temperature, and pressure. When combined, these images can reveal changes in complex two-dimensional features over time.

ARC achieves its extreme laser intensities through chirped-pulse amplification, a common architecture for short-pulse lasers.[11] In this process, an ultrashort laser pulse, only picoseconds or femtoseconds (10^{-15} seconds) long, is first stretched in time to reduce its intensity. The frequency content of the ultrashort pulse is distributed in time to create a nanosecond-long, frequency-swept (chirped) pulse that can be amplified without generating intensities above the damage limit of laser glass and optics. After amplification, the chirped pulse is passed through an arrangement of diffraction gratings called a pulse compressor to undo the frequency sweep and re-create the initial short pulse, thus producing a high-energy, high-power laser pulse.

Figure 1. Laser technicians commission the new short-pulse optical parametric amplifier (OPA) in the upgraded ARC front end. The inset shows a measurement of beamlet temporal pulse contrast at the output of a front end diagnostic compressor, demonstrating that the new architecture meets flow-down requirements for pre-pulse.

Multi-frame radiography employing x-ray back-lighters has been a standard diagnostic technique on NIF, but to date it has lacked the image quality, penetration levels, speed, and flexibility of the ARC design. ARC splits each of the four beams in one NIF quad into two apertures (beamlets), producing up to eight petawatt-class laser pulses that can be used to create high-energy x-ray images of the target (only four of which are planned to be implemented). When fully implemented, each of these beamlets will be capable of producing energy ranging from 0.4 to 1.7 kilojoules at pulse durations between one and 50 picoseconds with delays up to 80 nanoseconds. A single beam of ARC (two beamlets) will deliver up to 500 terawatts of power—the same level of power NIF generates with 192 beams.

This past year saw the completion of several important milestones in the development and commissioning of the ARC, specifically the installation of a new "high contrast" front end, the ramping of the first two ARC beamlines (four beamlets) to a total energy of four kilojoules on simple foil targets, and the acquisition of the first ARC radiograph.

The ARC front end is the section of the system responsible for producing the low-energy (a few millijoules) chirped pulses that are injected into the NIF amplifier. One of its many stringent performance requirements concerns pre-pulse, or the amount of laser light that can arrive at the target ahead of the compressed pulse. Too much pre-pulse adversely affects x-ray conversion efficiency and increases the apparent size of the backlighter source through plasma blow-off and target motion.[12] For the ARC, the allowable pre-pulse levels at the target flow back to a requirement for the allowable pre-pulse power at the output of the front end of ≤ 10^{-8} (-80 dB) of the peak power in the compressed pulse. To ensure this high level of temporal pulse "contrast," the front end was upgraded this past year to employ a state-of-the-art short-pulse optical parametric amplifier (OPA) architecture similar to that developed for the OMEGA EP laser at the University of Rochester.[13] In this scheme, a 1.053-micron wavelength sub-picosecond pulse selected from a commercial mode-locked neodymium (Nd):glass oscillator is amplified from a few billionths of a joule up to a few microjoules in a single beta-barium borate (BBO) crystal. The pump pulse for the OPA is derived from a second pulse from the same oscillator that is first passed through a regenerative amplifier to increase its energy to a few millijoules and broaden its pulse duration to about 10 picoseconds. It is then frequency-converted to the second harmonic wavelength of 0.5265 microns in a BBO crystal (see Figure 1). This architecture has the advantage of being inherently low noise on time scales important for pre-pulse, because any parametric fluorescence that occurs during the amplification process is confined to the 10-picosecond duration of the pump pulse. The amplified signal pulse exiting the OPA is stretched in time (chirped) and then split two ways to form the seed pulses for the two ARC beamlets that make up each ARC beam. A parallel set of "tweaker" compressors allow the chirp of each beamlet to be adjusted relative to the dispersion of the compressor for independent pulse width control. A parallel set of delay trombones and spectral shapers enable independent timing and pulse shape control. Amplification to the millijoule level is accomplished in a parallel set of Nd:glass regenerative amplifiers.

A single beam of ARC (two beamlets) will deliver up to 500 terawatts of power—the same level of power NIF generates with 192 beams.

The integrated performance of the ARC system with the new front end was tested during the fourth quarter of fiscal year 2015 in a carefully coordinated campaign that addressed diagnostic calibration, focal spot quality, precision pointing, precision timing, energetics, and back-scatter isolation. Optimizing the focal spot quality of each beamlet is achieved by firing low-energy regenerative amplifier pulses (one beam at a time) to a sensor located at the center of the target chamber and "dithering" the actuators of the deformable mirror in the main laser cavity to optimize the focal spot by maximizing the intensity in the central lobe of each spot. The resulting mirror figure is then offset to add the pre-figure needed to cancel the prompt wavefront distortion that occurs when the main amplifiers are fired. Direct measurement of the high-power focal spot(s) at the target is not possible, so this procedure has been validated by executing it to an equivalent focal plane camera in the ARC diagnostic package at the output of the ARC compressor. The results show that the focal spot quality varies among the four commissioned beamlets, but is consistent shot to shot, with the best beamlets performing on par with the optimized focal spot quality measured during NIF commissioning[14] upon which the ARC specifications are based. Additionally, x-ray images of the individual beamlets incident on the gold foil targets showed x-ray spots that were similar in size to the optimized focal spots. Precision timing of beamlets has been established to better than 10 picoseconds rms using standard NIF timing techniques,[15] and validated with the SPIDER diagnostic,[16] a fast x-ray streak camera that records hard x-ray emission vs. time from the ARC interaction with the target. The pointing accuracy has been verified to meet requirements by imaging the locations of the soft x-ray emission produced by a few hundred joules per beamlet focused onto special pointing targets, including geometries that simulate aligning to a wire similar to the HED backlighters. Operation up to one kilojoule per beamlet in a sequence of shots onto gold foil targets in which the pulse energy was increased incrementally while monitoring diagnostics in the front end confirmed that back-reflected signal levels remain negligible. The tests were conducted with the compressed pulse duration set to 30 ± 5 picoseconds consistent with specifications for the first planned physics experiments (see Figure 2).

After it was demonstrated that ARC could be fired onto a target with up to one kilojoule per beamlet, the first radiograph test was performed. The test target consisted of a 10-micron-diameter silver wire mounted on a 500-micron square flag and oriented along the line of sight to a resolution grid located 28 mm away (see Figure 3). This configuration provides a near-point source of x rays projected through the resolution grid onto an image plate located 553 mm away. The four ARC beamlets were co-pointed to the wire with 900 joules per beamlet and a 30-picosecond delay applied between pairs of beamlets to create a 60-picosecond-duration x-ray pulse. A high-resolution shadow image of the grid was obtained (see Figure 4). The signal level recorded is sufficient to provide the signal-to-noise ratio

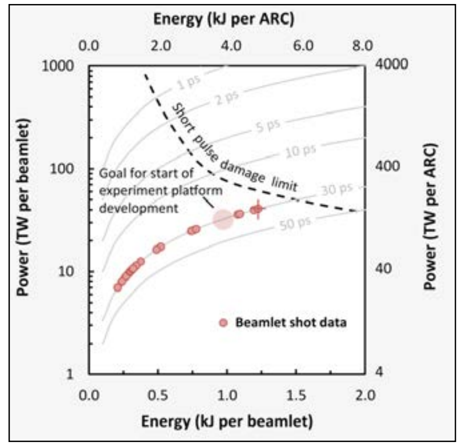

Figure 2. The ARC can produce energies above 1.5 kilojoules per beamlet and powers above 400 terawatts per beamlet, depending on pulse duration. The plotted points show beamlet data obtained during commissioning of four ARC beamlets at 30 picoseconds pulse duration.

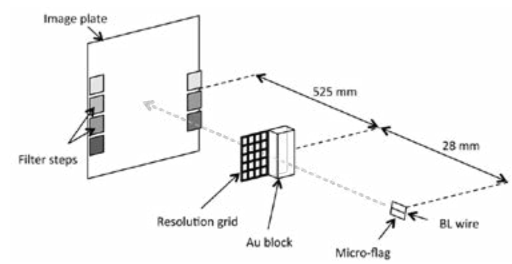

Figure 3. Schematic of the backlighter (BL) experiment configuration. The 10-micron silver wire produced a near-point-source x-ray emission to backlight a gold block and resolution grid. The resulting shadow image was recorded on an image plate. A series of filter steps were used to diagnose the backlighter spectrum (magnification of the system is 19.75x).

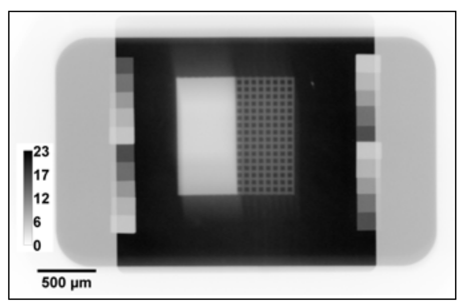

Figure 4. Image plate radiograph of a grid and block using a silver micro-wire heated by four ARC beamlets. The color scale is shown in Photo-Stimulated Luminescence (PSL) and the spatial ruler represents the scale at the target. Exposure on the image plate due to transmission through the filter steps was used to estimate the backlighter spectrum.

needed for complex hydrodynamics experiments, and the measured spatial resolution of approximately 22 microns meets requirements. The test results also indicated that prepulse was sufficiently low. Successfully acquiring the first high resolution x-ray radiograph with ARC gives confidence that ARC is ready to support platform development activities and the fielding of complex hydrodynamics and Compton radiography physics experiments in the coming year.

Acknowledgements

The authors thank the many members of the ARC team who delivered this important new diagnostic capability for the National Ignition Facility. We also extend our thanks to Christophe Dorrer and his colleagues at the Laboratory for Laser Energetics at the University of Rochester for their assistance in upgrading the ARC front end.

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Shocked Surface Stereo Imaging with Fiber-Optic Imaging Probes: A Next-Generation Diagnostic for Subcritical and Other Experiments *by Stuart Baker, Brent Frogget, and Abel Diaz (National Security Technologies, LLC)*

Introduction and Motivation

A picture tells a thousand words—this is a concept that captivates everyone, from the casual observer to the experimental physics scientist. To bring this concept to light in support of Stockpile Stewardship subcritical experiments executed at the Nevada National Security Site (NNSS), we have developed a new diagnostic tool to investigate the behavior of materials under high-explosive dynamic shock conditions. For the Leda subcritical experiment executed in August 2014, a single line-of-sight imaging system was designed and fielded as a stretch diagnostic goal for National Security Technologies, LLC (NSTec). For the Lyra series, beginning with the Orpheus experiment in September 2015, a newly created dynamic stereo surface imaging (DSSI) capability was deployed. The DSSI diagnostic records a high-speed image sequence that allows scientists to peer inside an imploding hydrodynamic test article with stereoscopic imaging.

The DSSI provides visual measurements of the shocked surface to supplement velocimetry data, which measures speed, recorded by the multiplexed photonic Doppler velocimetry (MPDV) diagnostic. When combined with MPDV and radiography datasets, DSSI data assist weapons designers to build confidence in the models used to predict material behavior under extreme shocks. DSSI will aid understanding of phenomena such as melt, phase change, or ejecta, conditions that are often difficult to resolve. Joined with several MPDV data points, DSSI enables measurement of the inside of an imploding weapon-relevant material in an actual weapon geometry at scale.

Early versions of this diagnostic were fielded in single line-of-sight borescope experiments with the Atomic Weapons Establishment (United Kingdom) in 2005. A borescope is an instrument used to inspect the inside of a structure through a small hole. The borescope version struggled with piping enough light into the vessel for the short exposure times required in the explosive experiment. But a proposal to improve the technology led to successful Site Directed Research and Development projects in 2006 and 2007 that explored the concept of using two imaging probes to provide depth perception in a stereo image. Dynamic stereo images of explosively shocked coupons were recorded at NSTec, where short-range photogrammetry techniques were tested on the images. At that time, the diagnostic still suffered limitations in image quality due to the small fiber-optic probe technology.

Recent advances in fiber-optic probe capabilities have made it possible to integrate the DSSI into the Lyra series diagnostic package. The original flash lamp strobe illumination system has been replaced with a multi-pulse laser system to illuminate the frame exposures. The dynamic experiment is confined in a vessel, which requires vessel lid feedthrough penetrations for the laser illumination and imaging fiber-optic bundles. The optical schematic is shown in Figure 1.

Challenges and Solutions

Projecting a bright image through a very small hole is no small task. During the Leda experiment, we were able to use a small probe through the glide plane to achieve this. For Lyra, the method was expanded to stereo imaging by the addition of another small probe and small optical wedges to make the two views overlap. To accommodate the wedges, a narrowband (laser) light was used to avoid a chromatic 'rainbow' effect of a prism. Laser light gives the added flexibility of increased power and multi-pulse shaping. For this system, laser speckle noise is negligible.

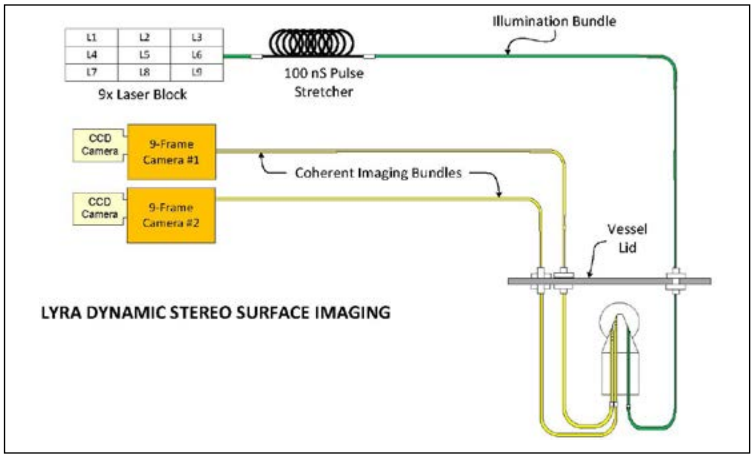

Figure 1. Optical layout for DSSI interface to the physics package.

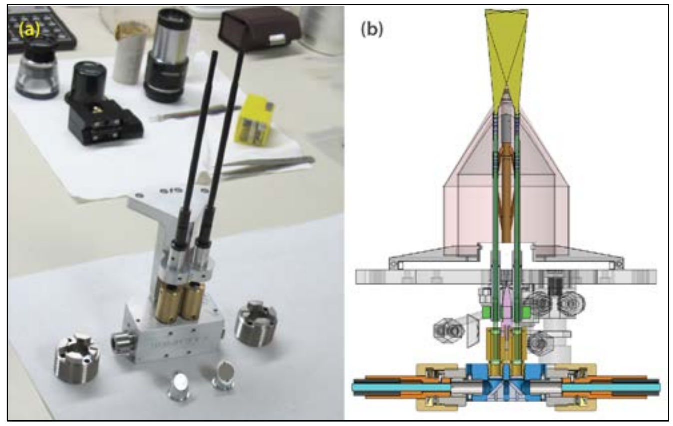

Figure 2. (Left) Imaging probe assembly with mirror box. (Right) Image probes coupled to image bundles in diagnostic package shown in the completed assembly design.

For each view, a small lens focuses light from the surface to a small-diameter, long-graded index (GRIN) lens rod. The GRIN lens directs the image out of the experimental package. Once out of the package, the image is expanded by a small magnifier lens relay for transmission by coherent fiber-optic bundles and pressure containment fiber plugs to cameras outside the chamber. A larger image results in better resolution through the coherent fiber-optic bundles. Views of the GRIN probe assembly are shown in Figure 2.

Stereo correlation is the process of recovering depth information from stereo camera images by quantifying the relationship between multiple views. The idea is to calibrate a stereo camera system by taking multiple images of a calibration target, such as a checkerboard pattern, at multiple orientations to map the three-dimensional (3D) image space. From correlating these images, estimates of the intrinsic properties of the camera system, such as focal length, relative position of the cameras, and lens distortions can be determined. By applying the intrinsic properties to a set of data images taken by the same system, a 3D visualization of the scene in real-world coordinates can be produced. By taking a number of stereo images at various times during an experiment, a 3D movie can be created allowing for a unique perspective. Stereo views of a test object are shown in Figure 3.

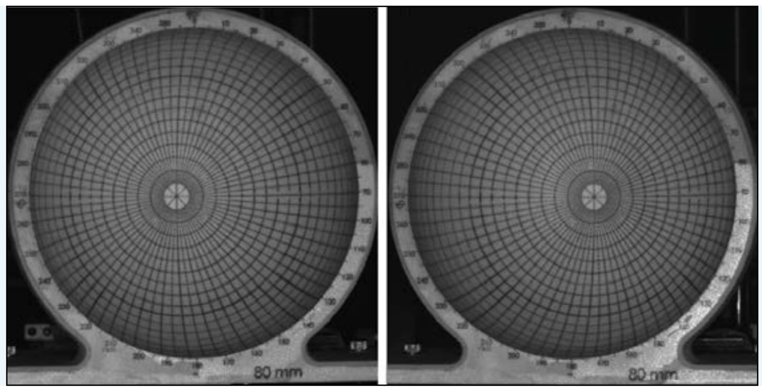

Figure 3. Left and right views of a large dome calibration target.

The stereo images are processed to provide a relief surface map. The DSSI data supplement the MPDV data to provide a more comprehensive evaluation of the dynamic shock behavior of the material. The DSSI field-of-view overlapping MPDV points are shown in Figure 4 (left).

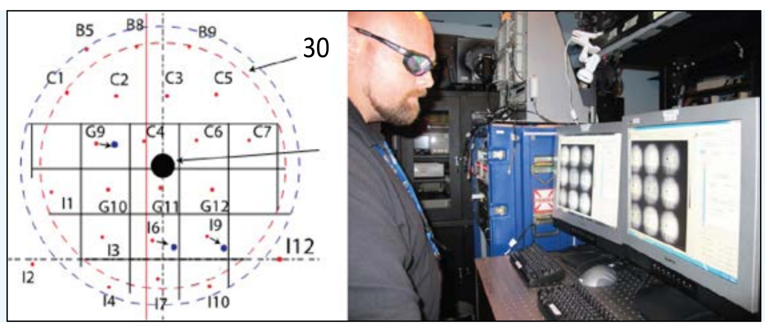

Figure 4. (Left) Surface field of view with MPDV points. (Right) Resolution test images.

The newly designed DSSI diagnostic debuted on Orpheus, the first experiment in the Lyra series. It will be used throughout the Lyra series. The framing camera data acquisitions of left and right views of a resolution target with pulsed laser illumination are shown in Figure 4 (left). Future developments include modifying the optical relay system, incorporating digital framing technology, and applying current digital image correlation techniques, which has the potential to provide stress and strain detail of the deformed surface.

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An Overview of Diagnostic Systems Used on OMEGA *by Craig Sangster (Laboratory for Laser Energetics, University of Rochester)*

Before focusing on our array of diagnostics at the Laboratory for Laser Energetics (LLE), we introduce the facility and context for the broad array of diagnostics discussed in this article. The Omega Laser Facility at LLE consists of a 60-beam, 30-kJ_{UV} symmetric illumination compression facility, OMEGA, and a 4-beam, 30 kJ_{UV} (National Ignition Facility (NIF) architecture) planar illumination facility, OMEGA EP (EP). Two of the EP beams can be compressed in time for high intensity (in excess of 10^{19} W/cm^2) high energy density physics (HEDP) and basic science applications. One of the high intensity EP beams can be directed into the OMEGA target chamber for backlighting and is often used to image the deuterium-tritium (DT) shell of an ignition hydro-scaled direct-drive implosion as it nears stagnation. A plan is being developed to bring a long-pulse EP beam into the OMEGA target chamber. The OMEGA facility has the most comprehensive set of inertial confinement fusion (ICF)/HED diagnostics (approximately 160 individual instruments can be requested on the Shot Request Form) of any facility in the world and has been a staging/development facility for NIF. The EP facility has become a workhorse for HEDP-relevant materials science, laser pre-heating studies for the Magnetized Liner Inertial Fusion (MagLIF) concept, and ultra-high-intensity physics; EP shares much of the diagnostic capability of OMEGA.

Between the cessation of operations at the LLNL Nova facility in 1999 and the beginning of the National Ignition Campaign on the NIF in 2009, the Omega Laser Facility performed approximately 15,000 experiments for the Stockpile Stewardship Program (SSP) and Basic Science (via the National Laser Users' Facility, and since 2008, the Laboratory Basic Science program). During that decade, much of the diagnostic and component technologies for NIF were developed and tested using thousands of shots on both OMEGA and EP. Examples include 1) the widespread use of CR-39, a plastic polymer used to record the spatial location and energy of incident charged particles;[1] 2) Chemical Vapor Deposited (CVD) diamond detectors for neutron time-of-flight (nTOF) spectroscopy;[2] 3) temporally-gated photomultiplier tubes (PMT) for low energy neutron spectroscopy;[3] 4) Cherenkov radiation for γ-ray spectroscopy and burn history measurements;[4] 5) image plates for high energy x-ray imaging;[5] 6) neutron imaging systems;[6] 7) new scintillator materials with properties designed for specific applications;[7] 8) the development of new optical and x-ray streak cameras with extended dynamic range and ultra-fast sweep speeds (2 ps);[8] and 9) a new generation of x-ray framing camera.[9] A full accounting of this work is beyond the scope of this report but is captured in the included references.

While OMEGA and EP have many optical and x-ray diagnostics used to measure laser-plasma coupling, this report will describe the diagnostic systems used to infer the burn-averaged hot-spot pressure (P_{HS}) and other key performance metrics for layered DT implosions on OMEGA. The P_{HS} is calculated[10] using the formula below assuming an isobaric hot spot:

$$P_{hs} \simeq \left[8Y\sqrt{\ln 2/\pi} \Big/ \left(\Delta t_{burn} \int_{V_{hs}} dV \langle \sigma v \rangle / T^2 \right) \right]^{1/2},$$

where Y is the primary DT yield, the Δt_{burn} is the fusion burn width, the integral over the hot-spot volume is $(4/3)\pi R^3$ where R is inferred from x-ray core images, and T the ion temperature. Other important performance metrics described in the document *Priority Research Directions of the National Inertial Confinement Fusion Program* (2016) include the fuel adiabat (inferred using shock timing measurements and the fuel areal density) and the implosion velocity.

Neutron Yield, Ion Temperature, and Areal Density

Neutron time-of-flight spectroscopy is used to measure the primary neutron yield, the fuel ion temperature (T_{ion}) and the fuel areal density (ρR) in ICF implosions. The temperature of the burning plasma is encoded in the distribution of the emitted neutron energies (the energies vary due to the thermal distribution of ion velocities in the plasma). Long flight paths to the various nTOF detectors ensure that the spread in neutron arrival times is comparable to or larger than the impulse response of the detector. In the absence of turbulent and collective fuel motion, the thermal temperature is then the quadrature difference in the measured neutron line width (in time) and the measured impulse response. The integral of the signal from an nTOF detector can be calibrated (e.g., against standard activation diagnostics) to provide the absolute neutron yield. To infer the areal density, one of the OMEGA nTOF detectors uses gated PMTs to measure the neutron backscatter from the dense tritium. The elastic (n,T) backscatter edge is shown in the green shaded area of Figure 1; the number of neutrons in this edge region is proportional to the fuel areal density[11] provided the T/D ratio is known. Here, the blue line is the measurement and the red line is the fit based on the known signal (the neutron backscatter cross section is quite well known) and background components in the neutron spectrum (explicitly shown in the figure). The peak at 2.45 MeV is the DD fusion line (the energy scale is at the top of the figure). The gated PMT ensures that the several hundred times larger signal from the primary DT fusion line is not recorded; this signal would overwhelm the backscatter edge and the DD line in the recording system.

Fuel Areal Density

The areal density is also measured using a magnetic recoil spectrometer (MRS) where the active detector is CR-39. The MRS was originally developed by the Massachusetts Institute of Technology

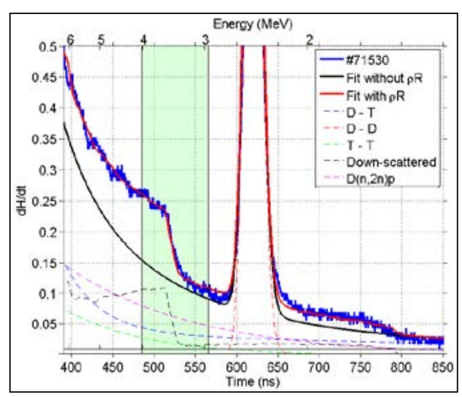

Figure 1. The measured neutron spectrum (blue) between 1 and 6 MeV is compared with the fitted spectrum (red) that includes the forward downscattered and backscattered components from the DT fuel, the measured TT fusion spectrum, and the (n,2n) breakup of deuterium (10x larger that the triton breakup which is negligible).

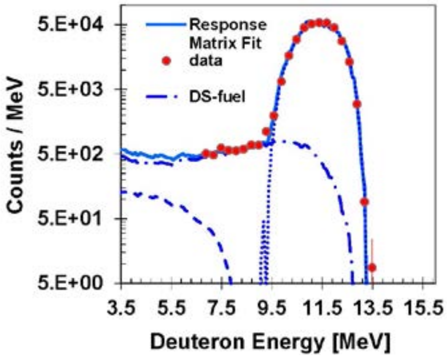

Figure 2. The deuteron spectrum measured by the MRS. The shape of the spectrum is determined by the incident neutron spectrum. The ρR is inferred from a fit (the dot-dash line) to the spectrum assuming the down scattering (DS) occurs in a uniform fuel distribution.

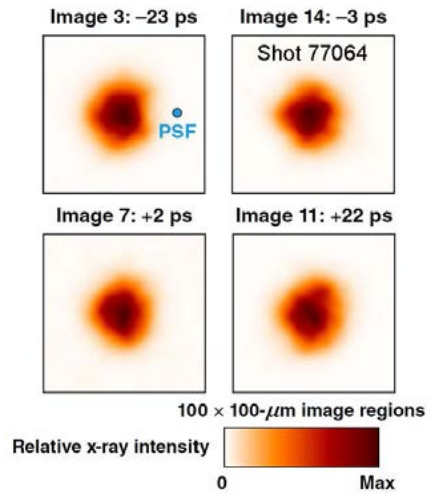

Figure 3. Four sequential images spanning the bang time (the time above each image is relative to the bang time) from a layered DT implosion on OMEGA recorded using the new KBFramed diagnostic. The blue dot represents the spatial blurring due to the instrument response.

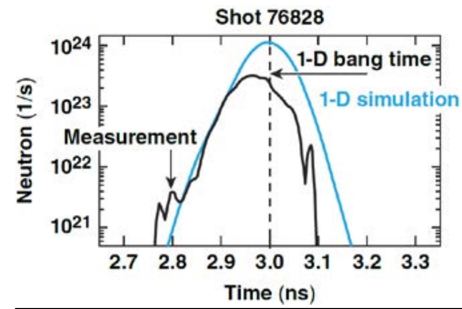

Figure 4. The measured NTD trace is shown in black for an OMEGA layered DT implosion. The 1D simulation (using the LLE code LILAC) has been broadened by the measured instrument response. The comparison shows that for over two orders of magnitude, the prediction matches the experimental neutron production rate, deviating only tens of picoseconds before stagnation when 3D effects further limit the increase in hot-spot pressure and neutron yield.

and LLE for OMEGA[12] layered DT implosions (first data in 2008) and was later duplicated for the NIF during the National Ignition Campaign. The MRS records the portion of the forward scattered neutron spectrum (from the DT fuel) between 10 and 12 MeV. Since this is an elastic scatter from the deuterium and tritium nuclei, the yield between 10-12 MeV is proportional to the areal density of the DT fuel provided the D/T ratio is known. The MRS works by momentum analyzing deuterons (using a dipole magnet) forward scattered by the emitted neutrons from a thin CD foil placed near the target. The deuterons are detected with unity efficiency by CR-39 placed along the focal plane of the magnet. The downscattered neutron spectrum is kinematically reconstructed from the measured deuteron energy spectrum. Figure 2 shows an example of the data from a recent implosion on OMEGA (not the same as the one shown in Figure 1). The forward scattered part of the deuteron spectrum is between 7 and 9 MeV while the large peak represents the DT neutron line broadened by the known response function of the instrument. The dot-dash curve is the fit to the scattered spectrum based on a uniform density model for the fuel distribution. With direct-drive implosions, both the forward and backscatter measurements of the ρR are not influenced by the hydrogen and carbon in the ablator; the ablator is completely removed during the laser irradiation. In this implosion, the yield was $4.3 \pm 0.3 \times 10^{13}$ and the ρR was 169 ± 13 mg/cm^2.

Hot-Spot Volume

The hot-spot volume is measured using a gated 16-channel Kirkpatrick-Baez (KB) x-ray microscope[13] (the instrument records in the 4-8 keV range where the compressed DT is transparent to the x-rays). This instrument was developed specifically to measure the temporal evolution of the hot-spot radius and qualified for operation on OMEGA in 2015. Sixteen independent KB optic pairs[13] are arranged on a re-entrant tube approximately 20 cm from the target. Each image is relayed onto unique positions of the four strips of a fast x-ray framing camera. The integration time of each image is approximately 30 ps and the image-to-image timing among the strips can be as short as 15 ps. This means that when properly timed all sixteen images are arranged across the roughly 100-ps burn width of a layered DT implosion. Figure 3 shows a sequential set of images (each is 100 µm x 100 µm) from a recent implosion (note that the core structure is visibly changing on a 20-ps time scale). These images are analyzed[10] to determine the minimum core radius which is used to calculate the hot-spot volume for the determination of the hot-spot pressure. The blue dot represents the spatial blurring due to the point spread function (PSF) of the instrument. Motional blurring is generally well under a micron given the short integration time and the low fuel velocities (tens of km/s) near stagnation.

Neutron Burn History

The neutron temporal diagnostic (NTD) is designed to measure the time-rate-of-change of the DT neutron fluence through a small scintillator 10 cm from the burning hot-spot. It is based on the original NTD from the LLNL NOVA laser.[14] The OMEGA NTD is unique in that the light is relayed out of the target bay to a Sydor Technologies Instruments ROSS streak camera[8] where the signal-to-background (background from direct neutron hits on the photocathode) is in excess of 100 providing unprecedented temporal accuracy on the fusion burn reaction history (the measured absolute timing accuracy of the instrument is ±25 ps). The measured impulse response of the instrument is 40 ps which is a factor of two shorter than the typical burn width for a stable mid-adiabat implosion. In 2016, the measured impulse response is expected to be lowered to approximately 25-30 ps (using a faster sweep speed for the streak camera). This response width will be adequate to resolve the shorter expected burn histories for implosions at ignition-relevant hot-spot pressures around 100 Gbar. An example reaction history is shown in Figure 4. The burn width is defined[10] as the full-width-at-half-maximum of the measured curve. For reference, a one-dimensional (1D) simulation of the burn history (blue) broadened by the instrument response shows that the onset of the implosion follows the prediction until 3D effects near bang-time (the peak of the curve) limit further increases in the hot-spot pressure and fusion yield.[15]

Shock Timing

The stability and performance of an ICF implosion depends on the design adiabat and the implosion velocity. In the absence of electron or x-ray preheat, the adiabat is set by a series of shock waves that successively and

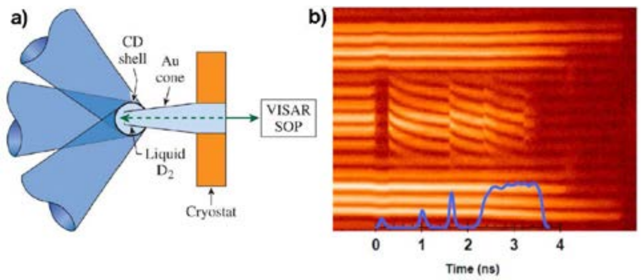

Figure 5. a) The cone-in-shell concept developed at LLE and used for both direct and indirect-drive shock timing measurements. b) A VISAR trace showing the four shocks launched by the laser pulse in blue coalescing (fringe jump). The first shock enters the D_2 at 0.3 ns, the second shock merges with the first at 1.6 ns and so on.

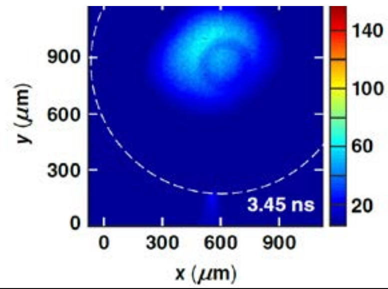

Figure 6. A soft x-ray radiograph of a layered cryogenic DT implosion approximately 300 ps before peak compression. The dark circle is caused by the attenuation of soft x-rays by the compressing DT fuel; the dashed circle is the original capsule size.

incrementally compress the fuel while adding the desired amount of entropy. The shocks transit the ablator and fuel in a tight sequence designed so that they merge very near the inner surface of the fuel. LLE, in collaboration with LLNL and Sandia, developed the technique to measure the shock strength and timing using velocity interferometry[16] with "cone-in-shell" targets. This target concept, shown in Figure 5a, is applicable for both direct and indirect-drive. The shell and cone are filled with liquid D_2 (an optically transparent surrogate for layered DT) and the shell is driven by the desired laser pulse (or x-ray pulse from a laser-driven hohlraum). The VISAR diagnostic[16] (Velocity Interferometer System for Any Reflector) records laser light reflected from the leading shock using an interferometer to create fringe shifts as the trailing shocks overtake and strengthen the leading shock. Figure 5b shows the VISAR signal from a direct drive experiment where three 100-ps pulses and a main drive pulse (the blue trace at the bottom of the figure) drove four shocks into the D_2-filled capsule. The VISAR fringes, whose vertical position is proportional to velocity, are streaked in time and show the jumps at 0.3, 1.6, and 2.3 ns due to shock mergers. At 3.1 ns, the fourth shock produced by the main pulse overtakes the third shock. This technique is used routinely on the NIF and OMEGA to confirm design prediction of laser energy coupling and the fuel adiabat following shock transit and coalescence.

Radiography

A short pulse (typically 10 ps), high energy (1,500 J), high intensity (typically a few 10^{15} W/cm^2) beam from the EP laser is routinely used in the OMEGA target chamber to radiograph the dense fuel of an imploding cryogenic DT shell "in flight" (after the laser is off and before the onset of core self-emission). Radiographs[17] such as the one shown in Figure 6 are acquired using 1.865 keV x-rays from the Si-Heα transition (the configuration is area backlighting so the short pulse beam is focused to a much larger spot which reduces the on target intensity and maximizes the brightness of the Heα line). The 10-ps x-ray burst ensures minimal motional blurring as the velocity of the shell in-flight exceeds 350 km/s. Soft x-rays are required to provide adequate contrast as the fuel density in-flight is much lower than at stagnation. During the fusion burn, the core self-emission is photometrically brighter than the Si-Heα emission. Stagnation images of the compressed fuel shell may be possible using 50-100 keV x-rays to generate a low-background "Compton" radiograph.[18] Photometric estimates of the Compton contrast are marginal for OMEGA implosions given the relatively low areal densities but look quite promising for layered DT implosions on the NIF using the Advanced Radiographic Capability (ARC).[18] The dark circle in Figure 6 is the extent of the DT shell approximately 300 ps before peak compression. The contrast provides a measure of ablator mixing (CH mixing would be quite obvious due to the much higher opacity of the carbon) while the in-flight shape and thickness are analyzed for drive and low-mode shell non-uniformities and high spatial frequency (imprint) perturbation growth, respectively.

Implosion Velocity

The Sydor Framing Camera (SFC) was developed for LLE several years ago by Sydor Instruments.[8] The head design (the strip lines and photocathode) was adapted from the original LLNL design for the X-Ray Framing Cameras used on the Nova laser (and still used routinely on OMEGA and EP), the pulser systems are commercially available from Kentech[19] and identical to the ones used on the NIF Gated X-ray Detector,[20] and the overall control architecture was designed for use with the OMEGA control system and database. A fast SFC (40-ps integration time) has been devoted to use with layered DT targets on OMEGA. The camera is routinely configured to measure the implosion velocity, the mass ablation rate, the length of the conduction zone, and the shape of the ablation surface during the acceleration phase via self-emission shadowgraphy.[21] Figure 7 shows a series of ablation surface self-emission images from a recent D_2-filled CH capsule implosion. The trajectory (radius as a function of time) of the ablation surface is a sensitive measure of the time-dependent coupling of the laser energy to the shell kinetic energy. Simulations and a separate comparison with shell radiography confirm that the ablation surface trajectory (and velocity) is an excellent surrogate for the shell motion.

Summary

The OMEGA and EP lasers will continue to serve as the test bed for new ICF/HEDP diagnostics and experimental platforms. The high shot rate (> 2,000 per year) and configuration flexibility ensure that platforms and instrumentation

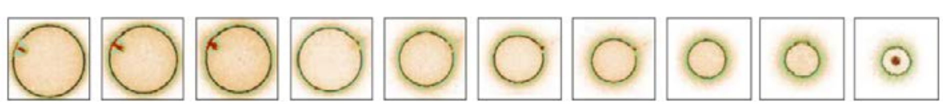

Figure 7. A time-series of ablation surface self-emission images. These images are an excellent surrogate for the shell motion and are used to measure the implosion velocity, mass ablation rate and conduction zone length to test the prediction of laser coupling in the radiation hydro codes used to design direct-drive ignition targets.

development on OMEGA and EP are programmatically cost-effective and can be transitioned to the NIF quickly and effectively. Instruments developed under the National Diagnostics Plans such as deep UV (~ 200 nm) Thomson Scattering and advanced Single Line-Of-Sight framing cameras based on hybrid CMOS technology will be thoroughly tested on OMEGA in the coming years (and likely be added to the list of qualified facility diagnostics available to all users).

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Laboratory Directed Research and Development: A Pathway from Idea to Impact

by NNSA Laboratory Directed Research and Development Working Group

The U.S. Department of Energy has charged the Laboratory Directed Research and Development (LDRD) program with supporting high-risk, potentially high-value research at the national laboratories. That LDRD is a proving ground for new concepts in research and development makes its many successes that much more remarkable. Investing in high-risk science and engineering means we may not succeed every time, and yet for more than 25 years, LDRD has supported some of the most impactful science and technology to come out of the National Nuclear Security Administration (NNSA) national laboratories. From reducing global nuclear dangers, to improving our energy security, to protecting our service men and women in the field, to assuring the security of our most precious cyber assets, LDRD has made seminal contributions to every facet of national security.

Many key NNSA programs, as well as leading R&D scientists and engineers, trace their roots to research that began with LDRD funding. Here are just a few examples of long-term mission solutions that made their way from idea to impact with support from the LDRD program.

Proton Radiography

The incredible efficacy and versatility of proton radiography (pRad) stems from the ability to produce multiple proton pulses in an accelerator coupled with multiple optical viewing systems that can result in 42-frame movies. This capability, whose foundations were developed by LDRD over a decade ago, has made contributions to the nuclear weapons program through more than 500 dynamic experiments. Today, pRad influences decisions regarding the reuse of pits from one weapon system to another, and it provides data to help the U.S. Army improve the penetration resistance of armor for our troops on the battlefield.

“Early on, LDRD provided the resources to develop the proof of principle that is foundational to pRad. Now a key capability for maintaining the Nation’s nuclear stockpile, pRad is the direct result of the synergy between the Laboratory’s defense mission and basic R&D scientists.”

— Chris Morris
Muon Tomography Team Leader
Los Alamos National Laboratory

Optical photograph of a composite material helmet just prior to a kinetic energy projectile impact and (inset) a proton radiograph of a jet penetration.

Accelerated Aging of Plutonium

In 1997, NNSA launched a comprehensive study at Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL) to examine in detail how plutonium (Pu) pits age and provide a firmer scientific basis for estimating the service life of these components. Experiments at the national laboratories produced the equivalent of 60-year-old Pu in a period of only four years. The work benefited greatly from capabilities that already existed because of LDRD. For example, at LLNL, the first direct measurement of helium bubble formation in aged Pu was based on LDRD investments in positron annihilation lifetime spectroscopy (PALS). This capability was developed and sustained through LDRD investment in the 1990s. Results from the NNSA study were used as the foundation for the 2006 Pit Lifetime Assessment and influenced the decision not to build a large capacity Modern Pit Facility—a multi-billion dollar savings. A current LDRD project at LANL to watch aging on a daily basis will form the basis for pit lifetime estimates that are physically sound and advance the understanding of fundamental radiogenic processes in delta-Pu.

"LDRD investment in radiation damage and PALS laid the foundation for using high-resolution transmission electron microscopy imaging to directly measure Pu aging for the stockpile."

— Patrick G. Allen
Plutonium Aging Program Lead
Lawrence Livermore National Laboratory

The positron annihilation lifetime system and transmission electron microscopy data showing helium bubbles in aged Pu (inset).

Optical Damage Reduction for Fused Silica Optics

Reducing optical damage to fused silica optics has been central to meeting the National Ignition Facility's (NIF's) stockpile stewardship mission. A decade of LDRD investments had enabled a series of fundamental discoveries and innovations in optical finishing science, the mechanisms of optical damage, and the discovery and mitigation of important damage precursors, which were key to reducing damage by a factor of over 10,000 from pre-2007 levels. These improvements have been implemented as production processes (Advanced Mitigation Processes 2 and 3) for large silica optics on all of NIF's 192 beamlines, allowing an increase in operation from below 1 MJ to routine operation at 1.8-MJ levels.

"Investing early and building a long-term program in the basic material science underlying optical processing was essential in moving NIF down the pathway to mission-relevant energies. There are 384 large custom UV silica optics installed on NIF at a time, some of which are replaced every year. Without the improvements enabled by this research, NIF would have to replace more than five times more of these per year, a level which exceeds the world-wide optical finishing capacity by more than a factor of two."

— Jeffrey Bude
Associate Program Manager in Optics and Material S&T
Lawrence Livermore National Laboratory

Advanced Mitigation Process for a 40-cm fused silica focusing lens.

Safe, Secure Nuclear Weapons Architecture

Traditionally, nuclear weapon interfaces tended to be discrete and dedicated in nature with little flexibility, making it difficult and costly to modify existing systems without extensive redesign. An LDRD-developed "communications backbone" bus-based architecture now simplifies weapons electronic system communications and interconnections, while ensuring system and component reliability and allowing for simpler upgrades in the future. Via two additional Early Career LDRD projects, formal verification methods were implemented into the architecture, thereby increasing safety and security of the system. The "foundation bus" communications architecture has been selected as a baseline for all current Life Extension programs.

Sandia National Laboratories researchers evaluate adaptable telemetry hardware components on W87 Mark 21 replacement fuse.

"These LDRD efforts have had significant impact on our nuclear weapons missions. The end product from this LDRD investment is now being used on all of the current life extension programs for both mission and instrumentation functions."

— Perry Molley
Digital Design & Verification Manager
Sandia National Laboratories

Multiplexed Photonic Doppler Velocimetry

For nearly 50 years, weapons designers could only see "time snapshots" of an imploding cavity. With the emergence of fiber-optic velocimetry, and later, photonic Doppler velocimetry (PDV), surface motion could be continuously recorded. Utilizing advanced, low-cost, commercially available digitizers, the Site Directed Research and Development program at National Security Technologies, LLC enabled velocimetry at 300+ points in a cavity. Using a method called multiplexing, tuned and optimized oscillators are added to each digitizer signal. Multiple time-delayed PDV signals can be recorded on a single channel, meaning 32 signals can now be recorded on one four-channel digitizer. With multiple tests and integrated experiments now complete, multiplexed PDV (MPDV) has transformed the weapons hydrodynamics program, providing designers with a wealth of information.

An advanced optical probe used with multiplexed photonic Doppler velocimetry for dynamic material experiments.

"Without the Site Directed Research and Development (SDRD) program, this capability would not exist today. The ramifications of this technology have gone well beyond anything envisioned when the SDRD proposal was first written."

— E. Daykin
Principal Investigator
National Security Technologies, LLC

Electronics for Hostile Environments

Radiation-hardened electronics are critical to the performance of nuclear weapons and for systems that operate in space, high altitude, defense systems, or in close proximity to nuclear reactors. Unfortunately, standard components and processes common for commercial microchip production are vulnerable to ionizing radiation from natural or deliberate sources (in hostile environments). Multiple LDRD projects developed special materials and processing techniques that enable the design of radiation protection right into the chip. This LDRD-developed capability is now being utilized in the B61 and W76 modernization programs, with Sandia National Laboratories scheduled to provide more than 25,000 radiation-hardened application-specific integrated circuits (ASICs) for both programs starting in 2016.

"Sandia's LDRD program has funded fundamental radiation-hardened ASIC technologies, and because of that investment, Sandia's Microsystems and Engineering Sciences Applications (MESA) Complex is able to provide rad-hard technology required by our nuclear weapons programs."

— Reno Sanchez
Microsystems S&T
Sandia National Laboratories

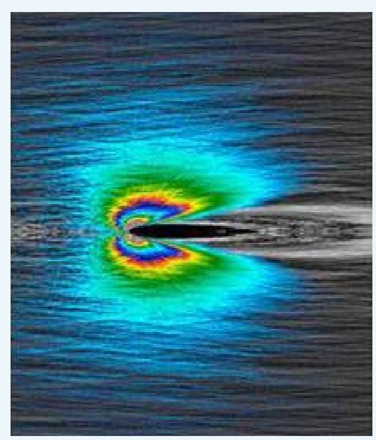
Dana Pulliam enters information before running an operation in Sandia's MESA fabrication complex. The fabrication complex has begun making radiation-hardened ASICs (inset) for use in the W76 and B61 weapon systems.

Massively Parallel Molecular Dynamics Simulation

Stockpile stewardship applications require a deep understanding of matter (specifically, plasmas) at a wide range of extreme conditions, which is a considerable coding challenge for computational physicists, who rely on theoretical plasma models. Lawrence Livermore National Laboratory's (LLNL's) Cimarron LDRD project developed a world-class, massively parallel molecular dynamics code to model warm dense and hot dense matter. Researchers used molecular dynamics to create a virtual representation of matter at extreme conditions (plasmas), which was then used to probe various physical properties. This research has addressed critical plasma physics model uncertainties for stockpile stewardship; the resulting capability was instrumental in completing a level-2 NNSA milestone. In addition, it is contributing to key uncertainties related to fusion ignition.

"The Cimarron project has provided an entry point for many [early career] new hires into LLNL, and has created a high-energy-density computational capability as well as a scientific community for hot dense matter that did not exist before."

— Frank Graziani
Cimarron Project Lead
Lawrence Livermore National Laboratory



This research has addressed critical plasma physics model uncertainties of importance to stockpile stewardship. The image shows the plasma wake produced as an ion slowed by the plasma in the stopping process.

New Roles and Faces at Research, Development, Test, and Evaluation (RDT&E)

Lois Buitano

Program Manager

Lois Buitano has been employed within DOE/NNSA's RDT&E for the past 10 years. She was recently appointed the Program Manager for Secondary Assessment Technologies (C4) in the Office of Research and Development. Previously, she worked in the Office of Inertial Confinement Fusion and was Program Manager for the Laboratory for Laser Energetics and for the National Laser Users' Facility Program. Her duties included programmatic leadership, in addition to contractual activities. Prior to joining NNSA, she worked on the design and development of the new US $20, $50, $10, and $100 banknotes and on the technical evaluation of new counterfeit deterrence features for U.S. currency at the Bureau of Engraving and Printing. Before, she spent 18 years as a Senior Research Scientist at Eastman Kodak Company in Rochester, New York and holds 21 U.S. patents in silver halide photographic technology. She completed the Council for Excellence in Government Executive Leadership Development Program in 2008 and the Grants Management Certificate Program in 2015. She has a bachelor's degree from the University of Massachusetts Lowell and a master's degree from the University of Rochester, both in Chemical Engineering.

Eric Machorro

National Security Technologies, LLC/ NNSS Detailee

For the past eight years, Dr. Eric Machorro has been at the Nevada National Security Site (NNSS). For the early part of most of his tenure there, he developed mathematics and algorithms for analyzing both legacy reaction history data and photonic Doppler velocimetry data collected on recent subcritical experiments. He was also a part of the Site Directed Research and Development program, and now manages NSTec's Diagnostic Development and Materials Studies group in North Las Vegas. For several years prior to that, he worked on algorithms for solving neutron transport problems for Lawrence Livermore National Laboratory.

Previous positions include a brief position at WaMu as Lead Quantitative Analyst and a 13-year career as a watershed manager for the City of Portland directing environmental salmon-habitat and floodplain restoration projects. Eric received a bachelor's degree from Reed College in Mathematics and his doctorate in Applied Mathematics from the University of Washington. He also holds master's degrees in Environmental Science and Engineering from the Oregon Graduate Institute.

Tiberius Morán-López

Program Manager

J. Tiberius Morán-López has been a member of the Office of Defense Programs since 2013, during which he has worked with the offices of RDT&E and Stockpile Management. His managerial responsibilities have encompassed weapon engineering and defense sciences, academic alliance programs, contract administration, and collaborative agreements with the Department of State and the Commissariat à l'Energie Atomique (CEA) of France. Prior to joining RDT&E, Tiberius was awarded the Defense Programs Award of Excellence in 2015 for his contributions to Integrated Surety Architectures. In addition to his responsibilities at NNSA, Tiberius also continues collaborative research with the Lawrence Livermore National Laboratory on predictive methods for shock-driven hydrodynamic instabilities and turbulent mixing for high-energy-density physics applications. As such, he remains active in publishing peer-reviewed work and presenting at scientific conferences.

Tiberius earned his doctorate and master's degrees from the University of Michigan in Nuclear Engineering and Radiological Sciences, and earned dual bachelor's degrees from Texas A&M University in Nuclear Engineering and Theoretical Physics. Tiberius has worked with the Lawrence Livermore and Los Alamos National Laboratories, General Atomics, and has served as a physics and mathematics civilian instructor for the Navy. Lastly, Tiberius is also fluent in Spanish, proficient in Korean, and has studied elementary Russia.

SSAA Center of Excellence Principal Investigator Receives Prestigious Rutgers University Award

Congratulations to Dr. Jolie Cizewski on being named the 2016 recipient of Rutgers University's Daniel Gorenstein Memorial Award. This award is given to an outstanding member of the faculty and includes a stipend and the honor of presenting the annual Gorenstein Memorial Lecture to the university and wider community on a topic of the winner's choice. Dr. Cizewski is the Principal Investigator of the Stewardship Science Academic Alliances Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science.

2016 Summer School: Foundations of High Energy Density Physics (HEDP)

To promote the spread of fundamental knowledge in the field of HEDP, the University of Michigan offers an intensive summer school course. Registrants will receive 40 hours of lectures based primarily on the book *High-Energy-Density Physics* by Professor R.P. Drake. The course, scheduled for June 12-25, 2016, is aimed at graduate students, young scientists, and experienced scientists seeking an HEDP foundation. For more information, visit http://clasp-research.engin.umich.edu/workshops/hedss/.

8th OMEGA Laser Users Group (OLUG) Workshop

The 8th OLUG Workshop will be held on April 27-29, 2016 at the University of Rochester Laboratory for Laser Energetics. The annual workshop explores ways to enhance and extend current research and collaborations at OMEGA as well as to help formulate further improvements to, and novel operating regimes for, the OMEGA facilities. To register, visit http://ouw.lle.rochester.edu/. U.S. citizens must register by April 15; the deadline for foreign nationals to register was March 7. Registration is limited.