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

For the Office of Research, Development, Test, and Evaluation, attracting and retaining world-class staff is vital. This coupled with employee demographics in the current workforce and the percent eligible for retirement creates concerns among NNSA and its Management and Operating partners. The national security laboratories have developed or maintained facilities that provide research opportunities that serve to attract and retain scientists and engineers. Additionally, NNSA provides opportunities for intellectual challenge and collaboration by promoting scientific interactions between the academic community and scientists at the DOE/NNSA laboratories. The Stewardship Science Graduate Fellowship (SSGF) Program is just one of many ways we work to develop and maintain a long-term recruiting pipeline to the DOE/NNSA laboratories by increasing visibility of the DOE/NNSA scientific activities to U.S. academic communities. In this issue of the Stockpile Stewardship Quarterly, we invite you to join us in celebrating the 10th Anniversary for the SSGF Program and get to know the incoming 2016-2017 SSGF fellows. You will also read about the High Energy Density Summer School offered by the University of Michigan that introduces students to the conceptual and theoretical framework of the key areas of high energy density (HED) physics. One of my favorite activities associated with my position is to speak to our academic fellows. I recently had that opportunity with the CSGF fellows (see photo on the right).

Graduate Fellowship Annual Program Reviews. Left - Charles W. Nakhleh, Divsion Leader, Theoretical Design at LANL, discusses "Future Opportunities and Challenges in the Stockpile Stewardship Program" at the Stewardship Science Graduate Fellowship Annual Program Review, June 27-30, 2016. This year marked the program's 10th anniversary. Right - Dr. Alexander welcomes attendees to the 2016 DOE Computational Science Graduate Fellowship Annual Program Review, held July 25-28, 2016. This year marked the program's 25th anniversary.

I'm also very pleased to share two articles related to Stockpile Stewardship diagnostics and an example of deployment of diagnostics in a sophisticated set of experiments. You will read about National Security Technologies, LLC's presentation of the history of synchroton x-ray based calibration and the need it has filled as well as details about new experiments being conducted at the National Ignition Facility studying the hydrodynamic instability growth of a multiply-shocked fluid interface at HED conditions.

Your efforts in support of RDT&E programs are outstanding!

Inside

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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10th Anniversary of the Stewardship Science Graduate Fellowship Program *by The Krell Institute*

It takes top-notch talent to meet the NNSA's national security mission, particularly a corps of nuclear science and technology specialists. Recognizing the need to cultivate and replenish the supply of research expertise, agency leaders founded the Stewardship Science Graduate Fellowship (SSGF), which marks its 10-year anniversary this year.

The program has seeded the science community with alumni working in areas important to the NNSA: high energy density (HED) physics, nuclear science, and materials under extreme conditions and hydrodynamics.

Each year, volunteers with expertise in these subjects screen more than 100 applications to narrow the list to the best few. NNSA headquarters staff make the final selection of approximately five new fellows.

The fellowship, renewable for up to four years, provides full tuition and fees, a generous yearly stipend, an academic allowance, and other benefits to highly qualified graduate students pursuing doctorates in areas of interest to stewardship science. Each recipient also serves a research practicum, usually in the summer, at one of the four national defense laboratories.

Fellows share their findings at an annual program review, usually held near one of the labs. This event also gives SSGF recipients the opportunity to build connections with each other and with NNSA and national laboratory staff.

The combination of graduate studies, academic research, and practical experience at a DOE/NNSA facility produces graduates capable of significantly contributing to research and development in stewardship science.

The SSGF and similar programs are vital to fill the pipeline of researchers the NNSA needs, according to Kathleen Alexander, Assistant Deputy Administrator for the Office of Research, Development, Test, and Evaluation in the Office of Defense Programs. "These programs encourage developing the next generation of stockpile stewards," Alexander told *Stewardship Science* magazine, the SSGF program's annual journal, in 2015. "Fellows also get exposure to our national labs through a 12-week practicum, so they get to see the important work that's done, and they get to visit the national laboratories."

A third of the SSGF's 30 alumni work at DOE labs, most at one of the four defense sites. At least seven conducted postdoctoral research at the labs, while another eight are at academic institutions. Many of the rest are spread across other government agencies.

Donald L. Cook, then NNSA Deputy Administrator for Defense Programs, told *Stewardship Science* in 2013: "SSGF addresses the core issue of the first element" of the agency's deterrence mission list: "the people. That's the basis for everything we do."

A third of the SSGF's 30 alumni work at DOE labs, most at one of the four defense sites. At least seven conducted postdoctoral research at the labs, while another eight are at academic institutions. Many of the rest are spread across other government agencies. Although the program is relatively young, these alumni already are making an impact.

Forrest Doss, a fellow from 2006-2010, is a principal investigator at Los Alamos National Laboratory (LANL) on a project to better understand turbulent mix in HED and National Ignition Facility (NIF) experiments. The data gathered in such experiments are vital to understanding and correctly modeling inertial confinement fusion (ICF) implosions. Doss uses data gathered in NIF shock/shear experiments to refine how simulation codes model turbulent mix.

Alumnus Alex Zylstra also is at LANL as a Reines Distinguished Postdoctoral Fellow. He also works on laser experiments at the NIF, based at Lawrence Livermore National Laboratory (LLNL), and the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics. Zylstra has contributed to NIF experiments validating direct-drive implosion models and testing beryllium capsule explosions. Earlier this year, he was part of the NIF discovery science team that investigated stellar nucleosynthesis reactions. Graduating Fellow Hong Sio of the Massachusetts Institute of Technology also was on the team.

Zylstra has collaborated with Laura Berzak Hopkins, an SSGF fellow from 2006-2010 who's now a physicist at LLNL. Berzak Hopkins was part of the NIF team that in 2014 reported the first ICF experiments that produced more energy output than the fuel put into the experiment. Leading up to the tests, she worked with physicist Sebastian Le Pape to study the shock structure of the as-shot laser pulses and tune them to merge at specific points within the deuterium-tritium capsule. She also was part of the larger team that determined how to adjust the frequency of the laser beam bundles so energy is redistributed between beams, improving implosion symmetry.

Before going to LLNL, Berzak Hopkins served a one-year stint in Washington as an American Physical Society Congressional Science Fellow, developing science policy in the office of former Sen. Kent Conrad, D-ND. "My initial introduction to science policy came through the fellowship," Berzak told *Stewardship Science* in 2013. "At our annual gatherings, there are always opportunities to connect to policymakers in D.C." Her 2007 SSGF practicum at Sandia National Laboratories (SNL) also was "an interesting and important introduction to the national lab system and opened my eyes to the career opportunities there."

It's not unusual for fellows to serve practicums at a lab and later return to join the staff. Matthew Gomez served his practicum at SNL-Albuquerque, New Mexico in 2009. He's now a physicist working on HED experiments like those conducted on the Z pulsed power machine. In 2014, he was a lead author on a *Physical Review Letters* online paper describing MagLIF (magnetized liner inertial fusion) experiments on Z-Machine at SNL that produced a trillion fusion neutrons—a significant increase over other inertial fusion experiments, increasing the probability of fusion.

Richard Kraus, a fellow from 2008-2012, did his practicum at LLNL in 2010 before earning a PhD in Earth and Planetary Sciences from Harvard University in 2013. Since returning to LLNL, he's used Z machine experiments to elucidate iron's behavior under extreme conditions. The results indicate that iron vaporizes at lower impact speeds and shock pressures than previously thought. That means iron in meteorites striking the early Earth probably would have vaporized and spread over the planet, condensing and raining down as iron particles that mixed with the molten mantle. The data also supports views that the planet's core formed earlier than in some predictions: 30 million years after the solar system developed, rather than 100 million. The study, published in *Nature Geosciences*, was named one of *Discover* magazine's top science stories of 2015.

At least one former fellow has sent an experiment into space. Kristen John, who was in the program from 2009-2013, now is a deputy project manager on STRATA-1, a NASA device on board the International Space Station. The test investigated the properties of regolith—impact-shattered "soil" on small, airless bodies like asteroids and the moon. According to NASA, the experiment is designed to understand how regolith behaves in microgravity, important information to have if spacecraft are to set anchors on airless bodies and move and process regolith. Researchers also want to predict and prevent risk to spacecraft and astronauts that may land on these bodies. The experiment is expected to be aboard the space station until September 2017.

Miguel Morales, the program's first graduate, has made significant contributions to the study of materials under extreme pressures and temperatures, earning a Presidential Early Career Award for Science and Engineering in 2014. The computer models he develops probe how materials behave at high pressures and temperatures. His research has delved into the properties of hydrogen and helium under extreme conditions, such as those found in Jupiter, Saturn, and other gas giant planets. Morales tells more about his research and the impact the SSGF has had on his career in the sidebar *An Alumnus 'Obsessed' with Enigmas*.

But the SSGF produces more than just great science and scientists. It also builds a community of talented and committed doctoral students, alumni, DOE/NNSA laboratory staff, and university researchers who share a common goal to further their science while advancing national defense. The friendships and connections fellows make continue throughout their careers. •

SSGF An Alumnus 'Obsessed' with Enigmas

Miguel Morales is a research scientist at Lawrence Livermore National Laboratory's Condensed Matter Physics and Materials Division. He was a DOE NNSA SSGF recipient from 2006 to 2009. The following interview is excerpted from *Stewardship Science*, the SSGF annual magazine. Read more in the latest issue at http://www.krellinst.org/ssgf/outreach/stewardship-science-magazine.

Stewardship Science: *You create and run first-principles models of materials under extreme pressures and temperatures. Why is it important to understand these things?*

Morales: There are technological and fundamental reasons. On the technological side, for example, there's the National Ignition Facility, which studies materials under the extreme physics found in nuclear detonations. You have to compress materials to extremely high temperatures and densities. You reach scales that are completely unknown and do things that we have never been able to do in a lab. The physics at these scales is not only new but unexpected, in some cases, so we need tools that allow us to understand the properties of these materials and some of the physical processes occurring in the experiment. Then we can use that information to design the experiment.

From a fundamental point of view, hydrogen, for example, is the most abundant element in the universe. Most of the giant planets are mostly made of hydrogen and helium. The pressures inside the cores of these planets are extremely high and materials behave differently there. We need to understand and predict that behavior in order to understand things about planets and galaxies.

What advantages does working at a national laboratory provide you?

I do computational work, and the national labs have some of the best computational resources on the planet. Also, because it's such a multidisciplinary environment, there are great chances for collaboration. And anytime I need to find an expert in any topic it's very likely I'll find someone around here who knows about it.

You were the first graduate of the DOE NNSA SSGF. In general, how is the program viewed, 10 years after it was founded?

We have many alumni in the labs, particularly here at Livermore, so as a recruiting tool it has been extremely successful. It also fills a void, funding-wise and opportunity-wise, for people working with materials in extreme conditions and other areas the fellowship funds. And it brings an incredible opportunity for people in the labs to access these fantastic students during practicums and for the students to learn what actually happens inside the labs. The program should be seen, I hope, extremely positively for both the universities involved and for people from the national labs.

How did your time as an SSGF recipient influence your career?

It influenced it completely. After doing my practicum at Livermore, it was clear this is the place where I wanted to end up. I'm not sure I had a clear long-term career path before I had the fellowship. But especially after the practicum it was extremely clear what my career path would be, or at least what I wanted it to be.

What element of your work excites you the most?

I love solving problems. Every time I stumble on a problem that I cannot quite figure out, I get obsessed.

2016-2017 Stewardship Science Graduate Fellowship Class *by The Krell Institute*

Seven doctoral candidates will join the DOE/NNSA Stewardship Science Graduate Fellowship (SSGF) program this fall, studying subjects such as materials under extreme conditions and hydrodynamics, nuclear science, or high energy density physics (HEDP) (see Figure 1). Each year, a screening committee of DOE/NNSA officials and program supporters choose the fellows, who receive full tuition, a stipend, a practicum at a DOE/NNSA national laboratory, and other benefits. Each student writes a research statement, from which the following information is derived.

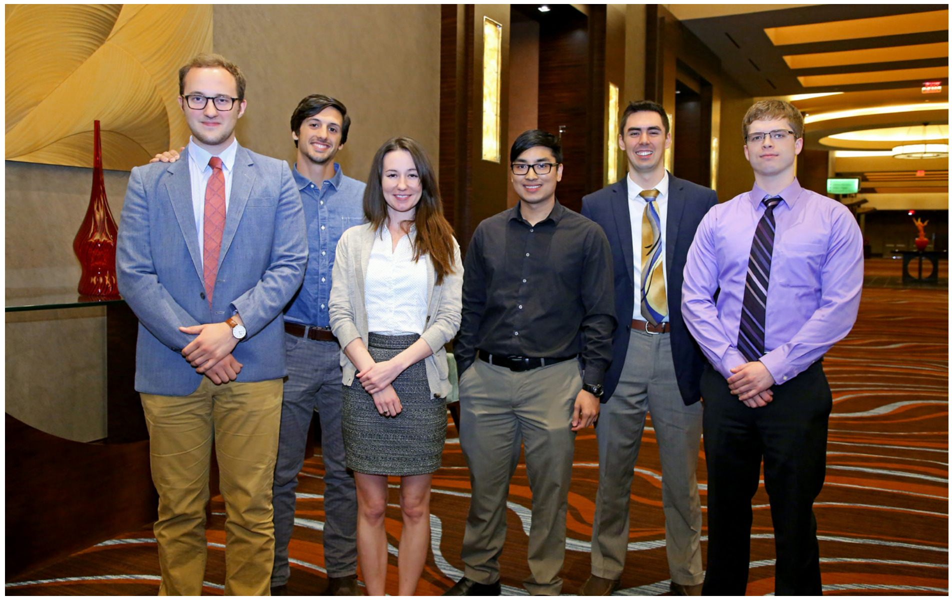

Figure 1. The 2016-2017 SSGF fellows took time during the SSGF Annual Meeting to pose for a class photograph. Left to right: Viktor Rozsa, Benjamin Musci, Heather Sandefur, Miguel Holgado, Daniel Woodbury, and Cody Dennett. Not pictured: Erin Good.

Fellow ***Cody Dennett***, working with Massachusetts Institute of Technology advisor Michael Short, will investigate a nondestructive method to quantify radiation damage in materials. Ion beam irradiation can emulate the microstructural evolution found in neutron irradiation testing, but differences in the techniques make it difficult to match their damage evolution. An *in situ* method is needed to monitor ion beam irradiation that directly accesses microstructural properties of interest. Dennett focuses on one possible solution: transient grating (TG) spectroscopy, a non-contact technique that measures surface acoustic wave propagation. TG spectroscopy is sensitive to tiny thermo-elastic parameter changes in material surface layers just microns deep. "As ion bombardment produces damage cascades localized to the surface of materials, this technique is perfectly suited to the investigation of damage induced by ion beams," Dennett writes. He plans to build a beamline test facility allowing for concurrent ion irradiation and monitoring with TG spectroscopy, letting him characterize radiation-induced microstructural changes with time resolution measured in seconds.

Louisiana State University's ***Erin Good*** and advisor Catherine Deibel are collaborating with Florida State University (FSU) researchers to investigate the fundamental reactions that generate the universe's elements in exploding stars and x-ray bursts. FSU houses the Enge Split-Pole Spectrometer (SPS), which Good will use to measure the properties of excited states in nuclei that influence reaction rates. She has designed an auxiliary instrument, the Silicon Array for Branching Ratio Experiments (SABRE), to detect charged-particle decays from excited states populated via transfer reactions in the target material. "This improved experimental setup will allow for the accurate determination of reaction rates important to classical novae and x-ray burst nucleosynthesis," she writes. Using the SABRE and SPS, Good will study transfer reactions from light, stable beams of nuclei striking heavy, stable targets. These collisions illuminate branching ratios, nuclei excited states and spins of energy levels corresponding to resonances in astrophysical reactions. Eventually, she will study the 19F(3He,t)19Ne*(α)15O reaction to accurately determine the 15O(α,γ)19Ne reaction rate, one of the most influential Type I x-ray burst reactions.

The mechanism driving cosmic rays (CRs) emanating from supernova remnants (SNRs) is the subject of ***Miguel Holgado's*** work with Paul Ricker at the University of Illinois at Urbana-Champaign. Such CRs are thought to originate in diffusive shock acceleration (DSA), which speeds particles from thermal energies to non-thermal energies at the shock front. "One of the main challenges of DSA theory is understanding how particles are injected into the acceleration process at magnetized shock fronts," Holgado writes. To get answers, he'll use the open-source FLASH astrophysics code to develop CR transport models in supernova environments and evaluate them with SNR astronomical data. He'll also simulate DSA in shock tubes to investigate small-scale features and the effects of shock orientation relative to magnetic fields, and model supernova explosions expanding in a background of interstellar medium. "The ultimate goal of my research is to determine the conditions at which supernova explosions become sites for DSA and investigate how DSA feedback affects explosion evolution."

At the Georgia Institute of Technology, ***Benjamin Musci's*** research will attempt to untangle turbulence, particularly shock-driven Rayleigh-Taylor instability (RTI), with a goal of understanding supernovae

SSGF Annual Program Review, Las Vegas, Nevada, June 27-30, 2016. Top left - Dr. Sarah Wilk, NNSA Deputy Director, Office of Research and Development, kicked off the popular Fellows' Poster Session. Top right and bottom - Attendees discuss research featured on posters.

and mixing in inertial confinement fusion experiments. He'll test the idea that for a diverging blast-wave-driven RTI, late-time turbulence depends on initial conditions, accounting for some of the discrepancies between supernovae observations and models.

Working with advisor Devesh Ranjan, Musci is building a three-dimensional conically divergent blast-tube experiment. Musci plans to seed the tube's gaseous interfaces with a range of initial conditions and use particle image velocimetry and planar laser-induced fluorescence imaging to measure the velocity and density, quantifying the developing turbulent flow field. Musci plans to supplement his observations with numerical simulations. This research "will allow me to prove or disprove whether initial conditions persist in high-energy turbulence and improve understanding of supernovae and RT mixing," he writes.

Viktor Rozsa is diving into water's properties at high pressures and temperatures (P/T) in his research with Giulia Galli at the University of Chicago. Establishing water's phase diagram and understanding its molecular behavior is essential to answering basic questions in planetary science and the physics of extreme conditions. Some of the mystery arises from interpretation of Raman spectra, which are difficult to collect for high P/T water. Rozsa uses a novel method his lab devised, based on density functional perturbation theory (DFPT), to calculate polarizabilities within the ab initio molecular dynamics framework. "My simulations will be a crucial standard for all future high-P/T aqueous Raman spectra," he writes, and will let him compute valuable data that are "impossible to isolate experimentally, such as intermolecular and intramolecular contributions to spectra." Rozsa is analyzing his ab initio Raman spectra at several of water's most controversial P/T conditions. "Looking beyond, I will build on this pure water reference to examine other hydrogen-bonded systems of critical significance."

The Hybrid Illinois Device for Research and Applications (HIDRA) tokamak at the University of Illinois, Urbana-Champaign will give fellow ***Heather Sandefur*** a nearly ideal opportunity to research plasma-material interactions. Working with David Ruzic in the Center for Plasma Material Interactions, Sandefur will study the interplay of hot dense plasmas with the surrounding materials found in engineered systems like fusion reactors. The center investigates the use of liquid lithium as a plasma-facing material, research that could have applications beyond magnetic confinement fusion, including improved techniques to produce nuclear fuel cladding and high-heat-flux cooling for electronics. Sandefur writes that she's also interested in generally advancing nuclear science simulations, an effort that's key to improving virtual testing of nuclear devices and materials without nuclear explosive tests. "While I am personally excited about the domestic applications of energy research in the nuclear engineering field, I also recognize the importance of the expansion of nuclear science for defense applications."

Daniel Woodbury, a doctoral student at the University of Maryland, College Park, works with advisor Howard Milchberg to develop bright, intense and short pulses of high-energy photons and relativistic charged-particle radiation for scientific and medical imaging applications. Milchberg's lab has developed ultrathin high-density hydrogen jets to enable relativistic electron acceleration using high-repetition-rate laser pulses at peak powers below 1 TW. Woodbury will explore using these jets to develop a high-repetition-rate source of accelerated protons, enabled by the critical density of the thin jet plasma at an 800 nm laser wavelength. The research will explore possible proton acceleration mechanisms, such as normal sheath and magnetic vortex acceleration. Woodbury plans to supplement the experiments with two- and three-dimensional particle-in-cell simulations. The research, he says, will support radiographic imaging of high energy density plasmas using ultrashort pulses of high-energy electrons, x-rays and protons, with the protons especially well-suited for imaging strong magnetic fields. •

Meeting Future Synchrotron Radiation-Based Calibration Needs *by Franz Weber, Wayne Stolte, Pete Torres, and Travis Pond (National Security Technologies, LLC)*

Over the last three decades, National Security Technologies, LLC (NSTec), and its various predecessors (EG&G, Bechtel Nevada) have been the historic stewards of synchrotron radiation-based x-ray and extended ultraviolet (XUV) calibrations of diagnostics instrumentation and components in direct support of Quantification of Margins and Uncertainties methodology. This article describes some technical principles of how such calibrations were accomplished on the prior synchrotron radiation based metrology facility, the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory (BNL) and the combined efforts of a multi-site Participating Research Team (PRT) to both migrate and enhance that capability to a new synchrotron source at the Stanford Linear Accelerator Center (SLAC) when the BNL source was closed.

Since the mid 1980s, Los Alamos National Laboratory has designed and built beam lines U3 and X8 at the National Synchrotron Light Source (NSLS) located at BNL which have been operated and maintained by NSTec and its predecessors to provide a broadband calibration and characterization facility for the accurate measurement of the properties of XUV and x-ray optical elements and detectors for the entire NNSA community.

These components primarily supported the experimental activities of NNSA national laboratories and included historic underground tests at the (former) Nevada Test Site (NTS). The unique site has since been renamed as Nevada National Security Site (NNSS) and re-designated in support of multi-facetted national security experiments as well as a majority of science campaign subprograms closely related to the Predictive Capabilities Framework.

At NSLS, two branch beam lines, out of the original contingent of four, were retained by the PRT, following the Comprehensive Test Ban Treaty of 1992. Located on a UV storage ring bending magnet, beam line U3C featured an extended range Grasshopper grating monochromator covering the spectral region from around 50 eV to 1 keV (see Figure 1). A multiple channel, quadruple reflection higher order trap ascertained high spectral purity of the beam to better than 0.01%.

A complementary bending magnet beam line, X8A on the x-ray storage ring, comprised a water-cooled, three-position monochromator with double crystal (Si 111, beryl) or double multilayer (W/WSi_2) arrangements continuously covering the photon energy range from 1 keV to 6 keV (see Figure 2). Higher photon energies up to around 40 keV could be accessed on an as-needed basis through a selection of "partner" beam lines.

Calibrations with associated low uncertainties were routinely performed on metallic vacuum x-ray diodes, grazing incidence x-ray mirrors, thin film filters, PN junction diodes, charge coupled devices (CCDs), complementary metal-oxide semiconductor-based radiation detectors and readout systems, photoconductive devices, pixelated diamond detectors, transmission gratings, figured surface and plane x-ray mirrors, multilayer mirrors (layered synthetic microstructures), micro channel plates, and x-ray film.

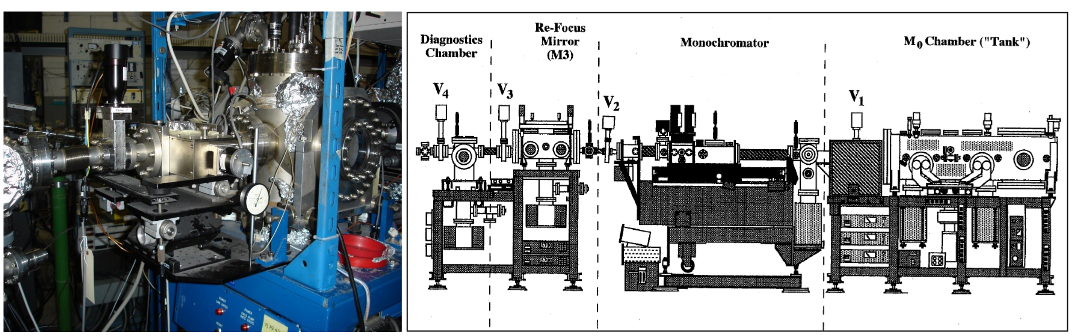

Figure 1. Simplified NSLS U3C branch line schematic with picture of "higher order trap," which was placed immediately after the diagnostics chamber.

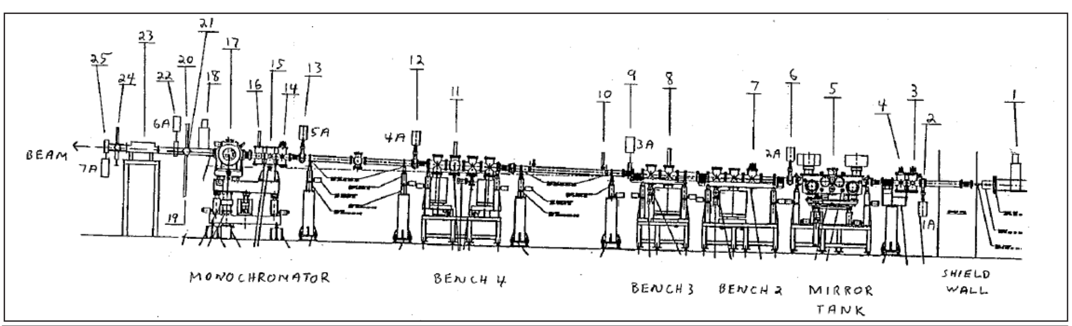

Figure 2. Historic NSLS beam line X8A design.

Based on the obviously heavy reliance on synchrotron radiation beam lines at NSLS to calibrate diagnostics and components that support NNSA missions undertaken at the national laboratories and NSTec, and coupled with the looming decommissioning of NSLS anticipated for late FY 2014, a sizeable effort was initiated for a path forward captured in an FY 2011 National Milestone: "Explore future plans for facility supporting x-ray calibration needs."

A working group comprised of subject matter experts from the national laboratories determined the diagnostic calibration requirements and then recommended x-ray source options to meet the defined needs. The assessment covered an expansive cross-section of NNSA programs

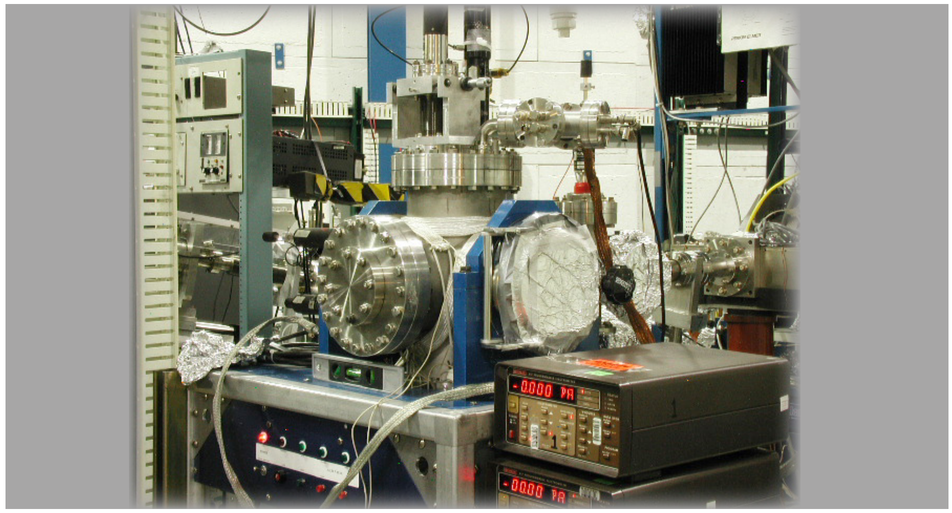

Figure 3. Upstream view of an early incarnation of a U3C end station, a suitable environment for low uncertainty detector calibrations.

Figure 4. Stanford Synchrotron Radiation Lightsources laboratory.

Figure 5. SSRL BL 16-2 M0 focusing mirror assembly.

and included related experiments on national high energy density science facilities like the National Ignition Facility, the Omega Laser Facility at the University of Rochester Laboratory for Laser Energetics, and the pulsed power Z machine at Sandia National Laboratories. Evaluated were particularly x-ray source characteristics such as spectral range, intensity, spectral purity, spatial size and resolution, temporal resolution, number of components to be calibrated, calibration accuracy, as well as access modalities pertaining to the source.

Working group findings established a substantial current need for a low-energy x-ray source, tunable over a range of 0.03-2.5 keV, with high spectral purity, good energy resolution ($\Delta E/E < 10^{-3}$) and sufficient flux ($> 10^8$ photons/s) to calibrate over 2,000 x-ray optical components annually for NNSA Defense Programs and other related mission areas (see Figure 3). Further findings indicated a current and growing need for a high-energy x-ray source, in the range of 2.5-30 keV, with high spectral purity, good energy resolution ($\Delta E/E < 10^{-3}$) and sufficient flux ($> 10^8$ photons/s) to calibrate hundreds of existing x-ray optical components per year, as well as developing, testing, and characterizing novel x-ray detectors at high energies.

That documented need,[1-2] coupled with light source management recognition of NNSA mission requirements, supported the decision to retain synchrotron radiation-based x-ray and XUV calibration resulting in a recommendation to design and construct a low energy bending magnet beam line at the Stanford Synchrotron Radiation Lightsources laboratory (SSRL) (see Figure 4). For higher photon energy coverage, a phased approach was adopted commensurate with the prevailing resource landscape and programmatic capital expenditure planning.

With the decommissioning of NSLS successfully completed by the end of the second quarter of FY 2015, and the subsequent loss of the metrology center located on beam lines (U3C and X8A) there, a new set of calibration beam lines (soft x-ray [SXR] and hard x-ray [HXR]) is presently under construction at SSRL.

Metrology beam lines require an extremely stable, reproducible, and high spectral purity x-ray beam. However, unlike most other experimental applications, the requirement generally does not include extremely high-energy resolution, ultra high flux, or even a small focused beam.

NSTec beam lines emanate from a common source—a bending magnet located within the SSRL storage ring (SPEAR3). The two beam line branches are being separated by virtue of an innovative, bendable silicon mirror (M0), whose support structure resembles a trestle bridge, allowing the high-energy x-ray beam to pass behind the mirror body. Simultaneously, the aspherical mirror surface (on the front side) focuses the SXR beam onto an exit slit assembly located approximately 10 meters downstream. Both beam lines then exit the storage ring shield wall (see Figure 5).

The SXR path traverses through a set of apertures, a variable line-space plane grating monchromator, an exit slit, and finally a four-bounce higher harmonic rejection mirror system. All optical components and beam guide elements have been carefully optimized to reduce aberrations and higher order harmonic light, while reliably generating a focus

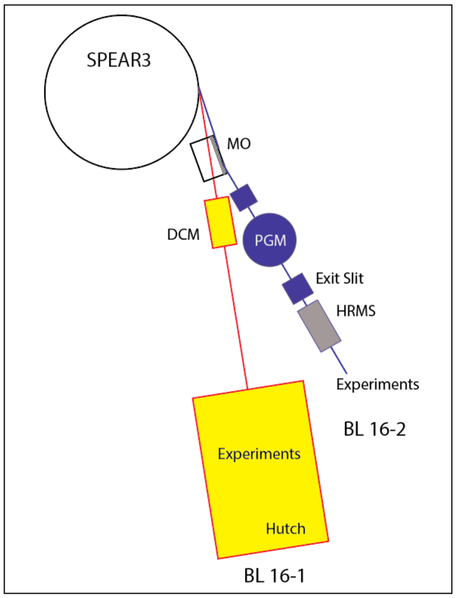

Figure 6. Schematic diagram of beam lines 16-1 and 16-2, currently under construction at SSRL.

of the beam onto a fixed position exit slit (see Figure 6). At the end of the beam line, metrology, calibration, and characterization experiments of diagnostics instrumentation and components will be performed. These will primarily be housed in specially designed and fabricated end stations containing various detectors such as photo-diodes, CCD cameras, and silicon drift detectors.

Per conceptual design, the HXR path emerges from the shield wall, propagates through an aperture downstream, and passes through the sole optical component on that branch, a double crystal monochromator, containing a pair of silicon (111) crystals. The beam finally enters a hutch, which will accommodate an experimental arrangement pertaining to calibration tasks at hand.

A new era of NNSA synchrotron radiation based x-ray and XUV calibration at SSRL is now appearing on the horizon with the completion of beam line construction and following commissioning process. First light on the XUV/SXR branch is currently expected for late 2016 with planning of experiments for the subsequent commissioning phase under way. This phase of the project will presumably be able to accommodate supportive NNSA users with diagnostics, instrumentation, and components closely aligned with mission need.

“Maintaining a safe, secure, and effective nuclear weapons stockpile in the absence of nuclear explosive testing remains one of the DOE’s fundamental responsibilities to our Nation.” This is the opening statement from Ernest Moniz, U.S. Secretary of Energy in his message contained in the FY 2016 Stockpile Stewardship and Management Plan. This single statement underscores the importance and relevance that diagnostic calibrations, characterizations, and data post processing have on the overall viability of the U.S. nuclear weapon stockpile.

References

[1]“NNSA X-Ray Calibration Needs: Report from the Feb. 2011 Working Group Review,” David S. Montgomery (chair), LANL et al.; OUO, Export Controlled Information.

[2]Thomas E. Tierney IV, et al., "Recommendations to Meet NNSA Synchrotron-Based X-Ray Calibration and Characterization Requirements Post-NSLS,” LA-UR-08-1311. •

High Energy Density Summer School, University of Michigan, Ann Arbor, June 13-24, 2016

The University of Michigan (UM) completed its sixth offering of the biennial summer school on high energy density (HED) physics. More than 30 scientists attended the course. Most of them are unable to take a course in this subject at their home institutions, so Michigan offers this seminar as a service to the community. The course provides 40 hours of lecture and substantial additional time for discussion in a two-week period. This year, the lecturers were Professor R. Paul Drake and Dr. Carolyn C Kuranz, with a guest lecture by Professor Chuang Ren of the University of Rochester.

The course covers HED physics in an academic way, introducing the students to the conceptual and theoretical framework of the key areas of the field. We discussed the selection and details of the equations one can use to describe HED matter. To close these equations, one needs to understand what HED matter is, as it is neither an ideal plasma nor condensed matter, so we explore this question. The next guiding question is how HED matter moves, which led us to the compressible hydrodynamics of shock waves, rarefactions, and instabilities. After that, we explored radiation hydrodynamics to address the issue of how energy moves through HED matter and what the consequences are. This involved some fundamental new concepts and equations, followed by applications to linear waves, nonlinear Marshak waves, radiative shocks, and heat waves. To understand the creation of HED matter, we considered the delivery of energy to a target by laser beams or x-rays, with some discussion of z pinches as well. All the above made us ready to consider inertial confinement fusion, including some of its key challenges. Then, via HED laboratory astrophysics, we made connections with many phenomena in the universe. Finally we considered relativistic HED systems, the province of wakefield accelerators and laser-driven fast ignition. •

UM's R. Paul Drake introduces another class of scientists to the conceptual and theoretical framework of HED physics.

Measuring Nonlinear Hydrodynamic Instability Growth of Multiply-Shocked Fluid Interfaces at High Energy Density

by Kumar Raman, Channing Huntington, Steve Maclaren, Sabrina Nagel, Luke Simmons, Ping Wang, Ted Baumann, Angela Cook, Danielle Doane, Sean Felker, Luke Savage, Rich Seugling (Lawrence Livermore National Laboratory); Kirk Flippo (Los Alamos National Laboratory); and Paul Fitzsimmons, David Kaczala (General Atomics)

Introduction

We report on new experiments at the National Ignition Facility[1] (NIF) studying the hydrodynamic instability growth of a multiply-shocked, i.e., "re-shocked," fluid interface at high energy density (HED) conditions. An interface can be re-shocked if the driving source has a time history that launches multiple shocks, if reflections of an initial shock return to re-perturb the interface later in time, or via combinations of these effects. This situation is relevant to inertial confinement fusion[2] (ICF) where nontrivial pulse shapes and layered capsules[3] can result in multiple shocks traversing, reflecting from, and re-shocking multiple interfaces. Experiments done in conventional shock tubes have shown that re-shocks can significantly enhance the instability growth rate over the single shock rate.[4] Re-shock configurations, therefore, are an effective way of driving an initial perturbation into the turbulent regime, making such experiments particularly useful for validating models of the transition to turbulence and shock-induced, turbulent mixing.[5-8]

The experiments use a dual-drive platform, originally developed for exploring HED shear flows,[9] to drive a physics package designed for studying re-shock phenomena. The experimental geometry, shown in Figure 1, is a rectangular shock tube, 2.5 mm × 1.9 mm in cross section and 4 mm long, driven at opposite ends by two gold halfraums. The shock tube has high-density, polyimide plastic (1.4 g/cc) regions at each end, which are separated by a low density, carbon foam region (0.1 g/cc). To seed instability growth, the interface initial condition is pre-machined at one of the plastic-foam boundaries. The halfraums each receive laser pulses produced by up to 60 of the 192 NIF laser beams, creating x-ray baths with peak radiation temperatures of 250-300 eV. Each halfraum drives a ~ 20 Mbar shock into its respective end of the target package, turning the initially solid target into a plasma, and the plastic-foam boundary into a fluid interface with the desired initial condition. Since the materials have different densities, the interface will grow after being shocked due to the Richtmyer-Meshkov instability[10-11] and, depending on the drive history, the Rayleigh-Taylor instability[12-13] may act as well. An additional 28 NIF laser beams focus on a large zinc foil outside the package,[14] creating ~ 9 keV x-rays that pass through the target at a specified time. These x-rays image the growing perturbation and are collected on a gated x-ray camera,[15] producing side-on radiographs of the evolving instability. To improve contrast and minimize the influence of three-dimensional (3D) edge effects on the image, a density-matched, tracer layer of high-opacity plastic (plastic doped with a small fraction of iodine) is embedded within the lower-opacity polyimide.

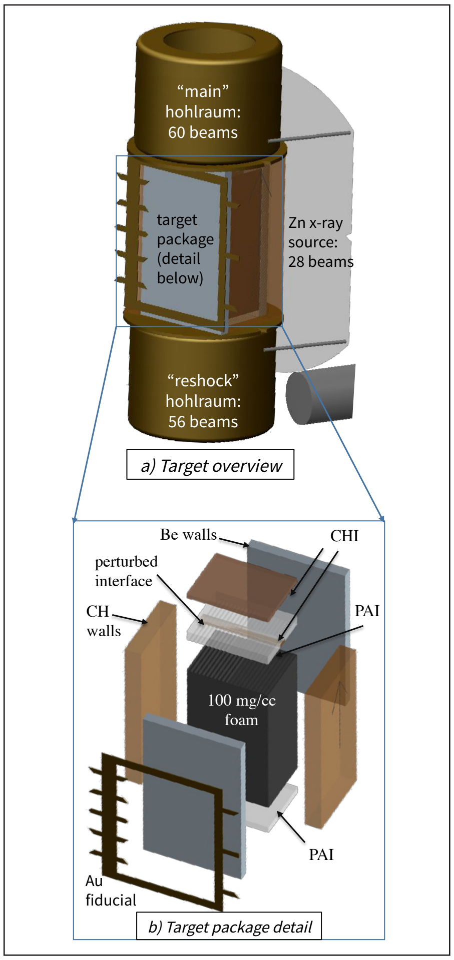

Figure 1. Experimental geometry: a) The target package is mounted between two identical hohlraums and the target is aligned along the NIF vertical axis. A Zn foil is used to generate the imaging x-rays used to diagnose the experiment. b) The components of the physics package are shown, including the main ablator, consisting of (3% iodinated plastic (CHI) and polyamide-imide (PAI), and the PAI reshock ablator. These two dense layers are separated by a block of low-density carbon foam.

The configuration highlights some advantages of the HED approach to the re-shock problem. In these experiments, the two halfraums generate, respectively, the primary shock that initially drives the interface and a second, opposing shock that re-shocks the interface later in time. These two drives can be independently controlled, in strength and time history, using the precision pulse shaping capability of the NIF laser. In contrast, conventional shock tubes often have just one driven end and are closed at the other end, with a re-shock generated by the reflection of the primary wave off the closed end. While some ability to explore drive variations is still possible,[16] the control is much more limited. Another advantage of HED experiments is the fine control over the initial fluid interface, including material densities and the initial shape of the boundary, because the package starts in the solid state. Thus far, we have explored 2D sinusoidal initial conditions, which non-HED approaches have also had success in generating,[17,18] though perhaps with less flexibility in varying the amplitude and wavelength. Future experiments will explore density variations and 3D multimode perturbations, leveraging this capability more highly. Moreover, NIF offers advantages over other HED facilities for this type of experiment due to its significantly higher energy: the ability to drive comparatively larger target packages, which helps mitigate edge effects that plague these experiments, and the ability to drive an initial condition further into the turbulent regime than previously possible.[19]

Figure 2 shows an image sequence of the instability growth obtained from several NIF shots done with nominally identical targets and drive, varying only the radiography timing. Here, the initial interface perturbation was a sinusoidal ripple of 120 micron wavelength,

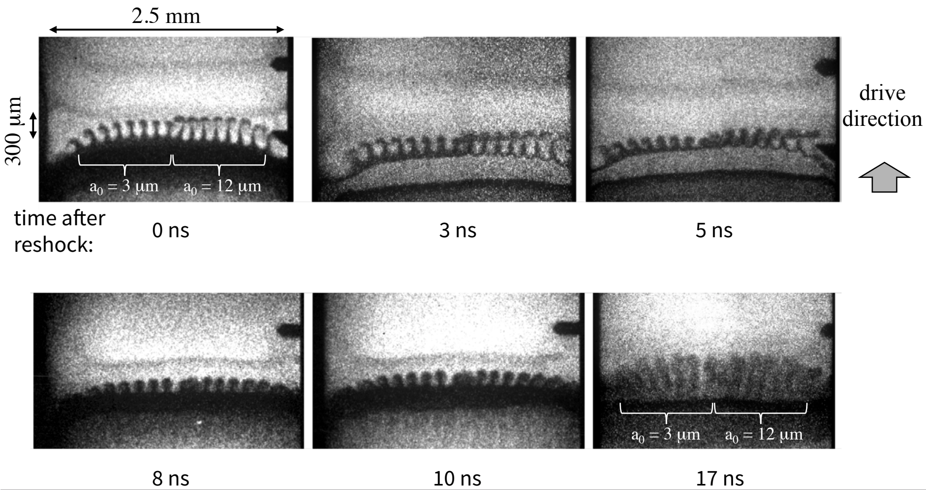

Figure 2. Image sequence of λ=120 μm initial perturbations. In each frame, the interface being driven from the bottom and the opposing (re-shock) is propagating from top to bottom. The first image is taken approximately 38 ns after the start of the main drive, at the time of reshock. Each subsequent image is labeled with the time since the re-shock first interacts with the spike tips. Each target included a region of smaller and larger initial amplitude ripples, as labeled in the first and final frame.

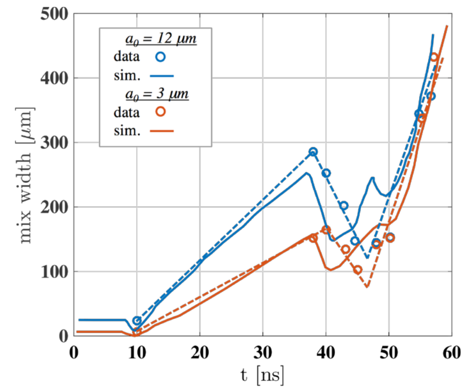

Figure 3. Mix width versus time for large (12 μm) and small (3 μm) initial ripple amplitudes. Individual data points are indicated by the open circles, following an evolution indicated by the dashed lines with phases of initial growth, compression upon reshock, and accelerated growth after reshock. Growth curves from 2D simulations are shown by solid lines.

but with different initial amplitudes (a_0 = 3μm and a_0 = 12 μm) on the two sides of the target. The first radiograph, taken 38 ns after the initial shock and just prior to the re-shock event, shows both sides having grown into nonlinear spike-bubble patterns, with the spikes displaying the characteristic "mushroom cap" structure.[20] At this time prior to reshock, the larger initial amplitude side is clearly still larger than the smaller initial amplitude side. The subsequent images show the re-shock wave compressing the perturbation to a minimum, after which it grows at an accelerated rate. After the re-shock, it is difficult to distinguish the larger initial amplitude side from the smaller initial amplitude side.

Measurements of the mix width, defined as the difference in position between the spike front and bubble front, are shown as open circles in Figure 3. Prior to the reshock occurring at approximately 38 ns, the two different initial amplitudes grow at different rates. That is, the slope of the mix width curve with time, as indicated by the dashed lines, is steeper for the large initial amplitude ripples. This is not unexpected, as the Richtmyer–Meshkov theory of the *linear* regime predicts a growth rate proportional to a_0/λ. This suggests that, for a given wavelength, the larger ripples would grow faster than the smaller ripples, though the data indicate the difference in slope is about a factor of two instead of four. Simulation results, shown as solid lines in Figure 3, indicate the perturbations would have left the linear regime, notionally defined[20] as when $a_0/\lambda \sim 0.1$, only a few nanoseconds after the initial shock. Therefore, the smaller difference in the slopes than linear theory is likely due to nonlinear saturation.

After the re-shock, the mix width curves for the different initial conditions have similar slope, indicating that the post-reshock growth rate is nearly independent of the initial condition. This result, predicted by pre-shot simulations, is consistent with what has been observed in all previous non-HED re-shock experiments. The data suggest that the growth rate is faster after the re-shock, which is also captured by the simulations. To quantify the rate of post-reshock instability growth, modeling analysis is underway to estimate what portion of the observed mix width is actually due to instability-driven growth versus simple material decompression, i.e., the accordion-like expansion that occurs due to the drive pressure decreasing with time, which can account for a significant fraction of the growth in this type of experiment.[21, 22]

Building on the single-mode work, upcoming experiments will focus on measuring the growth of the turbulent mixing region that arises from a multimode initial condition, which presents new challenges for the HED approach. In Figure 2, the main spike-bubble pattern is nonlinear but not turbulent, as the perturbation remains fairly 2D even in the post-reshock frames and the initial wavelength can still clearly be seen, though turbulence likely affects the fine structure. The challenge presented by a 3D turbulent mixing region is the difficulty identifying the bubble front.[23] Using a target like the one shown in Figure 1, the spikes of heavy, dense material are opaque in the radiograph, while the bubbles of light material appear transparent. In a turbulent mixing region, spikes and bubbles are not as easily distinguished but the spike front, i.e., the extent of penetration of heavy material into the light, will appear as a boundary between opaque and transparent regions that is readily identified. However, it is difficult to identify the bubble front, the penetration of light material into heavy, in this scenario because even a small amount of the spike material mixing in will cause the radiograph to appear opaque.

Our proposed solution to this is shown schematically in Figure 4a. It involves a "split" target where one side produces a "conventional" radiograph, while the other side produces an "inverse" image. On the inverse side, the light material is opaque and the dense material is comparatively transparent. Provided the two halves of the target are hydrodynamically equivalent, one can obtain the spike front from the conventional half and the bubble front from the inverse half, permitting a determination of the full mix width. This is illustrated schematically by the synthetic image in Figure 4b, which also illustrates the difficulty if only the conventional side were available. To

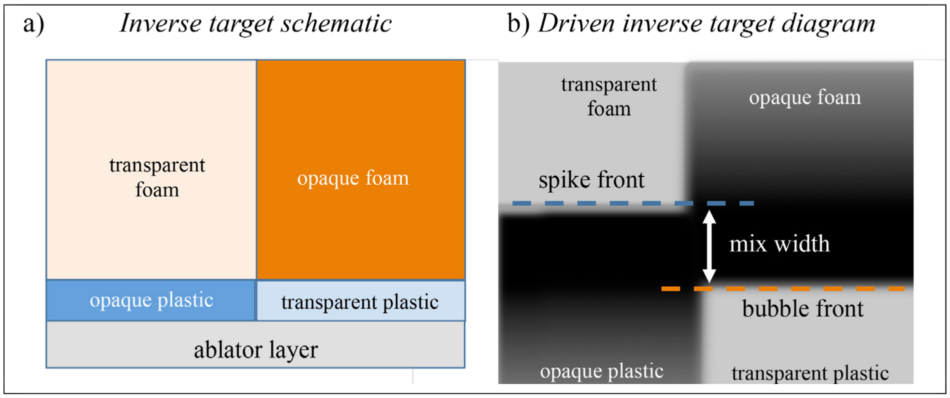

Figure 4. Schematic of the split target technique. a) In this cartoon each of the four fundamental regions is identified: opaque plastic paired with transparent foam, and transparent plastic mated to opaque foam. b) A rendition of the x-ray image that is generated when the target is driven and imaged with an x-ray source that is absorbed by the opaque regions. Because the spike front can be identified on one side and the bubble front on the other, a full mix-width can be measured.

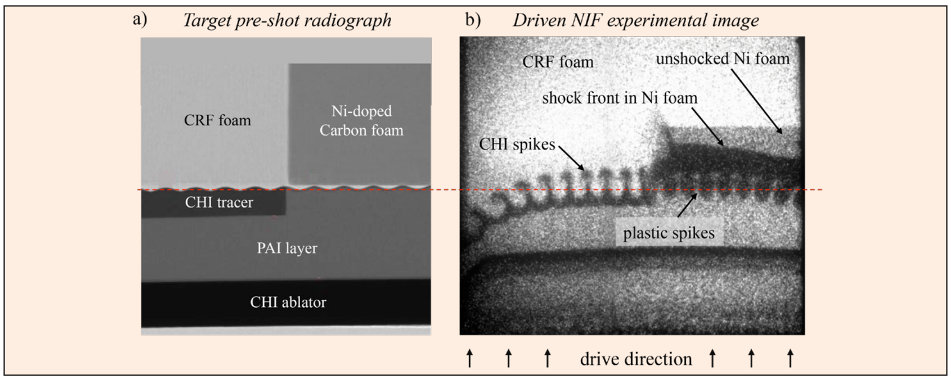

Figure 5. a) A pre-shot x-ray radiograph of a split-type NIF target, taken during construction. Each of the elements from Figure 4 is evident, as well as the ripple in the plastic at the interface. b) Initial proof-of-principle NIF experimental data using split target approach. Each of the shocked and unshocked materials is clearly distinguishable. For spatial scale, note the ripple wavelength is 120 microns.

achieve this, we have developed a novel, nickel–doped carbon foam that we use as a high opacity tracer layer within the low density, carbon foam, while removing the high-opacity tracer strip from the plastic side. Without the high opacity tracer layer, the plastic is fairly transmissive to the 9 keV x–rays of the zinc source. However, the nickel–doped foam is very effective at absorbing x–rays of this energy, which is related to the proximity of nickel to zinc on the periodic table. Therefore, at this x-ray energy, a foam with a small fraction of nickel dopant appears opaque in the radiograph, while behaving hydrodynamically equivalent to the undoped foam.

Figure 5a shows a pre-shot radiograph of an inverse image target, with a sinusoidal interface perturbation, that we used to demonstrate this concept on NIF. Each of the four fundamental components—opaque plastic and transparent foam on the "traditional" side and transparent plastic and opaque foam on the "inverse" side—are evident in this image. Data from the first NIF experiment are shown in Figure 5b. The pattern on the left side of Figure 5b looks similar to the traditional images in Figure 2. However, on the right side, the bubbles are dark while the spikes are light. The shock front is especially visible in the nickel-doped foam, which becomes very opaque after compression by the shock (for comparison, note that the normal carbon foam remains nearly transparent even when shock-compressed).

Having demonstrated the technique, the next experiments will use this type of split target with a multimode initial condition to measure the width of the turbulent mixing region that we expect to develop, where it is much more difficult to identify the bubble front using the traditional approach. Conventional shock tube measurements of the growth of a re-shocked, turbulent mixing region, beginning with the pioneering work of Vetter and Sturtevant,[4] have long been used to validate phenomenological turbulence models,[5-8] such as RANS models,[5] used in integrated ICF simulations.[25] If successful, this split foam approach will enable the same type of measurement to be made in the HED regime that, as noted above, also permits us to systematically vary the initial and drive conditions. We expect the data sets obtained from systematic experiment variations (e.g., foam density or strength of the re-shock drive) to provide especially strong constraints for guiding future model development.

The bubble front imaging problem is an example of a broader challenge with the HED approach to hydrodynamics, that efforts like ours must confront moving forward. HED diagnostics and techniques for hydrodynamics measurements are presently far less developed than in conventional facilities such as shock tubes or wind tunnels, where a variety of experimental methods exist for visualizing and measuring different aspects of the flow field (for example, see reference 18). Therefore, we expect the advancement of diagnostic and measurement techniques to have a critical role in unlocking the full potential of the HED approach for giving insight into the fundamental problems of fluid dynamics.

Acknowledgements

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Highlights

RDT&E Welcomes NGFP Fellow Dr. April Gillens

The Office of Research, Development, Test, and Evaluation (RDT&E) is pleased to welcome NNSA Graduate Fellowship Program (NGFP) fellow Dr. April Gillens. Gillens, who is supporting the Office of Research and Development, is a graduate of North Carolina Agricultural and Technical State University, where she received a bachelor's of science degree in biological engineering in 2010. The U.S. Department of Homeland Security Scholarship sponsored Gillens' last two years of college and allowed her to participate in two summer internships at Los Alamos National Laboratory, where she gained an interest in nuclear forensics.

After completing a post-baccalaureate at Los Alamos National Laboratory, Gillens pursued a doctorate in environmental engineering and science at Clemson University. Gillens was the first and only U.S. Department of Homeland Security Nuclear Forensics Graduate Fellow at Clemson University. This fellowship provided Gillens with the opportunity to participate in two summer research internships at the Lawrence Livermore National Laboratory supporting her dissertation research, which focused on the analysis of stable isotope ratios in tributyl phosphate (TBP) and its degradation products. Her work will help determine if information can be gleaned regarding the process history of TBP and its degradation products when monitoring the stable isotope ratios within the compounds.

Gillens received her PhD in August 2016, becoming the first African American to earn a PhD in environmental engineering and science from Clemson University. Gillens' experience within the national laboratory complex coupled with her education and involvement in nuclear forensics research inspired her to pursue opportunities to address national issues involving nuclear security.

Gillens is currently collaborating with personnel across the NNSA's national laboratories to produce strategic documents on the science focus areas of the Office of Research and Development in preparation for the new administration.

"Being a part of the Nuclear Security Enteprise has given me the chance to serve our Nation, which is something that I've always wanted to do. In the Office of R&D, I am able to incorporate my technical background into the science that supports our Nation's nuclear stockpile. My involvement as an NNSA Graduate Fellow has been a rewarding experience," said Gillens.

2016 Rosenbluth Doctoral Thesis Award in Plasma Physics

Dr. Mike Rosenberg, graduate of the Massachusetts Institute of Technology National Ignition Facility PhD Thesis Program (2014), has been selected as the recipient of the 2016 Marshall N. Rosenbluth Outstanding Doctoral Thesis Award. His thesis, supervised by MIT High-Energy-Density Division Head Dr. Richard Petrasso, of the Plasma Science and Fusion Center, was entitled "Studies of Ion Kinetic Effects in Shock-Driven Inertial Confinement Fusion Implosions at OMEGA and the NIF and Magnetic Reconnections Using Laser-Produced Plasmas at OMEGA. This makes him the second ever PhD student, supported by DOE/NNSA, to receive the prestigious award. Sponsored by General Atomics, Inc., the award was established to recognize exceptional young scientists who have performed original doctoral thesis research of outstanding scientific quality and achievement in the area of plasma physics. The citation that will appear on his certificate is as follows: "For first experimental demonstration of the importance of kinetic and multi-ion effects on fusion rates in a wide class of inertial confinement fusion implosions, and for use of proton diagnostics to unveil new features of magnetic reconnection in laser-generated plasmas."

The award will be presented during the 2016 American Physical Society Division of Plasma Physics Annual Meeting Banquet on November 2. At the same meeting on November 1, Dr. Rosenberg will present an invited overview of his award winning thesis research. •

Comments? Ideas?

We want to hear from you. Please send your comments and ideas for future articles to Terri Stone at terri.stone@nnsa.doe.gov.