


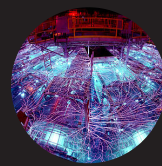


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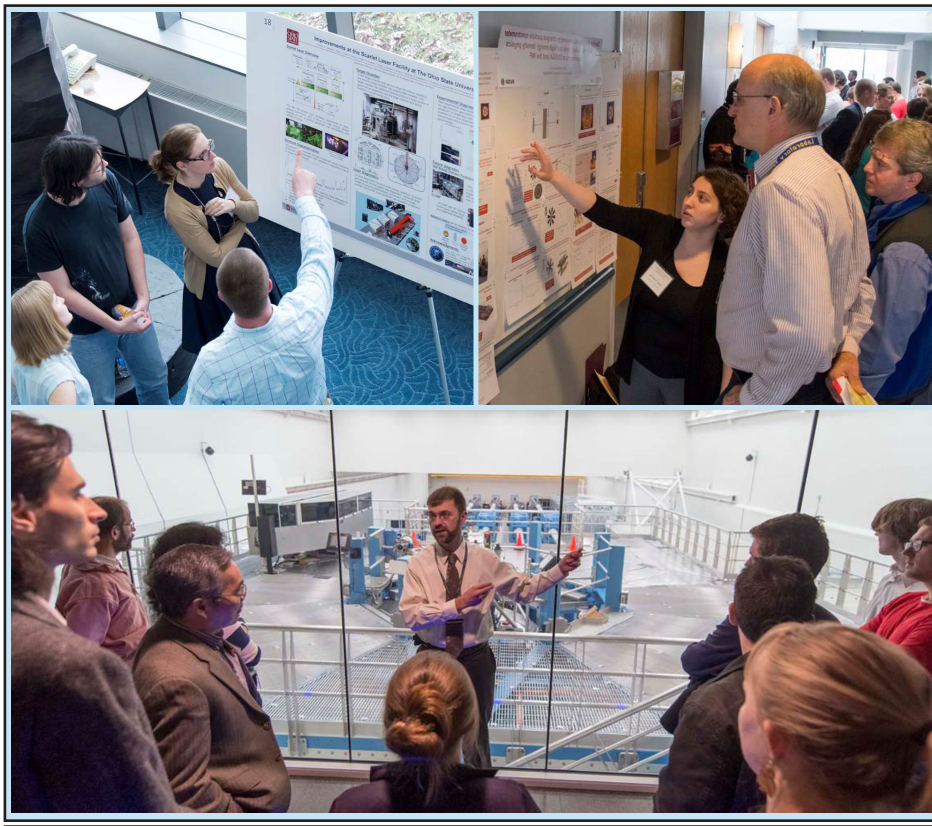
Message from the Assistant Deputy Administrator for Research, Development, Test, and Evaluation, Dr. Kathleen Alexander

This issue of the *Stockpile Stewardship Quarterly* addresses some of our latest research areas, ranging from computing to manufacturing. The first article on the 20-petaflop Sequoia supercomputer describes why it is number one in the world according to the Graph 500 data analytics benchmark. This is a remarkable tool which supports a required capability for stockpile stewardship. High energy density physics experiments are an important element of stockpile stewardship. An example is given in the second article which describes a new class of ablators, diamond and beryllium, which can result in more efficient implosions for National Ignition Facility ignition shots.

This issue also includes yet a different approach to achieving thermonuclear burn in the laboratory. It is a pulsed power approach utilizing magnetically driven cylindrical implosions. The approach, called magnetized liner inertial fusion (MagLIF) is being studied on the Z machine. Burn conditions are achieved through insulating magnetic fields. The last article presents how certain Laboratory Directed Research and Development projects have paid dividends for additive manufacturing (AM). Examples of AM projects are given and the staff who enabled this progress are highlighted.

With the arrival of the warmer season, I wish everyone a safe (and relaxing) summer with family and friends.



The University of Rochester Laboratory for Laser Energetics hosted the Seventh OMEGA Laser Users Group (OLUG) Workshop on April 22-24, 2015. Students and postdoctoral scholars presented approximately 70 posters, ranging from laboratory astrophysics to high-end simulations and to diagnostic development. Attendees received tours of the world-class OMEGA Laser Facility. Read more about the OLUG Workshop on page 12.

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The *Stockpile Stewardship Quarterly* is produced by the 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. | Technical Editor: Dr. Joseph Kindel | Publication Editor: Millicent Mischo

Sequoia's Graph 500 Performance Paves the Way for Future Stockpile Stewardship Work *by Don Johnston (Lawrence Livermore National Laboratory)*

In a feat of computational derring-do, scientists from IBM and Lawrence Livermore National Laboratory (LLNL) pushed the Sequoia supercomputer (see Figure 1) to the top performance on the Graph 500 data analytics benchmark in 2014. The Graph 500 gets its name from the graph processing algorithms at the core of many analytics workloads in application domains such as cyber security, bioinformatics, and social network analysis.

Figure 1. Sequoia, an IBM Blue Gene Q system, consists of 12 rows with 8 racks each for a total of 1.6 million cores. Peak power draw is 9.6 megawatts. The machine is 90 percent water cooled, which is significantly more efficient than air cooling and saves millions in energy costs.

Sequoia, a 20-petaflop IBM Blue Gene/Q system housed at LLNL, retained the No. 1 ranking in the world by completing the largest problem scale ever attempted—'41 scale' or 2.2 trillion vertices—with a performance of 23.751 trillion traversed edges per second (teraTEPS). An edge is a connection between two vertices in a graph and the metric consists of measuring the number of edges processed per second when following connected vertices.

Not unlike pushing a supersonic jet to new limits, achieving this record Graph 500 performance was a technical balancing act that stressed the machine's network performance capability and required the development of innovative algorithms. The end result was improved system efficiency and reliability, not just for a 'data analytics' graph problem, but for Sequoia's day-to-day stockpile stewardship applications.

The result also underscored the Blue Gene/Q system's versatility. "Sequoia's data analytics performance has been surprising," said Scott Futral of Livermore Computing. "We did not necessarily expect Sequoia to be performant in this way. But we see this data analytics capability as an additional benefit to the core workload capability of the machine."

Sequoia, a third-generation Blue Gene machine, was deployed as an advanced technology system to take on the most challenging nuclear weapons modeling and simulation calculations at the heart of the National Nuclear Security Administration's (NNSA's) stockpile stewardship mission. While data analytics was not intended to be a focus area for Sequoia, exploring the full computational capabilities of advanced architectures has always been a part of the Advanced Simulation and Computing (ASC) Program's charter; the Program is the computational backbone of stockpile stewardship.

The latest Graph 500 ranking was announced at the SC14: The International Conference for High Performance Computing, Networking, Storage and Analysis supercomputing conference in New Orleans last November with some fanfare (see Figure 2). The growing importance of data analytics, or 'big data,' to scientific research, including the NNSA's national security programs, has put the Graph 500 ranking in the high performance computing (HPC) community spotlight as a critical measure of performance along with the better-known Top500 LINPACK benchmark—the industry standard for measuring computer power. Sequoia held the No. 1 ranking on the Top500 in June 2012 soon after coming online as well as the No. 1 ranking on the Graph 500 and the Green 500 list of the world's most energy efficient HPC systems. The LINPACK benchmark focuses on CPU performance or speed in floating operations per second (flops) and Graph 500 is about memory and communication interconnect.

A graph is made up of interconnected sets of data with edges and vertices, which in a social media analogy might resemble a graphic image on Facebook, with each vertex representing a user and edges the connection between users. The Graph 500 ranking is compiled using a massive dataset test. The speed with which a supercomputer, starting at one vertex, can discover all other vertices determines its ranking.

Blue Gene/Q systems have dominated the Graph 500 over the last three years. What this means is that Sequoia is the world's highest performance supercomputer for processing gargantuan datasets of petabyte size (quadrillions of bytes).

Leading the algorithm development and optimization techniques that made the Graph 500 performance possible is Fabrizio Petrini of IBM's HPC Analytics Department at the company's Thomas J. Watson Research Center. The explosion of big data has made data analytics and related applications of great interest to industry as well as the scientific research and national security communities.

Figure 2. From left to right: Robin Goldstone of LLNL's HPC Advanced Technologies Office, Dona Crawford, LLNL Associate Director for Computation, and Maya Gokhale, LLNL Distinguished Staff Scientist and IEEE Fellow, display the No. 1 Graph 500 certificate at SC14 (Supercomputing conference) in New Orleans, LA last November (2014). They are standing in the DOE booth (which represented 17 national labs).

In the introduction to a paper produced for the 2014 IEEE International Parallel & Distributed Computing Symposium, IBM's Fabio Checconi and Petrini noted that: "Every day, we create 2.5 quintillion bytes of data—so much that 90 percent of the data in the world today has been created in the last two years alone. This data comes from everywhere: sensors used to gather climate information, posts to social media sites, digital pictures and videos, purchase transaction records, and cell phone GPS signals, to name a few."

Checconi and Petrini also note the challenge of sifting through massive datasets as well as the "nearly limitless opportunities" that same data represents. "Decoding data can help scientists share information from a single, hard-to-find specimen, making new discoveries more possible and frequent. Understanding big data can yield advances in the study of the human brain, offering the prospect, perhaps someday soon, to be able to help doctors and scientists find a cure for critical diseases."

From a national security perspective, extracting essential nuggets of information, sometimes called data mining and/or recognizing patterns in large datasets, is important to such NNSA missions as nonproliferation, atmospheric monitoring, intelligence, bioinformatics, and energy. For example, computer scientists develop techniques for organizing data that allow nonproliferation analysts to pinpoint anomalous behavior in a huge quantity of data.

The stockpile stewardship science to which Sequoia is dedicated also will benefit from the advances the Graph 500 performance represents as scientists prepare to work on next-generation supercomputers, such as Trinity, a 40-petaflop Cray XC30 system, and Sierra, a more than 100-petaflop IBM system that is scheduled for deployment at LLNL in 2018. While data analytics has not traditionally been a big driver for stockpile stewardship work, computational scientists believe it will play an important role as weapons codes are adapted to next-generation supercomputing systems.

"Increasingly multiphysics simulations are limited by both memory bandwidth and latency and network latency," said Dr. Maya Gokhale, LLNL computer scientist and IEEE Fellow. "The true benefit of the Graph 500 to traditional HPC is to focus on those aspects of the supercomputer that have become critical to scaling performance."

As a workhorse for NNSA's tri-lab ASC Program, Sequoia runs the integrated nuclear weapons physics and engineering simulation codes critical to understanding and predicting nuclear weapons performance. HPC modeling and simulation are a cornerstone of the effort to ensure the safety, reliability, and security of the remaining nuclear weapons stockpile since nuclear testing ended 23 years ago. The integrated simulation codes are critical to all elements of stockpile stewardship, including stockpile maintenance, the Life Extension Programs, addressing the discovery of any issues in weapons systems, and supporting dismantlement.

Sequoia represented a giant leap from previous systems employed by the ASC Program. The computational power of the Blue Gene/Q systems ushered in the use of uncertainty quantification (UQ) as a standard method for better understanding weapons performance. Traditionally, advanced technology systems such as Sequoia were primarily the domain of large, single physics simulation codes that could be ported to those machines relatively easily. Preparatory machines, such as the 500-teraflop Blue Gene/P machine named Dawn, the initial delivery machine associated with Sequoia, gave code developers working on the large, multiphysics weapons simulation codes an opportunity to begin the long, slow process of modifying those codes to be able to run on these new machines. Several years after the arrival of Dawn, weapons simulation codes could begin to take advantage of Sequoia, with its 98,304 nodes containing 1.5 million cores (16 cores per node), for running large ensembles of small jobs to quantify uncertainties in numerical simulations of weapons performance.

To date, UQ ensembles of up to 70,000 two-dimensional simulations have been performed. Each run differs from previous runs with slight variations in input parameters that measure the sensitivity of simulations to input variability. In this way, scientists can better understand the likelihood of certain outcomes when some inputs are not known with precision.

Future systems, such as Los Alamos National Laboratory's (LANL's) Trinity system and LLNL's Sierra, will permit UQ runs in three dimensions (3D). Trinity is scheduled for deployment in 2016. "As the stockpile ages, we become more reliant on weapons performance simulations to certify the stockpile," said Chris Clouse, Deputy Associate Program Leader for Computational Physics in LLNL's Weapons and Complex Integration Principal Directorate.

"Sequoia is a bridge to future architectures," Clouse said. "Sequoia gets us to the edge of 3D UQ with an entry-level capability. 3D UQ is critical to the long-term certification of the stockpile as the issues associated with aging become more 3D in nature."

"Adapting and optimizing nuclear weapons codes that have been developed over many years to new HPC architectures is no trivial matter," he said. "It took us 2 to 3 years to get to a point where we could make good use of Sequoia, but our codes are far from optimized for that machine, and we expect the challenges of future architectures to be even greater." Dawn provided the transition to Sequoia just as Sequoia is serving as a bridge to Trinity and Sierra.

"Sequoia made up for its relatively simple—and slow—processors by providing huge numbers of them, but our challenge was improving the codes to be able to out scale across the nearly 100,000 nodes of the machine," said Clouse. "Today, Sequoia allows weapons codes to run at scale."

Sierra will be an even greater leap in computing power with the commensurate technical challenges for ASC scientists that come with adapting to a new architecture. "There's a long list of issues we need to address for adapting codes to future architectures," continued Clouse. "As a transition machine, Sequoia has allowed us to work on a subset of the things we need to tackle for future systems. We're still reaching the peak of what we can do on Sequoia. With Sequoia, we've gotten a good jump on out-scaling [achieving parallelism across hundreds of thousands of nodes]," Clouse said. "Now we need to focus on in-scaling [achieving parallelism within each node]."

ASC scientists will have the opportunity to take the next step in 2016 when the Trinity supercomputer comes online at LANL.

While data analytics have not traditionally been a big driver for the stockpile stewardship mission, Clouse sees opportunities for applying

The stockpile stewardship science to which Sequoia is dedicated also will benefit from the advances the Graph 500 performance represents as scientists prepare to work on next-generation supercomputers, such as Trinity, a 40-petaflop Cray XC30 system, and Sierra, a more than 100-petaflop IBM system that is scheduled for deployment at LLNL in 2018.

big data techniques to weapons simulation science. For example, pattern recognition—finding unique features that would differentiate simulations and debugging—would have useful applicability. He also said that these techniques could be applied to tracking back to the original perturbations that disrupt or even kill code runs.

Looking to the more distant future, Clouse says data analytics as it applies to 'machine learning' has the potential to improve code performance on large, complex HPC systems. Machine learning consists of using data analytics to teach a machine "what to look for and what to do to prevent problems by adjusting inputs to the simulation."

"Currently, identifying problems is an iterative and time-consuming process," he said, adding that preventing problems before they occur would "greatly boost the throughput for users."

Computer scientists at LLNL are exploring machine learning and looking at other ways 'data analytics' may be applied to optimize code performance on future systems. With each generation of supercomputer generating ever greater quantities of data across the spectrum of applications, data analytics will inevitably play a bigger role in the management of applications, including the codes used by ASC scientists.

Traditionally, modeling and simulation have been regarded as being at the opposite end of the supercomputing applications spectrum from data analytics. Technologies, tools, and requirements for analytics were seen as distinctly different from the modeling and simulation used for stockpile stewardship and climate research.

"A few years ago the data analytics and traditional HPC communities seemed headed in opposite directions," said Rob Neely of LLNL's Center for Advanced Scientific Computing (CASC). "But that's changing."

In a commentary published in Innovation: America's Journal of Technology Commercialization in 2014, Dimitri Kusnezov, NNSA Chief Scientist, and Jim Brase, Deputy Associate Director for Computation at LLNL, said that the difference between the big data and traditional HPC communities was reflected both in technology development and investment.

"Looking ahead, this separation will change," Kusnezov and Brase wrote. "Particular aspects of simulation of complex phenomena and the tools of data analytics will need to converge, as societal issues demand more understanding coupled to the existing data analysis and reduction."

Kusnezov and Brase point out that national priorities today require "computing in parts of the spectrum that are driven both by data analytics and simulation."

Business and research communities are looking for the faster network communications and interconnects associated with traditional HPC and the greater memory bandwidth characteristic of big data.

As a bridge to future HPC systems, Sequoia offers a glimpse of what a well-balanced HPC system can do in both the data analytics and modeling domains, consequently helping to set the stage for what Neely calls "a marriage of traditional HPC and big data."

Neely underscores the importance of research in machine learning, deep computing and neural networks to running applications on future systems. These have the potential to be powerful tools that would allow "codes to teach themselves to be more robust" as well as allowing for improved mesh management for complex simulations.

"This may sound futuristic," he said. "But that's what we do at the labs." •

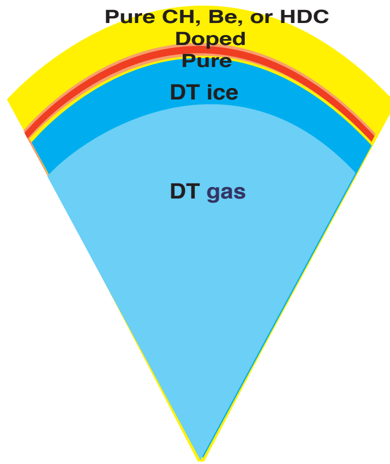
The Advantages of Beryllium and Diamond Capsules for the National Ignition Facility

by Douglas C. Wilson (Los Alamos National Laboratory [LANL]), and Darwin Ho (Lawrence Livermore National Laboratory [LLNL]), and the Inertial Confinement Fusion Teams at LANL and LLNL

As part of stockpile stewardship, the Inertial Confinement Fusion (ICF) program has focused on exploring fusion burn at the National Ignition Facility (NIF). The process attempts to use lasers, rather than nuclear fission, to generate x-rays, implode, and fuse deuterium (D) and tritium (T) in a small capsule. Laser light is directed into a gold or uranium cylinder (a "hohlraum") producing x-rays that penetrate, heat, and explode the exterior of a spherical capsule. The resulting inward pressure compresses the interior DT fuel, creating sufficiently high central temperatures and densities that the fuel fuses, releasing energy in the form of helium nuclei and neutrons. If these alpha particles and neutrons can deposit enough of their energy in the surrounding DT fuel before it can expand, the capsule will "ignite" releasing much more energy. To date, this DT ignition has been successfully created in boosting the yield of nuclear explosives. Achieving this in the laboratory has been a major goal for the national ICF program since its conception in the late 1960s. Overcoming the remaining challenges will require a better understanding of the detailed physics of fusion burn in conditions similar to those occurring in a nuclear device.

The vast majority of DT-containing capsules tested at NIF have been made from glow discharge polymer with a composition of ~ $C_{0.56}\,H_{0.44}$, i.e., plastic. If we think of the laser and hohlraum as providing a bath of x-rays, then the capsule material that most effectively absorbs x-rays would be the best. Ease of fabrication made plastic the first choice for NIF capsules. Only recently have beryllium (Be) and diamond-like high density carbon (HDC) begun to be tested at NIF. Be, because of its lower opacity, more effectively uses x-rays than either HDC or plastic. The higher density of HDC (3.5 g/cc) and Be (1.8 g/cc) offer other advantages compared to CH (1.06 g/cc). In this article, we will elaborate on these advantages and how they will be used in the coming years to further the pursuit of higher neutron yields and fusion burn.

Figure 1 and the table compare NIF capsules with CH[1], HDC[2], and Be[3] shells designed with similar DT fuel masses.



Ablator	DT thickness (μm)	R inner (μm)	R outer (μm)	Dopant	%	Dopant thickness
HDC	58	942	1082	W	0.3	24
CH	68	862	1124	Si	1,2,1	38
Be	70	835	1065	Cu	0.4,1,0.4	37

Figure 1. Schematic of CH, Be, and HDC NIF capsules.

The HDC capsule uses only one dopant layer; the CH and Be divide it into three. All ablators have a pure inner ~ 5-μm-thick layer, followed by doped layer(s) and an outer thick layer of pure ablator. Each ablator uses a different dopant: Be uses copper, HDC uses tungsten, and CH uses silicon. The dopant purpose is the same, to minimize instability growth at the ablator/DT ice interface as the capsule compresses.

And compress it must. Because the NIF laser (~2 MJ) cannot provide nearly as much energy as a fissioning nuclear device, the x-rays in an ICF hohraum can only compress a small fuel mass, approximately 0.2 mg. The small initial areal density of the fuel (~ 0.25 g/cm^3 * 70e-4 cm = 1.75e-3 g/cm^2) is not enough, once it is heated to several keV temperatures, to force alpha particles to deposit their energy, raise the burn rate yet higher, and ignite a run-away burn. A total fuel areal density of ~1.5 g/cm^2 is needed to ignite. Fortunately, areal density increases with spherical compression by ~$(R^{initial}/R^{final})^2$. A radial compression of ~25 is needed. But there is not enough energy to compress all of the fuel to high temperature. A minimum of ~0.3 g/cm^2 is required in a central hot spot with the surrounding fuel kept cold. To minimize the energy required to compress it, the entropy of the fuel outside the hot spot must be low. To achieve that, a relatively low pressure first shock (about 0.5 -1 Mbar) transits the DT fuel, which is then compressed nearly adiabatically.

Higher Density – Higher Picket Temperature and Shorter Laser Pulses

The high initial densities of HDC (3.5 g/cc) and Be (1.8) ablators give them several advantages over plastic (1.06). One is that a higher initial shock pressure can be used in these denser ablators to create the same pressure in DT as with CH. Because a shock crossing the ablator/DT ice interface is partially reflected (more if the density difference is greater), a higher pressure shock can be initiated in a Be ablator, and a yet higher pressure in HDC. This higher pressure shock is driven by a higher radiation temperature in the hohlraum, which for Be and CH leads to more radiative stabilization of the Rayleigh-Taylor instability at the capsule surface.[4] This greater stabilization is one of the reasons for the recent success in "high-foot" plastic capsule implosions that have demonstrated fuel temperature increase from alpha-particle heating[5] and is probably also an advantage for HDC. These targets are mounted by a thin membrane called a tent. A weaker tent perturbation could be a welcome advantage for higher density ablators. Experiments show a less significant signature of the tent supporting the HDC capsule.

An additional advantage of higher density is shorter laser pulses. Figure 2 compares NIF laser pulse lengths for HDC, Be, and CH capsules. The shortest pulse is for HDC, then CH, and slightly longer for Be. The shorter HDC pulse arises because a higher power laser picket (at 1 to 2 ns) drives a faster first shock through a thinner ablator. When two ablators have similar mass, then the higher density one will be thinner. The first shock will take less time to transit the ablator. If two designs use the same shock pressure and velocity in the fuel (giving it the same entropy), the time to transit the fuel is the same. The Be pulse is slightly longer because it uses the same picket power as CH but gives the fuel less entropy. The pulse shown here is being tuned for the first DT shot and will be shortened.

A shorter laser pulse interacts more favorably with the hohlraum. A shorter laser pulse allows less expansion of the hohlraum wall. There is less laser backscatter out of the hohlraum and greater x-ray production. In all three hohlraums, the wall is held back by a 1.6 mg/cc, helium gas fill. But this gas apparently also reduces the x-ray production,[6] and increases laser backscatter out of the hohlraum. Shorter laser pulses in lower density-filled hohlraums appear to be one path to increasing x-ray production and reducing laser backscatter.

Lower Opacity – More Efficient Absorption

The lower atomic number of beryllium (Z=4) compared to carbon (Z=6) is a fundamental advantage. It produces a lower x-ray opacity (κ) allowing the capsule to absorb x-rays deeper and more effectively, producing a higher mass ablation rate, M, and ablation pressure, P, when driven at the same radiation temperature. The M, P, and the speed, V, of a thermal wave driven by x-ray penetration are given by:

$$M \propto \sqrt{\frac{A}{1+Z}\,\frac{T^3}{\kappa}} \quad ; \quad V \propto \frac{M}{\rho} \quad ; \text{ and } \quad P \propto \frac{T^2}{\sqrt{\kappa}}$$

where Z is the ablator's atomic number, A its atomic weight, ρ (g/cm^3) its density, T (keV) the radiation temperature, and κ (cm^2/g) its temperature and density dependent opacity.[3] Fitting κ to power laws in ρ and T between 150 and 400 eV yields the following:

$M_{Be}/M_{HDC} \approx 3.3/T^{0.08}$; $M_{Be}/M_{CH} \approx 4.6/(T^{0.8}\rho^{0.2})$ and $P^{Be}/P_{CH} \approx 1.34/T^{0.4}$; $P_{Be}/P_{HDC} \approx 3.5/T^{0.08}$

Measurements of the mass ablation rate[7] are within a factor of 2 quantitatively consistent with these conclusions, confirming the advantages of low opacity.

Lower opacity at the same radiation temperature also results in a higher ablation velocity, V, and better stabilization of the Rayleigh-Taylor instability at the ablation front.[4] The higher densities of HDC and Be also allow higher radiation temperatures in the beginning of the laser pulse, leading to yet more stabilization.

The Future for Beryllium and HDC in ICF

Experiments are just beginning on the use of both Be and HDC as ablators, and shorter pulses with lower density gas fills. There have been only three DT-layered HDC capsules, and the first Be one is scheduled for June 2015. While the "high-foot" plastic capsules have potential in terms of different laser pulse shapes and rugby shaped hohlraums, Be and HDC capsules share those possibilities and also offer the advantages of higher density and improved implosion behaviors. The next few years will be exciting as we continue the challenging quest for alpha heating and ignition.

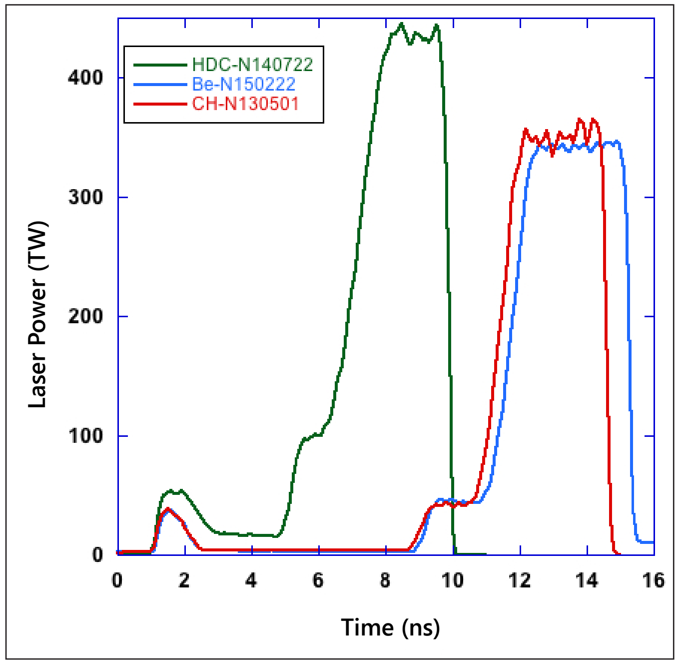


Figure 2. HDC, CH, and Be ablator pulses used at NIF.

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Recent Progress and Future Potential of Magnetized Liner Inertial Fusion (MagLIF) *by S.A. Slutz et al.**

(Sandia National Laboratories)

Introduction

The standard approaches to inertial confinement fusion (ICF) rely on implosion velocities greater than 300 km/s and spherical convergence to achieve the high fuel temperatures ($T > 4$ keV) and areal densities ($\rho r > 0.3$ g/cm^2) required for ignition.[1] Such high velocities are achieved by heating the outside surface of a spherical capsule either directly with a large number of laser beams (Direct Drive) or with x-rays generated within a hohlraum (Indirect Drive). A much more energetically efficient approach is to use the magnetic pressure generated by a pulsed power machine to directly drive an implosion. In this approach 5-10% of the stored energy can be converted to the implosion of a metal tube generally referred to as a "liner." However, the implosion velocity is not very high 70-100 km/s and the convergence is cylindrical (rather than spherical) making it more difficult to achieve the high temperatures and areal densities needed for ignition.

Magneto-inertial fusion (MIF) concepts can significantly relax implosion velocity requirements while still achieving high temperatures through the use of insulating magnetic fields to decrease the heat losses normal to the field and increase fusion product confinement.[2-3] MagLIF[4-5] is a specific MIF concept that is being studied on the Z facility at Sandia National Laboratories.

The three important stages of this concept are shown in Figure 1. The first step is to apply an axial magnetic field of 10-30 Tesla with external field coils. A laser beam then enters at one end of the tube to heat the fuel to an average temperature of 100-200 eV. Finally, an axially directed current from a pulsed-power machine generates a large azimuthal magnetic field on the outside of the liner creating pressure to drive the implosion. On the time scale of the implosion, the axial magnetic field is nearly frozen into both the fuel and the liner due to high conductivity and thus, the magnetic field rises to very high values ($\sim 10^4$ Tesla) as the liner is compressed. The axial magnetic field inhibits radial heat loss throughout the implosion, but particularly near stagnation when the losses would be the greatest due to the high temperatures. Heat loss and alpha particle transport in the axial direction are unaffected by the magnetic field, but acceptable because the liner is adequately long. Thus, closed field lines are not required. As with all ICF, the Rayleigh Taylor instability limits the convergence of MagLIF implosions. The fuel preheating reduces the required volume compression and thus, the convergence needed to achieve fusion temperatures. Numerical simulations and experiments[6-10] indicate thick-walled liners with an aspect ratio ($A_R = R_{outer}/\Delta R_{wall} \sim 6$) should maintain sufficient areal density to compress and confine fusion fuel despite instabilities. Numerical simulations[4] indicate that both the insulating magnetic field and preheat are necessary to obtain fusion conditions with these slow implosion velocities.

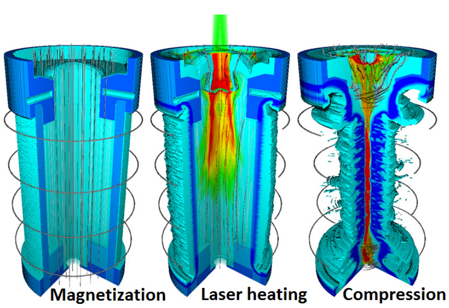

Figure 1. The three stages of the MagLIF concept.

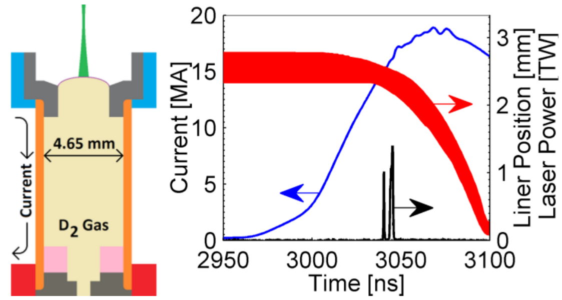

Figure 2. The left image shows the target geometry used in these experiments with parts color coded; anode (blue), cathode (red), AR=6 Be liner (orange), laser (green), 0.7 mg/cc pressurized deuterium gas fill (yellow), and polyimide foil (brown) to contain the deuterium and allow the laser to penetrate. Liner radius (red), current (blue), and laser power (black) are plotted on the right.

Integrated Experiments on the Z Machine

Experiments[11] integrating all three phases of the MagLIF concept have been performed on the Z Machine.[12-13] The geometry is shown in Figure 2. An initial axial magnetic field of 10 T was generated by field coils[14] above and below the liner. Z-Beamlet,[15] a frequency-doubled neodymium YAG laser, provided ~ 2 kJ to heat the deuterium. The Z Machine produced peak currents of 18 and 17 MA for 7.5- and 10-mm long liners, respectively. An experimental drive current, experimental laser power, and simulated liner trajectory[16] are plotted in Figure 2 (taken from Reference 11).

Fusion neutron yields and spectra were determined by activation and neutron time of flight techniques.[17-18] The shorter 7.5-mm liners produced the best deuterium neutron yields (5×10^{11}, 1×10^{12}, and 2×10^{12}) as compared to an average yield of $\sim 2.5 \times 10^{11}$ for the longer 10-mm liners. This could be due to the larger drive current delivered to the shorter liners or other changes such as the foil thickness. In the best performing experiment, the ion and electron temperatures at stagnation were 2.5 ± 0.8 keV and $3.1\ {+0.7/-0.5}$ keV, respectively. Secondary deuterium-tritium (DT) neutrons, a result of the tritons produced in the aneutronic branch of the DD reaction, were measured with yields up to 5×10^{10}, which indicates a high degree of magnetization[19], since the areal density is low. An x-ray (6 and 9 keV) self-emission image produced from a time-integrated spherical crystal diagnostic is shown in Figure 3 (taken from Reference 11). The 6-mm-tall column has a full width at half

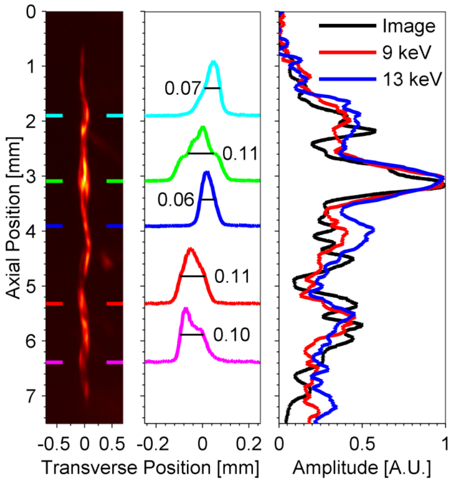

Figure 3. Self-emission image (left), horizontal image lineouts (center), and axial lineouts (right).

maximum of 60-120 μm and exhibits a small helical perturbation.

The results from these experiments validate key features of the MagLIF concept, demonstrating thermonuclear yields, fusion-relevant stagnation temperatures, and magnetic flux compression. However pre-shot simulations[16] predicted DD yields in excess of 10^{13}. Yields comparable to the experiments are obtained if one assumes only 10% of the laser energy is deposited in the fuel. The leading hypothesis for this discrepancy is poor laser coupling through the 1.5-3.5-μm-thick polyimide foil. Indeed recent laser only experiments using Z Beamlet[20] indicate that only ~10% of the laser energy penetrates a 2.0-μm foil. This is probably due to the large variations in laser intensity of the unsmoothed Z Beamlet beam near focus, which could drive laser plasma instabilities. Beam smoothing is not required for backlighting, which has been the primary application of Z Beamlet. Experiments using Omega lasers at the University of Rochestester Laboratory for Laser Energetics are underway to test laser transmission with smoothed beams. The preliminary results are encouraging and plans have been made to obtain phase plates to smooth the spatial beam profile of Z Beamlet. This should allow more effective laser heating of the fuel for future MagLIF experiments.

MagLIF on Future Accelerators

It has been shown numerically[21] that both high thermonuclear yield and gain could be obtained using MagLIF with the addition of a layer of DT ice on the inside of the liner. However, significantly higher drive currents are required than can be delivered by the present Z machine. Two high performance pulsed-power machines (Z300 and Z800) have been designed[22] using the Liner Transformer Driver technology. The Z300 design provides approximately 48 MA to a MagLIF load, while Z800 would provide about 61 MA. A parameterized Thevenin equivalent circuit was used to drive a series of Lasnex[23] simulations. At each value of the current, the MagLIF target was optimized by varying the length, the radius, the fuel density, the initial magnetic field and the preheat energy. These optimized results are plotted in Figure 4. As can be seen, very high yields (> 1 GJ) are predicted for liners with a layer of DT ice (Ice Burner), which would be a very significant achievement for laboratory fusion and very valuable for stockpile stewardship.

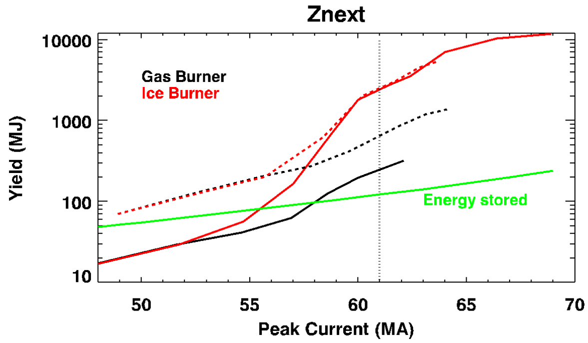

Figure 4. Optimized MagLIF simulated (dashed=1D solid=2D) yields as a function of drive current. The smallest current corresponds to the Z300 design and the vertical dotted line corresponds to the Z800 design.

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*Contributing Authors

M.R. Gomez, A.B. Sefkow, D.B. Sinars, K.D. Hahn, S.B. Hansen, E.C. Harding, P.F. Knapp, P.F. Schmit, C.A. Jennings, T. J. Awe, M. Geissel, D.C. Rovang, G.A. Chandler, G.W. Cooper, M.E. Cuneo, A. J. Harvey-Thompson, M.C. Herrmann, M.H. Hess, O. Johns, D.C. Lamppa, M.R. Martin, R.D. McBride, K. J. Peterson, J. L. Porter, G.K. Robertson, G.A. Rochau, C.L. Ruiz, M.E. Savage, I.C. Smith, W.A. Stygar, and R.A. Vesey (Sandia National Laboratories) •

Lawrence Livermore Additive Manufacturing LDRD Investments Pay Strong Dividends to the Nuclear Security Enterprise *by Rokaya Al-Ayat and Jason Carpenter (Lawrence Livermore National Laboratory)*

Since its creation by Congress in 1991, the Laboratory Directed Research and Development (LDRD) Program has enabled DOE labs to explore high-risk, potentially high-payoff research in support of their current and future missions. Lawrence Livermore National Laboratory (LLNL) has been investing LDRD resources in projects that advance fundamental science and technology with an eye to anticipating and addressing DOE and NNSA challenges, as well as helping develop the staff critical to execute them. LLNL's investments in the diverse, dynamic field of additive manufacturing (AM) exemplify how LDRD has been supporting the NNSA stockpile mission.

The manufacturing needs of the Nuclear Security Enterprise (NSE)—a combination of high quality and complexity, low volume, and unique materials—are not common drivers for industry (see *Additive Manufacturing (AM)* sidebar). As such, NNSA must advance its own AM capability base. LLNL LDRD-funded AM projects explore needed solutions to the NSE. AM has the capacity to transform not only stockpile-stewardship component production, but also the way in which those components are qualified and certified. LLNL's AM work focuses on this qualification and certification effort because of the speed, flexibility, and cost improvements it promises to bring to the stockpile stewardship arena.

In addition to addressing its stockpile stewardship mission, LLNL's LDRD AM portfolio has achieved many successes in science, technology, collaboration, and the recruitment and retention of talent. Projects contributing to these successes range from those that predate AM activities at LLNL, such as the Transformational Materials Initiative, to current projects addressing deterministic multifunctional materials and manufacturing and the accelerated certification of additively manufactured metals.

Landmark LDRD Project Pays AM Dividends

When the Transformational Materials Initiative (TMI) began in 2006, it was the largest LDRD project in LLNL history. TMI investigated and developed advanced research options that the Stockpile Stewardship Program could use to transform the NSE by reducing the cost and time of stockpile maintenance and production, improving weapon safety, ensuring the stockpile's longevity, and optimizing its performance. TMI spawned several follow-on investigations, many of which have led to LLNL's rapidly developing exciting work in the field of AM. TMI investigations into novel sensors for embedded evaluation, for example, led directly to current work on cushion manufacturing (see Figure 1).

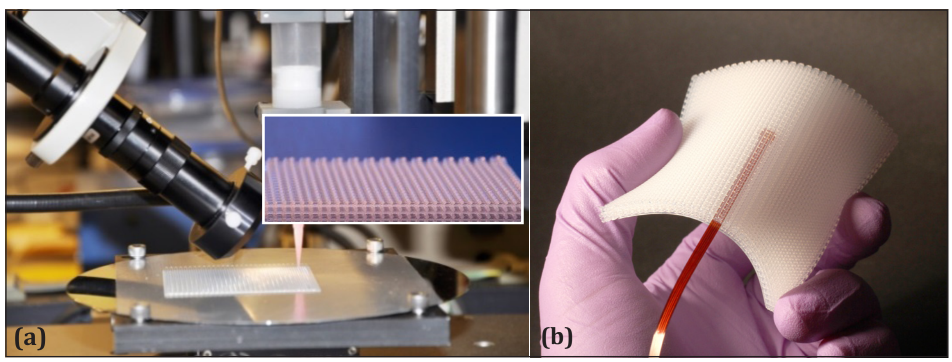


Figure 1. (a) LLNL's direct-ink writing capability led to this advanced material, whose properties can be carefully controlled and digitally modified. (b) Because direct-ink writing prints the material in layers, printers can include other components, such as a stress sensor (the metallic ribbon), during printing so that weapons experts understand aging issues in the foam and the objects it cushions.

Staff Highlight: Yong Han

Chemist Yong Han (PhD, University of California-Santa Barbara) was recruited to help recrystallize triaminotrinitrobenzene (TATB), a notoriously difficult high-explosive molecule that is critical to the stockpile. "My involvement in the TMI LDRD introduced me to the greater implications of fundamental science on programmatic work," says Han. "Our success transitioned to Science Campaign funding from NNSA to continue to develop and mature our initial investment in TATB recrystallization." Han went on to new roles in the Enhanced Surveillance Campaign, working on other crystals in the stockpile. He is now the Detonator Surveillance Program Chemistry Subject Matter Expert, and he continues to support other LDRD projects, using them to attract new talent.

Additive Manufacturing (AM)

AM processes create layers of a polymer- or metal-based material from a 3D model or other electronic data. AM methods can quickly, easily, and precisely create complex objects. Commercial AM tools cannot make many mixed-material components desired by the NSE, nor do commercial platforms have the resolution to design and create features at the micro- and nano- scales. When combined with the high-performance computing (HPC) and deep materials expertise available within the NNSA, however, AM dramatically expands the design space to produce better, cheaper stockpile components and offers the potential to certify and qualify these components and related systems more efficiently.

Multifunctional Materials to Transform NSE Manufacturing

The Deterministic Multifunctional Materials and Manufacturing Initiative aims to produce unique multifunctional materials that support stockpile stewardship, nuclear-fusion ignition, and global security missions. According to Chris Spadaccini, who leads this LDRD initiative, LLNL is well poised to address NNSA's needs.

"Thanks in large part to our LDRD work," Spadaccini explains, "we have grown to more than 80 material scientists, chemists, physicists, engineers, and computational scientists developing advanced materials and manufacturing processes, and we have created five state-of-the-art AM labs." This initiative has advanced AM in a multitude of ways, involving collaborations across the NNSA, including the Y-12 National Security Complex, the Kansas City National Security Campus, the Pantex Plant, and the Los Alamos and Sandia National Laboratories. Key university collaborations have been established with the University of Illinois at Urbana-Champaign, Harvard University, MIT, and UCLA.

Staff Highlight: Andrew Pascall

Before he came to LLNL to work for Chris Spadaccini, material scientist Andrew Pascall (PhD, University of California-Santa Barbara) thought that research on nuclear weapons had ended with the Comprehensive Test Ban Treaty in 1992. "I thought all the warheads the U.S. had just sat on a shelf somewhere," he admits. "Little did I know how much science and engineering go into maintaining the stockpile, or the breadth of knowledge necessary for stockpile stewardship." Currently, Pascall is developing two new AM techniques to enable printing of high-quality, high-purity metal components focusing on NNSA-relevant materials.

"I thought all the warheads the U.S. had just sat on a shelf somewhere. Little did I know how much science and engineering go into maintaining the stockpile, or the breadth of knowledge necessary for stockpile stewardship."

— Andrew Pascall, LLNL

The work begun in this and other AM-related LDRD projects has the potential to transform a number of NSE manufacturing processes. Cushions and pads manufactured to protect and position components within a nuclear weapon, for example, could require significantly less time and cost to produce using AM methods.

For more information on LLNL's work in this area, contact Chris Spadaccini (spadaccini2@llnl.gov) or read this *Science and Technology Review* article (https://str.llnl.

Accelerating Stockpile Certification and Qualification

Manufacturing methods and materials used to produce critical NSE components must be formally qualified to ensure they perform to specification. This process often requires thousands of tests, costs millions of dollars, and takes 5 to 15 years. Later on, even a minor process change could require complete requalification. To realize AM's full potential for speed, flexibility, and cost savings, NNSA must also accelerate the processes to qualify components and certify systems. Livermore scientists and engineers will be helping to drive this effort, drawing on foundational capabilities in materials synthesis, predictive simulation, advanced manufacturing, and materials characterization.

An LLNL team working on stainless-steel AM has used a combination of simulations, experiments, and data-mining techniques, for example, to uncover patterns in the simulation results, identify variables that affect results, and streamline the optimization process. The team expects that a similar approach could be used to optimize other properties of a manufactured part or other materials.

Since the cessation of nuclear testing, LLNL has focused particular attention on developing predictive models for regimes where experimental data are not always available. Researchers have used information provided by these models running on LLNL HPC resources to improve AM processes, obtain desired microstructures, and reduce manufacturing errors. Two models, based on LLNL-developed codes, have already shown significant promise at both the component/part scale and the smaller powder scale (see Figure 2).

For more information on LLNL's work in this area, contact Wayne King (king17@llnl.gov) or read this *Science and Technology Review* article (https://str.llnl.gov/january-2015/king).

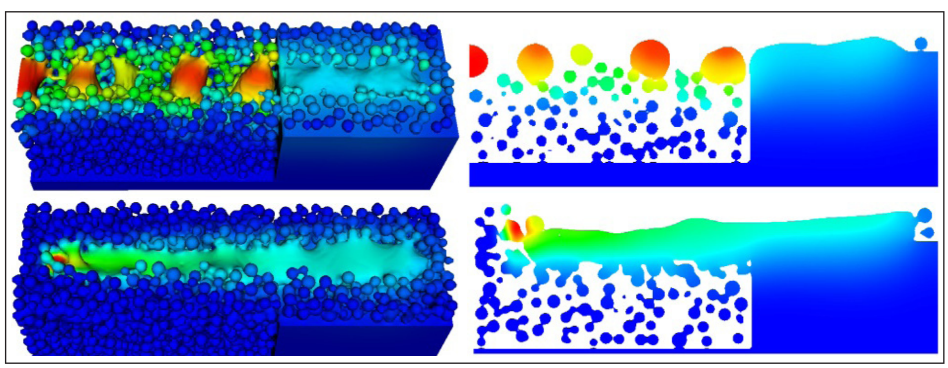
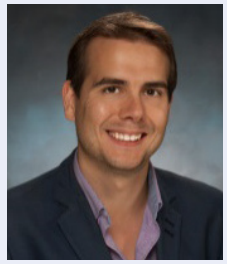


Figure 2. Powder-scale modeling using the massively parallel multiphysics code ALE3D clarifies, for example, how to set process parameters to build a part with an overhang geometry. Top: both laser power and scan speed are high, producing an undesirable balling effect (shown by the red and yellow features). Powder-scale modeling shows that lowering scan speed and power (bottom scenario) yields a better build.

Staff Highlight: James Lewicki

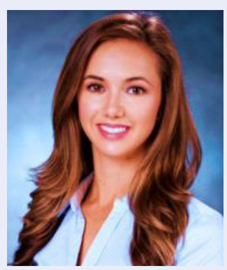


James Lewicki (PhD, University of Strathclyde, Scotland) is the principal investigator for an FY 2015 LDRD project addressing the rational design and optimization of AM carbon fiber/polymer composites. "The opportunity to compete internally for funding to do innovative R&D was and still is a big driver for me at LLNL," Lewicki says. "I came from a background in academia and industry and had little idea of just how much fundamental and applied research goes on within the NSE. It's both a great opportunity and highly scientifically rewarding to be part of it."

LDRD AM Projects Attract and Retain Top Talent for Programmatic Missions

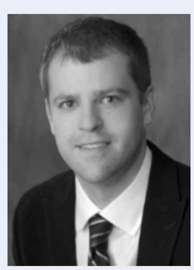
Given the current workforce turnover across the NSE and especially the anticipated turnover in the next decade, the LDRD Program's ability to draw, train, and retain talent is critical. LDRD efforts attract top-tier postdoctoral researchers and early-career staff to the NNSA laboratories. Most of these convert to full-time staff after engaging firsthand in the national security mission; LLNL's conversion rate from postdoc to staff increased in FY 2015 from ~50% to ~75%. Without such opportunities, many of these individuals would likely choose academic or industrial careers. LDRD-funded projects have frequently earned national recognition through awards, presentations at international conferences, papers published in peer-reviewed journals, and patents. About one-half of patents and one-half of LLNL's R&D 100 awards have come from LDRD projects. •

Staff Highlight: Julie Jackson



Mehanical engineer Julie Jackson (BS, University of California-Davis) started at LLNL in 2012 as an undergraduate summer intern and has worked on several LDRD projects. "I was interested in being an experimentalist," she explains, "so in 2013 I started work on an AM LDRD project on disruptive fabrication technologies. I was lucky enough to transition from a student intern to a post-bachelor appointment, and then to a staff employee. LDRD projects acted as a stepping stone for my career here at LLNL. I still spend a large percentage of my time on LDRD-related projects, constructing various components that are additively manufactured with projection micro-stereolithography."

Staff Highlight: Eric Duoss



Material engineer Eric Duoss (PhD, University of Illinois at Urbana-Champagne) is currently working to advance some of the technologies developed during his LDRD projects to create unique and cutting-edge components that will go into upcoming hydrodynamics tests—components that could provide tremendous value to the NSE. Says Duoss, "We started throwing around LDRD research ideas during my interview. After accepting but before arriving at LLNL, I helped write parts of the LDRD proposal, and after starting here, I supported the proposal presentation. It was certainly a unique opportunity for a postdoc to get that level of insight. Before coming to LLNL, I did not know much about the NSE. Because of my LDRD work early in my career, I have gained exposure to the NSE that really would have been otherwise impossible."

Highlights

2015 Stewardship Science Graduate Fellowship (SSGF) Program Review

The 2015 SSGF Program Review will be held June 29-July 2, 2015 in Washington, DC at the Grand Hyatt Washington. Highlights of this year's review will include presentations by each of the students completing their fellowship in 2015, insight from alumni now working in Department of Energy (DOE) laboratories, and Fellows' Poster Session featuring the research supported by the DOE NNSA SSGF program. For more information, visit www.krellinst.org/ssgf/conf/2015.

2015 Computational Science Graduate Fellowship (CSGF) Program Review

The 2015 CSGF Program Review will be held at the Crystal Gateway Marriott in Arlington, Virginia on July 27-30, 2015. DOE CSGF scholars are part of an innovative group learning to use high performance computing to solve scientific and engineering problems. The DOE CSGF Program Review makes it possible for these fellows—as well as program alumni, DOE staff, faculty and other members of the fellowship community—to share ideas, support one another and discover research opportunities at the DOE/NNSA laboratories. Jointly funded by the Department of Energy and National Nuclear Security Administration, the CSGF Program was developed to meet the Nation's growing need for science and technology professionals with advanced computer skills. For more information, visit www.krellinst.org/csgf. •

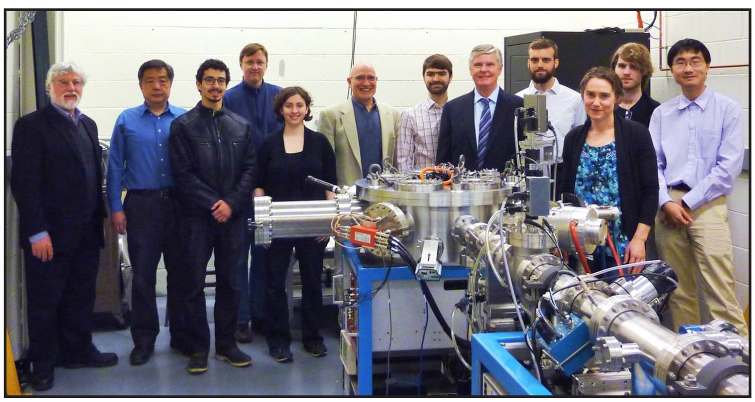
The Seventh OMEGA Laser Users Group (OLUG) Workshop

Attendees of this year's successful Seventh OMEGA Laser Users Group Workshop held in April.

More than 63 graduate students and postdoctoral researchers attended the National Nuclear Security Administration (NNSA)-supported OLUG Workshop held on April 22-24, 2015 at the University of Rochester Laboratory for Laser Energetics (LLE). Forty-six of those attendees received travel assistance from an NNSA grant administered by the Massachusetts Institute of Technology. Welcoming remarks were presented by LLE Director Robert McCrory and University of Rochester Dean Robert Clark. Dr. Keith LeChien, Director of the NNSA Office of Inertial Confinement Fusion, presented the NNSA perspective to attendees. Among the workshop highlights were the following:

- 70 contributed posters
- 2 outstanding posters by LLE summer high school students
- 7 posters by undergraduates
- 44 posters by graduate students and postdocs
- Invited science talks by world-class experts
- 14 Findings and Recommendations
- A young researcher forum on way to improve the Omega Facility.

OLUG, the Users Group for the Omega Laser Facility, comprises 428 scientists—students, academics, and researchers from 55 universities, more than 35 centers and national laboratories, and 21 different countries and four continents. The Eighth OLUG Workshop is scheduled for April 27-29, 2016 at LLE.



Massachusetts Institute of Technology

Deputy Administrator for Defense Programs Don Cook recently visited the Massachusetts Institute of Technology's High Energy Density Plasma Accelerator Facility for Diagnostic and Platform Development for NIF, Omega, and Z. From left to right: Fredrick Séguin, Chikang Li, David Orozco, Johan Frenje, Emily Armstrong, Richard Petrasso, Hans Rinderknecht, Don Cook, Alex Zylstra, Maria Gatu Johnson, Brandon Lahmann, and Hong Sio. (Rindernnkecht and Zylstra ultimately decided to accept the Lawrence and Reines Postdoctoral Fellowships at Lawrence Livermore National Laboratory and Los Alamos National Labotatory, respectively.)

University of Nevada, Reno

The Third International Workshop on Radiation from High Energy Density Plasmas (RHEDP 2015) was held on June 9-12, 2015 in Stateline, Nevada. There were 68 researchers in attendance, 29 of which were students and 6 postdocs. There were a total of 58 presentations with 33 invited oral talks in six subtopic areas: Inertial Fusion, Theoretical Modeling and Diagnostics, Pulsed Power Driven Plasma, Gas-puff Z-pinches, Laser Produced Plasmas, and Astrophysics and a poster session with 25 presentations. The presentations highlighted progress in the field, while identifying current issues and exciting future directions.