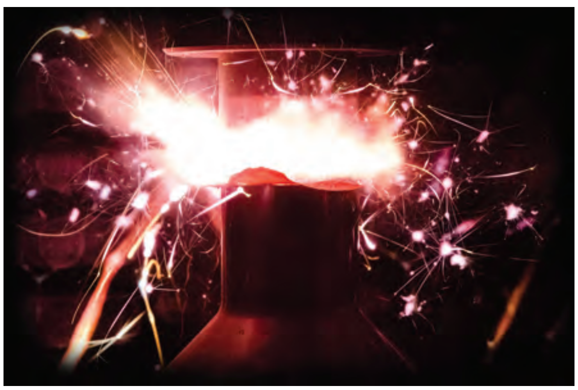
DOE/NA-0038

2016
Stewardship Science Academic Programs Annual

- Stewardship Science Academic Alliances
- High Energy Density Laboratory Plasmas
- National Laser Users' Facility
- Predictive Science Academic Alliance Program II

National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY



On the Cover

Explosives are designed to explode, as in this response to an impact. Many kinds of explosives response—wanted or unwanted—can result from mechanical stimuli to the explosive material. Predicting the outcome for each explosive to each kind of stimulus is critically important to their function and safety. Measuring the elastic properties is a starting point to predicting safety and performance characteristics for an explosive material (see page 62).

Photo Credit: Daniel Preston, Los Alamos National Laboratory

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Dr. Kathleen Alexander with (left to right) Dr. Richard Petrasso, head of the High-Energy-Density Physics Division of the Massachusetts Institute of Technology (MIT) Plasma Science and Fusion Center; Dr. Mario Manuel, the 2014 recipient of the Marshall Rosenbluth Outstanding Thesis Award presented by the American Physical Society, and Dr. Donald L. Cook, former Deputy Administrator for Defense Programs. Both Drs. Cook and Manuel received their PhDs from the MIT Nuclear Science and Engineering Department.

National Nuclear Security Administration

Mission First...Through Teamwork

Welcome from the Assistant Deputy Administrator for Research, Development, Test, and Evaluation

One of the primary missions of NNSA is to ensure a safe, secure, and effective nuclear deterrent, and since 1992 we have done so without nuclear explosive testing. Focusing on this mission, NNSA and its national laboratories have developed a science-based Stockpile Stewardship Program to maintain and enhance its scientific, engineering, and computational capabilities to ensure its mission. NNSA developed the Stewardship Science Academic Programs (SSAP) more than a decade ago to provide the future capability for stockpile stewardship by supporting students and their professors to develop the unique skills required of future stewards of the stockpile. We are pleased that many participants from the SSAP have chosen a career with the NNSA national laboratories. These talented scientists and engineers are an important part of our current and projected future success.

Every day, we have evidence that our efforts are keeping the United States, its allies, and the world at-large safe. World-class, state-of-the-art theoretical, computational, and experimental science and technology is key to maintaining the effectiveness of our country's nuclear deterrent. The high quality of the work performed under the SSAP is clearly reflected in this 2016 Stewardship Science Academic Programs Annual. The work presented herein, however, only represents a small fraction of the outstanding work done in the SSAP to provide an excellent pipeline of talent and new ideas relevant to stockpile stewardship.

To all of you, I extend my best wishes for continued future success and congratulations on your successes to date.

Dr. Kathleen B. Alexander

Assistant Deputy Administrator
for Research, Development, Test,
and Evaluation
National Nuclear Security Administration

Contents

2016 Stewardship Science Academic Programs Annual

NNSA Office of Research, Development, Test, and Evaluation

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The Stewardship Science Academic Programs Annual is produced by the NNSA Office of Research, Development, Test, and Evaluation. It features select research conducted by the following NNSA-supported research programs: Stewardship Science Academic Alliances, High Energy Density Laboratory Plasmas, National Laser Users' Facility, and the Predictive Science Academic Alliance Program II. For more information, visit www.nnsa.energy.gov/stockpilestewardship.

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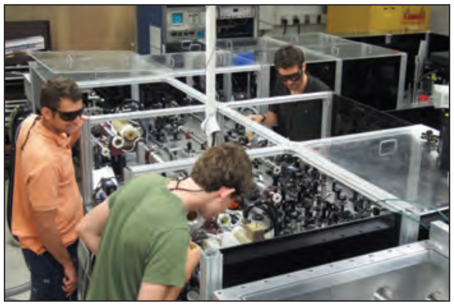
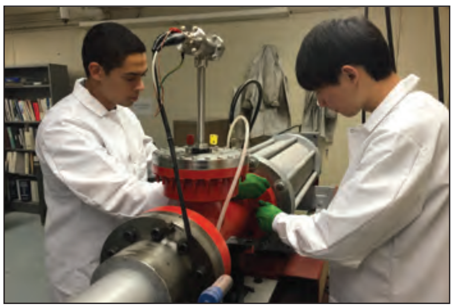
Published February 2016

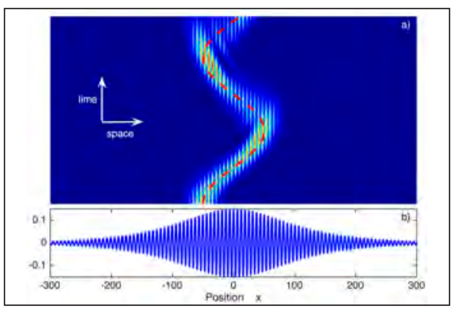
4



9



18



28

Overview

Research

Stewardship Science Academic Alliances (SSAA)

High Energy Density Laboratory Plasmas (HEDLP)

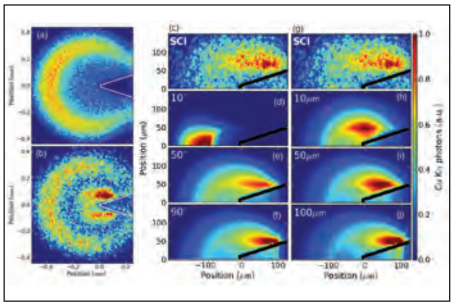
National Laser Users' Facility (NLUF)

Predictive Science Academic Alliance Program II (PSAAP II)

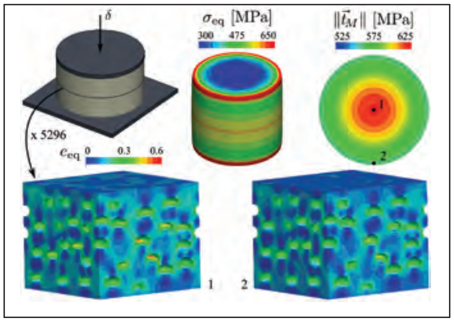
Stewardship Science Graduate Fellowship (SSGF)

Feature Articles

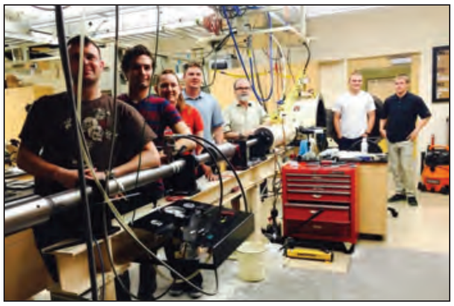
Grants and Cooperative Agreements



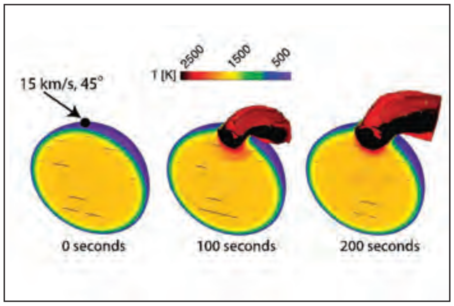
34



46



58



63

Stewardship Science Academic Programs

— *Developing the Next Generation of Stockpile Stewards*

The Nation's nuclear weapons stockpile is a vital part of our national security infrastructure. Ensuring that this deterrent is second to none requires the best science and technology, especially in this post-nuclear testing era. Having top tier scientists and engineers in the areas critical to stockpile stewardship is the only way to ensure the best science and technology. The National Nuclear Security Administration (NNSA) supports this effort through the Office of Research, Development, Test, and Evaluation's Stewardship Science Academic Programs (SSAP).

2015-2016 Stewardship Science Graduate Fellowship Class. Pictured above, left to right: Nathan Finney, Columbia University, Micro/Nanoscale Engineering; Christopher Miller, Georgia Institute of Technology, Materials Science; Brooklyn Noble, University of Utah, Engineering; Amy Lovell, Michigan State University, Theoretical Nuclear Physics; Leo Kirsch, University of California, Berkeley (UCB), Accelerator Physics; and Alison Saunders, UCB, Warm Dense Matter.

In this annual report, some of the outstanding work performed under the SSAP is highlighted. The SSAP includes the following programs:

- Stewardship Science Academic Alliances (SSAA) Program;
- High Energy Density Laboratory Plasmas (HEDLP) Program;
- National Laser Users' Facility (NLUF) Program; and
- Predictive Science Academic Alliance Program II (PSAAP II).

These research elements support U.S. research at universities in scientific areas important to stockpile stewardship. A fundamental objective is the support and training of doctoral and masters degree students studying science and engineering, with a view towards some of these students becoming future stewards of the stockpile. A second fundamental objective is to connect highly skilled academic and NNSA scientists, so that new ideas and techniques can be introduced into the NNSA's arsenal. A third fundamental objective is to ensure that there is a strong community of technical peers throughout the country, external to the NNSA national laboratories, i.e., Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratories, that is capable of providing peer review, scientific competition, and depth and breadth to the basic fields of research important to NNSA.

Also a part of the SSAP are the Stewardship Science Graduate Fellowship (SSGF) Program and the Computational Science Graduate Fellowship (CSGF) Program, the latter jointly sponsored with the U.S. Department of Energy's (DOE's) Office of Science. These programs support PhD students in areas of interest to stockpile stewardship. They provide a yearly stipend, tuition, fees, and an academic allowance. This issue highlights an alumnus and four students from the SSGF Program. These individuals share information about their experiences as fellows and how the program has helped shape their careers. For more information about these programs, please visit http://www.krellinst.org/fellowships.

Stewardship Science Academic Alliances (SSAA) Program

Launched in 2002, this program emphasizes areas of fundamental research and development that are relevant to the Stockpile Stewardship Program mission, typically underfunded by other federal agencies, and for which there is a recruiting need at the NNSA national laboratories. Advanced experimental activities are supported through Centers of Excellence and research grants in the fields of properties of materials under extreme conditions and/or hydrodynamics; low energy nuclear science; radiochemistry; and high energy density physics.

High Energy Density Laboratory Plasmas (HEDLP) Program

The NNSA's Office of Inertial Confinement Fusion and the DOE's Office of Fusion Energy Sciences established this joint program in 2008. It involves the study of ionized matter in laboratory experiments where the stored energy reaches approximately 100 billion joules per cubic meter (i.e., pressures of approximately 1 million atmospheres). Some of the areas of interest include high energy density hydrodynamics, radiation-dominated hydrodynamics, material properties, nonlinear optics of plasmas, laser-plasma interactions, and warm dense matter.

National Laser Users' Facility (NLUF) Program

The primary purpose of this program is to provide facility time for university- and business-led high energy density experiments on the Omega Laser Facility at the Laboratory for Laser Energetics, University of Rochester. Through this program, two of the world's premier laser systems for high energy density research, OMEGA and OMEGA-EP, are accessible to a broad community of academic and industrial research interests, for use as tools for conducting basic research experiments in both low and high energy density physics and laser-matter interactions, and in providing research experience necessary to maintain a cadre of trained scientists to meet the Nation's future needs in these areas of science and technology.

Physics undergraduate student, Zackary Rehfuss, assembling a pumping system for a dilution refrigerator in the laboratory of Professor Brian Maple at UC San Diego. The dilution refrigerator will be used to cool high pressure cells down to millikelvin temperatures for electrical transport and magnetic measurements on f-electron materials at high pressures into the megabar range.

Visiting graduate student, Gauri Khanolkar (University of Southern California), examining optical fibers in preparation for a shock compression experiment at the Institute for Shock Physics, Washington State University.

Michigan graduate student Alex Rasmus works with faculty member Carolyn Kuranz on target alignment for an experiment on the OMEGA-EP laser.

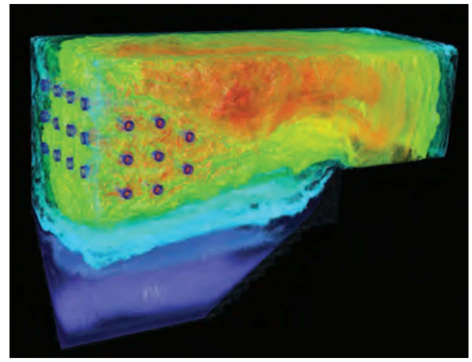
A fundamental objective is the support and training of doctoral and masters degree students studying science and engineering, with a view towards some of these students becoming future stewards of the stockpile. A second fundamental objective is to connect highly skilled academic and NNSA scientists, so that new ideas and techniques can be introduced into the NNSA's arsenal.

• • •

Predictive Science Academic Alliance Program II (PSAAP II)

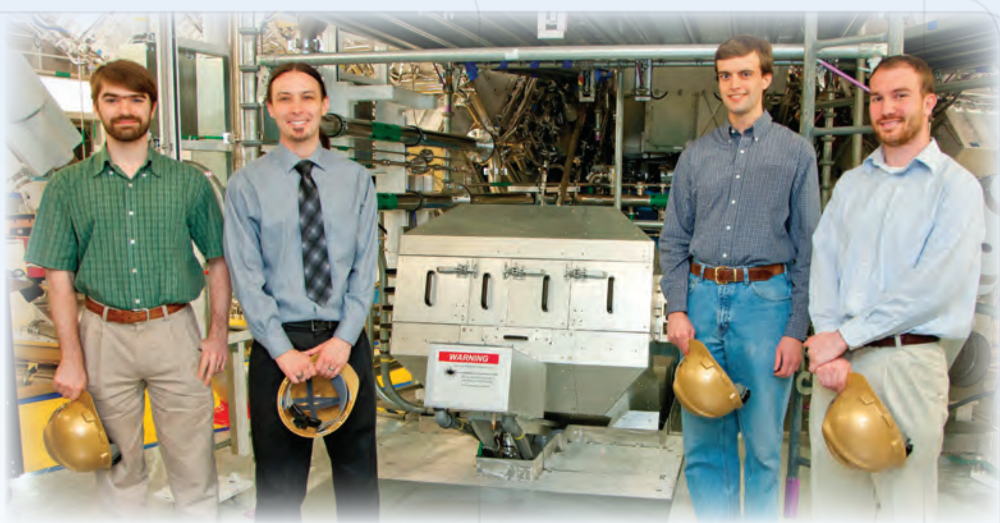
The primary focus of this program is the emerging field of predictive science, i.e., the application of verified and validated computational simulations to predict the behavior of complex multiscale, multiphysics systems, with quantified uncertainty. This is potentially applicable to a variety of applications, from nuclear weapons effects to efficient manufacturing, global economics, to a basic understanding of the universe. Each of these simulations requires the integration of a diverse set of disciplines; each discipline in its own right is an important component of many applications. Success requires using the most powerful computing systems. Consequently, a key component is computer science research (on both software and algorithmic frameworks) that will contribute to effective utilization of emerging architectures leading to exascale.

For more information about the SSAP and the NNSA Office of Research, Development Test, and Evaluation, visit www.nnsa.energy.gov/stockpilestewardship.



Volume rendered image of the new design of an oxy-coal boiler for high efficiency, low-cost carbon capture. The simulation was performed using Carbon Capture Multidisciplinary Simulation (CCMSC) tools running on Vulcan from LLNL. The visualization was performed using volume-rendering tools developed by the CCMSC visualization team and running in VisIt from LLNL. (See *page 47.)*

Productive Partnerships: Massachusetts Institute of Technology (MIT)



Four recent MIT PhDs, whose work in each case was sponsored under the SSAP, are shown standing next to the National Ignition Facility (NIF) neutron spectrometer (a diagnostic based on a collaboration of MIT, the University of Rochester Laboratory of Laser Energetics (LLE), and Lawrence Livermore National Laboratory (LLNL)). From left to right, Hans Rinderknecht (also featured on page 39 of this Annual), Dan Casey, Alex Zylstra, and Mike Rosenberg. Rinderknecht and Zylstra are currently Lawrence and Reines Postdoctoral Fellows at LLNL and Los Alamos National Laboratory, respectively. Rosenberg is a postdoctoral researcher at LLE, and Casey is now a staff scientist at LLNL. In each case, their thesis work involved implementation of nuclear diagnostics, and analysis of associated data, at both NIF and Omega. For Casey, the myriad aspects of the NIF neutron spectrometer comprised a large portion of his thesis. SSAP allowed all four young researchers to be deeply involved in programmatic and fundamental high energy density science at these facilities, and the opportunity to interact and collaborate with a broad cross section of outstanding colleagues in our community. They are the very first graduating PhDs whose theses featured NIF data and analyses.

Stewardship Science Academic Alliances (SSAA)

Recent Activities in the Center for High Energy Density Science at the University of Texas at Austin

University of Texas at Austin ✦ PI: Todd Ditmire (tditmire@physics.utexas.edu)

Research in high energy density physics at the University of Texas at Austin (UT) within the NNSA Stewardship Science Academic Programs commenced in 2003 with the establishment of the Texas Center for High Intensity Laser Science. This Center was renamed the Center for High Energy Density Science (CHEDS) in 2010 when it was elevated to the status of an independent organized research unit within the College of Natural Sciences, illustrating the importance that high energy density (HED) plasma research has assumed at UT. As is the case throughout the SSAA centers, CHEDS focuses on recruiting and educating students in a field of research of foundational importance to the NNSA laboratories. CHEDS does this through experimental and computational studies of the physics of high energy density plasmas and shocked materials, created and probed with high-peak-power and high-energy lasers. CHEDS is composed of over forty people including six full time faculty, technical and science staff, postdoctoral researchers, graduate and undergraduate students. The Center currently supports over twenty-five students (including fifteen graduate and ten undergrad students) and has sent a number of graduates into positions at Sandia National Laboratories (SNL) and Los Alamos National Laboratory (LANL) in recent years.

Educating Students in Science Vital to Stockpile Stewardship

The educational mission of CHEDS is undertaken on a number of facilities both at UT and at the NNSA labs. CHEDS has a particular emphasis on teaching students how to conduct successful science campaigns on mid-scale to large "single-shot" type machines to prepare them for active research careers in the NNSA and other large DOE and Department of Defense laboratories. While most of the research executed in CHEDS is on laser facilities, the Center also has a scientific presence on a number of other (pulsed power and gas gun) HED facilities in the complex, particularly at SNL where two CHEDS students are currently working full time on their dissertation projects. CHEDS research spans a range of challenges in dense plasma physics with particular focus on three main research areas: (1) study of the properties of warm and hot dense plasmas, (2) acceleration of particles to high energy and production of intense radiation bursts with these particles, and (3) investigation of shock waves and blast wave hydrodynamics. CHEDS also includes supporting research in the technology of high peak power lasers, and almost all CHEDS students spend some time during their graduate career learning laser technology before turning to their respective fundamental science focus areas for their PhD thesis.

The core of the CHEDS research program rests with the Texas Petawatt Laser facility (TPW) which CHEDS operates on campus at UT. This laser is internationally unique: it delivers laser pulses with energy above 150 J per pulse in pulse duration less than 150 fs. No other facility anywhere in the world offers this set of high energy, short pulse parameters. Since commissioning of the TPW in 2009, this facility has served as the platform for numerous PhD dissertation projects both for students in CHEDS (see Figure 1) and for many students and researchers from around the world through an open peer reviewed user-collaborator access program.

HED Experimental Highlights on the Texas Petawatt

The extremely high laser fields of the TPW are ideal for creating conditions where copious particles are ejected at high energy. These fields can accelerate considerable numbers of protons to multi-MeV energies through irradiation of thin solid density foils. CHEDS students and staff led by Dr. Gilliss Dyer and Prof. Todd Ditmire have used these TPW accelerated protons to heat solid density targets, copper in particular, to temperatures between 10 and 50 eV to measure the equation of state (EOS) of these materials in this warm, dense plasma regime. CHEDS results have been used to compare to the latest EOS calculations in copper from both Lawrence Livermore National Laboratory and LANL. A CHEDS group led by Prof. Manuel Hegelich produced a peak neutron flux an order of magnitude higher than any existing source.[1] To achieve this, the TPW was focused on a plastic sheet producing electron jets, and the electron jets impinged on a stack of copper plates where they produced bremsstrahlung x-rays which further produced neutrons in (γ,n) reactions. By focusing the TPW into a helium gas cell, Professor Mike Downer's group from UT used a laser wakefield to accelerate electrons to more than 3 GeV kinetic energies with charge per bunch and reduced divergence which exceeds similar results from around the world by almost an order of magnitude.[2] This energetic electron pulse, when directed into a tungsten slab, produced 10^4 muons, a result of interest to Homeland Security. Finally, the TPW has been used to drive explosions in deuterium cluster targets which have led to production of deuterium-deuterium (DD) fusion neutrons with thermal neutron energy spectra and fusion yields in excess of 10^7 n/shot. This experiment was led by CHEDS graduate student Woosuk Bang who is now a postdoctoral staff member in P-division at LANL.

In addition to the numerous experiments led by CHEDS students and staff, the TPW has seen a number of very exciting experiments led by

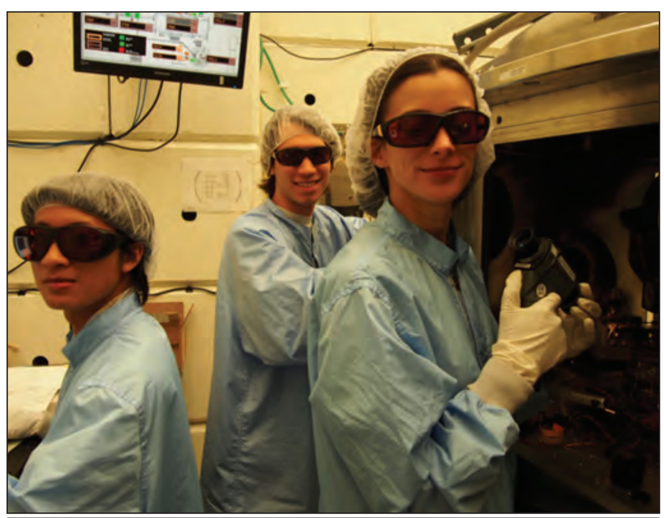


Figure 1. CHEDS students aligning solid targets on the Texas Petawatt laser in Target Chamber 1 during a collaborative experiment with Rice University.

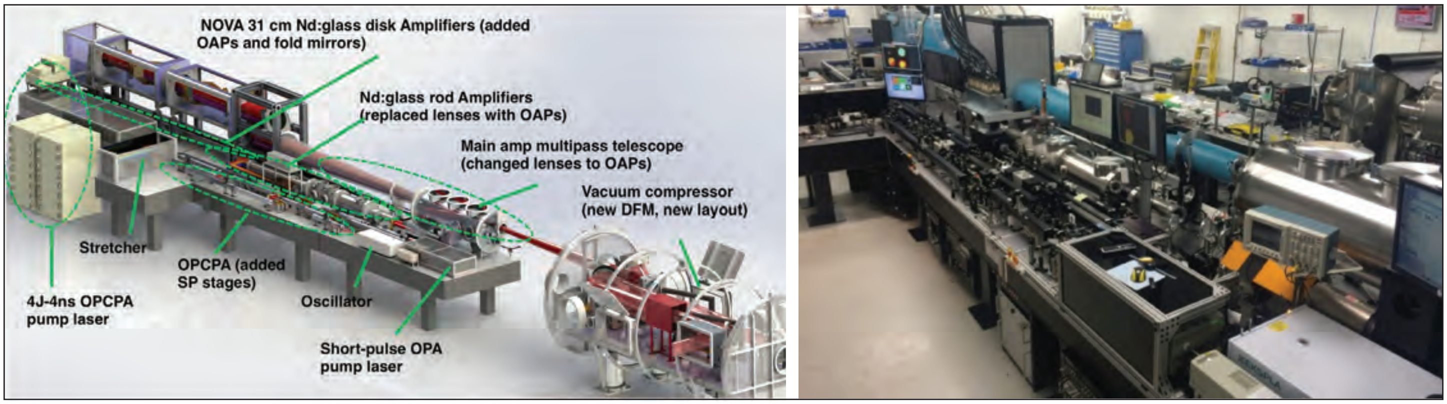


Figure 2. A graphical summary of the improvements made to the TPW laser (left) and a photo of the upgraded laser chain (right).

outside user collaborators. Successful experiments by researchers from Rice University, the Ohio State University, the University of California, San Diego, LANL, and the Max Planck Institute in Garching, Germany are among successes of this user-collaborator program. For example, a collaborative experiment with Professor Edison Liang from Rice University produced positron to electron ratios greater than 50%, a significant step towards producing a pair-dominated plasma.[3]

Texas Petawatt Laser Upgrade

The past year has seen a hiatus in experimental activities on the TPW accompanied by a major upgrade to the laser, greatly enhancing its capabilities (see Figure 2). This $1M upgrade, funded primarily by the Defense Advanced Research Projects Agency and the Air Force Office of Scientific Research, involved an almost complete rebuild of the laser to enhance the temporal contrast of the laser pulses to better than 10^{10}:1 and install optics which allow intensity in excess of 3 x 10^{22} W/cm^2. This significant improvement to the laser puts the TPW at the forefront of technological capability among high energy petawatt-class lasers around the world. The TPW in this new high contrast trim is now once again shooting experiments. While still early in the experimental campaign, there appears to be some quite exciting results from the system within an experiment being conducted by four graduate students working under Dr. Toma Toncian. This experiment is examining an ion acceleration mechanism studied extensively at the LANL Trident laser facility in which very thin foils (under 100 nm in thickness) are irradiated by high temporal contrast laser pulses. Initial results from the upgraded TPW suggest that protons with energy above 90 MeV are being produced, a significant improvement over proton acceleration results on the TPW before the upgrade.

Collaborative Research at NNSA Laboratories

While the TPW is the primary focus of CHEDS research, students and staff in the Center perform experiments on smaller scale lasers within the Center (see Figure 3) and on the HED facilities at the NNSA labs. CHEDS has, for example, a long standing active collaboration with the Pulsed Power effort at SNL and these activities have led to two CHEDS PhD students, Sean Grant and Nathan Riley, working full time on site at SNL on their thesis projects. A highlight of note is the work of Nathan Riley working under Prof. Ditmire with Dr. John Porter and his staff at SNL on the study of the stability of high Mach number radiative blast waves in the presence of dynamically significant magnetic fields. This work began at UT on the TPW using a SNL-constructed 1 MA pulse power magnetic field generator and has now been moved back to SNL to utilize the higher energy multi-kJ Z-Beamlet laser there. This collaborative experiment has potential impact in understanding some astrophysical phenomena around super novae remnants and is relevant to SNL's magnetized liner fusion efforts. Such an integrated experiment is possible only through a combination of the pulsed power expertise of SNL and the pump-probe laser plasma diagnostics expertise of CHEDS.

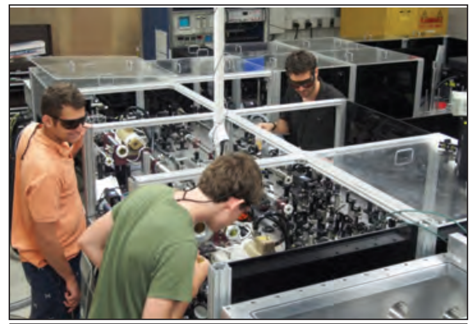


Figure 3. CHEDS students working on the GHOST 20 TW table top laser in preparation for solid target experiments.

A complete accounting of CHEDS activities with NNSA labs is too extensive to recount here. However, a second highlight of note involves CHEDS ongoing collaboration with LANL colleagues on the LANL Trident laser. A recent achievement involves a nice experiment involving CHEDS student Rebecca Roycroft and characterization of proton heating on Trident. With the successful upgrade of the TPW at UT, the successful integration of the SNL pulse power device with the TPW and the Z-Beamlet laser, and ongoing collaborations with all three NNSA labs and numerous academic labs around the world, the scientific productivity from CHEDS is promising.

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[2]X. Wang et al., "Quasi-monoenergetic Laser-plasma Acceleration of Electrons to 2 GeV," Nature Commun. 4:1988; doi: 10.1038/ncomms2988, 2013.

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High Flux Femtosecond X-ray Emission from Controlled Transverse Injection in a Laser Wakefield Accelerator

University of Michigan, Ann Arbor ⌘ PI: Dr. Karl Krushelnick (kmkr@umich.edu)

The SSAA research program at the Center for Ultrafast Optical Science (CUOS) at the University of Michigan has been ongoing for about two years and is investigating the interaction of intense laser pulses with plasmas using the high power HERCULES laser system – which operates at a peak power of 300 Terawatts. Two Michigan graduate students, Tony Zhao and Keegan Behm, are performing experimental work for their PhD theses on this project using x-rays produced by the transverse oscillations of highly relativistic electrons as they are accelerated in the laser wakefield. These x-rays are being used for femtosecond time-resolved x-ray absorption spectroscopy as well as time-resolved x-ray imaging of dense matter with micron resolution. The Principal Investigator, Professor Karl Krushelnick says, "Our research grant from the SSAA has enabled us to optimize the generation of these highly directional x-ray beams, and to uncover fascinating physics with regard to the dynamics of high energy density matter on femtosecond timescales."

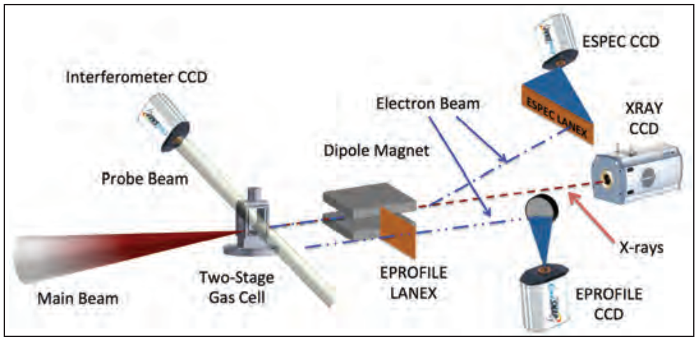

Figure 1. Schematic of the experimental setup. The main beam is focused using an f/20 mirror onto a two-stage gas cell. Electron beams exiting the gas cell were either deflected by a magnet and imaged using a scintillator (ESPEC) or undeflected and imaged on-axis at 12 cm from the cell exit using a second scintillator (EPROFILE). The dash-double-dot line shows the trajectory of the undeflected electrons.

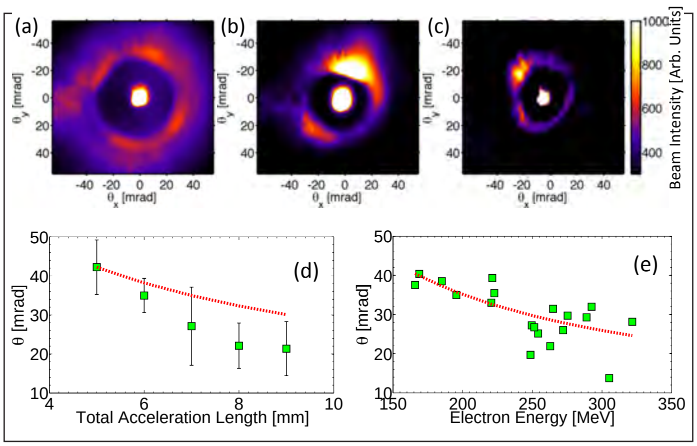

Figure 2. Representative images of the two component electron beams. Top row: images of the undeflected beams taken at 12 cm from the cell exit. The length of the acceleration stage is (a) 6 mm, (b) 7 mm, and (c) 8 mm. Panels (d) and (e) indicate that the angle of conical emission decreased as either the length of the acceleration stage or the energy of the annular beam increased. (f) Electron spectrometer images reveal the monoenergetic nature of the annuli, in direct contrast to the broad spectral distribution of the axial beams.

In Laser Wakefield Acceleration (LWFA) relativistic plasma waves are driven by an intense laser pulse as it propagates through a low density plasma. This process can produce accelerating electric fields for electrons which are orders of magnitude higher than those available from conventional accelerators. Short-pulse (sub-100 fs), petawatt-scale laser facilities have therefore made possible the generation of GeV-scale electron beams and these beams are now being used to produce ultra-bright, pulsed synchrotron x-rays. Laser plasma accelerators (LPAs) are competitive with standard linear accelerators (linacs) for this application and, in certain aspects, are superior since they can produce femtosecond electron and x-ray beam durations and typically have very high peak beam current.

The HERCULES laser system at the University of Michigan is a Titanium:Sapphire laser operating at a wavelength of 800 nm. In these experiments, the laser beam produced ultrashort pulses of only 34 femtoseconds (10^{-15} seconds) which contained about 3 J of energy. Figure 1 shows the experimental setup: The laser beam was focused onto a target using a long focal length mirror to a spot of about 25 µm in diameter. On-target peak intensities were about 10^{19} W/cm^2. A 3D-printed plastic cell filled with helium gas was used as the target and was composed of a 1-mm-long higher-density stage, a 0.5 mm divider slit for stage separation, and an adjustable 5-10 mm lower density "acceleration" stage.

In this research project, the observed electron beams were composed of two components: a collimated axial beam with a continuous energy spectrum and a quasi-monoenergetic annular beam carrying up to 20% of the total charge. Images of the beams show that the annular component had up to 80 mrad full angle divergence, compared to 10-20 mrad divergence of the axial beam (as shown in Figure 2). Electrons in the annular beam have an average energy of 200-400 MeV and have less than 10% relative energy spread. Generation of these annular electron beams was associated with formation of the electron beam on a steep density down gradient. This produces a bunch of electrons that are injected into the accelerating plasma wave with significant transverse momentum so that the electron beam performs very large oscillations in the plasma wakefield. As the electrons oscillate in this way they emit x-rays and, consequently the generation of this annular beam resulted in a significant increase in the synchrotron x-ray yield. The total radiated x-ray photon energy per unit charge increased by almost an order of magnitude – so this technique opens a route to increasing the brightness and flux of compact x-ray sources relative to other plasma-based schemes.

Radiation from Wire Array Z-Pinches at High and Low Impedance University-Scale Generators*

University of Nevada, Reno ✖ PIs: Drs. A.S. Safronova (alla@unr.edu) and V.L. Kantsyrev (victor@unr.edu)

One of the primary methods of understanding the nature of high energy density plasmas (HEDP) is through the radiation that they emit. In particular, the radiation from HED plasmas produced by pulsed power continues to be a very important topic in experiments on Magnetized Liner Inertial Fusion, and with wire array and gas puff plasmas on the largest device, the high-current generator at Sandia National Laboratories (SNL). In contrast to large facilities, university scale generators more readily accommodate research on novel loads and new pulsed power technology and can be excellent test beds for the development of radiation studies of HEDP. Such novel wire array loads, Planar Wire Arrays (PWAs), were developed and tested on the high-impedance Zebra (1.9 Ω, 1 MA, 100 ns) at the University of Nevada, Reno (UNR) during the last 10 years. In more than 40 publications by the UNR research group on radiative and implosion properties of PWAs, their high radiation efficiency (producing up to 30 kJ of radiation), compact size (1.5-3 mm), and usefulness for various applications were demonstrated. For example, Double PWAs (DPWAs) are very suitable for the new compact multi-source hohlraum concept, astrophysical applications, and as an excellent radiation source.

During almost a decade of NNSA funding, four faculty, two postdoctoral researchers, fifteen graduate and six undergraduate students have been supported. In 2015, seven graduate, five undergraduate students, and two postdoctoral researchers were involved in this research. Our recently graduated PhD students are currently working at SNL, Lawrence Livermore National Laboratory, Naval Research Laboratory, Naval Air Warfare Center, and at UNR.

A new pulsed power technology, Linear Transformer Driver (LTD), allows high current and power to be achieved in relatively small sizes, promising more efficient Z-pinch accelerators than those driven by conventional Marx technology. Presently, there is a unique 1 MA LTD cavity operating in a single-shot mode at the University of Michigan (UM). Because there are almost no data on how wire arrays radiate on LTD-based machines in the USA, it is very important to perform radiation and plasma physics studies on this new type of generator. Recently, the first PWA experiments were successfully performed by a joint UNR and UM team on the UM's low-impedance MAIZE LTD generator (0.1 Ω, 0.4-1 MA, 100-200 ns). Implosion of Al PWAs of different load configurations were achieved, analyzed, and recently presented in two invited talks. The second joint campaign on UM's MAIZE in summer 2015 (see Figure 1) continues to focus on gaining comprehensive understanding of radiation from PWAs on a university-scale LTD device. As an example, Figure 2 shows implosion characteristics of Al DPWA on MAIZE with low aspect ratio of array width to inter-planar gap of 0.58 and a 179 ns rise time which is about 30 ns longer than in the first campaign. For such low-aspect ratio DPWA loads, it was believed that the global magnetic field penetrates to the central symmetry axis of the load and produces a potential saddle point between planes with no observable mass accumulation on axis during the wire ablation and therefore no plasma precursor formation. The multi-frame shadowgraphy images (obtained with a 2 ns, 532 nm frequency-doubled Nd: YAG laser) capture implosion dynamics with remarkable details (see Figure 2b). The first frame indeed displays independent implosions of two planes moving to the center (similar to that observed before). However, the second frame displays the moment when the two independent plasma flows start to connect in the center, and the following frame shows the precursor in the center that was never observed before for such load geometry.

Figure 1. The joint UNR and UM research team during experiments on UM's MAIZE in summer 2015 (in the center David Yager-Elorriaga (UM), Clockwise: Adam Steiner (UM), Ishor Shrestha (UNR), Veronica Shlyaptseva (UNR), Max Schmidt-Petersen (UNR), and Nick Jordan (UM)).

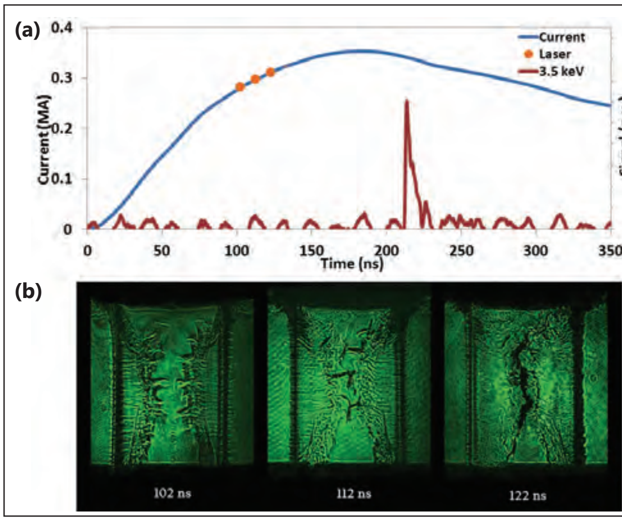

Figure 2. Al DPWA in MAIZE shot 931. a) Experimental current (blue) and Si diode (red) signals along with shadowgraphy timing (orange dots). b) Images recorded with 532 nm Nd:YAG at 102 ns, 112 ns, and 122 ns after current start. The whole anode to cathode gap of 1 cm (in vertical direction) and the inter-planar gap of 6 mm (in horizontal direction) are observed. Load aspect ratio (array width to inter-planar gap) is 0.58.

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Radiochemistry Center of Excellence at the University of Tennessee, Knoxville

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In 2013, NNSA's Stewardship Science Academic Alliances program established the Radiochemistry Center of Excellence (RCoE) at the University of Tennessee-Knoxville (UT). Radiochemistry and nuclear chemistry are key scientific areas that support a number of NNSA mission areas. The Center is directed by Dr. Howard Hall, Governor's Chair Professor in the Department of Nuclear Engineering. The RCoE involves faculty and students in nuclear engineering, chemistry, chemical engineering, and materials science. The primary focus of the RCoE is to train undergraduate and graduate students in methods relating to nuclear science and engineering by providing opportunities to perform cutting-edge research. The Center supports nine graduate students and has another six graduate students funded through other sources. There are also three undergraduate students participating in RCoE-related research.

According to RCoE PI Dr. Hall, "The SSAA grant allows us to train the next generation of radiochemists by providing them the opportunity to conduct fundamental and applied research that has an immediate impact on stockpile stewardship and nuclear security. Through our association with the UT Institute for Nuclear Security, we've been able to establish a vehicle for our students to participate in collaborative work with DOE and NNSA labs. After just two short years, we already have two former students working at NNSA labs, and we're committed to making that pipeline grow in the coming years."

The RCoE is organized into a set of two major and three minor research thrusts, each selected to develop new scientific understanding in areas of strategic interest to the needs of the NNSA. The two major thrust areas are Advanced Radiochemical Separations and Radiochemical Probes for Physical Phenomena. The three minor thrust areas include Nuclear Cross Sections, Bulk Actinide Oxide Materials Processing and Behavior, and Radiochemical Properties of Francium.

Advanced Radiochemical Separations

The goal of this research focus area, led by Dr. Hall and Dr. John Auxier, is to improve the specificity, timeliness, detection limits, and/or operational suitability of radiochemical separations. Radiochemical separations ultimately underlie all NNSA applications of radiochemistry. Part of this work focuses primarily on exploiting gas-phase chemistry to develop and improve separations, with a particular emphasis on faster and higher specificity separations.

One of the major focus areas within this group is the development of surrogate melt-glass samples (post detonation debris samples formed near the point of detonation). A recipe calculator was developed so that data from land use profiles, construction materials databases, vehicle composition data, and population data were taken into consideration. The calculated mass in a melt-glass sample is composed of contributions from three primary urban components: infrastructure, vehicles, and soil. Information regarding the mass and elemental composition from each component along with estimates of the fraction consumed in the fireball are then used by the calculator to provide recipes of the elemental composition of the melt glasses for different cities. As part of this effort, realistic surrogates of New York City and Houston were developed, which required extensive changes from the group's existing trinitite surrogate procedure for melting in the furnace. Figure 1 shows Cadet Brent Bremer of the United States Military Academy removing a surrogate sample from the furnace and preparing another for dissolution and subsequent analysis.

An initial irradiation campaign has been performed for the surrogate trinitite nuclear melt glass, as well as complete development for the procedure and characterization efforts. A sample of surrogate trinitite was irradiated at the High Flux Isotope Reactor at Oak Ridge National Laboratory. The results of this effort were highly successful and led to a publication on the irradiation protocol for surrogate nuclear melt glass.

Radiochemical Probes for Physical Phenomena

A major research thrust led by Dr. Art Ruggles uses imaging technology adapted from nuclear medicine to develop experimental capabilities to assess the performance of turbulent flow computer models. This is an interesting intersection of radiochemistry and engineering model validation needs of the NNSA. In these studies, activated resin beads are mixed into a water flow test section which is then placed into a CT scanner used for Positron Emission Particle Tracking (PEPT). The data generated from these studies are then used for validation and verification of

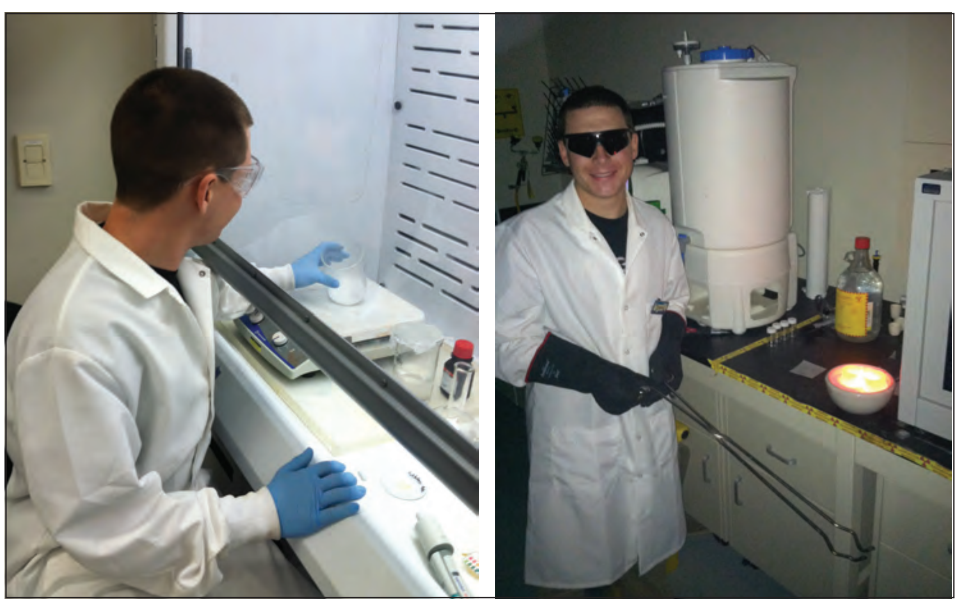

Figure 1. Cadet Bremer preparing a surrogate mixture for a melting (left) and removing the sample from the furnace (right).

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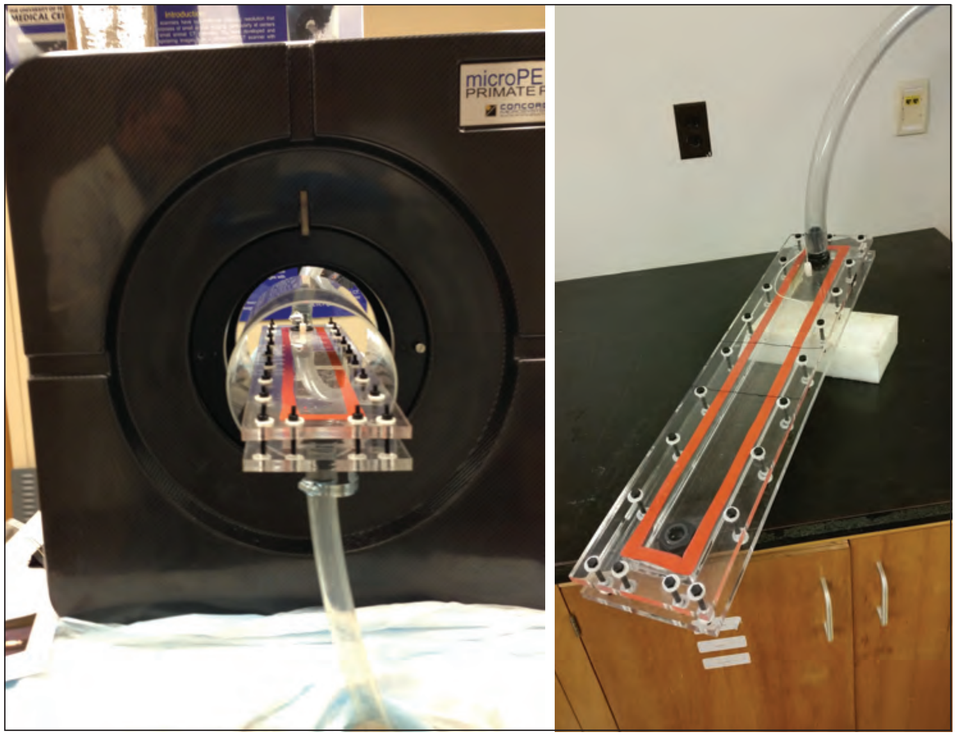

Figure 2. The PEPT flow test section inside the P4 scanner (left), and on the bench with the inlet hose and white nylon injection port (right).

Computation Fluid Dynamics (CFD) calculations along with comparisons to results from other flow measurement techniques.

During the past year, the first test of PEPT software with real flow data was performed with activated (18F) 600 micron diameter resin beads, in a water flow using the test section (shown in Figure 2) designed by graduate student Sarah Rupert. The placements of the inlet and outlets are normal to the top and bottom of the test section, resulting in the development of a flow containing counter-rotating vortices. A total of 15 activated particles were injected into the test section and tracked with the group's multiple-particle tracking algorithm as they flowed once through the bore of the scanner. The results from the PEPT experiment were then compared to results from other flow measurement techniques and compared with CFD calculations. Graduate student Seth Langford also assists in this research

The PEPT flow test section inside the P4 scanner (see Figure 2, left), and on the bench with the inlet hose and white nylon injection port (see Figure 2, right).

Nuclear Cross-Sections

The nuclear cross section group utilizes radiochemical separation techniques to measure production cross sections of actinides and lanthanides. Justin Griswold, a graduate student of cross-section Co-PI Lawrence Heilbronn, has measured ^{232}Th(p,4n)^{229}Pa cross sections as a function of proton energies between 20 and 35 MeV. These measurements augment other ^{232}Th(p,X)^{229}Th measurements (^{229}Pa decays to ^{229}Th) that are of interest in the targeted alpha therapy community as well as cross section measurements of interest for stockpile stewardship.

Bulk Actinide Oxide Materials Processing and Behavior

This effort supported by the RCoE is focused on improving the understanding of bulk actinide separation and solidification processes, with a special focus on understanding the complete behavior of trace chemicals and byproducts. Processes that are relevant to current or new NNSA efforts, such as the Uranium Processing Facility and the Mixed Oxide fuel plant, are high priority. This work, led by Professors Kirk Sickafus (Materials Science) and Brian Wirth (Nuclear Engineering) focuses on computational materials science coupled with experiments to assess new materials synthesis and formulation options for better performance. Recent research has utilized density functional theory to investigate the structure of four particular uranium lanthanide oxide compounds: ULa2O6, ULaO^4, UCe2O6, UCeO^4.

Radiochemical Properties of Francium

The research in this group, led by Dr. Pete Counce and conducted by graduate student Mark Moore, involves the study of the radiochemical properties of francium and the development of an improved radiochemical source for clinical treatment of some forms of cancer. Research in the past year included sorption studies to test the sorbent resin used for radiochemical separation of ^{221}Fr and ^{225}Ac. To test the sorbent, ^{133}Cs was used as a non-radioactive simulant for Fr and ^{139}La was used as a non-radioactive simulant for Ac. These studies will be used to design the resin bed operation for future use.

Neutron Capture Cross Sections Measurements Using a Lead Slowing Down Spectrometer

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Increasingly simulations and models are being used to design nuclear systems instead of full scale testing and demonstrations. High fidelity simulations of nuclear systems require accurate nuclear data. The Gaerttner Linear Accelerator Center (LINAC) at Rensselaer Polytechnic Institute (RPI) is currently being used to measure nuclear data, and in particular, neutron capture cross sections and prompt fission neutron spectra. The NNSA through the SSAA Program has been supporting research at the LINAC for nine years, and is currently supporting two PhD students and a research scientist who recently finished his PhD under the support of the SSAA Program. Two additional PhD students have been funded by the SSAA Program in the past six years and have gone on to work at Oak Ridge National Laboratory and Knolls Atomic Power Laboratory.

The LINAC Center houses a 60 MeV electron linear accelerator, which is used to produce short, high intensity, bursts of neutrons. Most measurements at the facility are performed via time of flight, with measurement stations located 25 m, 40 m, 100 m, and 250 m away from the neutron producing target. The LINAC Center also hosts one of the few Lead Slowing Down Spectrometers (LSDS) in the world. The RPI LSDS is a large cube (1.8 m) of high purity lead, with a neutron producing target in the center. The LINAC is used to create a burst of neutrons in the center of the lead, which begin to scatter off of the lead. Neutrons slow down over time through successive scattering interactions with the lead; the neutrons all slow down at roughly the same rate, creating a correlation between average neutron energy and time of the initial neutron pulse. In this way, events in the LSDS are recorded as a function of time after the pulse, which is translated into average neutron energy.

This work is specifically exploring measuring neutron capture cross sections with the LSDS, building on the work of Perrot et al. (Perrot, 2003) and other groups. This is being done by placing a small sample and a scintillator in the LSDS, where some neutrons will be captured in the sample, and capture gammas will be detected by the scintillator as a function of time. With this technique, small samples with low cross sections can be measured. The goal of this work will be to make measurements at higher energies than were done previously, test new techniques for measuring small samples, validate existing cross section libraries, and perform accurate measurements of capture cross sections in the unresolved resonance region.

It was determined through a set of simulations and experiments that $YAlO_3$ (yttrium aluminum perovskite, or YAP) scintillators gave the best balance of low neutron capture cross section, low neutron scattering cross section, short decay time, and high light output. A series of measurements were performed with tantalum, nickel, indium, silver, molybdenum, gold, iron, zirconium, tin, carbon, and niobium samples. These measurements were also compared to expected results from Monte Carlo N-Particle Transport Code simulations. Figure 1 is an example of a measurement and simulation compared to one another. These results demonstrate that the method is working properly and can be simulated accurately.

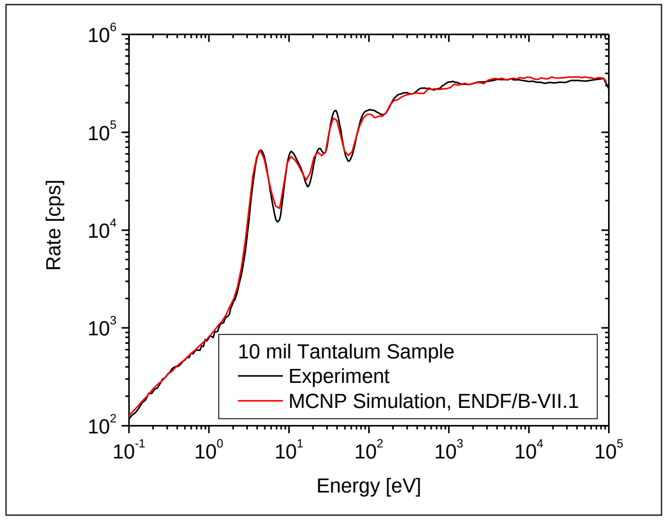

Figure 1. Simulation and Experimental Results of the Neutron Capture Rate of a 10 mil Tantalum Sample.

Figure 2. PhD students Adam Weltz and Nicholas Thompson set up an experiment with the Lead Slowing Down Spectrometer.

"The SSAA grant helped the LINAC center to develop new capabilities for prompt fission neutron spectrum measurements, a new method to utilize the LSDS for fission fragment yield measurements, and a method for neutron induced cross section measurements. Students supported by the program have an opportunity to develop new experimental techniques and perform measurements that provide new accurate nuclear data. The acquired skills are excellent preparation for their future in the DOE complex, nuclear industry, or academia," said Dr. Danon.

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Development of New Techniques to Determine Neutron and Charge-Particle Induced Reaction Rates

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Cross-sections of neutron and charged-particle induced nuclear reactions determine the dynamics and fate of various energy producing scenarios ranging from stars to radioactive material undergoing neutron capture and fission. A vast majority of these reactions involve short-lived, unstable nuclei that cannot be studied with direct methods and therefore require surrogate techniques to extract indirect information about these processes. The research group from the Cyclotron Institute of Texas A&M University (TAMU CI) has worked for several years in collaboration with specialists from IFRU-CEA in Saclay, France and CERN in Geneva, Switzerland to utilize Micromegas (Micro-mesh gaseous structure) technology[1] for a detector setup that uses beta-decay as a surrogate for studying charge-particle induced reactions in stellar scenarios.[2] From this study, it was realized that the excellent energy resolution for detecting heavy ions can be transferred to improve the detection setup used for heavy-ion induced neutron-transfer reactions with a high resolution, broad range multiple-dipole-multipole (MDM) spectrometer. This SSAA grant, over the past two years, has helped to build and commission the upgraded detection setup, and to extend the research program of neutron-transfer reactions to a mass region that has been inaccessible previously due to lack of isotopic resolution of the detection setup.

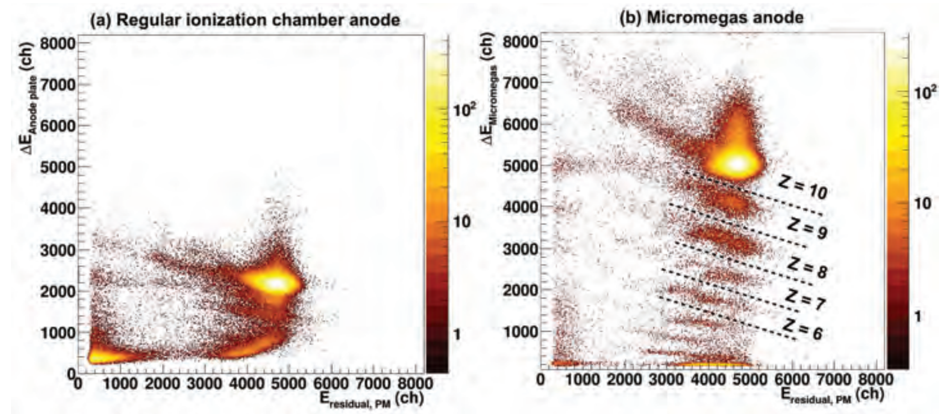

Figure 1. A comparison of measured particle energy loss (ΔE) in an ionization chamber versus the measured residual energy (E) in plastic scintillator in cases where the ionization chamber was (a) regular ionization chamber anode plate, and (b) the newly developed Micromegas anode plate. The measured energies are given in digitized values (ch) and the color scale shows the intensity of the particles. Both data were collected by bombarding a ^{13}C foil with a 12-MeV/nucleon ^{22}Ne beam at the same scattering angle. The enhanced isotopic resolution of the new detector is evident as the different elements (labeled with their proton number, Z) are clearly separated from the main beam (Neon, Z = 10). This allows for a much enhanced particle identification, which produces improved energy resolution and a reduction of background.

According to Professor Robert Tribble, the principal investigator at Texas A&M University, "The support from the SSAA Program has helped my TAMU group develop these new capabilities. We are now carrying out experiments with the upgraded detector system to verify the techniques that we had proposed. The new approach that we have developed will be used well into the future to provide an important new tool to understand neutron capture reactions."

"The support from the SSAA Program has helped my TAMU group develop these new capabilities. We are now carrying out experiments with the upgraded detector system to verify the techniques that we had proposed."

During the past year, PhD student Alexandra Spiridon has collected an extensive dataset for characterizing the upgraded detector system and to study the $^{13}C(^{27}Al,^{28}Al)^{12}C$ neutron-transfer reaction for her PhD thesis. This study is under analysis and will provide information about the mirror system of the $^{27}Si+p \rightarrow ^{28}P$ reaction rate in stellar environments. Figure 1 illustrates the enhanced isotopic resolution of the new Micromegas-based detector when compared to the old system. The upgraded detector will allow for studies of nuclear systems up to at least atomic number Z~20. These initial studies have been followed by an ongoing campaign to measure $^{13}C(^{26}Mg,^{27}Mg)^{12}C$, $^{13}C(^{28}Si,^{29}Si)^{12}C$, and $^{13}C(^{32}S,^{33}S)^{12}C$ reactions that will form the PhD thesis of Murat Dag. The NNSA grant has been instrumental in partially supporting one graduate student, one postdoctoral research associate, and one senior scientist. The work has been presented in a major technical conference, The International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS 2015), where it received strong positive response from the community. The work has resulted in two papers submitted to the Nuclear Instruments and Methods in Physics Research in connection to the EMIS conference. More detailed technical papers will be developed as more data is analyzed.

The upgraded detector has been utilized already in several experiments with the MDM spectrometer by another research group working at the TAMU CI. This new system will be also an important tool for the studies of reaccelerated radioactive ion beams resulting from the facility upgrade of the TAMU CI. One of the projects benefiting from the upgraded detector will be the TIARA array, a combination of Si and Ge detectors, which will be coupled to the MDM spectrometer in the near future. This combination will be a powerful tool for studies of transfer reactions in inverse kinematics. The preparations to relocate the TIARA array (a charged particle detector) from the Grand Accélérateur National d'Ions Lourds (GANIL) to the TAMU CI are underway, and it is expected to arrive in 2016.

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High Pressure Science and Engineering Center: A Center of Excellence for Materials Study Under Extreme Conditions

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The High Pressure Science and Engineering Center (HiPSEC), a Center of Excellence funded by NNSA, was founded in 1998 to improve understanding at the atomic and/or molecular levels of pressure-induced thermal, mechanical, and electronic changes of materials relevant to the Stockpile Stewardship Program. The Center has since established a multi-disciplinary research program focusing on fundamental experimental and computational studies of material properties at extreme conditions. HiPSEC has been involved with the High Pressure Collaborative Access Team (HPCAT) at the Advanced Photon Source (APS) since its inception. HPCAT has been one of the most productive beamlines at the APS and has led to numerous breakthroughs in high-pressure physics. The Center currently supports 17 graduate students and 33 undergraduate students. HiPSEC has supported more than 275 students since its inception. Students at all grade levels are encouraged to seek opportunities in various government agencies and national laboratories. In addition, the access to HPCAT allows University of Nevada, Las Vegas (UNLV) students to have an unparalleled exposure to synchrotron research. Numerous HiPSEC alumni have spent time either as interns, students, postdoctoral researchers, or staff members at DOE/NNSA-funded facilities, and a few will be mentioned. Tony Zukaitis (PhD 2001) is a Technical Staff Member at Los Alamos National Laboratory (LANL). Matthew Jacobsen (PhD 2010) is a Seaborg Post-Doctoral Fellow at LANL. Daniel Mast (current graduate student) has worked as an intern at Lawrence Livermore National Laboratory (LLNL) and is a fellow in the Nuclear Energy University Program. William Wolffs (current graduate student) is a Graduate Research Assistant at LANL.

"We have been able to give students a unique experience by allowing them first hand to develop expertise in high pressure synchrotron science," said HiPSEC Deputy Director Andrew Cornelius. "This has only been possible due to NNSA funding of HiPSEC. It has allowed me to enhance my career and inspired undergraduate students to continue their education at the graduate level, and made graduate students more attractive for future employment at DOE/NNSA laboratories. All three of my recent PhD students have had postdoctoral research positions offered to them at DOE/NNSA laboratories."

The success of student researchers within HiPSEC was displayed at the 2015 SSAP Annual Review Symposium held in Santa Fe, New Mexico. Eleven students attended the symposium as shown in Figure 1. They displayed their work in poster form while learning about other SSAP funded research and future employment opportunities. While over 100 posters were presented at the symposium, only 11 Best Poster Awards were given. Of those, two went to UNLV students Patricia Kalita and Daniel Sneed (his second such award).

Patricia was awarded for her work "High Pressure Behavior of Mullite-Type Oxides: Phase Transitions, Amorphization and Microstructural Implications." Even though mullite occurs rarely in natural rocks, it is perhaps one of the most important phases in both traditional and advanced ceramics and thus one of the most widely studied ceramic phases. The work used two experimental techniques ideally suited to provide a synergic interplay in the study of mullites under high-pressure conditions:

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Raman spectroscopy is a technique for investigating short range order phenomena while x-ray diffraction accesses phenomena occurring at the long range order. High-pressure experiments along with ab-initio calculations allow critical examination of computational tools and thus advance predictive science (predicting the behavior of critically important materials by calculations). Progress in

Figure 1. UNLV students who attended the 2015 SSAA Symposium in Santa Fe, NM in March 2015 are pictured. The insets show Patricia Kalita (left) and Daniel Sneed (right, and page 24) who received Best Poster Awards for their work.

research in predictive science is relevant to the NNSA mission and the Stockpile Stewardship Program.

Daniel was awarded for his work "Forcing Cesium into Higher Oxidation States Using X-Ray Induced Photochemistry at Extreme Pressures." This was done by pressurizing fluorine and cesium fluoride together in a diamond anvil cell and irradiating with x-rays. This work builds on the previous studies of Professor Michael Pravica's group that focused on the chemistry that one can perform using x-ray induced photochemistry. Daniel is looking for different possible oxidation states of cesium that have been predicted. This novel form of high-pressure chemistry is relevant for understanding of electron shell stability and chemical bonding at high pressure.

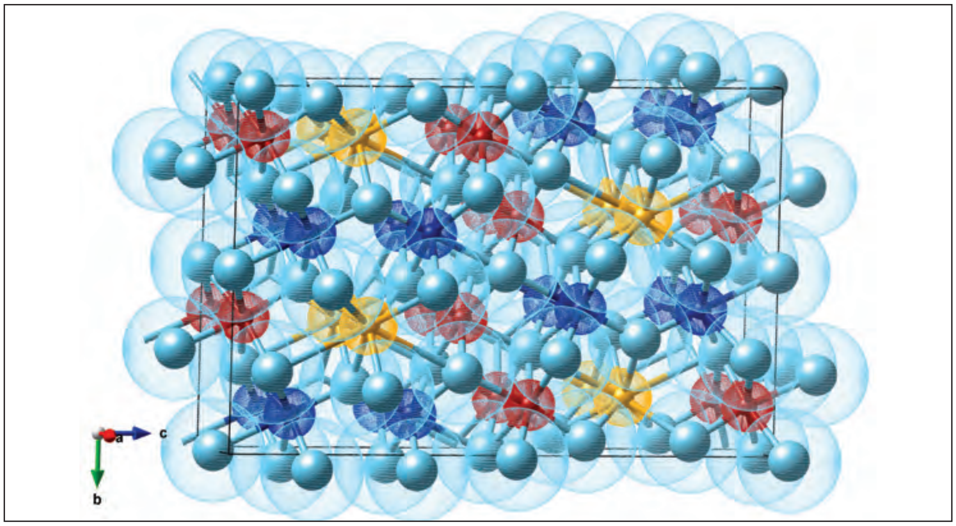

Figure 2. The crystal structure of newly discovered Fe_5O_6 determined at high pressure is shown. There are three different Fe sites labeled 4c (yellow), 8f (blue) and 8f (red).

Professor Barbara Lavina's work on high-pressure synthesis has led to the discovery of new iron oxides. Iron oxides have long been of interest due to the different possible oxidation states. Using techniques similar to her discovery of Fe_4O_5, she pressurized iron (Fe) and hematite (Fe_2O_3) to at least 10 GPa (100,000 atmospheres) and heated using a laser to temperatures over 2,000°K (3,100°F). The resulting heterogeneous sample was found to have many different iron oxide phases including Fe_5O_6.[1] Using the state of the art capabilities of HPCAT, she was able to determine the different crystal structures of various small micron size grains using multi grain indexing. One of these structures is Fe_5O_6, shown in Figure 2. There are three different Fe sites in the orthorhombic crystal structure, shown as three different colors in the figure. From a crystal chemistry viewpoint, the structure is layered with edge-sharing FeO_6 octahedra alternating with FeO_6 trigonal prisms.

Science-based understanding of materials behavior under high-pressure, high-temperature, and high-strain is at the heart of NNSA stockpile stewardship programs for validating and improving materials codes. HiPSEC continues to be a leader in static high-pressure research while training the next generation of scientists needed to maintain a high-quality workforce.

Recent HiPSEC work has found the hardest superconducting metal nitride.[2] Powders of Na_2MoO_4 and BN were compacted into pellets that were placed in a high pressure cubic press and pressurized up to 5 GPa and heat treated in different manners. One of the subsequently observed phases was δ-MoN. This was found to be the hardest metal nitride to date with a Vickers hardness of 30 GPa, which is about a quarter of the value of diamond but twice that of tungsten carbide. Electrical transport and magnetization measurements found that δ-MoN is a superconductor with a relatively high transition temperature of 12°K. The unusual properties of δ-MoN are due to three dimensional, covalent Mo-N bonding networks.

The aforementioned work highlights HiPSEC's commitment to perform high quality research at the forefront of high-pressure materials research. Science-based understanding of materials behavior under high-pressure, high-temperature, and high-strain is at the heart of NNSA stockpile stewardship programs for validating and improving materials codes. HiPSEC continues to be a leader in static high-pressure research while training the next generation of scientists needed to maintain a high-quality workforce.

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Dynamic Strength of Metals Under Extreme Conditions

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Dynamic plastic flow of metals at high strains and high strain rates, studied extensively for nearly 50 years, has recently attracted renewed interest because of the discovery of strong effects at very high strain rates and elevated temperatures, and because of growing acceptance of the importance of these effects in dynamic failure mechanisms. More data is required before physics-based models for the dynamic response of crystalline metals over a wide range of strains, strain rates, and (near melt) temperatures can be developed.

To provide this data, the single-stage gas-gun at CWRU (see Figure 1), capable of accelerating 0.8 kg projectiles to speeds of 600 m/s, has been significantly upgraded. First, a precision-machined steel tube at the breech-end of the gas-gun has been added, to accommodate an 800-W resistive coil heater rated for a maximum temperature of 1,200°C in 100 m-Torr vacuum. The heater head is attached to a vertical stem with axial and rotational degrees of freedom, allowing thin metal specimens to be uniformly heated to more than 1,000°C prior to impact. Second, a new sabot design is utilized to minimize heat transfer to the projectile body (by conduction) and to the gun barrel (by radiation) by the heated flyer plate in front of the sabot. Special precautions have been taken to prevent thermal softening as well as thermal expansion of the sabot body so as to prevent seizure of the sabot in the gun barrel. Third, additional diagnostics have been implemented.

A fiber-optics-based photon Doppler velocimeter (PDV) can measure simultaneously both normal and transverse components of the particle velocity at the rear-surface of the target plate. Two additional optical probes measure the diffracted beams generated by a reflective holographic grating at the target surface, providing simultaneous measurement of normal and transverse components of the particle velocity of the target surface.

Using these new experimental capabilities, we are investigating the dynamic plasticity (including dynamic strength) of high purity low melting point polycrystalline metals, such as Al and Mg (melting temperatures 660°C for Al and 649°C for Mg at ambient pressures). These are chosen for their usefulness in understanding ultra-high strain rate plastic deformation in metals as they pass through melt, and because the fcc structure of Al combined with the hcp structure of Mg will provide a broad perspective on the behavior of metals under extreme conditions.

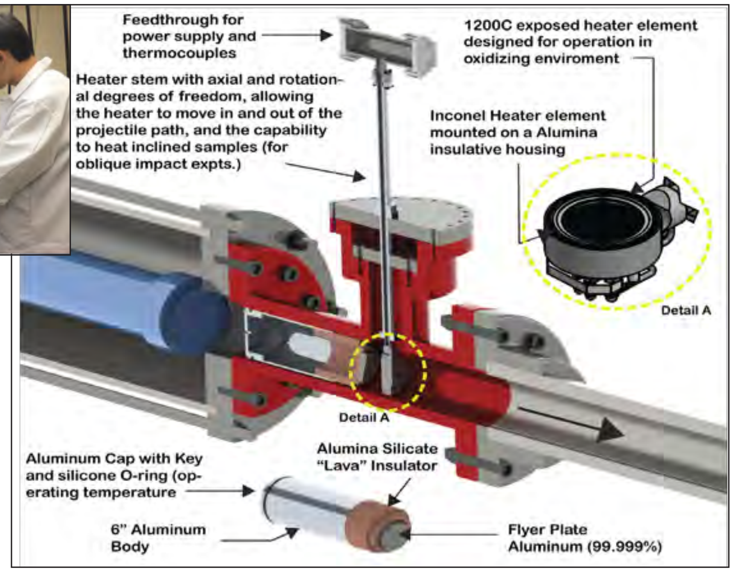

Figure 1. Schematic of the newly designed resistive heater assembly at the breech end of the gas gun to facilitate elevated temperature plate impact experiments.

Typical experimental results obtained from normal shock-compression plate impact experiments on polycrystalline Al are shown in Figure 2. In all cases the high purity Al, which can be pre-heated, is used as the flyer plate (specimen) and Inconel as the target. The Inconel remains essentially elastic under the impact conditions used. Impact occurs in a vacuum chamber to avoid cushioning of the impact by trapped air.

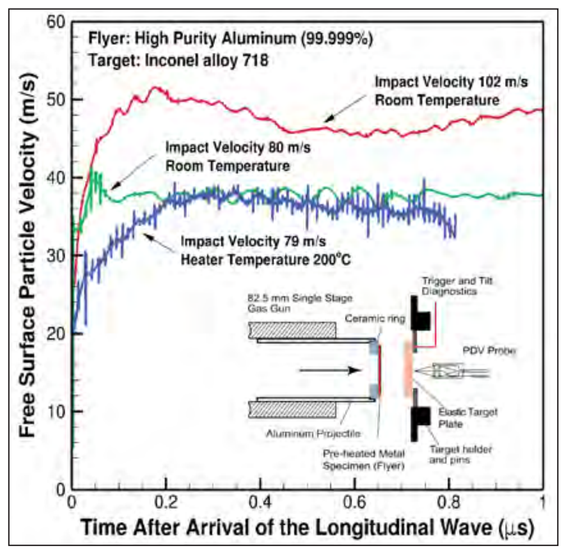

Figure 2. Free-surface particle velocity vs time profiles obtained from normal shock-compression plate impact experiments on high purity polycrystalline aluminum.

Of particular interest is the softening/hardening observed in the measured dynamic response of the Al sample as the impact velocity is increased with the specimen kept at room temperature (green curve versus the red curve) or as the test temperature of the metal sample is increased while maintaining the same impact velocity (green curve versus the blue curve). The much lower particle velocities in the blue curve immediately following impact is an indication of material softening at the elevated test temperatures.

Theoretical analysis and numerical studies are under way to understand the results. In particular, we will focus on understanding the role of transitions between fundamental (dominant) mechanisms of viscoplastic flow (for example, thermal activation versus viscous drag) in controlling the macroscopic strength at ultra-high plastic strain rates as they approach their melt temperatures.

Dynamics of Turbulent Rayleigh-Taylor Instability

Georgia Institute of Technology ✖ PI: Devesh Ranjan (devesh.ranjan@me.gatech.edu)

The Shock Tube and Advanced Mixing (STAM) Laboratory has taken pride in providing ground-breaking experimental research on the Rayleigh-Taylor (RT) instability. For the past five years, support from the SSAA Program has allowed the laboratory to collect extensive data sets that characterize the statistics of turbulence in the fluid instabilities most commonly affecting Inertial Confinement Fusion (ICF). These data sets have been used by Alliances' members for hydrocode validation and turbulence modeling development. Along the way, four graduate and five undergraduate students have benefited from the project, with two students spending summer internships at Lawrence Livermore National Laboratory and Los Alamos National Laboratory. Today, SSAA funding supports two doctorate students and allows the Laboratory to continue pushing the limits of diagnostic and experimental techniques in order to broaden the scope of understanding of RT instability. "By providing students laboratory experience and the opportunity to learn about modeling and computing at National Laboratories, I believe we are training well-rounded and capable future researchers. This could not have been possible without NNSA support," said project director Devesh Ranjan.

Figure 1. The operation of the Gas Tunnel facility during visualization experiments. The flow is back-lit and fog is seeded into one stream of fluid. The intensity of light received by the camera is linearly proportional to the concentration of the seeded fluid.

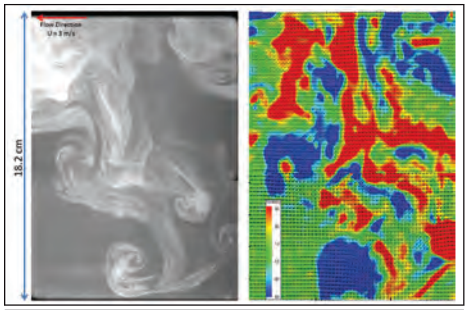

Figure 2. Two PIV images from two different cameras with overlapping field of view stitched together, and the resulting vorticity field in units of (1/s). An unintentional difference in fog seeding uniformity between the heavy and light fluids is used to visualize the spike structure.

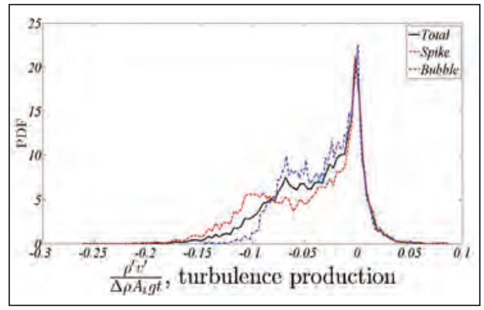

Figure 3. The probability density function of the non-dimensionalized turbulent mass flux, $\rho' v'$. Conditional statistics are applied which separate the statistics caused by the bubble and spike. The long tail on the spike side indicates a larger mean and therefore, greater turbulence production.

The RT instability occurs at the interface between two fluids of different densities when acted upon by a gravitational field.[1] Small-scale perturbations in the interface between the fluids grow in time and form rising bubbles of low-density fluid and falling spikes of high density fluid. Understanding the RT instability is vital to understanding the perturbation growth in ICF implosions and has wide-reaching applications to atmospheric, oceanic, and astrophysical sciences.

The Gas Tunnel facility at Georgia Tech, shown in Figure 1, creates the RT instability by flowing two fluids parallel to one another in a wind tunnel. Initially separated, the fluids eventually reach a test section in which the separation plate is removed and mixing begins. The mixing is studied through flow visualization techniques, Particle Image Velocimetry (PIV) (see Figure 2) and hot wire anemometry (HWA) in order to determine the density, concentration, and velocity of the fluid at many locations in the flow. Unlike most facilities, the long-running nature of the Gas Tunnel allows us to capture statistically steady information about the turbulence that is vital for modeling variable-density fluid interaction.

By using air and helium as the mixing fluids, a large density ratio was achieved.[2] Visualization experiments have illustrated bubble and spike sizes as the instability grows. At large density ratios, significant asymmetry is found between the two, with the spikes found to be 60% larger than bubbles. The growth rate of the instability is found to be similar to the value typically presented from numerical simulations. PIV shows velocity fluctuations having a Gaussian shaped profile across the mix. However, the peak of this profile shifts downwards as the instability develops, again pointing towards the asymmetry of the instability at large density ratio. Combined density/velocity statistics are collected through novel HWA techniques, including a two-wire probe capable of directly measuring fluid concentration. These statistics allow measurement of turbulent mass flux, which is the leading driver of turbulence in variable-density flows. Conditional statistics on the HWA results, shown in Figure 3, indicate that the turbulent mass flux is greater in the spike. This leads to an understanding that the falling spike is the driving factor in turbulence, and hence, mixing between the fluids. Future work hopes to incorporate Laser Induced Fluorescence to increase understanding about the relationship between density and velocity.

References

[1]B. Akula, M. Andrews and D. Ranjan, "Effect of Shear on Rayleigh-Taylor Mixing at Small Atwood Number," Physical Review E 87, 3, 2013.

[2]B. Akula and D. Ranjan, "Dynamics of Buoyancy Driven Flows at Moderately High Atwood Numbers," Journal of Fluid Mechanics (under review).

"The SSAA Program via CDAC has been instrumental in my development as a scientist in the field of high pressure science, culminating in my current position at LANL."

— Raja S. Chellappa, Los Alamos National Laboratory

"As an undergraduate, the SSAA Program allowed me to begin work as a research assistant with Dr. Michael Pravica, giving me the rare opportunity to perform hands-on research early on in my academic career. With the help of funding from the SSAA Program, I was able to go on many research trips to national labs; giving me the opportunity to co-author multiple peer-reviewed papers as an undergraduate."

— Daniel Sneed, University of Nevada, Las Vegas

"The SSAA Program provides me not only the funding for my graduate studies, but also travel to SSAP annual meetings and a winter internship at Los Alamos National Laboratory. It also gives me opportunities to participate directly in synchrotron experiments at Argonne National Laboratory."

— Xintong Qi, Stony Brook University

"The SSAA Program has provided me with the opportunity to work extensively with scientists from Lawrence Livermore National Laboratory, which has been a key experience during my PhD."

— Peter Humby, University of Richmond

"In addition, the SSAA Program has provided our lab with the resources to meet the necessary equipment demands required of these experiments. All of this has allowed us to perform some fascinating research, the results of which we have been able to publish in prestigious journals and present at international conferences and workshops."

— Christian Wolowiec, University of California, San Diego

Raja S. Chellappa, Los Alamos National Laboratory (raja@lanl.gov)

Years at LANL: 2009-Present ✖ Degree: PhD, Metallurgical Engineering ✖ SSAP Program: 2001-2005, University of Nevada, Reno

My doctoral research focused on the thermodynamic modeling of organic compounds that undergo solid-solid phase transformations with the release/absorption of thermal energy. For thermal energy storage (TES) applications, it is essential to tailor the phase transition temperatures by creating mixtures of these compounds and evaluating their thermal characteristics. It is useful to guide these experiments through a predictive approach that involves calculation of phase diagrams of binary (and higher order) systems (Temperature-Composition, T-x) from basic precepts as well as incorporating experimental data. Throughout this time, I was often encouraged by Professor Dhanesh Chandra (my dissertation advisor) to be hands-on with experimental techniques. During the latter half of my doctoral work, I was presented with a great opportunity to visit the Geophysical Laboratory, Carnegie Institution of Washington (GL-CIW) to explore the high pressure (*P*) behavior of these organic TES molecular crystals. I received financial support through the Carnegie-DOE Alliance Center (CDAC), an SSAA Center of Excellence, for this portion of my doctoral research; this also allowed me to interact with senior scientists in the field of high pressure science. During this time, Dr. Stephen Gramsch (Coordinator, CDAC) provided guidance and this research experience as a CDAC graduate student motivated me to pursue a career investigating materials phenomena at high *P-T*.

The diamond anvil cell (DAC) is an elegant tool in which the flat surfaces of two diamond anvils squeeze the material of interest, confined in a small hole in a metal gasket, to high pressure *P*. It can be fitted with heaters so that both high pressure (typically Gigapascals, GPa) and high temperature *T* (up to 1,000°K) can be reached simultaneously. The wide optical window of diamonds allows us to probe (in situ) the effect of high *P-T* on the structure and bonding of materials as well as explore chemical reactions using vibrational spectroscopy, x-ray diffraction (XRD, both laboratory and synchrotron sources), and other techniques. My first postdoctoral position at the University of Nevada, Reno (UNR) was funded in part by a CDAC-UNR Academic Partnership that transitioned into a postdoctoral research associate position at GL-CIW (mentored by Dr. Russell Hemley and Dr. Maddury Somayazulu) fully supported by CDAC. During this time I travelled often to the synchrotron facilities at the Advanced Photon Source (APS) and at the erstwhile National Synchrotron Light Source (NSLS) to conduct experiments to understand pressure-induced transformations and chemistry in low-Z hydrogen storage materials, and to explore mineral-water reactions.

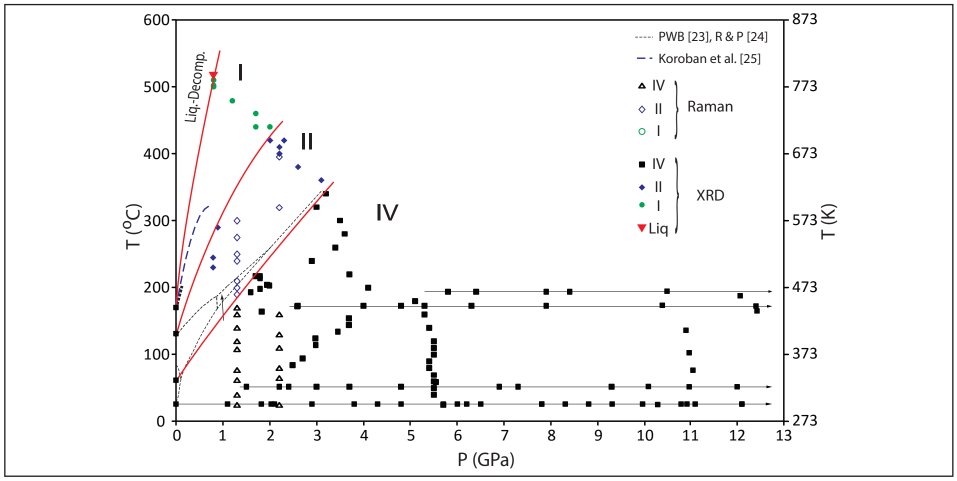

Figure 1. P-T phase diagram of Ammonium Nitrate (solid red lines) based on XRD and Raman measurements. This work updates the only known phase diagram of this compound reported by P. Bridgman (1916, black dotted lines). Note that phase stability of AN-IV extends up to 40 GPa at 25°C (298°K) and 37 GPa at 194°C (467°K).

As a CDAC postdoctoral researcher at GL-CIW, I was fortunate to interact with colleagues, including numerous visiting scientists, that allowed me to gain a multidisciplinary perspective on various frontier challenges in high pressure science. My research portfolio diversified to include both the effect of pressure on hydrogen bonded organic molecular crystals as well as pressure-induced chemistry in simple molecular systems. When the opportunity arose to join the static high pressure team led by Dr. Dana Dattelbaum in the Shock and Detonation Physics division at Los Alamos National Laboratory (LANL), I accepted the position to work on pressure-induced chemistry in simple organics. I also worked on a challenging problem of mapping the high P-T phase diagram of ammonium nitrate (widely used as a blasting agent). Results are shown in Figure 1. I began to focus on high P-T research on high explosives relevant to stockpile stewardship science by investigating their melt/decomposition behavior at high *P-T*, as well as obtaining critical equation of state data that serve as input for high-level simulations. At present, I am a Staff Scientist in the Materials Science & Technology division where I am also a part-time Instrument Scientist for the Filter Difference Spectrometer (FDS) beamline at the Lujan Neutron Scattering Center. High pressure science continues to be my passion, and to play a key role in several projects that are funded through Science Campaigns within the Office of Research, Development, Test, and Evaluation.

The SSAA Program via CDAC has been instrumental in my development as a scientist in the field of high pressure science, culminating in my current position at LANL. I am in the midst of excellent colleagues who enjoy similar research pursuits, and I plan to continue my development as a scientist and serve as a mentor to students, postdoctoral researchers, and junior colleagues.

L. Sarah Thomas, National Security Technologies, LLC (thomassa@nv.doe.gov)

Years at NSTEC: 08/2015 -Present ✖ Degree: High Pressure Physics, 2013 ✖ SSAA Program: 2010-2013, University of Alabama at Birmingham

I earned my graduate degree at the University of Alabama at Birmingham (UAB) while supported by the SSAA program. My research focused on changes in magnetic transitions in heavy rare earth metals under static high pressures and low temperatures. We found that certain magnetic transitions in these materials were suppressed at high pressures, where the material underwent a structural transition. This research was carried out in the high pressure lab at UAB, as well as at the Advanced Photon Source (APS) at Argonne National Laboratory, and the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory, under the supervision of my advisor, Dr. Yogesh Vohra. At UAB, we used designer diamond anvil cells to measure the electrical resistance of rare earths at increasing pressures as we cooled to 10 K, and then as we warmed back up to room temperature. At APS, we used x-ray diffraction to determine the crystal structure at a range of temperatures and pressures. At SNS, we used neutron diffraction to examine both the crystal and magnetic structures of these materials for increasing pressures and low temperatures.

"Without the support of the SSAA Program, much of my work would not have been possible. Because of the SSAA Program, I have been able to conduct worthwhile research, as well as experience a number of different cultures, both around the globe and within the US."

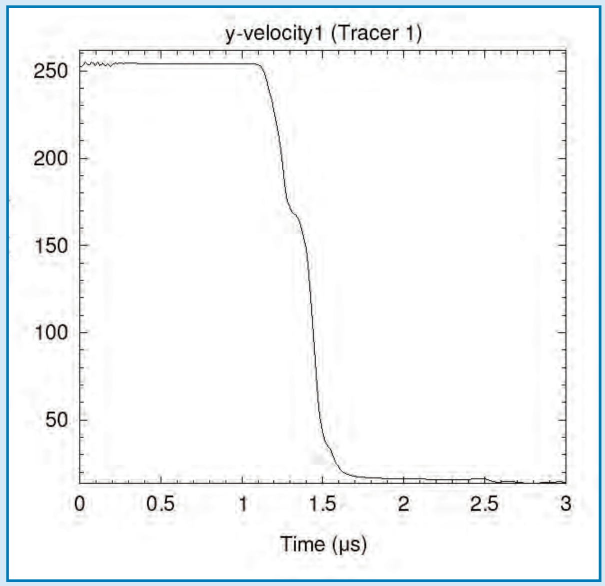

Figure 1. Hydrocode simulation of the shock velocity in the aluminum target due to a symmetric impact of 0.5 km/s.

The work I did pursuing my graduate degree directly prepared me for my first postdoctoral position at the University of Edinburgh in Scotland. I worked under Professor Colin Pulham in the School of Chemistry studying explosive precursors under static high pressures. The purpose of the work was to look for high-nitrogen precursors with the potential to form polymeric nitrogen under pressure. Polymeric nitrogen explosives, if found, would be both very powerful, and environmentally friendly. We used Merrill-Bassett diamond anvil cells to examine these precursors under pressure via both x-ray diffraction and Raman spectroscopy. The 17 months I spent working in Edinburgh were very rewarding. I was able to attend conferences in Russia, the Czech Republic, and the United States, all of which broadened my understanding of explosive materials and exposed me to a variety of cultures and people.

Shortly after finishing my work in Edinburgh, I began working for National Security Technologies (NSTec) in Los Alamos, New Mexico. At NSTec, I am learning about another aspect of high pressure physics: dynamic compression. With Dr. Rob Hixson as my mentor, I have been studying shock physics and building computational models of experiments. The first experiment we plan to carry out in the near future will look into the dislocation kinetic times of different purities of aluminum. The experiment will consist of four shots on a gas gun, with the projectile moving at about 0.5 km/s (see Figure 1). This should generate pressures of around 4 GPa.

In addition to carrying out shock experiments, I am involved in building a new gas gun for NSTec's Las Vegas office. We hope that having another gun accessible will allow us to conduct more and a greater variety of experiments. I am also gaining hands-on experience with the various technologies NSTec designs and builds in support of the national laboratories.

I feel very fortunate to have been afforded all the opportunities I've had. Without the support of the SSAA Program, much of my work would not have been possible. Because of the SSAA program, I have been able to conduct worthwhile research, as well as experience a number of different cultures, both around the globe and within the US.

Peter Humby, University of Richmond (phumby@richmond.edu)

Degree in Progress: PhD, Physics ✖ Academic Advisor: Dr. Cornelius Beausang ✖ SSAA Program: 2013-Present

Research Topic:
Investigation of Nuclear Structure in the Rare Earth Region Via Few-Neutron Transfer Reactions

What are your research responsibilities?
My primary responsibility is the investigation of proton induced few-neutron transfer reactions in the rare earth region via combined charged particle and gamma-ray spectroscopy. This involves performing experiments at the Cyclotron Institute of Texas A&M University utilizing the STARLiTeR array and the new HYPERION array. This consists of 13 high-purity germanium Clover detectors and a Si telescope for the detection of light ions. My research spans from the study of discrete nuclear states at low excitation energy, the properties of large quasi-discrete structures at medium excitation energy, to probing the angular momentum transfer in the high excitation energy continuum region, which is of significant interest in terms of the surrogate reaction method.

How have you benefitted from the SSAA Program?
Funding from the SSAA Program has provided me with an excellent environment in which to pursue my research, allowing me to be based in the nuclear physics group at the University of Richmond under the guidance of Dr. Con Beausang. It has allowed me to travel to experiments to collect the data that forms the core of my research, as well as attend conferences and have invaluable discussions with other researchers, which has had a direct impact on my work.

Did the SSAA Program give you the opportunity to work with others you might not have otherwise?
The SSAA Program has provided me with the opportunity to work extensively with scientists from Lawrence Livermore National Laboratory, which has been a key experience during my PhD. Experimentally, this collaboration has allowed me to gain a large amount of technical knowledge and insight, greatly aiding my development as an independent researcher, and allowed me the opportunity to be part of the construction of the HYPERION array. Additionally, the SSAA Program has provided the opportunity to visit the laboratory to discuss the theoretical underpinning of my research, including receiving guidance from leading theorists in the field of the surrogate reaction method.

Xintong Qi, Stony Brook University (xintong.qi@stonybrook.edu)

Degree in Progress: PhD, Geosciences ✖ Academic Advisor: Dr. Baosheng Li ✖ SSAA Program: 2014-Present

Research Topic:
Ultrasonic Studies on the Physics of Strongly Correlated Electron Systems Related to Rare Earth Elements and Actinides Under High Pressure and High Temperature

What are your research responsibilities?
As a graduate student at Stony Brook University, my research responsibility is to study the elasticity of transition metals and rare-earth based bulk metallic glasses. My current project deals with pressure-induced polyamorphism in $La_{32}Ce_{32}Al_{16}Ni_5Cu_{15}$ metallic glass which was investigated by the measurement of acoustic velocities using ultrasonic interferometry in a multi-anvil apparatus up to 12 GPa at room temperature. The acoustic velocities and densities obtained from the experiment allowed us to gain insight into the mechanism of polyamorphism and the roles of f-electron delocalization in the structural evolution under pressure. In combination with the first sharp diffraction peaks study, we are also trying to build a metallic glass structural model and explore its response to the stress.

How have you benefitted from the SSAA Program?
The SSAA Program provides me not only the funding for my graduate studies, but also travel to SSAP annual meetings and a winter internship at Los Alamos National Laboratory (LANL). It also gives me opportunities to participate directly in synchrotron experiments at Argonne National Laboratory (ANL). Thanks to the program, I have greatly benefitted from meeting with the top scientists and researchers in the related field, which has broadened my horizons and improved my research a lot.

Have you spent time at one of the national laboratories?
I've been to ANL three times working on the synchrotron experiments. In addition to the data obtained from the experiments, these hands-on experiences were invaluable to me. In February 2015, I was awarded a full scholarship to the 11th LANSCE School on Neutron Scattering at LANL. It was the first time that I had access to neutron scattering and electron scattering facilities and had hands-on exercises, instruments, and data analysis in neutron scattering techniques such as the Surface ProfilE Analysis Reflectometer (SPEAR), Low-Q Diffractometer (LQD), Neutron Powder Diffraction Facility (NPDF), and High-Pressure Preferred Orientation Diffractometer (HIPPO). The friendships that I have developed in this internship have made my time in graduate school one of the best experiences of my life. The experiences at ANL and LANL let me know how the labs operate and what life would be like as a beamline scientist at a national laboratory. These experiences have inspired me to work in a research university or a national lab after graduation and I look forward to more collaboration with multiple national laboratories and researchers all over the world.

Daniel Sneed, University of Nevada, Las Vegas (sneedd3@unlv.nevada.edu)

Degree in Progress: MS, Physics ✦ Academic Advisor: Dr. Michael Pravica ✦ SSAA Program: 2012-Present

Research Topic:

Forcing Cesium Into Higher Oxidation States Using Hard X-ray Induced Photochemistry at Extreme Conditions

What are your research responsibilities?

Currently I am working on a project involving reacting molecular fluorine with cesium fluoride under pressures greater than 20 GPa in order to force higher oxidation states of cesium. This work is inspired by a paper published in *Nature* titled "Caesium in high oxidation states and as a p-block element" by Dr. M. Miao, postulating that, under given pressures, cesium will undergo p-shell bonding with up to 6 fluorine ions. The implication of this research is that it could prove that bonding doesn't have to occur using only valence electrons, but can also occur using inner shell electrons given the proper conditions. By utilizing the highly focused and ionizing properties of hard x-rays, we have been able to decompose a fluorine-rich compound into molecular fluorine, *in situ*, allowing us to work with the highly reactive and toxic fluorine, in a safe and controlled manner. By combining our technique of *in situ* loading of molecular gases with x-ray diffraction and x-ray absorption fine structure spectroscopy, I hope to be able to experimentally verify this novel form of bonding under extreme conditions.

How have you benefitted from the SSAA Program?

The SSAA Program has greatly benefited both my research, and me personally. As an undergraduate, the SSAA Program allowed me to begin work as a research assistant with Dr. Michael Pravica, giving me the rare opportunity to perform hands-on research early on in my academic career. With the help of funding from the SSAA Program, I was able to go on many research trips to national labs; giving me the opportunity to co-author multiple peer-reviewed papers as an undergraduate. As a graduate student, the SSAA Program has afforded me the opportunity to utilize the facilities at Argonne National Laboratory to complete my current line of research.

Have you spent time at one of the national laboratories?

I have spent a significant amount of time at the Argonne National Laboratory Advanced Photon Source Sector 16 beamline performing various experiments. This experience helped our group to develop our new technique of producing reactive fluorine gas *in situ* via hard x-ray induced decomposition, which has in turn led to my current area of research. Having had the opportunity to play a fundamental role in multiple experiments at the Advanced Photon Source has truly helped me to build a very strong experimental basis for my future career as a scientist.

Christian Wolowiec, University of California, San Diego (cwolowiec@physics.ucsd.edu)

Degree in Progress: PhD, Condensed Matter Physics ✦ Academic Advisor: Professor M. Brian Maple ✦ SSAA Program: 2012 -Present

Research Topic:

Physical Properties Measurements of *d*- and *f*- Electron Materials Under High Pressure and Extremely Low Temperature

What are your research responsibilities?

Much of our research in the Maple Lab consists of measuring the physical properties of novel *d*- and *f*- electron materials under extreme conditions of high pressure, high magnetic field, and low temperature. Typically, I perform standard four-wire measurements of electrical resistivity down to temperatures as low as 1 K on materials under pressure up to 2.5 GPa using a quasi-hydrostatic piston cylinder pressure cell. These measurements allow one to gain information about the structural and electronic phases that occur in these materials. This has led to several publications about an extraordinary pressure-induced phase transition that occurs in a new class of BiS_2-based layered superconducting compounds in which T_c is enhanced in the high pressure phase by a factor of three over T_c in the low pressure phase. We are currently involved in research projects with our collaborators at Lawrence Livermore National Laboratory (LLNL) and the University of Alabama, Birmingham, in the application of designer diamond anvil cells (dDACs) for measurements of the electrical resistivity and alternating current magnetic susceptibility of materials at very high pressures in the 100 GPa range.

How have you benefitted from the SSAA Program?

There is a long history of pressure related studies in our lab. The SSAA Program has given me the opportunity to carry on this tradition of studying materials under pressure. Pressure experiments are inherently technical and require a certain level of skill and a minimum standard of equipment for successful results. Through travel and collaboration with other experts in the field, the SSAA program has allowed me to acquire the skill set necessary to perform successful experiments under pressure. In addition, the SSAA Program has provided our lab with the resources to meet the necessary equipment demands required of these experiments. All of this has allowed us to perform some fascinating research, the results of which we have been able to publish in prestigious journals and present at international conferences and workshops.

Did the SSAP give you the opportunity to work with others you might not have otherwise?

Yes, I am performing electrical resistivity measurements under pressure using a dDAC in collaboration with our coworkers at LLNL who provide the designer diamond anvils for our high-pressure experiments. The SSAA Program will provide me the opportunity to spend time at LLNL with our collaborators and gain experience in loading dDACs for the experiments I am performing in our lab at UCSD.

High Energy Density Laboratory Plasmas (HEDLP)

From Z to Planets: Life on Exoplanets?

Harvard University ✖ PI: Stein B. Jacobsen (jacobsen@neodymium.harvard.edu)

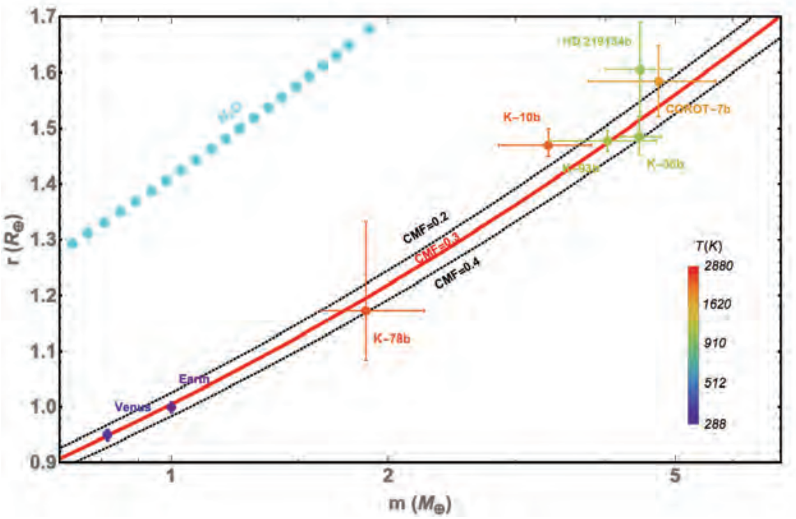

Figure 1. Radius versus mass plot for Venus, Earth and exoplanets with up to five Earth masses, given in units of Earth radii and Earth masses (⊕ = Earth). The color of the symbols for each planet indicates their surface temperatures (see scale in kelvins). The blue dotted curve is for planets made of pure H2O. The solid red curve is for planets with the same bulk chemical composition as the Earth (including the CMF as the Earth of 0.3). For comparison curves for CMF values of 0.2 and 0.4 are also shown. Previous work suggested a core mass fraction of about 0.17 for the exoplanets, and their bulk chemistry would then be different from the Earth. Our new equation of state estimate for real Earth chemistry shows, however, that the exoplanets are consistent (within error) of an Earth-like chemical composition.

The discoveries of numerous extra-solar planets (exoplanets) have fundamentally challenged our theoretical understanding of planetary systems. In addition to traditional astronomical observations, computer modeling of exoplanets' internal structure and laboratory experiments simulating pressures, temperatures, and equations of state (EOS) are necessary. Therefore, the main objective of our project entitled "From Z to Planets" is the experimental measurements of physical properties of the major building blocks of Earth-like planets in order to improve models of (i) the planetary accretion process, (ii) moon-forming giant impacts, (iii) early silicate vapor atmospheres, (iv) interiors of Earth and of large Earth-like planets, (v) planetary thermal evolution and differentiation, (vi) core formation and dynamo evolution. In our work we are studying fundamental material properties of end member compositions for Earth-like planets using the unique Z accelerator at Sandia National Laboratories (SNL). Specifically, we have been measuring the vapor curves of pure Fe, MgO, $MgSiO_3$ and Mg_2SiO_4, the major components of Earth-like planets, up to their critical points. Our efforts would not be possible without the support of NNSA's HEDLP program and the SNL Z facility. An integral part of our work is training future leaders in high energy density (HED) science. For example, Rick Kraus, the recent Harvard PhD graduate, is now a post-doctoral fellow at Lawrence Livermore National Laboratory (LLNL) (see page 52).

In a recent Nature Geoscience paper entitled "Impact Vaporization of Planetesimal Cores in the Late Stages of Planet Formation" Rick Kraus and colleagues reported the results of iron EOS measurements on the Z machine. At the late stages of accretion, the Earth and Moon grew by high-velocity collisions with differentiated planetesimals that delivered iron-rich material in their cores. The way of accreting this material has important implications for the geochemical evolution of the Earth–Moon system and the timing of Earth's core formation. Therefore, understanding of what fraction of a planetesimal's iron core gets vaporized by impact is crucial. Using a shock-and-release experimental technique developed by us and implemented at the SNL Z-Machine, the entropy in the shock state of iron was determined. Corresponding shock pressure of iron vaporization, 507 GPa, is readily achieved in high velocity impacts at the end stages of accretion. This means that impact vaporization of the planetesimal's cores planetesimals disperses iron over the surface of the growing Earth, leading to chemical equilibration with the mantle. Also, we found that the comparatively low abundance of highly siderophile elements in the lunar mantle and crust can be explained by the retention of a smaller fraction of vaporized planetesimal iron on the Moon, as compared with Earth, due to the Moon's lower escape velocity. This supports the "late veneer hypothesis"—that volatiles in the Earth's atmosphere and oceans were delivered by late comet-like impactors on the Earth to seed it with the ingredients for life.

Another graduate student, Li Zeng, has recently submitted to the Astrophysical Journal a related study entitled "Mass-Radius Relation for Rocky Planets based on PREM" (Preliminary Reference Earth Model). The main tool for evaluating chemical compositions of exoplanets, a mass-radius diagram (see Figure 1), shows that exoplanets with up to five Earth masses may have chemical compositions very similar to the Earth as suggested by their core mass fractions (CMF). Similar CMFs in rocky exoplanets hint for the oxidization states similar to the Earth. Although all six dense exoplanets discovered so far are much hotter than the terrestrial planets Earth and Venus, as indicated by their symbol colors corresponding to the surface temperatures, this may be due to the current observational constraints allowing detection of only hot exoplanets within 0.1 AU of their parent stars. Therefore, it is possible and likely that abundant colder exoplanets with similar core mass fractions may orbit their host stars within the habitable zone. Some of them might have surface environment and chemistry similar to the Earth, implying that life may be relatively common in the universe. So far the CMF calculations are based on extrapolation of the EOS for the terrestrial mantle (PREM) to higher P and T. These may be improved by the Z experiments on real Earth mantle and core compositions that are one of the tasks of our current NNSA proposal.

HEDLP Studies of Fields, Matter, Transport, Nuclear Physics, and ICF with New Diagnostics at the NIF, OMEGA/OMEGA-EP, and Z

Massachusetts Institute of Technology ✦ PIs: R.D. Petrasso (petrasso@psfc.mit.edu) and C.K. Li (li@psfc.mit.edu)

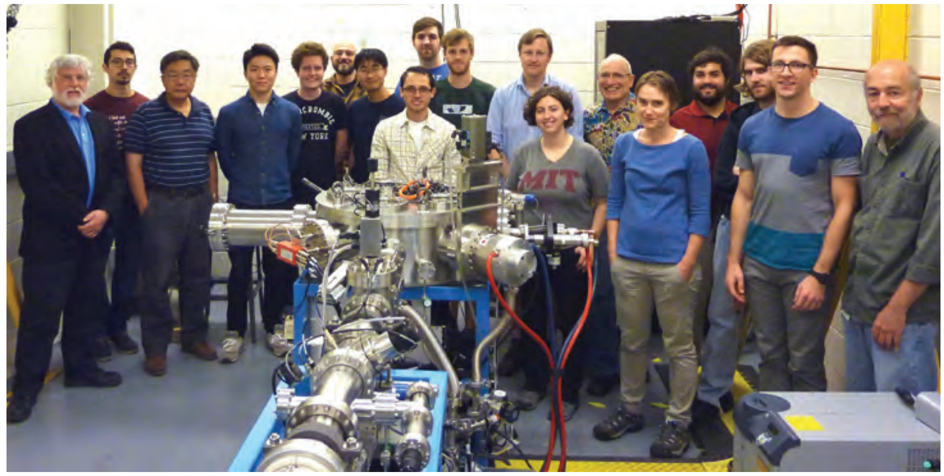

Figure 1. Scientists, graduate students, undergraduates, and staff at MIT's Accelerator Facility for HED Diagnostic Development. The Facility includes a linear accelerator (shown), two neutron generators, and x-ray and γ-ray generators, which have been used to develop, test, and calibrate a wide range of diagnostics. So far, MIT-led collaborations with LLE and LLNL have led to 11 diagnostics on OMEGA (with two more under development) and MIT-led collaborations with LLE and LLNL have resulted in seven diagnostics on the NIF (with two more under development). Diagnostics for the Z machine are under development in collaboration with SNL.

The High Energy Density Physics (HEDP) Division of the MIT Plasma Science and Fusion Center has participated in NNSA-sponsored research since the late 1980s. The Division has performed a very wide range of experiments in inertial confinement fusion (ICF), high energy density plasma physics, nuclear science, and laboratory-scaled astrophysics experiments at the Omega Laser Facility of the University of Rochester's Laboratory for Laser Energetics (LLE), the National Ignition Facility (NIF), and now at the Sandia National Laboratories (SNL) Z machine. Nine graduate students and seven undergraduate students worked in the Division this year. Three outstanding students completed their PhD theses: Dr. Michael Rosenberg (thesis "Studies of Ion Kinetic Effects in Shock-Driven Inertial Confinement Fusion Implosion, at OMEGA and the NIF, and Magnetic Reconnection Using Laser-Produced Plasmas at OMEGA") now works at LLE; Dr. Hans Rinderknecht ("Studies of Non-Hydrodynamic Processes in ICF Implosions on OMEGA and the National Ignition Facility") is now a Lawrence Fellow at Lawrence Livermore National Laboratory (LLNL), and Dr. Alex Zylstra ("Using Fusion Product Spectroscopy to Study Inertial Fusion Implosions, Stopping Power, and Astrophysical Nucleosynthesis at OMEGA and the NIF") is now a Reines Fellow at Los Alamos National Laboratory. Two of the undergraduates hope to become graduate students in the Division next year.

Our students and scientists base most of their research and publications on NNSA-sponsored experiments at the MIT Accelerator Facility for HED Diagnostic Development (see Figure 1), OMEGA, NIF, and Z machine. Student education and MIT-developed diagnostics used at the national laboratories begin at the MIT Accelerator Facility. Fusion products from the accelerator and other generators are used to test concepts for, and to calibrate, a wide variety of charged particle and neutron detectors for spectrometry, imaging, and temporal measurements at OMEGA, NIF, and Z.

Figure 2 illustrates one kind of recent research on the stopping of ions. That work, which is important to ignition experiments in ICF, utilized charged fusion products from ICF implosions and measurements of their energy losses in passing through the ICF-capsule plasma using charged-particle spectrometers. Another kind of stopping-power research focused on energetic protons passing through moderately coupled, degenerate "warm-dense matter." The data demonstrated agreement with stopping models based on an ad hoc treatment of free and bound electrons, as well as an average-atom, local-density approximation. In this case the stopping medium was an isochorically heated, solid-density Be plasma, and the source of mono-energetic, 14.7-MeV D^3He protons was an "exploding pusher" ICF implosion functioning as a proton backlighter.

The same type of MIT-developed proton backlighter, which supplies 3-MeV protons as well as 14.7-MeV protons, was also used at OMEGA for important experiments utilizing proton radiography to study magnetic reconnection and the behavior of laboratory-scaled astrophysical jets. This type of work has been extremely successful at OMEGA in MIT's own experiments and in experiments designed by LLNL scientists (for example studies of the properties of collisionless plasma jets).

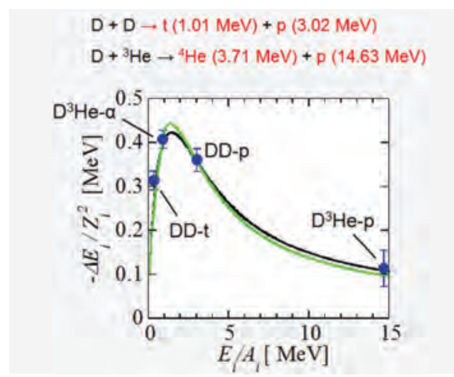

Figure 2. Sample data from a study of ion stopping in plasmas, important for its relevance to ignition experiments in ICF. The study was performed at OMEGA by measuring the energy losses (shown on the vertical axis) of four types of charged fusion products (see equations) with different initial energies (shown on the horizontal axis) as they passed through the plasma in ICF implosions. Data points are in blue, and the black and green lines show best fits using two stopping theories. Related measurements showed how ion stopping at energies around the Bragg peak (or peak ion stopping) depends strongly on electron temperature (Te) and number density (ne). The data in this plot correspond to Te ≈ 0.6 keV and ne ≈ 10^{23}.

It is now being developed for use at the NIF by a collaboration of MIT and LLNL scientists.

Fundamental Issues in the Interaction of Intense Lasers with Plasma

Princeton University ✖ PI: Professor Nathaniel J. Fisch (fisch@princeton.edu)

The main objective of this grant is to identify and quantify limits of achieving extreme laser intensities using plasma. It is a further objective to discover fundamental effects in high energy density plasma and to identify new unanticipated mechanisms in intense wave interactions in plasma. The Principal Investigator (PI) has worked with the SSAA program since its inception. Students supported at least in part under grants from this program and now working at NNSA laboratories include Y. Ping 2002 (Lawrence Livermore National Laboratory [LLNL]), D. Clark 2003 (LLNL), N. Yampolsky 2005 (Los Alamos National Laboratory), and P. Schmit 2012 (Sandia National Laboratories), see page 31. Currently, there are four graduate students supported in part by the program.

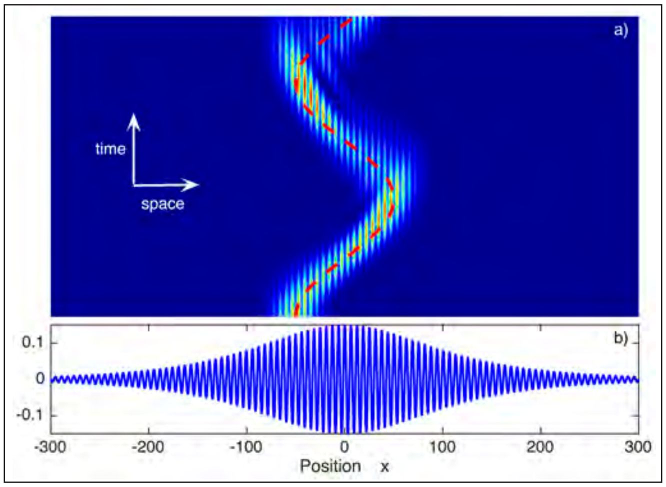

Figure 1. Full-wave simulation of a nonlinear adiabatic interaction of two scalar waves. (a) Spacetime trajectory of the narrow envelope of the signal wave (lighter regions correspond to a higher amplitude); (b) prescribed modulating wave (arbitrary units). The figure illustrates that, although the two waves are supposed to repel each other in the geometrical-optics approximation, having comparable wave numbers makes their interaction attractive. The attraction here is strong enough for the two waves to become trapped, i.e., to form a "molecule". The dashed line shows a ray tracing simulation of the signal wave propagation using the ponderomotive Hamiltonian (Ruiz and Dodin, in preparation).

The PI, Professor Nathaniel Fisch, states, "Through its support of new paradigms, concepts, and powerful formalisms, the grant program has benefitted my postdoctoral colleagues and me, as well as the students that work with us. With stockpile stewardship facilities undergoing rapid advancement, there is an added challenge to search for new, fundamental effects and to maintain with mathematical rigor the theoretical underpinnings of this emerging field. In the last year, Dr. Ilya Dodin, with key help from student Daniel Ruiz, pursued a particularly promising research direction, namely a powerful variational approach to describing plasma waves in a quantum-like form."[1-4]

Even when the Planck constant ħ is negligible, quantum equations are more natural than classical ones. For example, describing plasma particles using simple linear Lagrangian densities free from ħ gives a complete field-theoretical formulation of plasma kinetics. Conservation theorems follow naturally. This approach simplifies plasma theory and makes it more rigorous. Even more significantly, in unifying the classical and quantum description, waves can be treated like particles, so that their interactions are described by unified Lagrangians. These Lagrangians can be readily used as building blocks for developing theories of specific effects, with such theories manifestly conservative.

For example, using the Lagrangian formulation, it is immediately apparent that the time-averaged, or "ponderomotive" forces on charged particles in oscillating electromagnetic fields also describe general wave-wave interactions.[5] Thus, it follows directly that a photon traveling in modulated plasma can see either attractive or repulsive ponderomotive potentials, with one-way wall effects, with extensions going beyond the geometrical optics regime (see Figure 1). These ponderomotive effects can also be extended to manipulating plasmon spectra with low frequency perturbations, in analogy with quantum ladder climbing.[6] The powerful field theoretical description has been extended further to calculate fully relativistic ponderomotive Lagrangian of the Dirac electron in a vacuum laser field.[7] As a spin-off, polarization-driven bending of classical ray trajectories was rigorously unified with semi-classical spin-orbital coupling in quantum mechanics.[3,4] These advances may enable new rigor in ray-tracing simulations in plasma physics. In addition, by combining field and particle Lagrangians, dispersion relations are derived for the nonlinear electrostatic plasma waves formed in intense laser-plasma interactions,[8] shedding light, for example, on nonlinear detuning in Raman scattering.

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Center for Laser Experimental Astrophysics Research (CLEAR)

University of Michigan ✖ PIs: R.P. Drake (rpdrake@umich.edu), C.C. Kuranz, and P.A. Keiter

CLEAR performs research in the areas of radiation hydrodynamics, complex hydrodynamics, magnetized flows, and x-ray diagnostics. We select specific research topics that are at the forefront of high energy density physics and that also have relevance to issues in astrophysics. Our general approach is to use major laser facilities to explode targets, with the structure of the targets and the design of the diagnostics chosen to advance knowledge on some specific topic. An example from complex hydrodynamics is in Figure 1. Our research has been supported by SSAP and their predecessors since 1999. We graduated 10 PhDs from 2007 through 2014. Five of these were hired by the NNSA laboratories. We also had one graduate hired by another DOE laboratory, two graduates hired by university HEDLP programs, and one postdoctoral researcher hired by an NNSA laboratory. We have 10 current graduate students who have been partially or fully supported by our SSAP grant.

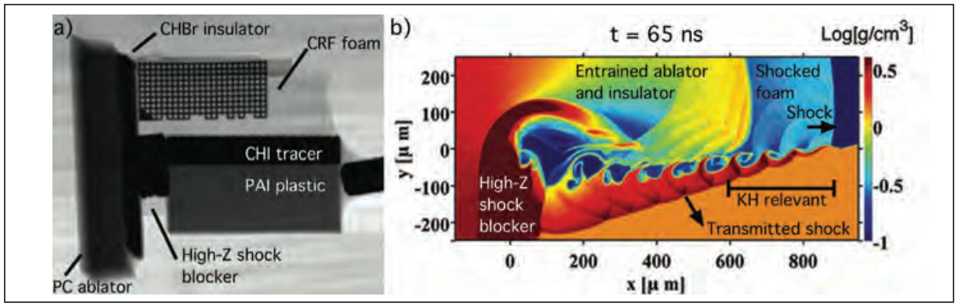

Figure 1. a) Pre-shot radiographic image of a target (Credit: J. Cowan), which is about 3 mm by 3 mm. The laser beams are incident from the left. b) Density plot from a 2D DAFNA simulation (adapted from reference 2). The KHI develops behind the shock, which is moving to the right, at the interface with the shocked plastic, which has been deflected downward.

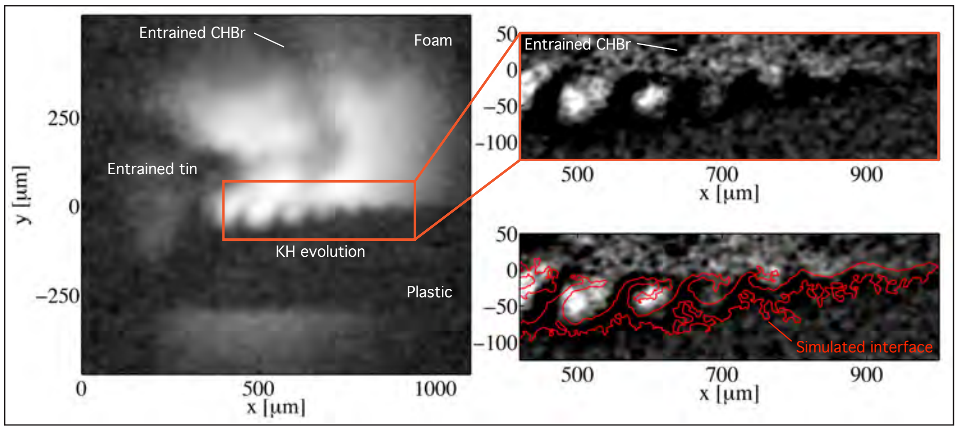

Figure 2. a) Raw radiographic data. b) Contrast-enhanced data. c) Interface extracted from the DAFNA simulated radiograph and overplotted onto the experimental data. (Adapted from reference 2.)

The Principal Investigator, Professor R. Paul Drake, states, "Our goal at Michigan is to enable students to become outstanding researchers, capable of making important contributions to nationally important research. Our SSAP grants have enabled us to train students in areas of fundamental science that are directly relevant to NNSA missions."

Hydrodynamic instabilities can lead to the development of small-scale structure and the intermixing of fluids in both natural and engineering flows. It is important to understand their behavior in high-energy-density systems, to ensure that one can properly predict and understand the data from fusion experiments and astrophysical research. The Kelvin-Helmholtz instability (KHI) is found in shear flows, where small modulations create forces that cause small perturbations to evolve into "rollups" that eventually become turbulent. In a supersonic flow, some of the energy that would contribute to the growth of the instability is instead used to support the compression of the fluids, reducing the growth rate of the KHI.

Figure 1a shows a typical target for these experiments, performed at the OMEGA-EP laser facility. One can see the precision-machined surface whose sinusoidal modulation has a wavelength of 100 μm and amplitude of 5 μm. The lasers drive a shockwave through the target, eventually producing the structure shown in Figure 1b. Toward the right edge of this target, the material behind the shock flows over the material below it, producing the KHI. The experimental design is published.[1]

This system enabled the novel observations of the KHI in a supersonic flow, with results accepted for publication in Physical Review Letters.[2] The work is doctoral thesis research by Willow Wan (see page 32), who will also help train the students who follow her. A spherical-crystal imager recorded x-rays from copper that were transmitted through the target. Figure 2 shows a sample of the data. One can see from Figure 2c that the interface extracted from the simulations, featured in red, is in good agreement with the data in the region labeled as "KH relevant" in Figure 1b. There are discrepancies on spatial scales near our diagnostic resolution (~10-15 μm) that could be the result of instrumental limitations, experimental variability, or true errors in how simulation codes handle the development of small-scale structures and turbulence. Future experiments can seek to explore these discrepancies.

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Channing Huntington, Lawrence Livermore National Laboratory (huntington4@llnl.gov)

Years at LLNL: 10/2012 - Present ✦ Degree: PhD, Applied Physics ✦ SSAP Program: 2010-2012, University of Michigan

Before I began my PhD studies at the University of Michigan, I had neither heard of high energy density (HED) science, nor the OMEGA or National Ignition Facility (NIF) laser facilities. I did not know what area of physics I would specialize in, but I was confident that enrolling at a large research institution would afford me the opportunity to explore and find what I was the most passionate about. When I met Professor Paul Drake and began learning about the experiments designed and executed by the graduate students in his group, I was immediately fascinated by the dichotomy of scales—an enormous laser could focus its energy onto a tiny target, which in turn informed our understanding of astrophysical systems measured in light-years. I immediately joined the group and began exploring HED science.

As a graduate student at Michigan, I was able to lead several experiments at the Omega Laser Facility, which was made possible by support from the National Laser Users Facility (NLUF) program. Those experiments investigated the physics of radiative shocks, which occur when the radiative energy flux from a shock front is comparable to the incoming kinetic energy flux. Using x-ray Thomson scattering and x-ray transmission radiography to probe the shock structure and plasma conditions, results from these experiments contributed to the SSAA-supported Center for Radiative Shock Hydrodynamics (CRASH) radiative hydrodynamics code that was developed at Michigan during this time.

My experience leading experiments at OMEGA meant that when I joined Lawrence Livermore National Laboratory in 2012, I was able to immediately contribute to a number of projects already underway. One such effort explores the physics of counter-streaming, collisionless plasmas flows. In this experiment two flat foils are separated by 8 mm and their opposing surfaces are each laser irradiated, generating fast, counterstreaming plasma flows. Though they are essentially collisionless flows (the mean free path for collisions between the flows is much longer than the system size), the region where the flows interpenetrate is unstable to the Weibel instability, and strong magnetic fields drive filamentation of the plasma. These fields are probed using protons generated by compression of a capsule filled with a mix of deuterium (D) and helium (^{3}He), which produces a near-point source of protons at 3 and 14.7 MeV. A schematic of the experiment and several frames of proton images are shown in Figure 1, from Reference 1. Based in part on these OMEGA results we have been allocated shot time to study collisionless shocks and Weibel instabilities in greater detail on at the NIF; these shots are underway.

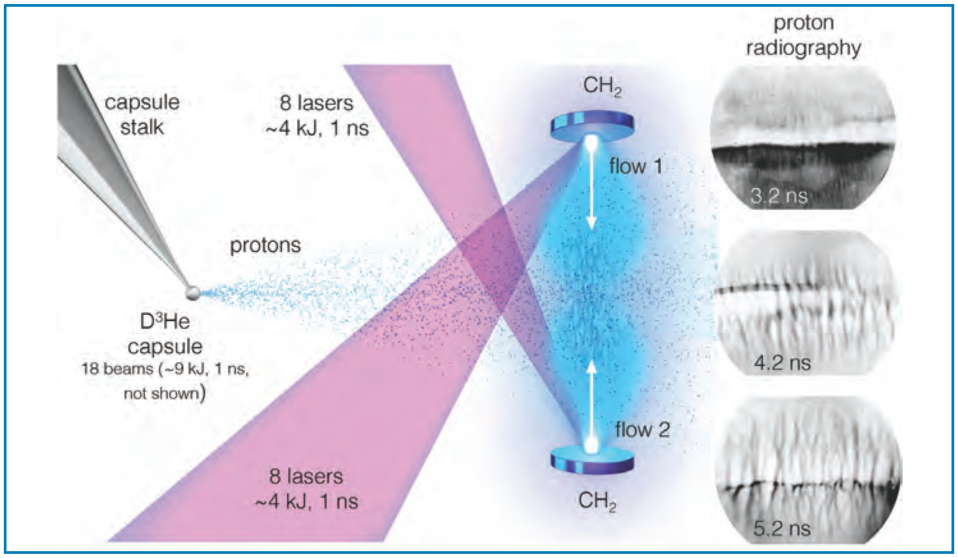

Figure 1. Interpenetrating plasma flows are created by irradiating opposing foils with several beams from the OMEGA laser (only a single representative beam is shown for clarity). The counter-streaming plasmas interact between the foils, and this region is probed with protons generated by imploding a capsule filled with D and ^{3}He. Examples of the resulting images are seen on the right, at three different probe times. In each, the strong magnetic fields around the plasma filaments are evident, as are broad, horizontal "plates" that result from the Biermann-battery magnetic fields common in laser-plasma experiments.

In addition to the collisionless shock work, since joining LLNL I have been involved in a broad range of projects, including experiments to study the strength of compressed solids, experiments exploring the effect that a radiative shock has on Rayleigh-Taylor instability growth, and a set of complex hydrodynamics experiments investigating Richtmyer-Meshkov growth after an unstable interface has been shocked multiple times.

"As a graduate student at Michigan, I was able to lead several experiments at the OMEGA Laser Facility, which was made possible by support from the National Laser Users Facility program."

The opportunity to work on such a compelling, diverse set of projects has been tremendously rewarding, and is certainly one of the most attractive features of a career at the NNSA national laboratories.

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Paul F. Schmit, Sandia National Laboratories (pfschmi@sandia.gov)
Years at SNL: 11/2012 to Present ✦ Degree: PhD, Plasma Physics ✦ SSAP Program: 2010-2012, Princeton University

The Stewardship Science Academic Programs (SSAP) played an integral role in facilitating my graduate work at Princeton University. Through its financial support and annual meetings, the program provided opportunities to push my research further, disseminate key results to the broader scientific community in the scientific literature, and obtain feedback in person from other members of the DOE and NNSA communities. Perhaps most importantly, my exposure to the exciting world of stewardship science being conducted at the nation's leading national laboratories provided vital context to turn my rather abstract, academic thesis studies into a vibrant research career at a leading NNSA laboratory.

My thesis work at Princeton involved an in-depth, exploratory investigation of the physics of waves embedded in materials undergoing compression to extreme conditions, such as those encountered in high energy density (HED) plasmas. My coauthors and I uncovered several potentially useful mechanisms that could allow researchers to concentrate some of the energy of compression into plasma waves, which then become amplified. At some predetermined instant, this energy could be transferred as heat and/or directed kinetic energy to specific constituents of the bulk plasma.[1] This research focused primarily on the theoretical exploration of these mechanisms through analytics and direct numerical simulations of simplified systems.

A push to extend these academic results into a practical application-space led to my selection to be a Harry S. Truman Fellow in National Security Science & Engineering at Sandia National Laboratories in 2012. This remarkable opportunity to expand my research for three years as the principal investigator on my own project, which came with access to the immense technical resources and deep topical expertise exemplified by the NNSA laboratories, would not have been possible without the early exposure, provided by the SSAP, to the cutting-edge experimental efforts in inertial confinement fusion (ICF) and HED science on flagship NNSA facilities like the National Ignition Facility and Z. During my three-year tenure as a Truman Fellow, I expanded my work into several new and exciting realms of ICF/HED physics and delighted in having the opportunity to make a personal, real-time impact on experimental programs so large and complex that they could only be executed with the support of the entire nation.

Now, as a technical staff member at Sandia, I am engaged in the theoretical exploration and practical design of ICF/HED systems on Z, the world's leading pulsed power facility. In collaboration with my Sandia colleagues, we have created novel methods[2] (see Figure 1) to examine fusion neutron emission data from the world's first tests of the Magnetized Liner Inertial Fusion (MagLIF) concept[3] to confirm the existence of extreme magnetic fields in the burning MagLIF plasmas—a vital component of the fusion platform that otherwise defies direct measurements. I am also engaged in understanding the role kinetic plasma effects play in ICF systems, formulating improved models of deleterious hydrodynamic instabilities, and designing and interpreting novel pulsed-power-driven ICF platforms using some of the most complex multiphysics codes ever written.

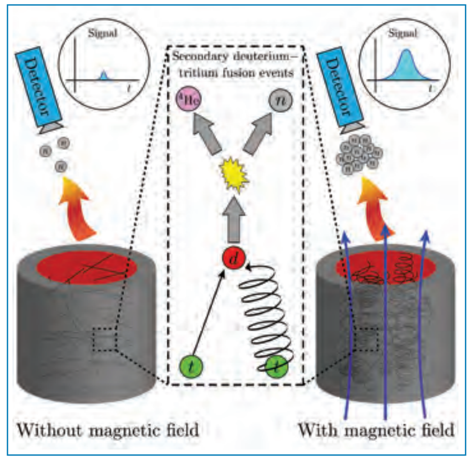

Figure 1. Graphic depicting the impact of extreme magnetic fields on secondary fusion reactions in MagLIF. Center: Illustration of "secondary" fusion events in pure deuterium fuel, where fast tritium nuclei produced by fusing deuterium react with additional deuterium nuclei, producing a high-energy neutron. Bottom left: schematic of a burning cylinder of fusion fuel without a magnetic field, with the black tracks indicating fast tritium trajectories. Tritium escapes along straight lines, producing few secondary neutrons. Bottom right: schematic of tritium trajectories in the presence of strong magnetic fields inferred on the first MagLIF experiments. Effective tritium confinement manifests in neutron detectors (top right and left) as a 100-fold stronger secondary signal than what would have been anticipated in the absence of the extreme magnetic fields.

Perhaps the greatest benefit of the SSAP to future candidates is gaining exposure to the compelling experimental and theoretical exploration occurring outside traditional university environments. The DOE/NNSA national laboratories are a veritable playground for ambitious young scientists, where opportunities to lead the world into entirely new scientific arenas with the help of unparalleled technical resources abound. This is certainly why I chose to pursue a career at Sandia, and I look forward to watching the next generation of scientists experience similar jaw-dropping personal revelations as the SSAP continues to connect them with those of us actively engaged in this critical research.

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Brandon Lahmann, Massachusetts Institute of Technology (MIT) (lahmann@mit.edu)
Degree in Progress: PhD, Nuclear Science and Engineering ⌘ Academic Advisor: Dr. Richard Petrasso ⌘ SSAP Program: 2014-Present

Research Topic:

Development of Nuclear Diagnostics for Analyzing the Properties of Inertial Confinement Fusion (ICF) and High Energy Density Plasmas

What are your research responsibilities?

I am responsible for the fielding and analysis of the compact solid-state state charge particle diagnostics known as Wedge Range Filters and Step Range Filters routinely utilized in experiments at the National Ignition Facility (NIF). I was involved in the development of a Neutron Temporal Diagnostic (NTD) for measuring fusion burn histories at the NIF and in the design of a compact neutron spectrometer for NIF, OMEGA, and Z in collaboration with Sandia National Laboratories (SNL). My role with the Wedge Range Filters at NIF has played a fundamental role in this effort by allowing me to calibrate the neutron detection efficiencies of the future design (whose first implementation has been fielded at Z), using NIF data. In this way, NIF data has had the added benefit of directly helping me with the development work of the neutron spectrometer at Z.

How have you benefitted from the SSAP?

My research is primarily funded by the NNSA which has provided me a myriad of unique opportunities that would have otherwise been impossible. This funding has allowed me to attend events such as the SSAP Symposium and the APS Annual Division of Plasma Physics Meeting where I've been able to discuss my research and ideas with scientists and researchers throughout the ICF community. Additionally, I am regularly able to collaborate with scientists from various national laboratories thanks to funding from NNSA. These opportunities have provided me with invaluable contacts and collaborators as well as providing me crucial feedback and exposure.

Have you spent time at one of the national laboratories?

I spent the summer of 2014 working as an intern in the High Energy Density Physics group at SNL. While there, I met several scientists who shared my excitement regarding the prospect of future fusion energy which fundamentally helped shape my career goals. This is also where I got most of my initial exposure to ICF and when I decided to begin my involvement with SSAP through MIT. I remain very excited about the potential of SNL's Magnetized Linear Inertial Fusion program and hope to help foster a strong collaboration between SNL and MIT.

Willow Wan, University of Michigan (wwan@umich.edu)
Degree in Progress: PhD, Atmospheric, Oceanic, and Space Science ⌘ Academic Advisors: Professor R. Paul Drake and Dr. Carolyn Kuranz ⌘ SSAP Program: 2010-Present

Research Topic:

Supersonic, Shock Wave Driven Kelvin-Helmholtz Instability Experiments

What are your research responsibilities?

My research addresses the evolution of the Kelvin-Helmholtz instability in a steady, supersonic flow from well-defined initial conditions. The Kelvin-Helmholtz instability is a fundamental hydrodynamic process that causes small-scale structure and turbulence to develop from perturbations in a shear flow. In a supersonic flow, some of the energy that would ordinarily contribute to the growth of the instability is instead used to support the compression of the fluids, resulting in an inhibition of the growth rate of the instability. Previous attempts to study the Kelvin-Helmholtz instability utilized uncontrolled multimode initial conditions, or blast wave driven flows that rapidly decayed to subsonic velocities.

I am responsible for developing an experimental platform that can sustain a steady, supersonic flow, while still taking advantage of the tightly controlled initial conditions of laser-driven hydrodynamic instability experiments. This platform successfully produced the first observations of well-characterized single and dual-mode seed perturbations evolving under the effect of the Kelvin-Helmholtz instability in a steady, supersonic flow. I am also responsible for processing and analyzing the data against two-dimensional hydrodynamic simulations, to validate and benchmark simulation codes with a new level of precision.

How have you benefitted from the SSAP?

As a graduate student, it is rare to have the opportunity to contribute to, much less lead, a campaign on world class laser-facilities such as those found at the national laboratories and the University of Rochester's Laboratory for Laser Energetics. With the support of the SSAP, I was able to participate in large-scale collaborative experiments that push the limits of our scientific and engineering capabilities. It goes without saying that these experiences provided a unique level of training, valuable professional connections, and interactive exposure to the exciting research projects of other scientists in the field.

Have you spent time at one of the national laboratories?

My most memorable trip to a national laboratory was for a two-month campaign at the Jupiter Laser Facility of Lawrence Livermore National Laboratory to study self-generated magnetic fields. This kind of hands-on immersion helps to not only broaden the skillset of young scientists, but also to invigorate our interest and provide for a more engaging graduate student experience. Through this campaign and others like it, I was able to work with the most prominent minds in the field to develop and refine many of the techniques that I would need later in my research.

National Laser Users' Facility

Study of Fast Electron Transport into Imploded High Density Plasmas Using Cu-Doped CD Shell Targets

University of California, San Diego ⌘ PI: F.N. Beg (fbeg@ucsd.edu)

The High Energy Density Physics (HEDP) Group research focus has been on Inertial Confinement Fusion (ICF), magneto inertial fusion, intense particle beam generation from short pulse high intensity laser matter interactions, and pulsed power driven Z-pinches. In order to address the critical issues pertinent to the above-mentioned topics, the HEDP Group carries out experiments on all the major high power laser facilities in the country. These include the National Nuclear Security Administration's (NNSA) large and medium size facilities; OMEGA and OMEGA-EP lasers at the University of Rochester's Laboratory for Laser Energetics, the Titan Laser at the Lawrence Livermore National Laboratory, the Trident Laser at the Los Alamos National Laboratory, and the Texas Petawatt Laser at the University of Texas at Austin among others. In addition to a strong experimental program, the HEDP Group has a proficient modeling program where radiation hydrodynamics, Particle-in- Cell and magnetohydrodynamics codes have been used to validate the experimental data and explore new physics regimes. These codes include the Large Scale Plasma (LSP), PSC, Hyades, EPOCH and MACH 2. The HEDP Group has trained a large number of undergraduate and graduate students, who are pursuing their careers in this field. For example, four PhD students (i.e., Sophia Chen, Tammy Ma, Drew Higginson, and Charlie Jarrott) joined Lawrence Livermore National Laboratory as postdoctoral fellows in the last five years. Significant portions of their PhD work were carried out at the NNSA national laboratories. Two of these students were awarded the prestigious Lawrence fellowships.

Figure 1. Lead graduate student Charlie Jarrott (top left) with the PI, Farhat Beg, and UCSD post docs as well as collaborators from LLE and General Atomics on a shot day at the OMEGA facility.[1]

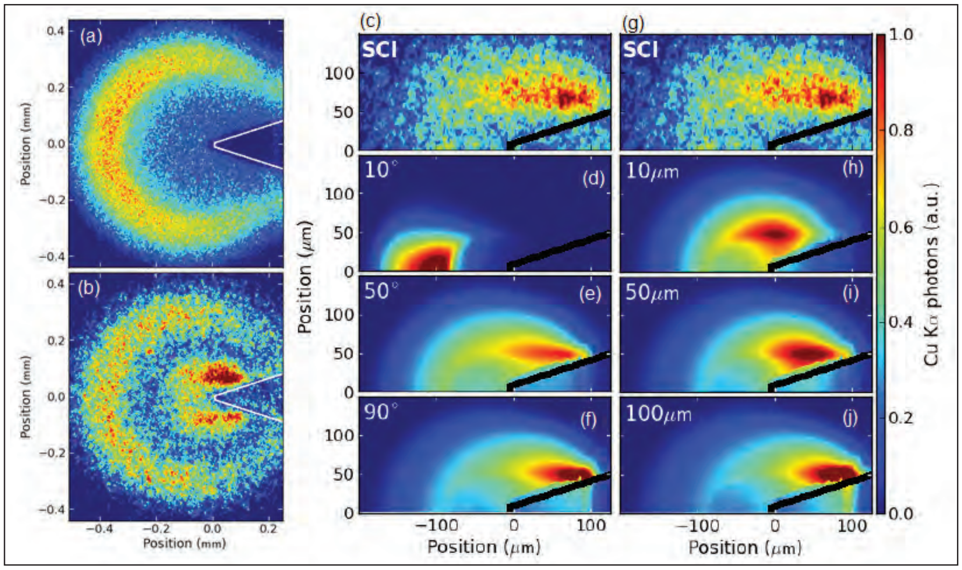

Figure 2. Cu Kα image data from an OMEGA-only (a) and integrated shot (b). White lines show the approximate position of the inner cone walls. Zoom-ins of the averaged data (c, g) are compared to simulated data with varied source angle (d-f) and position from the cone tip (h-j).

The focus of our electron transport National Laser User's Facility (NLUF) project has been on the visualization of fast electrons' energy deposition in imploded plasmas using the joint capabilities of OMEGA and OMEGA-EP. Understanding the generation of fast electrons by the OMEGA-EP short pulse and their subsequent transport into hot dense plasmas is crucial to the success of the cone guided fast ignition (FI) scheme of inertial confinement fusion. In this work, a new platform was developed that measured, for the first time, the spatial map of fast electron transport in the vicinity of the cone tip and imploded shell in integrated experiments. The development of the platform and its first application in demonstrating improved coupling is described here and in an

"The work is a truly collaborative effort between various universities and national laboratories. Graduate student L. Charlie Jarrott was funded on the project and now he is a postdoctoral fellow at the Lawrence Livermore National Laboratory working on the National Ignition Facility (see page 38)."

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upcoming Nature Physics publication.[1] The work is a truly collaborative effort between various universities and national laboratories. Graduate student L. Charlie Jarrott was funded on the project[2] and now he is a post-doctoral fellow at the Lawrence Livermore National Laboratory working on the National Ignition Facility (see page 38).

In these experiments, cone-in-shell targets consisted of a reentrant hollow gold cone in a two-layer plastic shell composed of an outer CH ablator layer and an inner CD fuel layer doped with Cu at 1 atomic percent. The Cu-dopant enables the characterization of fast electron spatial energy deposition via two-dimensional (2D) imaging of Cu Kα radiation by a spherically bent, quartz crystal while the total photon number is measured by a calibrated x-ray spectrometer. Figure 2 compares the measured 2D Cu Kα images in a typical implosion shot using only the OMEGA driver beams and an integrated shot with the short pulse delayed to 3.65 ns relative to the driver. Cu Kα fluorescence emission was observed in all OMEGA-only shots from the in-flight shell excited by the driver-produced suprathermal electrons with energies of ~20 keV, confirmed by the time-resolved hard x-ray detector. Location of the peak Cu Kα emission (with a radius of ~ 290 μm) from the in-flight shell correlated well with the simulated size of the imploding shell at the end of the driver pulse (2.60 ns) using the 2D Draco code. In the integrated shots, in addition to the emission from the in-flight shell, Cu Kα emission excited by the OMEGA-EP laser produced fast electrons was observed from a small region within 150 μm surrounding the cone tip. These two emission regions were well separated. Signal and size of the Cu Kα emission due to fast electrons changed with the OMEGA-EP beam injection time, while the emission from the in-flight shell did not change. Fast electron induced Cu Kα emission was found to be peaked off the outside of the cone wall and extended as far as ~100 μm up from the tip, indicating fast electrons were created, not at the cone tip, but in an extended pre-formed plasma that filled the cone to a large off-set distance. The Cu Kα images provide unprecedented spatial information about where the fast electrons deposit their energy in the compressed plasma.

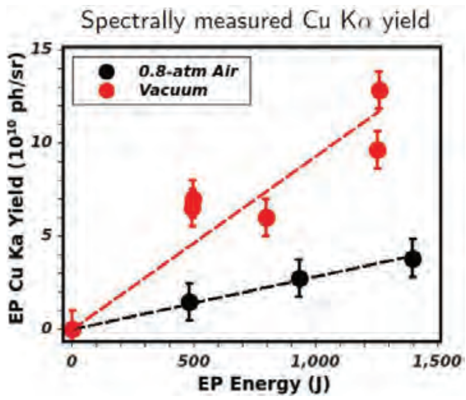

Figure 3. Measured Cu Kα yield enhancement as a function of OMEGA-EP laser energy from the integrated experiments with fixed delay from the x-ray spectrometer diagnostic. Kα yield from the driver beam contribution has been subtracted. Data shown in black were obtained from the earlier experiments with a 10 μm cone tip and 0.8 atm air trapped inside the shell. Data shown in red are from the latest, optimized experiment with the improved target design utilizing a 40 μm cone tip and pre-evacuated shell.

These results facilitated information about the energy deposition by fast electrons and energy coupling into the imploded plasma. The energy coupling was primarily restricted by two factors: large distance of electron source from the imploded plasma and relatively smaller ρr of the compressed plasma. In the light of these results, the target design was revised with a larger diameter cone tip and vacuum shells. These changes reduced the distance of the electron source to the compressed core and also increased the ρr to approximately 100 mgcm^{-2}. With these changes, the coupling was increased to 7%. Figure 3 shows the total Cu Kα yield as a fuction of EP laser energy for two targets. We benchmarked the experimental data with integrated radiation/hydrodynamic PIC simulations.

In summary, novel cone-in-Cu-doped-shell targets were successfully used to diagnose the spatial energy deposition of fast electrons in integrated FI experiments for the first time. Comprehensive modeling analysis of the experiment reconstructed the measured spatial energy deposition and total yield, providing a clear understanding of the key contributing factors in the observed low-energy coupling: large source-to-core distance due to pre-plasma, large source divergence, and higher-than-ideal electron slope temperature for the core produced. Coupling to the core was shown to increase with OMEGA-EP energy by three independent diagnostics and increased significantly with the improved target and implosion design that minimized pre-plasma and increased core density. Up to 7% laser-to-core energy coupling has been obtained, the highest value reported so far on OMEGA.

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When Shock Waves Collide

Rice University ✖ PI: Patrick Hartigan (hartigan@rice.edu)

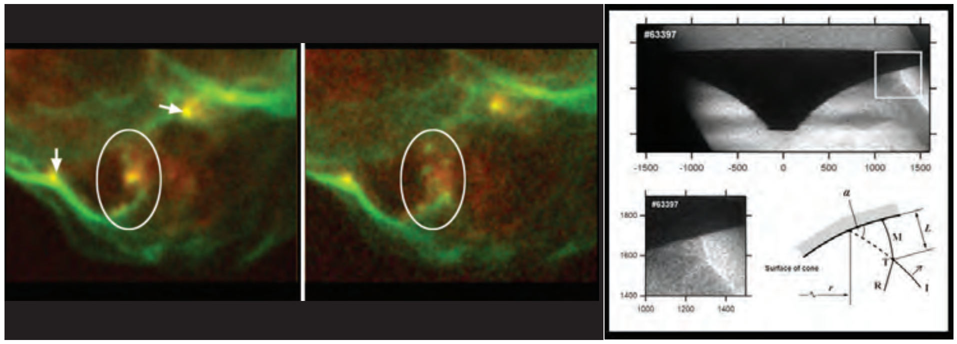

Figure 1. Left and Center: HST images of the HH 34 bow shock taken 9 years apart. The bright knots indicated by white arrows are possible Mach stems, and the circular area highlights transient features. Right: Radiograph of an experiment at OMEGA, showing a Mach stem (scale is in μm).

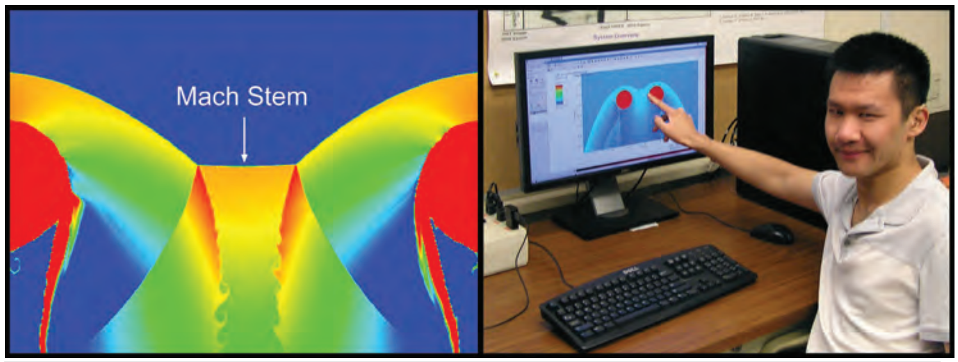

Figure 2. *Left*: A Mach stem forms between two bow shocks around two obstacles in a supersonic flow. *Right*: Graduate student Andy Liao analyzes an Astrobear simulation of intersecting shocks.

As part of a decades-long study of several stellar jets, in 2011 we published a paper in the Astrophysical Journal that summarized the complex morphologies and transient phenomenon we observe in these shock fronts. As shown in Figure 1, some bow shocks showed a curious serrated structure, while in others bright knots would come and go, typically near what appear to be areas where shock waves intersect.

Motivated by these observations, in August of 2011 we initiated a series of laboratory experiments to study intersections of high Mach-number shock waves. Since that time, our NLUF support has enabled us to support several PhD students. The NLUF grant currently supports PhD students Andy Liao (Rice University), Edward Hansen (University of Rochester), and Rachel Young (University of Michigan) with a combination of stipend support, supercomputer access, and experimental data that forms the basis for their thesis work. Several Rice University past and current undergraduates including Scott Carlsten, Anna Wright, and Sharad Jones have completed senior research projects related to the project. The program is inherently interdisciplinary, and combines experimental and numerical design with astronomical observations and analysis. Past-program alumnus Kris Yirak worked for several years at Los Alamos National Laboratory. Without the NLUF support these students would be involved in different areas of research and study.

It has been well-known from low-Mach number wind-tunnel experiments that when the intersection angles between shocks become oblique that a triple point forms and creates a normal shock where the shocks intersect. Known as a Mach stem, this normal shock could give rise to transient hot spots like we observe in stellar jets. The experiments drove a blast wave along the surface of a cone, where the shape and smoothness was milled in such a way to control the incident angle of the shock with the surface. In this manner we were able to quantify the critical angles for Mach stem formation, understand how Mach stems evolve along irregular surfaces, as well as quantify the growth and decay rates associated with the phenomenon.

The experiments were used to test the Astrobear code, an astrophysical code that we adapted for use in laboratory experiments. The advantage of Astrobear is that it includes non-LTE radiative cooling as well as magnetic fields. While laboratory materials are typically characterized by a constant specific heat ratio gamma, that is not true for astrophysical flows where codes must follow the energy lost by optically thin radiation in order to account for the cooling observed. The codes and experimental data both show that Mach stem growth rates remain high when the shock intersection angles approach 90 degrees. However, a limit must occur where the Mach stem transforms from a separate shock into a single curved shock that surrounds the obstacles (see Figure 2).

As a result of these experiments we are now reassessing transient knots in serrated bow shocks like that in Figure 1 as possibly arising from time-dependent intersection points that occur as wind moves past the irregular surface of the bow shock. Whether or not a single bow shock, a Mach stem, or separate bows form around any given obstacle depends upon the diameter of the obstacles, their separation, the Mach number of the flow, and the ‘effective' gamma of the gas.

The experimental and numerical work resulting from these several years of OMEGA shots are now complete and have been submitted to the Astrophysical Journal for publication. Our current experiments focus on an exciting new endeavor, where we are looking to reproduce dynamical effects of magnetized astrophysical shocks in a controlled laboratory setting.

"As a graduate student, I designed and executed five experimental campaigns as a PI on the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics through NLUF, and participated in many more. These opportunities shaped my growth as a scientist and allowed me to contribute to the cutting edge of high energy density science while still a student."

— Hans Rinderknecht, Lawrence Livermore National Laboratory

"I am truly grateful for how the NLUF program has broadened my horizons, in terms of experience as well as in opportunities. Through its support for interdisciplinary collaboration, I was immediately immersed in an exciting field of research that lies at the boundaries of experiment, numerical simulation, and astrophysical observation. One particularly important part of this immersion came from the support for traveling to LLE, where I would be exposed directly to the operations at the Omega Laser Facility both as a Principal Investigator-in-training and as a research collaborator."

— Andy Liao, Rice University

"My experiment time allocation on OMEGA is provided through the NLUF program. My graduate funding is provided by a DOE/NNSA Stewardship Science Graduate Fellowship. The important financial funding aside, I have benefited greatly from the accumulated knowledge and support of the high energy density physics/inertial confinement fusion community, and SSAP helped build this community."

— Hong Sio, Massachusetts Institute of Technology

L. Charlie Jarrott, Lawrence Livermore National Laboratory (jarrott1@llnl.gov)

Years at LLNL: 05/2015-Present ⌘ Degree: PhD, Engineering Physics ⌘ SSAA Program: 2009-2015, University of California, San Diego

"... Additionally, through the NLUF program, I have established collaborations with scientists from around the world and, more specifically, at the national laboratories. It is without a doubt that my job at LLNL came about in part because of my interactions with scientists in the high energy density field which began as a graduate student."

As a graduate student at the University of California, San Diego, my research was funded by SSAP's NLUF program. My research was performed at the University of Rochester's Laboratory for Laser Energetics where I did experiments relating to Fast Ignition Inertial Confinement Fusion. In these experiments, the OMEGA laser beams were used in a direct drive configuration to compress a spherical plastic shell target with a reentrant gold cone attached. The OMEGA-EP short pulse laser beam was then focused onto the inner cone tip of the gold cone producing relativistic electrons which then deposit their energy in the compressed plastic shell. The focus of my research was on the transport and energy deposition of the relativistic electrons produced by the high-intensity OMEGA-EP heating beam. To better understand the dynamics of the relativistic electrons, my work incorporated a copper tracer into the plastic spherical shell targets. With this copper tracer, the transport and energy deposition of relativistic electrons could be visualized via impact ionization of copper's k-shell producing K-alpha radiation. This radiation was then imaged using a spherically bent, two-dimensional Bragg crystal imager tuned to copper K-alpha radiation. The implementation of this experimental and target configuration was made possible through the support of the NLUF program which provided resources for target manufacturing and laser time.

Currently, as a postdoctoral research staff member at Lawrence Livermore National Laboratory (LLNL), I work as an experimentalist, working with x-ray diagnostics and running experiments on the National Ignition Facility (NIF) under the Inertial Confinement Fusion program. My experience as a graduate student, executing experiments at the Omega Laser Facility and optimizing x-ray diagnostics has proven to be an invaluable skill which certainly improved my candidacy for my current position. Additionally, through the NLUF program, I have established collaborations with scientists from around the world and, more specifically, at the national laboratories. It is without a doubt that my job at LLNL came about in part because of my interactions with scientists in the high energy density field which began as a graduate student.

One of my current projects here at LLNL involves measuring the electron temperature of the compressed hotspot at the center of an inertially confined, layered deuterium-tritium (DT) fuel capsule. The importance of this measurement is readily understood when considering that current measurements of the DT and DD ion temperatures using neutron time-of-flight detectors are complicated by the contribution of hotspot motion to the peak width, which may produce an apparent temperature higher than the thermal temperature. Rather than using ions to measure the temperature of the hotspot, my work is centered on taking measurements of the x-ray continuum produced by free-free bremsstrahlung radiation in the hotspot using a differential filtering diagnostic. The electron temperature is not sensitive to this non-thermal velocity and is thus a valuable input to interpreting the stagnated hotspot conditions. What my work has shown is that the current differential filtering diagnostic provides insufficient temperature resolution for the hotspot temperatures of interest (>3 keV). Because of this, a new differential filter configuration utilizing larger pinhole size to increase spectral fluence, as well as thicker filtration to better constrain higher photon energies has been proposed and is in the process of being implemented on the NIF. This new configuration will improve the electron temperature measurement uncertainty by more than a factor of three, allowing for a more accurate comparison with neutron-based hotspot temperature measurements.

The reason for seeking employment at Lawrence Livermore National Laboratory was straightforward: I wanted to work with outstanding scientists on cutting edge research at the largest laser facility in the world. This great opportunity would not be possible without the NLUF program and I am very thankful for all that has been provided to me throughout my graduate school tenure.

Hans Rinderknecht, Lawrence Livermore National Laboratory (rinderknecht1@llnl.gov)
Years at LLNL: 09/2015-Present ⌘ Degree: PhD, Physics ⌘ NLUF Program: 2008-2015, Massachusetts Institute of Technology

The NLUF Program provided the basis of my graduate research in the High Energy Density Physics division at the Massachusetts Institute of Technology (MIT), led by Dr. Richard Petrasso. As a graduate student, I designed and executed five experimental campaigns as a Principal Investigator on the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics (LLE) through NLUF program, and participated in many more. These opportunities shaped my growth as a scientist and allowed me to contribute to the cutting edge of high energy density (HED) science while still a student.

My thesis research investigated the kinetic plasma dynamics of implosions by measuring trends in nuclear yield production and comparing them to theory and hydrodynamic simulations. Because of the complex nature and small size of laser-driven HED experiments, hydrodynamic simulations are often relied on for understanding, but they usually ignore physics on the scale of ion collisions (i.e., kinetic physics) as well as the interaction of multiple ion species. To study the impact of kinetic and multiple-ion physics in plasmas, I imploded gas-filled, shock-driven targets, which have high hydrodynamic stability and high plasma temperatures ($T_i \sim 10$ keV). These conditions accentuated the importance of kinetic physics in the plasmas because the mean-free-path of the ions was comparable to the scale size of the experiment.

By varying the initial density and composition of the gas in the targets, my colleagues and I discovered several anomalous trends in the fusion production of the implosions, when compared to theory and hydrodynamic simulations. As one example, an implosion with deuterium (D) in the shell and ^{3}He in the gas produced substantial D-^{3}He fusion, despite the fact that there was no hydrodynamic mechanism that could mix the fuels (see Figure 1).[1] Many of the observed trends were explained by a combination of two effects: ion diffusion, which changes the local ion species concentration during the experiment; and perturbations to the ion distribution due to long mean-free-paths. However, some results suggest that the deuterium and ^{3}He populations are not always in thermal equilibrium, and therefore fully kinetic methods are required to accurately model them.[2]

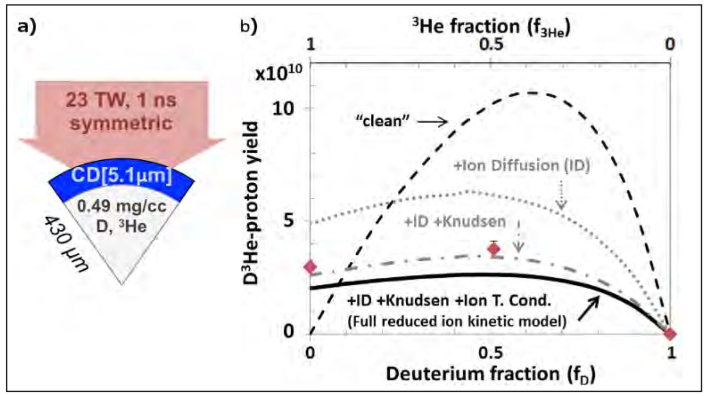

Figure 1. a) Schematic of spherical, deuterated-plastic shells filled with mixtures of deuterium and ^{3}He and imploded on the OMEGA laser to study the impact of kinetic physics on ICF-relevant plasmas. b) Measured D^{3}He-proton yield (red points) as a function of the initial fuel composition show a clear disagreement with the trend predicted by "clean" 1D-hydrodynamic simulations (black dashed). Sequentially including "reduced" ion kinetic models in the simulation[3]—ion diffusion (dotted), loss of ions with long mean free paths ("Knudsen", dash-dot), and ion thermal conduction (solid)—recapture the experimental trend and produce better absolute agreement with the data. Figure is adapted from Reference 4.

I supported this work with experiments on smaller facilities. I used charged particle accelerators at MIT and The State University of New York at Geneseo, the Multi-Terawatt Laser at LLE and the Jupiter Laser Facility at Lawrence Livermore National Laboratory (LLNL) for diagnostic development studies. These facilities taught me the irreplaceable lessons about experimental science that you only get by working with your hands, which helped make my experiments on OMEGA a success. The NLUF program also provided support for me to attend conferences, such as the American Physical Society Division of Plasma Physics annual meeting, where I developed valuable research connections in the plasma physics community.

After graduating in 2015, I came to LLNL, where I received the Lawrence Fellowship and continue my research into kinetic physics in HED experiments. My current research aims to experimentally quantify the strength of the various kinetic mechanisms that have been identified, using OMEGA and other laser systems. I also aim to establish how significantly these mechanisms affect the plasmas produced in ignition experiments, to determine whether kinetic physics is responsible for the difficulty in reaching ignition conditions on the National Ignition Facility (NIF).

At LLNL I interact daily with a community of physicists whose expertise in experiment and theory is matched by their enthusiasm for work on hard problems. The facilities and opportunities at LLNL also provide a great platform for new and ongoing collaborations with academic scientists from around the world. With NIF opening up for more physics experiments and ignition closer than ever, now is a fantastically exciting time to work in the field of HED.

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[2]H.G. Rinderknecht et al., "Thermal Decoupling and Species Separation in Shock-Driven Implosions," Phys. Rev. Lett. 114, 025001, 2015.

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[4]H.G. Rinderknecht et al., "Kinetic Mix Mechanisms in Shock-driven Inertial Confinement Fusion Implosions," Phys. Plasmas 21, 056311, 2014.

Andy Liao, Rice University (andy.liao@rice.edu)

Degree in Progress: PhD, Astrophysics ✦ Academic Advisor: Dr. Patrick Hartigan ✦ NLUF Program: 2013-Present

Research Topic:

Magnetized Laser Astrophysics

What are your research responsibilities?

I build numerical models of laser astrophysics experiments from design to diagnostics. In one such project, I used the magnetohydrodynamics (MHD) code AstroBEAR to simulate the dynamics of a bow shock as it formed around a 2-D experimental analogue of a planetary magnetosphere, and how it responds to varying conditions in a laser-driven flow. Then I post-processed the MHD code's results and computed projected emissivity maps that directly simulated the appearance of the plasma as it would appear to instruments available at the University of Rochester's Laboratory for Laser Energetics (LLE). Finally, I analyzed the results of the experiments when they were completed at the Omega Laser Facility.

How have you benefited from the NLUF program?

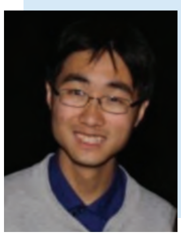
I am truly grateful for how the NLUF program has broadened my horizons, in terms of experience as well as in opportunities. Through its support for interdisciplinary collaboration, I was immediately immersed in an exciting field of research that lies at the boundaries of experiment, numerical simulation, and astrophysical observation. One particularly important part of this immersion came from the support for traveling to LLE, where I would be exposed directly to the operations at the Omega Laser Facility both as a Principal Investigator-in-training and as a research collaborator. In these collaborations, I have taken full advantage of the opportunity to work with and learn from the leaders in the field. I feel that I am being prepared well for a future career involving high energy density laboratory astrophysics (HEDLA).

Did the NLUF Program influence your choice of research area and university?

The NLUF appointment was crucial in helping me define a career in computational astrophysics. When I enrolled at Rice University, my interests were rather unfocused. In my first semester, I took a broad distribution of courses in topics that were more conveniently suited for an aspiring applied physicist, and also, a course in astrophysics. Once I became involved in laser experiments through my affiliation, a degree in astrophysics soon became synonymous with a career in HEDLA. When I was given the opportunity to continue working in HEDLA through the SSAP's NLUF program, I made the decision that led me to where I am now. Thanks to the support from the NLUF Program for this type of interdisiplinary research, I am now working in a field I would not have otherwise considered.

Hong Sio, Massachusetts Institute of Technology (hsio@mit.edu)

Degree in Progress: PhD, Physics ✦ Academic Advisor: Dr. Richard Petrasso ✦ NLUF Program: 2011-Present



Research Topic:

High Energy Density Plasma Physics and Inertial Confinement Fusion

What are your research responsibilities?

On a typical day, I test and develop diagnostics at the Massachusetts Institute of Technology (MIT) accelerator laboratory, prepare for experiments on OMEGA, and analyze data from programmatic and basic science campaigns at the National Ignition Facility (NIF). My projects include charged-particles spectrometer analysis at MIT, kinetic mix experiments and multiple nuclear burn diagnostic on OMEGA, and particle-time-of-flight detectors at the NIF.

How have you benefitted from the NLUF Program?

My work is funded through NNSA grants. My experiment time allocation on OMEGA is provided through the NLUF program. My graduate funding is provided by a DOE/NNSA Stewardship Science Graduate Fellowship (SSGF). The important financial funding aside, I have benefited greatly from the accumulated knowledge and support of the high energy density physics (HEDP)/inertial confinement fusion (ICF) community, and SSAP helped build this community.

Did the SSAP give you the opportunity to work with others you might not have otherwise?

One of the most rewarding aspects of my work is the opportunities to work with—and learn from—other scientists in the HEDP and ICF community. Whether it is planning an experiment on OMEGA, or understanding diagnostic output at the NIF, they are always there to lend sound advice. At the same time, when I provide diagnostic support for experiments, I learn about important, open questions in my field and innovative approaches to addressing them. These are all made possible by SSAP support.

Have you spent time at one of the national laboratories?

As part of my SSGF practicum, I spent three months at Lawrence Livermore National Laboratory, and had a chance to participate in a Jupiter Laser Facility (JLF) experiment and a Linac Coherent Light Source (LCLS) experiment. It turned out that spending time at two different user facilities with scientists outside my usual field was very helpful for my own research. I want to address basic science questions in HEDP, and I want to use laser-driven plasma to answer questions in other fields of science. That summer gave me a chance to step outside my research bubble, and for a bit at least, poke my head into other target chambers (literally, in the case of JLF) to see how research is carried out in other HED facilities.

Predictive Science Academic Alliance Program II (PSAAP II)

Center for Compressible Multiphase Turbulence

University of Florida, Gainesville ⌘ PI: S. Balachandar (bala1s@ufl.edu) ⌘ Technical Manager: Thomas L. Jackson (tlj@ufl.edu)

The overarching goals of the Center for Compressible Multiphase Turbulence (CCMT) are threefold: (1) to radically advance the field of compressible multiphase turbulence (CMT) through rigorous first-principle multiscale modeling; (2) to advance very large-scale predictive simulation science on present and near-future platforms; and (3) to advance a co-design strategy that combines exascale emulation with a novel energy-constrained numerical approach.

The Center is performing petascale, and working towards exascale, simulations of instabilities, turbulence and mixing in particle-laden flows under conditions of extreme pressure and temperature to investigate fundamental problems of interest to national technological leadership. Beginning in March 2014, CCMT currently engages roughly 25 graduate students and research staff in fundamental research in the areas of physics, uncertainty budget, computer science, and exascale modeling and simulation.

The Principal Investigator, Professor S. Balachandar, states that “PSAAP has brought international attention to the University of Florida.” He notes that the PSAAP is committed to high-speed computing on current and near-future platforms, and the Program engages students from a wide spectrum of research interests to work together in tackling some of the world’s most difficult problems. Most noteworthy, new classes and course materials are being developed in response to the program.

The overarching demonstration problem consists of a cylindrical core of a simple explosive grain surrounded by an annular region of polydisperse metal particles of spherical shape. The shape and amount of the explosive charge and the size distribution of the metal powder and its material (aluminum, steel, tungsten, etc.) are parameters that will be varied. The following features makes this problem an excellent choice for demonstration: (i) the explosive dispersal exercises all the major CMT physics, (ii) the extreme conditions makes this a demanding test, and (iii) this problem requires exascale for true predictive capability. Year 1 simulations of the demonstration problem were successfully carried out on the DOE supercomputers Mustang, Vulcan and Cab, and a number of prediction metrics were compared to experiments; see Figure 1 (left) for a typical simulation output. The state-of-the-art simulations of this problem at the micro (at the scale of a cluster of O(100) particles), meso (at the scale of O(106) particles) and macroscales (system scale), along with companion validation-quality experiments, will allow us to better understand the fundamental physics of compressible multiphase turbulence and translate this understanding to a rigorous multiscale modeling and simulation approach that can impact a wide variety of problems of national and societal importance. For example, at the microscale, recent three-dimensional simulations have been carried out for a shock wave propagating through a random bed of particles; see Figure 1 (right). Uncertainty reduction is a key goal of the Center and it will drive micro and mesoscale-informed model development, apart from error reduction in both experimental and numerical approaches. Yearly uncertainty budget will determine the biggest contributors to the overall uncertainty in the prediction metrics and the drive to reduce these biggest uncertainties will dictate the center’s focus on development of improved models, software, simulation, and calibration/validation experiments.

Shown in Figure 2 is a concept diagram of our exascale behavioral emulation project within CCMT. The objective is to develop behavioral emulation (BE) methods and tools to support algorithmic design-space exploration (DSE) of key CMT applications (i.e., CMT-nek: the spectral discontinuous-Galerkin compressible multiphase flow code being co-designed at the center) on notional future-gen architectures and systems. BE is a coarse-grained simulation approach which will provide an accurate first-order approximation of performance to enable DSE on extreme-scale, future-gen systems before (and complemented by) time-consuming detailed simulation. The key kernels and communication patterns of CMT-nek are abstracted into a mini-app (CMT-bone) and modeled as application Behavioral Emulation Objects (App-BEOs). Similarly, existing systems and architectures are modeled as architecture BEOs. These models are calibrated and validated through testbed benchmarking and experimentation. Validated models are then extended to represent notional systems to support algorithmic DSE of CMT-nek on anticipated future-gen systems up to exascale. The key challenge is to maintain the tradeoff between simulation accuracy (BE methods) and simulation speed (software and hardware solutions to accelerate simulation) as we approach exascale.

Faculty: A. George, R. Haftka, N. Kim, H. Lam, S. Ranka, G. Stitt, S. Thakur

University Partners: R. Adrian (ASU), J. Zhang (FIT), P. Fischer (Illinois), B. Rollins (Embrey-Riddle)

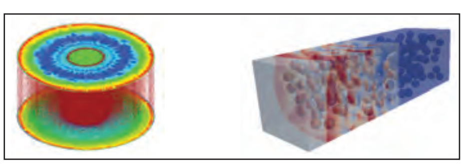


Figure 1. (Left) Multiphase three-dimensional simulations of cylindrical blast wave. (Right) Mesoscale simulations of shock propagating through a random pack of particles.

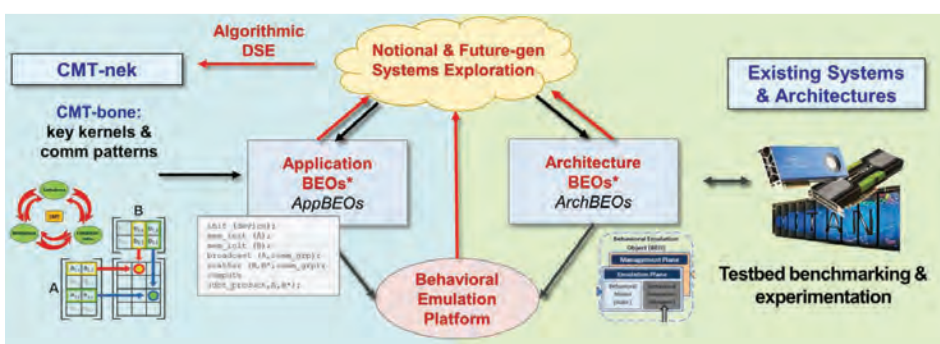


Figure 2. Concept diagram for exascale emulation for future-generation systems.

Predictive Simulations of Particle-laden Turbulence in a Radiation Environment

Stanford University ✠ PI: Gianluca Iaccarino (jops@stanford.edu) ✠ Co-PI: Ali Mani (alimani@stanford.edu)

Stanford University Multidisciplinary Simulation Center, funded by the National Nuclear Security Administration (NNSA), is focused on "Predictive Simulations of Particle-laden Turbulence in a Radiation Environment." This poorly understood physical process is important for the design of high-energy systems, reducing emissions in power generation devices, and studying heat generation in clouds. Our overarching application is the study of the effect of the multiphysics coupling of turbulence, radiation and particle transport on the efficiency of solar thermal receivers, with specific applications in energy conversion and chemical splitting in hydrogen production plants.

About twenty graduate students and ten postdoctoral fellows work on the project across four departments in the School of Engineering at Stanford, together with five external university collaborators. The Center is developing computational techniques to perform simulations at unprecedented fidelity by accessing the largest supercomputers in the United States, while simultaneously introducing a novel programming paradigm to enable computations on next generation computer architectures. This paradigm is based on Domain Specific Languages and provides a framework to develop large-scale multiphysics codes that can efficiently operate on diverse computer systems without requiring the users to implement architecture specific syntax or knowledge. A dedicated experimental campaign is also underway to provide overall validation data to assess the predictive ability of the physical models and software tools developed within the project.

The Center simulations have demonstrated that in a specific flow regime characterized by unitary Stokes number (the ratio of particle inertial relaxation time to the flow time scale) the particles are strongly clustered, i.e., concentrated in regions of high shear and centrifuged out of vortical swirling flow structures. This localized increase in particle concentration has a profound effect on the thermodynamic conditions of the multiphase mixture, resulting in a highly inhomogeneous gas temperature at the exit of the irradiated section and a reduced absorption of radiative flux. This computational result has not been yet confirmed experimentally, and therefore it is imperative to assess the effect of uncertainties on the predictions. For example, although the system is designed to operate with particles having a diameter of 10 microns, it is impossible and too costly to control the size of the millions of particles being injected in the experimental apparatus. What is the effect of variability in particle sizes on the overall thermal performance? A detailed uncertainty quantification study shows that the changes in particle size and consequently in the Stokes number, significantly change the particle clustering patterns as illustrated in Figures 1 and 2. It also results in reduced radiation absorption by the particles, but more efficient heating of the gas phase through conduction.

The project continues a 15-year history of strong collaboration between NNSA laboratories and Stanford University, including the Advanced Simulation and Computing and PSAAP programs.

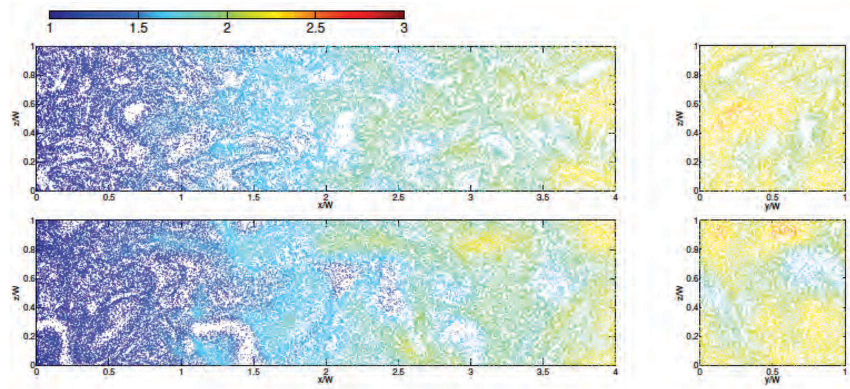


Figure 1. Temperature of the particles transported in a turbulent flow subject to radiation for a case with low local particle clustering (Stokes Number of 0.1). Left: streamwise plane (flow is left to right); right: cross-section at the exit. Top: mono-disperse particle simulation; bottom: polydisperse particle simulation. The effect of particle size uncertainty is very small.

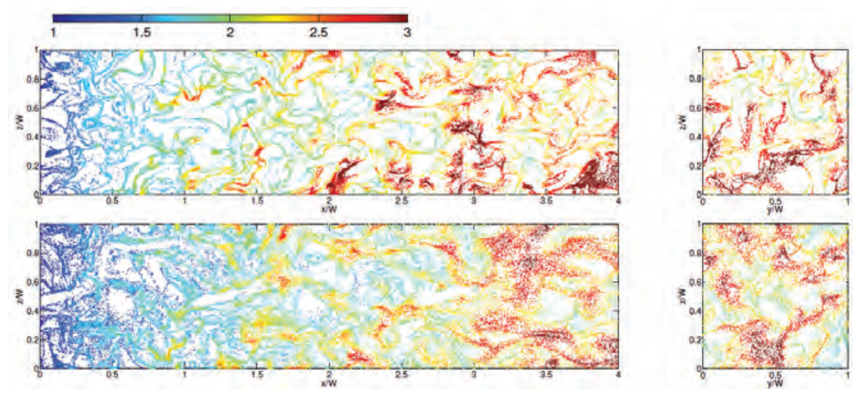


Figure 2. Temperature of the particles transported in a turbulent flow subject to radiation with high local particle clustering (Stokes Number of 1). Left: streamwise plane (flow is left to right); right: cross-section at the exit. Top: mono-disperse particle simulation; bottom: polydisperse particle simulation. The effect of particle size uncertainty is high and leads to lower overall radiation absorption and reduced preferential concentration.

Center for Exascale Radiation Transport

Texas A&M University ✖ PI: Jim Morel (morel@tamu.edu)

The Center for Exascale Radiation Transport (CERT) is led by Texas A&M University with the University of Colorado and Simon Fraser University as partners. CERT research includes development of: "exascale" algorithms for propagation of thermal radiation through high-temperature matter (in the high-energy density physics (HEDP) regime), general-purpose exascale computer-science algorithms, numerical methods and subgrid models for radiation propagation, methods for quantifying prediction uncertainties, and experiments that test computational predictions and associated uncertainty quantification. "Exascale" refers to algorithms and methods designed to operate efficiently on the computers currently being developed to perform over 10^{18} (1,000,000,000,000,000,000) operations per second.

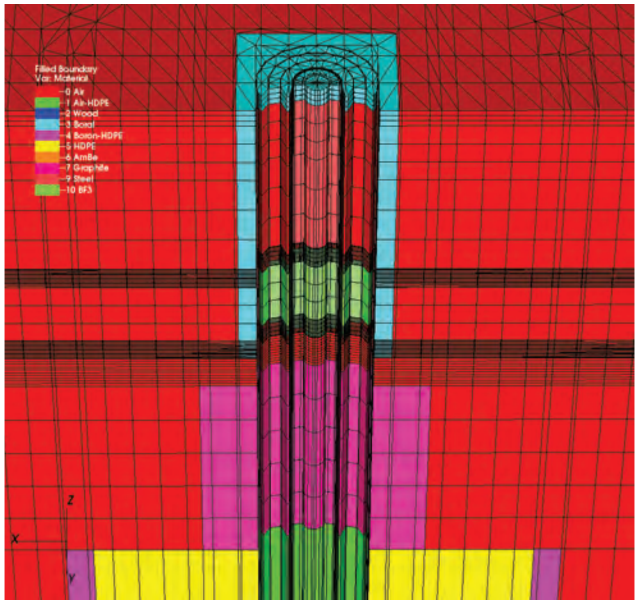


Figure 1. Cut through of the mesh for the experimental geometry generated using a new extruded polyhedral capability.

Professor Jim Morel, Director of CERT and Project Principal Investigator, states that "The PSAAP funding for CERT enables our faculty and students to engage in an integrated research program that is significantly improving predictive capability for thermal radiation propagation in problems of interest to the NNSA. In addition, this funding enables our students to work in a professional software development environment using the largest and fastest computers in the country."

Exascale computers will have the potential to be fifty times faster than the fastest existing computers. However, computing on exascale machines will present new challenges, due to the need to drastically reduce both energy consumption per operation and memory per processor. Another challenge is that hardware errors may occur with greater frequency. In addition, the cost of moving data relative to the cost of computing with data will dramatically increase. CERT is helping to address these challenges.

Thermal radiation propagation is important to many NNSA programs—including those associated with the National Ignition Facility at Lawrence Livermore National Laboratory and the Z-Machine at Sandia National Laboratories—and to many aspects of stockpile stewardship. Simulations of HEDP experiments involve many types of physics. Thermal radiation propagation calculations are essential in such simulations and usually consume far more computational resources than the other types of physics calculations. Thus efficient HEDP simulations demand efficient radiation propagation calculations. Using their latest algorithms, CERT researchers have performed radiation propagation calculations using 786,432 processors with an excellent effective speedup of more than 500,000 relative to computing on a single processor.

A unique aspect of the CERT project is the use of neutron experiments as a surrogate for thermal radiation experiments. This is feasible because thermal radiation transport and neutron transport fundamentally require the same numerical methods, and neutron experiments are relatively easy to diagnose and interpret. This type of information could not be obtained from radiation experiments in the HEDP regime because many types of physics are required to model such experiments, and uncertainties in the other physics cloud the understanding of radiation propagation. CERT researchers will be able to experimentally determine both the numerical errors in the neutron simulations and the sources of those numerical errors.

The impurity concentrations in the graphite material through which neutrons will propagate are unknown. This year CERT researchers developed a model for simulating the impact of impurities on the quantities of interest measured in their experiments, and performed an initial calibration of this model using statistical theory in conjunction with simulations and experiments. Such a calibration does not just set values for free parameters in the model, but yields a distribution of possible values consistent with experimental error and simulations of changes in measured quantities due to changes in free parameters. CERT researchers will soon conduct validation experiments that will quantify the overall accuracy of the model. An accurate impurity model is an essential foundation from which CERT researchers can use experiments of ever increasing complexity to precisely assess the errors in their predictions.

CERT goals require myriad improvements in computational capability. Figure 1 shows a cut through of a mesh for the experimental geometry generated using a new extruded-polyhedral mesh capability, an improvement that is essential for high-fidelity modeling of CERT's complex geometries.

The Center for Exascale Simulation of Plasma-Coupled Combustion (XPACC)

University of Illinois at Urbana-Champaign ✦ PI: William Gropp (wgropp@illinois.edu) ✦ Co-director: Jonathan Freund (jbfreund@illinois.edu)

The Center for Exascale Simulation of Plasma-Coupled Combustion (XPACC), led by the University of Illinois, has an overarching mission to advance the science and technology of plasmas to initiate and control turbulent combustion. This mission drives research efforts in both multi-physics predictive simulation and the computer science techniques to harness the exascale-class computational platforms necessary for high-fidelity simulations. The Center funds 20 PhD-level student projects, most of whom will do or have done 10-week internships at NNSA labs.

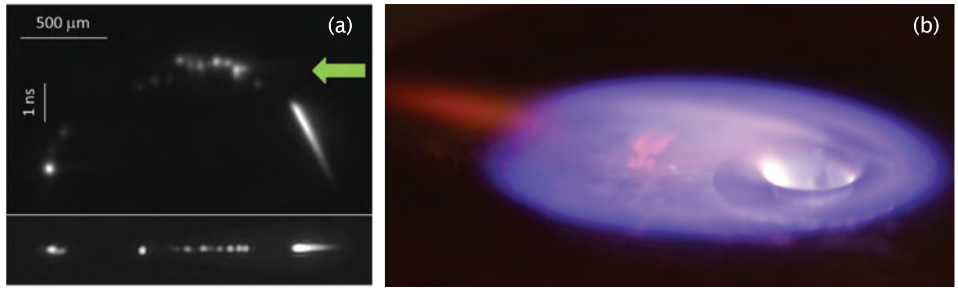


Figure 1. XPACC plasma sources: (a) scattered laser light in the first stage of the laser-induced breakdown seed of ignition, and (b) plasma glow (purple) and faint (orange) H2 diffusion flame at the fuel jet orifice.

The impact of this Center at Illinois is substantial. Professor Gropp states that "PSAAP II has created a core of activity in computational Predictive Science, where faculty from diverse disciplines pursue joint scientific goals. This engages students—both in XPACC and beyond—within the broader context of their PhD studies."

XPACC plasma activities will advance engineering of plasmas to access mechanisms unavailable in traditional combustion in order to boost performance and efficiency. Radicals produced directly in plasmas can short-circuit standard chemical reaction pathways; electric fields affect flame stability; and joule heating affects both flow and chemistry. In designing these simulations and assessing their predictive capacity, uncertainty quantification methods are used to incorporate results from low-dimensional, physics-targeted configurations. The mechanisms in these reduced configurations and corresponding sub-models are integrated for the principal demonstration simulations: the prediction of the sustained ignition threshold of a fuel jet in a turbulent crossflow.

Each of the physical subcomponents of the coupled plasma-combustion system—the flow turbulence, plasma physics, reaction pathways, and electrodynamics—require large-scale computational resources for physics-based predictions. Coupling across necessary length and time scales to make quality predictions demands the co-development of simulation models with tools to harness the heterogeneous architectures of anticipated exascale computing platforms.

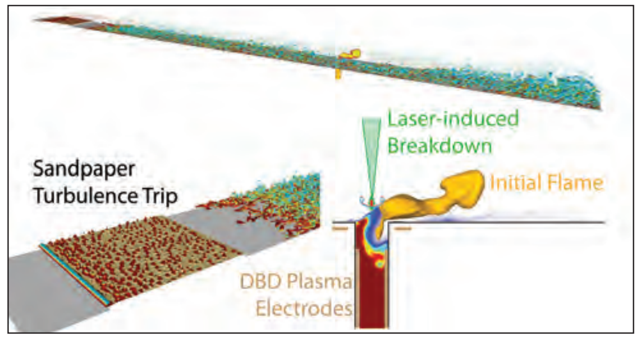


Figure 2.Three-dimensional simulation of the plasma-induced and plasma-sustained ignition of a hydrogen fuel exhausting into a turbulent boundary layer with chaotic fluid motions visualized with colored vorticity isosurface plots.

To achieve its goals, the Center is developing its principal simulation tool PlasComCM in concert with approaches and tools that provide portable computational performance and scalability. These tools employ data structures and code optimizations for memory efficiency, exploitation of high-throughput computing elements, automatic performance tuning, and load balancing. Researchers have demonstrated flexible load-balancing and fault recovery via over decomposition with the adaptive message passing interface (AMPI) runtime system, single-source multi-hardware flexibility on GPU-CPU heterogeneous system with multi-core cross-platform architecture (MxPA), and automated just-in-time recompilation of subroutines to achieve performance for their specific input variables. A detailed analysis of PlasComCM with XPACC's VectorSeeker tool has exposed opportunities for improving its baseline performance. All of these approaches are being demonstrated within XPACC, but are designed for any applications with similar needs. In particular, they have been demonstrated on DOE/NNSA benchmarking suites.

In the full application, a laser-induced plasma breakdown provides the ignition source (see Figure 1a), and a co-annular dielectric-barrier discharge (DBD) plasma actuator (see Figure 1b) is designed to sustain ignition of the fuel jet in a turbulent crossflow (see Figure 2). A suite of low-dimensional, physics-targeted configurations, both at the University of Illinois and at The Ohio State University, has been developed to enable advanced bench-top experimental diagnostics to identify mechanisms and calibrate models. Representing the full system requires coupling of the physical mechanism of these model configurations. In the full application, the flow is tripped turbulent with a sandpaper strip (see Figure 2), which is included with a detailed geometric model that is based upon a microscope scan of the actual sandpaper trip. This year XPACC achieved its principal objective of predicting the height of the laser-induced breakdown at which the hydrogen fuel jet would achieve sustained ignition in this configuration.

Center for Shock Wave-Processing of Advanced Reactive Materials (C-SWARM)

University of Notre Dame ✦ PI: Dr. Karel Matouš (kmatous@nd.edu), www.cswarm.nd.edu

C-SWARM is dedicated to developing predictive computational tools for multiscale modeling of heterogeneous materials under extreme conditions that will execute effectively on future exascale platforms. Using verified and validated (V&V) simulations with uncertainty quantification (UQ), C-SWARM's goal is to predict conditions for shock synthesis of novel materials. In particular, researchers at C-SWARM plan to predict conditions for synthesis of cubic boron nitride (c-BN). c-BN's hardness is similar to diamond, but it has superior thermal and chemical stability. This makes c-BN ideal for cutting tools, for example. Shock synthesis of c-BN enabled by exascale predictive computations would be a significant scientific achievement.

"Complex multiscale and multidisciplinary problems cannot be solved without sustained support for predictive science and high-performance computing from NNSA," said Dr. Karel Matouš, College of Engineering Collegiate Associate Professor of Computational Mechanics and the project's director. "Our research staff and students get first class exposure to a difficult problem that requires an interdisciplinary approach and use of parallel computers."

C-SWARM scientists employ adaptive multiscale and multi-time computational schemes to model materials that will form during shock wave processing (see Figure 1). Moreover, the C-SWARM team is developing novel numerical techniques such as the Wavelet Adaptive Multilevel Representation and the Parallel Generalized Finite Element Method. In the last calendar year, researchers of the Computational Physics team have focused on establishing data-driven materials modeling, enhancing multiscale solvers, developing constitutive theories, and implementing front tracking and parallel asynchronous space-time algorithms. A paper on effective thermo-mechanical properties of granular Platonic solid packs using third-order statistical micromechanics appeared on the cover of Proceedings of the Royal Society A.[1]

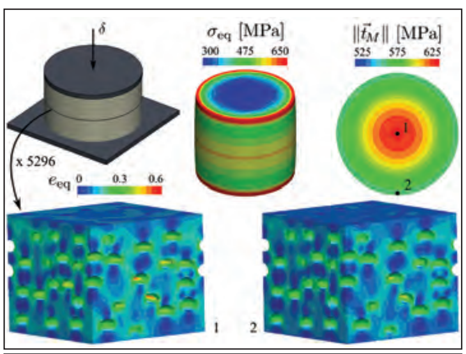


Figure 1. Large multi-scale simulation of a heterogeneous material interface. Clockwise from top left: Schematic of the macro-scale domain and loading conditions, response of the macro-scale adherends, macroscopic response of the interface, micro-scale effective strain of the heterogeneous interfaces at the marked points. Full multiscale simulation consists of 53.8B finite elements, 28.1B nonlinear equations, and was computed using 393,216 computing cores (786,432 threads) on the Vulcan machine at Lawrence Livermore National Laboratory.

C-SWARM software applications are supported by an advanced runtime system, the High Performance ParalleX (HPX). HPX-5 supports large-scale irregular applications with implementation of features like Active Global Address Space (AGAS); ParalleX Processes; Complexes (ParalleX Threads [programmed instructions] and Thread Management); Parcel (active message) Transport and Parcel Management; and Local Control Objects (LCOs) (event-driven actions) and Localities (computing nodes) (see Figure 2). The current version of the HPX-5 runtime system represents a significant leap in terms of performance and stability. Moreover, to separate scientific applications from details of the runtime system, C-SWARM researchers are developing a Domain Specific Embedded Language (DSEL) and Active System Libraries (ASLib) that are based on concepts of generic and meta-programming techniques to effectively eliminate the performance penalty. In the last calendar year, researchers of the Computer Science team have focused on the performance optimization of the HPX runtime system, formulating the DSEL specifications and reifying the C-SWARM software stack using progressive abstraction of applications away from the runtime system.

The integrated V&V/UQ program provides a platform for computational model verification, validation and uncertainty quantification. C-SWARM employs carefully co-designed experiments and data-driven simulations (with quantified uncertainties) that enable meaningful and rigorous comparisons of computational predictions with experimental measurements. In the last calendar year, researchers of the Experimental Physics team have focused on code verification, deploying Software Engineering tools, material characterization and calibration, as well as validation experiments.

On the educational side, research performed in C-SWARM provides a unique setting for the multidisciplinary education of students and research staff in critically significant areas of national importance. Intensive interactions with NNSA laboratories have been established in terms of student, staff, and faculty visits. C-SWARM continues a vibrant seminar series. Recurring effort continues to deliver outstanding U.S. nationals to a PhD program.

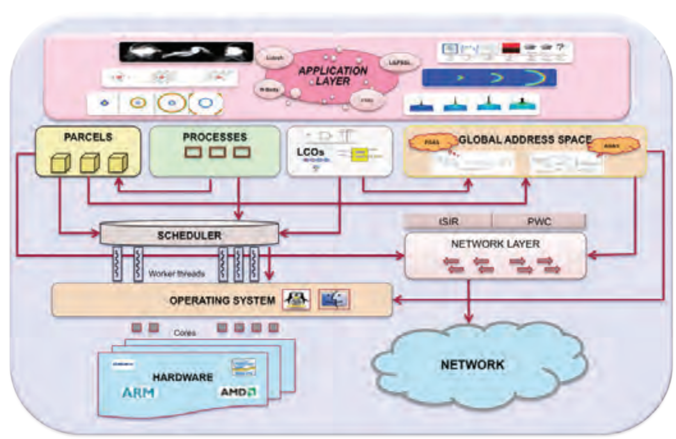


Figure 2: HPX runtime system (version 1.3.0), which reifies the ParalleX execution model.

Reference

[1] A. Gillman, G. Amadio, K. Matouš, and T.L. Jackson, "Third-order Thermo-mechanical Properties for Packs of Platonic Solids Using Statistical Micromechanics," Proceedings of the Royal Society A, 471 (2177), 20150060, 2015.

Carbon Capture Multidisciplinary Simulation Center (CCMSC)

The University of Utah ⌘ PI: Philip J. Smith (philip.smith@utah.edu)

The Carbon-Capture Multidisciplinary Simulation Center (CCMSC) was established in February 2014. The goal of the Center is to use exascale simulation, validation and uncertainty quantification (V/UQ) tools for design, risk assessment, and deployment of a new low-cost, electric power energy technology with carbon capture; namely, a high efficiency advanced ultra-supercritical (AUSC) oxy-coal power boiler (see Figure 1). This overarching problem integrates a group of multidisciplinary scientists and engineers from The University of Utah, the University of California, Berkeley, and Brigham Young University. The participating universities have contributed 10% mandatory cost sharing and The University of Utah has contributed another 10% non-mandatory cost sharing to help accomplish the goals of the Center. The Center has partnered with Alstom Power, which was recently acquired by General Electric (GE), to use the technology developed at the Center for worldwide projects delivering power from coal. Alstom Power equipment currently generates electricity equivalent to the needs of 1.2 billion homes. Since its inception, the Center has provided financial support and research and educational opportunities to 24 graduate students and six undergraduate students. Over this past summer five of these supported students participated in internships at Los Alamos National Laboratory and Lawrence Livermore National Laboratory (LLNL). Over the past year the Center has had four alumni graduate, and has had two participants employed by the NNSA laboratories.

Professor Philip Smith, the CCMSC PI has said: "The collaboration between the three DOE defense labs, and the three universities of this multidisciplinary Center combine with the strong partnership with Alstom Power to demonstrate a deep commitment to the future of new energy solutions, predictive science, and the simulation-based workforce of the future."

Three equally funded teams contribute to our overarching predictive design of the new AUSC oxy-coal power boiler. The computer science team, the physics team, and the V/UQ team. CCMSC uses hierarchal validation to obtain simultaneous consistency between a set of selected experiments at different scales embodying the key physics components (large eddy simulations, multiphase flow, particle combustion and radiation) of the overarching problem. Uncertainty obtained from the V/UQ from the sub-scale, sub-physics analysis is used to bridge through four levels or scales to a final prediction of the full-scale (500 MW) utility power boiler. This validation and prediction process is constrained so that the final prediction is consistent with all of the experiments and with all of the validation metrics of the validation hierarchy simultaneously.

"The collaboration between the three DOE defense labs, and the three universities of this multidisciplinary Center combine with the strong partnership with Alstom Power to demonstrate a deep commitment to the future of new energy solutions, predictive science, and the simulation-based workforce of the future."

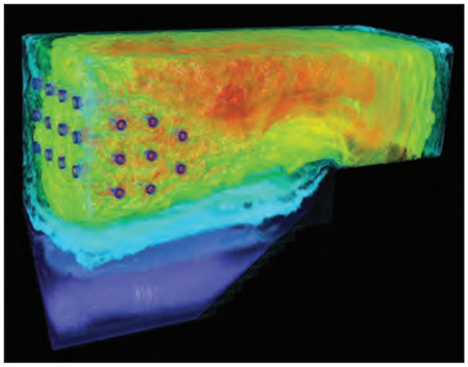


Figure 1. Volume rendered image of the new design of an oxy-coal boiler for high efficiency, low-cost carbon capture. The simulation was performed using CCMSC tools running on Vulcan from LLNL. The visualization was performed using volume-rendering tools developed by the CCMSC visualization team and running in VisIt from LLNL.

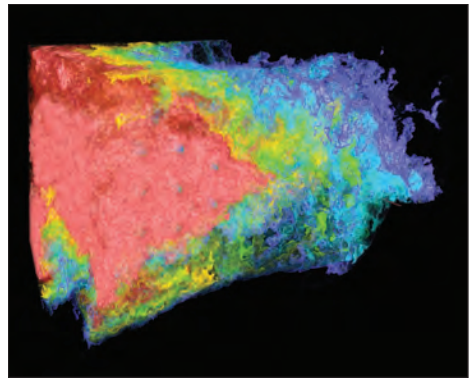


Figure 2. Volume rendered image of the oxygen concentration in a new oxy-coal boiler design. The simulation was performed using CCMSC tools running on Vulcan from LLNL. The visualization was performed using volume-rendering tools developed by the CCMSC visualization team and running in VisIt from LLNL.

In the first 1.5 years of research, the Center has demonstrated strong scaling characteristics up to 262,000 cores on three problem sizes. The Center achieved the first year goal of full system integration across all levels of the validation hierarchy. Computations have been performed on the first draft of the design for a horizontal oxy-fired, pulverized coal boiler. Figure 1 shows a volume rendered image of the temperature of the gas from a simulation of this new boiler design. For comparison, Figure 2 shows the concentration of the oxygen from the same simulation. This computation was performed with the Center simulation tools being run on Vulcan at LLNL. The images were produced using volume-rendering tools developed by the Center and integrated into VisIt (LLNL visualization software). The faculty, staff, and students working on this project are delivering: 1) exascale computing software that is regularly released through open-source licensing, 2) tools for V/UQ for use with other large applications with expensive function evaluations and sparse/expensive experimental data, and 3) new advances in computer science, software engineering, computational fluid dynamics, multiphase reacting flow, and radiative heat transfer.

"PSAAP provides a number of great research opportunities. PSAAP provides me with funding for my graduate studies, but it also gives me access to a network of experts spanning a broad number of fields, both from the national labs and other Centers. The computational resources made available to me have also given me a chance to develop fast and efficient code and gain experience on state-of-the-art techniques."

— Ari Frankel, Stanford University

"Although I was already doing research on electronic structure methods, PSAAP focused my research area to electron emission, and the important role of surface-interactions. So, while I was already interested in the general research area, PSAAP provided me with a very interesting problem, and further insight about where my research could be applied."

— Purnima Ghale, University of Illinois at Urbana-Champaign

"The opportunity to work as part of a large interdisciplinary team has proven to be unique and rewarding—I'm constantly exposed to different perspectives and new techniques to tackle research problems. The structure of PSAAP has also provided me with many networking opportunities."

— Klye MacKay, University of Illinois at Urbana-Champaign

"Our PSAAP II Center has unparalleled access to the most advanced computing resources in the world located at SNL, LANL, and LLNL. Having access to large portions of these machines for simulation & visualization accelerates the pace of scientific discovery. The PSAAP has allowed me to collaborate with top researchers in various scientific fields."

— Christopher Neal, University of Florida

Ari Frankel, Stanford University (frankel1@stanford.edu)

Degree in Progress: PhD, Mechanical Engineering ✖ Academic Advisors: Professors Ali Mani and Gianluca Iaccarino ✖ PSAAP: 2012-Present

Research Topic:

Radiation Transport in Particle-laden Turbulence

What are your research responsibilities?

My research responsibilities are broadly centered on analyzing radiation heat transfer in discrete particulate media as driven by a turbulent gas flow. There are two different sides to this topic: accuracy and efficiency. On the accuracy side, I have been investigating the feasibility of using continuum models of the particle concentration field for use in transport calculations and the convergence behavior of radiation transmission under grid refinement around the discrete particle field. On the efficiency side, I have been looking into algorithms for one of the approaches to solve the radiative transfer equation, the discrete ordinates method, including the implementation of sweeps on parallel computers. Moving forward, I will be looking into other algorithms for solving the discrete ordinates equations with a close eye on scalability and convergence behavior. I have also performed some work on the dynamics of heated particles settling under the influence of gravity and the turbulence-radiation interaction.

How have you benefitted from the PSAAP?

PSAAP provides a number of great research opportunities. PSAAP provides me with funding for my graduate studies, but it also gives me access to a network of experts spanning a broad number of fields, both from the national labs and other Centers. The computational resources made available to me have also given me a chance to develop fast and efficient code and gain experience on state-of-the-art techniques. My interactions with the researchers at Los Alamos National Laboratory have also provided me with a valuable perspective on my own work and the relevance of the problems our team is considering in a broader context.

Have you spent time at one of the national laboratories?

I spent the summer of 2015 visiting Los Alamos National Laboratory. The researchers there are highly knowledgeable and skilled scientists, from whom I gained invaluable knowledge on the field of radiation transport. I was motivated to push my research in directions I otherwise would not have considered and have since proven to be fruitful. I also gained insight into the work done at the labs and what the current research problems in the field are, providing me with a long-term vision of understanding what continuing research in this field with the labs would be like.

Purnima Ghale, University of Illinois at Urbana-Champaign (ghale2@illinois.edu)

Degree in Progress: MS, Mechanical Science and Engineering ✖ Academic Advisor: Dr. Harley Johnson ✖ PSAAP: 2014-Present

Research Topic:

Electronic Structure in the Context of Materials Properties

What are your research responsibilities?

My research is within XPACC–Exascale Plasma Assisted Combustion Computation, and as part of this effort, I am interested in computing the electronic structures of materials used as boundaries to the plasma. One of my primary responsibilities is to shed light on the microscopic phenomena going on at smaller length scales, that affect the behavior of different plasma species, which then change the behavior of combustion.

How have you benefitted from the PSAAP?

PSAAP has provided funding for my research since 2014. It has also given me access to a vast array of computational resources, which I am starting to make use of. As a result of Center meetings and collaborations, I have had the chance to meet many professors and colleagues with expertise in different but overlapping areas, and from which I can draw inspiration. Furthermore, I have had the opportunity to work in a very interdisciplinary environment where I learn methods as well as potential applications of my theoretical and computational work.

Did the PSAAP influence your choice of research area and university?

Although I was already doing research on electronic structure methods, PSAAP focused my research area to electron emission, and the important role of surface-interactions. So, while I was already interested in the general research area, PSAAP provided me with a very interesting problem, and further insight about where my research could be applied.

Have you spent time at one of the national laboratories?

I recently finished a summer internship at Los Alamos National Laboratory (LANL) with support from PSAAP, which was a great learning experience. There too, I was part of an interdisciplinary team that was developing novel approaches to modeling large systems while still including the quantum mechanical behavior of electrons. The internship was beneficial for my research because it gave me further insight into larger code development, an area that is not in my background, but will definitely be useful in my future endeavors. Before my internship at LANL, I had not considered pursuing research at a national lab, now it is a strong option after graduation.

Kyle MacKay, University of Illinois at Urbana-Champaign (kkmacka2@illinois.edu)
Degree in Progress: MS, Mechanical Engineering ✦ Academic Advisors: Drs. Harley Johnson and Jonathan Freund ✦ PSAAP: 2013-Present

Research Topic:
Simulations of Atomic Scale Plasma-Surface Interactions

What are your research responsibilities?
My work is focused on increasing the accuracy of large-scale plasma-assisted combustion models using data collected from atomistic simulations. In particular, I focus on the effect of boundary conditions and surface chemistry on the plasma-coupled combustion process. First, I determine which chemical species have the most significant effect on combustion and flame stability using a continuum model. I then design and carry out molecular dynamics simulations of radical–surface interactions to determine appropriate boundary conditions for the plasma model. The sticking, reflection, and recombination of radicals such as atomic hydrogen and oxygen alter flame chemistry and can generate significant amounts of heat near surfaces. These effects play a critical role in attachment and extinction in weak flames and microcombustion.

How have you benefitted from the PSAAP?
The PSAAP has provided me with the funding I need to perform research throughout my graduate career and even provided support throughout an internship at Lawrence Livermore National Laboratory (LLNL). The opportunity to work as part of a large interdisciplinary team has proven to be unique and rewarding—I'm constantly exposed to different perspectives and new techniques to tackle research problems. The structure of PSAAP has also provided me with many networking opportunities. Regular meetings and interactions with national laboratory personnel and collaborators at other universities give my fellow students and I a chance to learn about the work done at these institutions.

Have you spent time at a national laboratory?
This past year, I was offered a summer internship at LLNL to apply my knowledge of molecular dynamics simulations to the realm of high-temperature, high-energy plasmas. While there I was able to work on two projects. The first investigated species separation due to shocks in plasma mixtures and the second tested a new time-integration technique to better resolve high-energy particle collisions. This internship introduced me to several new tools and techniques for simulating large-scale atomic systems that I will use in my own research, and significantly expanded my knowledge of plasma behavior in high-energy environments. Over the course of the summer, I worked with several collaborators at LLNL. This internship allowed me to see what a career at a national laboratory would look like—a career path I consider as a definite possibility in the future.

Christopher Neal, University of Florida (chrisneal@ufl.edu)
Degree in Progress: PhD, Mechanical Engineering ✦ Academic Advisor: Dr. S. Balachandar ✦ PSAAP: 2014-Present

Research Topic:
Modeling of Forces & Heat Transfer Experienced by Particles in Extreme Compressible Flows Environments

What are your research responsibilities?
My responsibilities as a PhD student at a PSAAP II Center involve running large-scale simulations with a highly parallelized research code on DOE/NNSA supercomputers. I also work to make sure our simulation code compiles and runs on different DOE/NNSA supercomputers. I work with the research code to debug programming issues that arise when increasing the number of processors that the code runs on. New issues often arise when scaling up an order of magnitude of cores i.e., 10 to 100, 100 to 1000. The large simulations that the Center runs present a visualization challenge because of the size of the data sets. My responsibility is to provide assistance to the students and staff in our Center that want to visualize their data directly on the DOE/NNSA computers without having to download enormous data sets. My responsibilities are made possible by the excellent support offered by the computing facilities at Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL).

How have you benefitted from the PSAAP?
The research grant that NNSA awarded to the Center at the University of Florida has allowed me to focus directly on my research to advance the state of the art models for predictive science simulations. Our PSAAP II Center has unparalleled access to the most advanced computing resources in the world located at Sandia National Laboratories (SNL), LANL, and LLNL. Having access to large portions of these machines for simulation & visualization accelerates the pace of scientific discovery. The PSAAP has allowed me to collaborate with top researchers in various scientific fields.

Have you spent time at one of the national laboratories?
I spent summer 2015 at LLNL as a graduate student intern in the Computation Directorate. The internship program at LLNL was a wonderful experience, and I would highly recommend it to any prospective interns. I was paired with an excellent mentor who shared many of my research interests. I went right to work running simulations because of my familiarity with the topics that we were investigating. While at the lab, I learned about the critical work that the DOE/NNSA labs do as part of their mission of stockpile stewardship, and I saw how my work contributed to the mission.

Stewardship Science Graduate Fellowship (SSGF)

Richard Kraus, Lawrence Livermore National Laboratory (kraus4@llnl.gov)

Years at LLNL: 2013-Present ⌘ Degree: PhD, Earth and Planetary Sciences, 2013 ⌘ Years in SSGF: 2008 to 2012, Harvard University

I was first introduced to the Stockpile Stewardship Academic Programs as an undergraduate at the University of Nevada, Reno. With the help of my research advisors, I became interested in how my research might be relevant to science being done at our national laboratories. Back then, I didn't know that I would eventually work as a scientist at a national laboratory, but it was this sense of utility and applicability that, coupled with an interest in dynamic material properties, propelled me to focus my graduate research on the behavior of materials at extreme conditions.

The challenge many young scientists face is recognizing their individual interests in a field of research, and finding a viable career path that is in alignment. I was fortunate to find that there was an NNSA program in place to fund graduate students interested in the areas relevant to science-based stockpile stewardship. With the support of the NNSA's Stewardship Science Graduate Fellowship, I began my graduate research in shock physics and planetary science at Harvard University.

Fast-forward five years later, having done part of my thesis research at Lawrence Livermore National Laboratory (LLNL) and Sandia National Laboratories (SNL), I became a Lawrence Postdoctoral Fellow at LLNL, working in the shock physics group. As a postdoctoral fellow, I learned more about the importance of the work we do at national laboratories, and contributing to the bigger picture became more of a focus. This real-world education helped me make the long-term decision that a career at the NNSA laboratories would be fulfilling as well as intellectually stimulating.

Now as a staff scientist at LLNL, my research focus is no longer purely dominated by what I myself find most interesting, or what would be best just for my career – rather, my efforts are driven by the opportunity to help the laboratory achieve its mission.

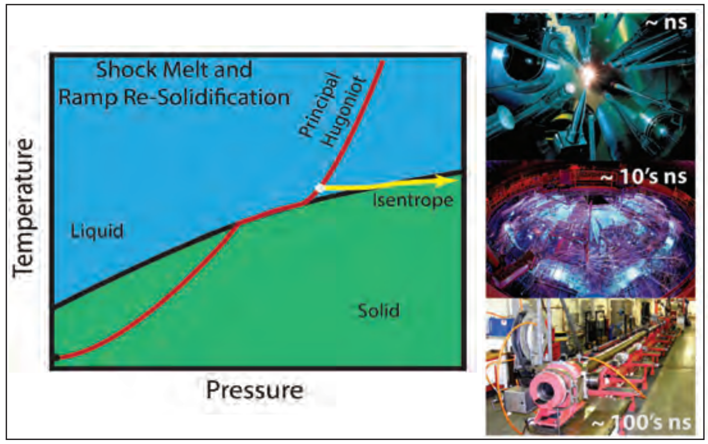


Figure 1. Schematic description of the thermodynamic path taken during our experiments to measure the high pressure melt curve of materials. The thermodynamic path of shocking the sample into the liquid and isentropically compressing back into the solid can be followed on the nanosecond timescale of the laser platform, the 10's of nanosecond timescale of the Z machine at SNL, and the 100's of nanosecond timescale of the two-stage gas gun.

One of the major research areas at the laboratory is in the properties of materials at extreme conditions. LLNL and the other NNSA laboratories need to be able to accurately simulate how materials behave at extremely high pressures, temperatures, and strain rates. In support of this goal, my current research focuses on improving our understanding of the melting transition. The high pressure melt boundary is essential to our predictive simulation capability for two reasons: it defines a line in phase space where the Gibbs free energies of the liquid and solid phases are equal and therefore the boundary is a sensitive constraint on the equation of state. The melting transition is also the largest rheological transition a material can undergo, as it defines the boundary between a material with strength and one without.

I have been developing a technique that uses a temporally shaped laser pulse to drive a strong shock wave into a sample, which melts the sample, and then subsequently increases the laser power relatively slowly such that the sample is isentropically compressed back into the thermodynamic stability field of the solid. Figure 1, left panel, illustrates the process. We then use *in situ* x-ray diffraction to confirm the existence of the solid. And all of this takes place in a few billionths of a second.

Through the Discovery Science program at the National Ignition Facility and with a team of professors and LLNL scientists, I will use this new technique to study the ultra high-pressure melting curve of iron (from 500 GPa to 25,000 GPa). Information about the melting curve of iron at these extreme conditions will help to answer important questions about the types of exoplanets that can have a stable magnetosphere and possibly a habitable surface environment.

To test whether the short timescale of our experimental measurements affects our scientific conclusions, we are also beginning a cross-platform experimental effort between laser-driven dynamic compression experiments at LLNL, pulsed power dynamic material property experiments at SNL, and impact experiments using a two-stage light gas gun at LLNL. By studying the same, albeit lower pressure, thermodynamic transitions at vastly different timescales (few nanoseconds on laser, few 10's of nanoseconds with pulsed power, few 100's of nanoseconds with gas gun, see the right panel of Figure 1), we can better understand the time dependence of phase transitions and improve the accuracy in the interpretation of our short timescale ultra-high pressure melt curve measurements.

These ultra-high-pressure experiments and cross-platform comparisons will be used to increase the accuracy of our equation of state and strength modeling, and ultimately improve our capability to accurately simulate the behavior of materials at extreme conditions.

Cameron Meyers, University of Minnesota (meye2100@umn.edu)
Degree in Progress: PhD, Rock and Mineral Physics, Geophysics ✦ Academic Advisor: Dr. David Kohlstedt ✦ SSGF Program: 2014-Present

Research Topic:
Role of Anisotropic Viscosity on the Dynamics of the Earth's Mantle

What are your research responsibilities?
My research is aimed at understanding the mechanical properties of crystalline geological materials under the extreme conditions of high temperature and pressure found in planetary interiors. I am responsible for designing, executing, and analyzing deformation experiments in a variety of specialized apparatuses. This includes synthesis of dense crystalline specimens, operating high pressure and temperature deformation apparatuses, quantification and analysis of mechanical properties, and characterization of specimen microstructures using electron and optical microscopy.

How have you benefitted from the SSGF program?
The generous support of the SSGF Program has given me the freedom to dive full-time into my research interests, allowing me to explore the interdisciplinary nature of my field. The annual SSGF program review has provided a forum that brings together a diverse scientific community that has opened my eyes to new ideas and opportunities. This year I will have the opportunity to work with a team of scientists at Lawrence Livermore National Laboratory as part of the SSGF laboratory practicum program. This program will provide a new perspective on scientific research and will result in relationships that may foster exciting future collaborations.

Did the SSGF Program influence your choice of research area and university?
Although I am a graduate student in an Earth Sciences department, receiving a degree in Geophysics, most of my coursework has been in the Materials Science and Aeronautical Engineering and Mechanics departments. This is related to the deeply interdisciplinary nature of the Earth Sciences –constantly adopting ideas from other sciences and applying them to understand how the Earth works. Being accepted into the SSGF program to study materials under extreme conditions, such as the conditions of high pressure and temperature found in planetary interiors, has motivated me to make these interdisciplinary connections a central part of my approach to research. Further, the SSGF program has broadened the scope of my scientific interests and introduced me to variety of opportunities – in part by hosting an annual program review, introducing a program of study to help craft the role coursework during my graduate education, and the opportunity to visit and work at DOE/NNSA national laboratories. During my upcoming SSGF laboratory practicum, I will have the opportunity to apply my experience and knowledge of synthesis and characterization of dense ceramic materials. Instead of manufacturing synthetic rock specimens, I will be using cutting edge additive manufacturing technology to create ceramic laser gain material.

J. Scott Moreland, Duke University (jsm55@duke.edu)
Degree in Progress: PhD, Nuclear Theory and Particle Physics ✦ Academic Advisor: Professor Steffen Bass ✦ SSGF Program: 2012-2015

Research Topic:
Hydrodynamic Modeling of Relativistic Heavy-Ion Collisions

What are your research responsibilities?
Relativistic heavy-ion collisions produce small, extremely hot fireballs of dense nuclear matter which liquefy to form an exotic state of matter known as a quark-gluon plasma (QGP). These fireballs rapidly cool and hadronize, producing a burst of final state particles which are picked up by a detector.

I'm working to develop and improve transport models used to simulate these collisions and extract fundamental properties of hot and dense nuclear matter via systematic model-to-data comparison. My research responsibilities include the development of new computer codes to simulate the initial state of the produced fireball immediately after impact. In addition to software development, I spend much of my time interfacing theoretical predictions with data–a task which spans the responsibilities of both theoretical and experimental nuclear physics.

How have you benefitted from the SSGF program?
The SSGF program has afforded me numerous opportunities to advance my career in fundamental science which would not have been possible otherwise. The annual program reviews have allowed me to network with scientists at Lawrence Livermore, Sandia, and Los Alamos National Laboratories and opened doors to potential career opportunities at the "bleeding edge" of nuclear physics research. The generous tuition support and academic allowance have enabled me to attend conferences and workshops all over the world. I've been able to listen to and converse with leading researchers in the field. It has extended my interaction with the broader scientific community and the benefits are reflected in my work.

What do you want students considering SSGF to know?
If I could speak to students applying for fellowships, I would tell them that applying to the SSGF program was one of the best decisions I've made. In many respects, career planning beyond a PhD is a murky subject rife with unknowns. The SSGF program sheds light on career science and supports fellows with a degree of mentorship which is unparalleled at the graduate level. The SSGF program has encouraged me to plan five years ahead, and as I approach the twilight years of my PhD I'm looking forward to the next stage of my career with confidence.

Sabrina Strauss, University of Notre Dame (sstrauss@nd.edu)

Degree in Progress: PhD, Physics ✠ Academic Advisor: Professor Ani Aprahamian ✠ SSGF Program: 2012-Present

Research Topic:
Spectroscopy of Beta-Delayed Neutron Emission using Ion Trapping Techniques

What are your research responsibilities?
My research addresses beta-delayed neutron emission, an exotic type of decay from neutron-rich nuclei. Understanding this decay from specific nuclei helps in understanding neutron flux in a variety of situations, including the stellar processes and nuclear reactors.

I am analyzing the data from the previous Beta Paul Trap (BPT) experiment on beta-delayed neutron emission, involving isotopes of both astrophysical and nuclear reaction interest. The analysis of this data feeds directly into the design and optimization of a new generation of ion traps for this technique. Once the analysis is complete, I will be building and commissioning the new generation of trap at Argonne National Laboratory, studying isotopes of importance to the astrophysical r-process, one of several processes responsible for the creation of elements heavier than iron.

How have you benefitted from the SSGF program?
The SSGF program gave me the freedom to explore and pursue multiple types of research topics within nuclear physics. My practicum at Lawrence Livermore National Laboratory (LLNL) gave me a chance to learn about research not done at my university, specifically involving super heavy elements.

During the practicum, I was able to work with one of the collaborators on the BPT and learn more about it from him, something that would have been otherwise difficult, given the distance between the experimental site and LLNL.

Have you spent time at one of the national laboratories?
During my time with the fellowship, I spent several months at LLNL. While there, I was able to work with an ongoing collaborator on new projects. The bigger benefit, however, were the new connections I made. I met and spoke with many of the people within the group I was in. I learned about a variety of topics in the process, but more importantly, I was able to show those in the group my abilities and my work ethic. All of the people I interacted with during my practicum are colleagues, and could be future collaborators. Being able to give them an impression of who I am, and what my abilities are, makes me less of an unknown when I am applying for a job or collaborating.

Chris Young, Stanford University (cvyoung@stanford.edu)

Degree in Progress: PhD, Mechanical Engineering ✠ Academic Advisor: Dr. Mark Cappelli ✠ SSGF Program: 2011-Present

Research Topic:
Plasma Dynamics and Electron Transport in Devices with Crossed Electric and Magnetic Fields

What are your research responsibilities?
Broadly, my research in the Stanford Plasma Physics Laboratory seeks to further our understanding of how electrons and ions fundamentally behave in a variety of devices that employ a magnetic field to confine plasma, with such diverse applications as fusion plasma confinement, satellite propulsion, and plasma materials processing. My research characterizes plasma dynamics in great detail, using a combined experimental and computational approach that has led to various projects over my research career. I have designed and fabricated the devices themselves, e.g., the Cylindrical Cusped Field Thruster and a small magnetron discharge. Improvements made to diagnostics for interrogating the plasmas, such as our laboratory's sample-hold laser-induced fluorescence technique for time-resolved spectroscopy, has enabled successful Hall thruster measurement campaigns at the Air Force Research Laboratory (Edwards AFB, California). Additionally, I have adapted our group's particle-in-cell simulation codes to my experimental conditions to validate and help interpret results.

How have you benefitted from the SSGF program?
Besides the competitive financial incentives of the SSGF program, the greatest intangible benefit afforded to fellows is flexibility. Gaining financial independence from my advisor's grants allowed us to pursue avenues of research that would otherwise not have been possible, and many have yielded interesting new results. My academic allowance funded one additional conference trip each year, including one to an international meeting in Japan, gaining further exposure for my research and enabling interactions with colleagues. My graduate school experience would have been fundamentally different without the support of this excellent program.

Have you spent time at one of the national laboratories?
I had the pleasure of working at Lawrence Livermore National Laboratory (LLNL) for two summers, first as a regular graduate student employee, and second as my SSGF practicum. Both projects involved large-scale facilities unique to the national laboratories, providing welcome opportunities to branch out, and the latter led to a publication and conference presentation. I am drawn to the laboratory environment, where highly intelligent, passionate researchers tackle the most difficult problems of scientific and national security importance. There are always opportunities to learn something new from meetings and presentations in a wide array of disciplines. Those experiences, coupled with the sustained connection to the laboratories enabled by the SSGF program, have led directly to opportunities for postdoctoral employment at LLNL after graduation.

Feature Articles

"Researchers from the Massachusetts Institute of Technology and Washington State University performed novel measurements using stimulated scattering techniques and investigated the frequency dependencies of the measurements to compare directly with other measurements. A student from the University of Nebraska came to LANL as a postdoctoral researcher to set up a new Brillouin spectroscopy apparatus, to complement the system that has been a core part of the Nebraska laboratory for years. In ongoing work, LANL and Northwestern University staff are working to understand the effects of temperature, pressure, and other variables on the measurements."

— *Explosive Elasticity*, Los Alamos National Laboratory

"The Z Fundamental Science Program is a vehicle for collaborations between scientists at Sandia National Laboratories and several universities that was launched with a call for proposals in 2010 and has had dedicated time on Z since then. The research opportunities at Sandia's Z-machine attract scientists across the world and the interactions with outside collaborators in turn benefit the Stockpile Stewardship Program, Sandia's main mission."

— *Quantitative Planetary Science and Improving the Precision of Measurements for Materials in the Stockpile Stewardship Program*, Sandia National Laboratories

"The DCS was established through a partnership between Washington State University and the Advanced Proton Source, and is driven by the scientific need to examine time-dependent changes at the microscopic scales in materials subjected to dynamic loading conditions—a major theme central to the DOE/NNSA Stockpile Stewardship Program. To address this need, DCS will provide x-ray diagnostics, such as x-ray diffraction and x-ray Phase Contrast Imaging, to obtain new in-situ, real-time data that access the atomistic length scales directly."

— *The Dynamic Compression Sector: A New User Facility for Dynamic Compression Science*, Los Alamos National Laboratory

The Path from Basic Science to Technology

Introduction

It is a perennial challenge faced by national laboratories: how to move basic science to technology, and then iterate back to fundamentals for continued improvement and broadening of understanding and impact—the path from basic science to technology. As one of the challenges in science, the national laboratories actively seek new opportunities to transfer discoveries and new understanding into innovative technologies that serve the nation. One proven method of enhancing innovation and broadening impact is for national laboratories to partner with universities, leveraging expertise and experience between both. We present four articles that highlight recent and ongoing work that teams national laboratories with universities. Together they address outstanding high impact questions in fundamental science, developing and maintaining a scientific workforce, developing diagnostics and techniques, and bringing to market new technologies that are founded in basic science discoveries.

The first article addresses the use of additive manufacturing (AM) for Titanium-based parts (metals are particularly challenging). The AM process explored by National Security Technologies fabricates a part layer by layer, which provides opportunities to tailor geometry and optimize structural performance in addition to minimizing the amount of material waste for odd shaped parts. Working with the University of Nevada, Las Vegas, differences in deformation and failure of six different types of titanium were documented for three different impact velocities. In the study it was determined that AM, forged titanium, and multilayered stacks produce similar velocity profiles during the early stage of impact, with the AM targets exhibiting spall at lower velocities and the multilayered stacks exhibiting vibrations between plates.

Our second article comes from Lawrence Livermore National Laboratory (LLNL) and the University of Texas at Austin, and again relates to the production of metal parts by AM, but concerns manufactured metal lattice structures. A combination of modeling and synchrotron radiation microtomography experiments helped identify and correct some initial printing problems compromising structural integrity. This time we see how a national laboratory/university collaboration can enhance the quality and progress toward AM parts.

Our third article comes from Los Alamos National Laboratory, the Massachusetts Institute for Technology, Washington State University, and the University of Nebraska, who have been exploring explosive elasticity. Explosives get squeezed routinely, loaded mechanically in assembly, and impacted suddenly in accidents or in use. It seems simple enough to understand elasticity, but our explosives are incredibly complicated composites, made of even more complicated crystalline explosive constituents. Through academic collaborations, and the most state of the art advances in crystal growth and measurement techniques, the team has been able to make some of the first measurements of these critical materials properties over about the last 10 years. The outcomes represent ongoing science and collaboration efforts that are leading to new explosive materials and developments in measurement science.

The last article describes how basic science discoveries about meteor impacts have been achieved using the Z-machine at Sandia National Laboratories (SNL). A team of scientists at SNL, Harvard University, University of California, Davis, and LLNL have revolutionized our understanding of vaporization associated with material interactions at high pressure (impacts with planetary bodies). The team developed an experimental technique to determine the entropy gain during shock compression, or the amount of heating that occurs from the rapid compression by the shock wave, and this in-turn has led to far reaching implications on the development of the early solar system.

The discoveries described within these four articles capture the excitement of science, and also how the science moves into new technologies and a better understanding of nature.

One proven method of enhancing innovation and broadening impact is for national laboratories to partner with universities, leveraging expertise and experience between both.

Lawrence Livermore National Laboratory

Los Alamos National Laboratory

Nevada National Security Site

Sandia National Laboratories

Comparison of Failure Mechanisms Due to Shock Propagation in Forged, Layered, and Additive Manufactured Titanium

by Thomas Graves,[a] Robert Hixson,[a] Edward Daykin,[b] Cameron Hawkins,[b] Zach Fussell,[b] Austin Daykin,[b] Michael Heika,[b] Brendan O'Toole,[c] Mohamed Trabia,[c] Shawoon Roy,[c] Richard Jennings,[c] Melissa Matthes,[c] Eric Bodenchak,[c] and Matthew Boswell[c]

National Security Technologies, LLC (NSTec) and the University of Nevada, Las Vegas (UNLV) partnered on a Site-Directed Research and Development (SDRD) project that focused on characterizing the shock propagation and failure mechanisms in forged, layered, and additive manufactured (AM) materials. The AM process fabricates a part layer by layer, which provides opportunities to tailor geometry and optimize structural performance in addition to minimizing the amount of material waste for odd-shaped parts. This technique is of a particular interest to the National Nuclear Security Administration (NNSA) as it can be used for many NNSA-specific applications, including armoring, complex elements of nuclear weapons, and customized diagnostic components in subcritical experiments. Additionally, AM materials can provide a means for replacing aging components quickly and at a lower cost than other techniques. However, wide-scale use of AM materials cannot start until their behavior under shock conditions is understood.

Experimental and simulation techniques were explored for understanding the behavior of AM titanium under shock loading. The AM material of interest was Electron Beam Additive Manufactured (EBAM) Titanium. This AM process is currently being used in industry, and quasi-static analyses of material properties show only 3-5% lower properties than a forged counterpart. It was shown that the microstructural morphology as well as the quasi-static mechanical response are significantly different.[1,2] To understand the behavior of AM titanium under shock loading, the same experiments were repeated using single and multilayered stacks of forged titanium.

The team utilized a two-stage light gas gun at UNLV (see Figure 1) for performing experimental measurements. A series of ballistic impact experiments were conducted using the two-stage light gas gun on titanium targets using Photonic Doppler Velocimetry (PDV) diagnostics to measure free surface velocity on the back of each target. The experimental measurements were used to validate computational simulations, which describe the behavior of these advanced materials under shock. Two computer codes (CTH and LS-DYNA) were used to perform the corresponding simulations. This approach has shown to be successful in verifying the material models and equations of state (EOS) used in computational simulations of ballistic experiments with homogeneous target materials.[3]

Differences in deformation and failure of six different types of titanium were documented for three different impact velocities. In the study, it was determined that AM, forged titanium, and multilayered stacks produce similar

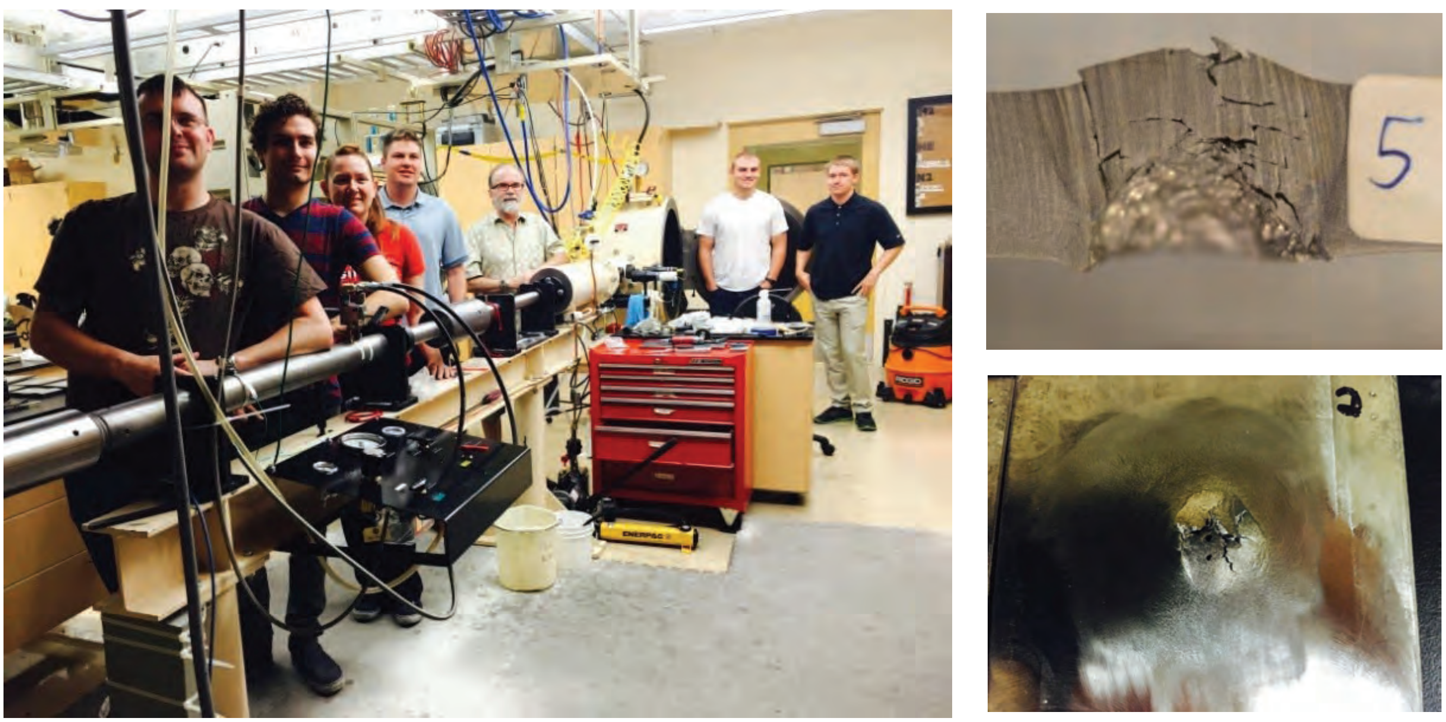


Figure 1. (left) Two-stage light gas gun at UNLV and (right) internal fracturing leads to spalling at high impact velocities.

[a]National Security Technologies, LLC, New Mexico Operations, Los Alamos Office
[b]National Security Technologies, LLC, North Las Vegas
[c]University of Nevada, Las Vegas

The AM process fabricates a part layer by layer, which provides opportunities to tailor geometry and optimize structural performance in addition to minimizing the amount of material waste for odd-shaped parts. This technique is of a particular interest to the National Nuclear Security Administration (NNSA) as it can be used for many NNSA-specific applications, including armoring, complex elements of nuclear weapons, and customized diagnostic components in subcritical experiments. Additionally, AM materials can provide a means for replacing aging components quickly and at a lower cost than other techniques.

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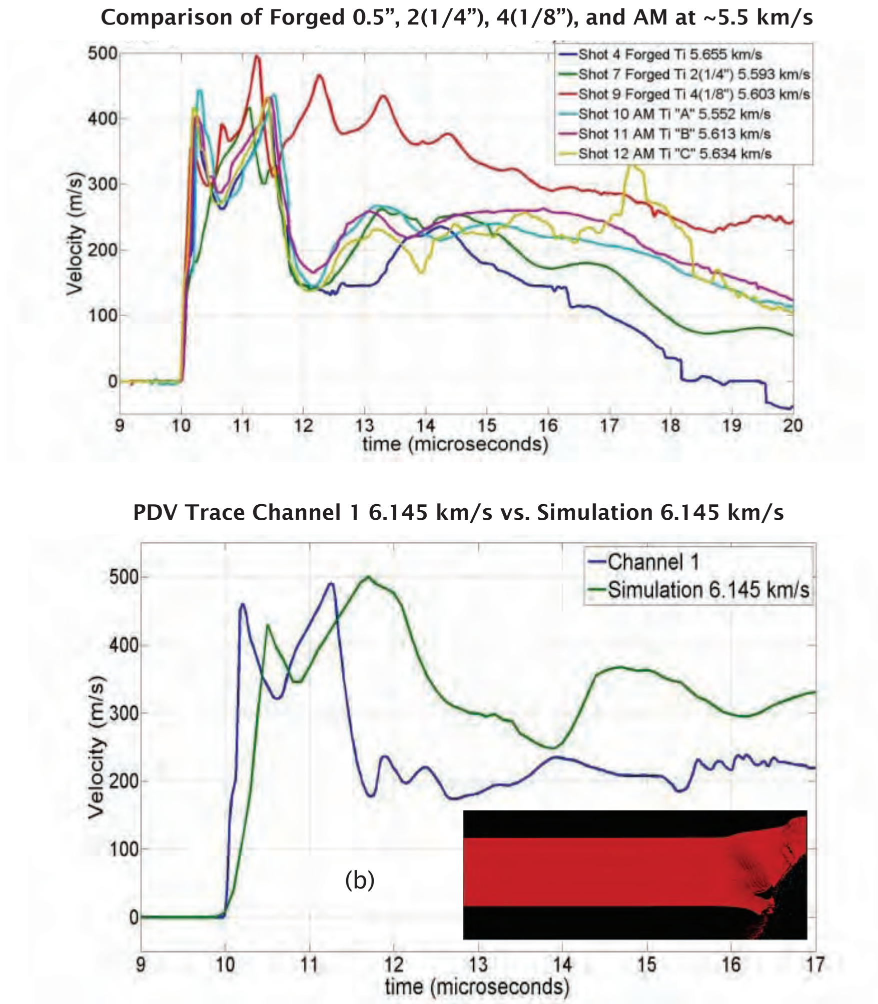

Figure 2. Velocity traces of (a) Experimental forged, layered, and AM Titanium and (b) AM titanium experimental and computer code (LS-DYNA) simulation. In (a), 2(1/4) indicates two stacked 1/4"-thick plates. 4(1/8) indicates four stacked 1/8"-thick plates. In (b), the picture shows the symmetric cross section of an impacted plate.

velocity profiles during the early stage of impact, with the AM targets exhibiting spall at lower velocities and the multilayered stacks exhibiting vibrations between plates. Figure 2a shows a comparison of the many different types of cases studied. The forged computational model compared with experimental data is shown in Figure 2b. Simulation of stacked plate targets should be possible in the future and were not performed due to current limitations in the software. The EBAM targets are extremely challenging to model because of the microstructure, porosity, and quasi-static property differences.

It is important to continue studying the basic science of how these materials behave dynamically so they can be applied to current needs. Continued exploration of different approaches in the future will improve the accuracy of the computational models. As further study continues, additional adjustment of the material model and EOS parameters will be made to increase the accuracy of the simulations. This will bring about a better understanding of AM materials, allowing for a better use in specific applications as well as how to continue tailoring these materials for applications. We expect this project will fuel additional analysis and enhance fundamental science understanding of the AM materials.

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University of Texas at Austin and Lawrence Livermore National Laboratory Form Collaboration for Metal Additive Manufacturing by Wayne King, (Lawrence Livermore National Laboratory)

In 2011, Lawrence Livermore National Laboratory (LLNL) began looking into the possibility of applying metal additive manufacturing to National Nuclear Security Administration (NNSA) parts with an eye toward accelerating the innovation cycle for manufacturing. An example of a metal lattice produced by additive manufacturing at LLNL is shown in Figure 1. Interest in metal additive manufacturing is growing exponentially and sales of metal additive manufacturing machines are doubling each year. But despite the intense interest, 47% of manufacturers surveyed indicated that uncertain quality of the final product was a barrier to adoption of additive manufacturing.[2] In the process of entering the field of metal additive manufacturing, LLNL staff contacted Professor David Bourell of the University of Texas at Austin (UT Austin) because of a roadmap document that he authored in 2009.[3] In that document, Bourell et al. identified the need for modeling and simulation of the metal additive manufacturing process. Specifically, the Bourell team said, "This is certainly required to have predictive models for the various processes to enable the performance of manufactured parts to be predicted. To feed into the model, a much better understanding of the basic physics of the systems is required as is accurate baseline data to optimize results."

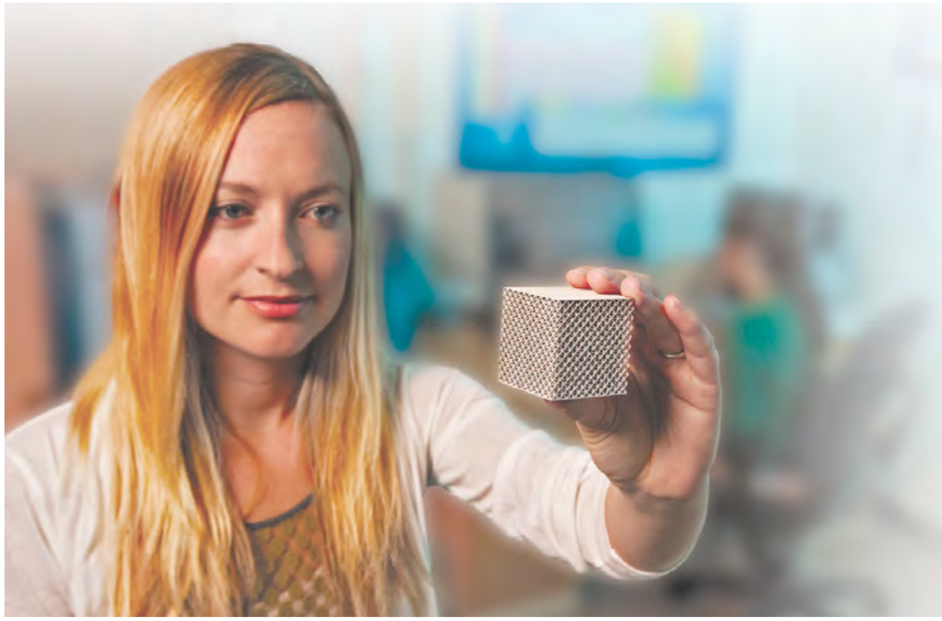

Figure 1. Materials scientist Holly Carlton holds an additively manufactured metal lattice structure. A combination of modeling and synchrotron radiation microtomography experiments helped identify and correct some initial printing problems compromising structural integrity.[1] (Photo by George Kitrinos.)

This roadmap was one of the key documents that led to the Laboratory Directed Research and Development (LDRD) Strategic Initiative proposal titled "Accelerated Certification of Additively Manufactured Metals (ACAMM)." While it was possible to produce parts quickly with additive manufacturing, the qualification and certification of the parts could take years. ACAMM's focus is on accelerating qualification and certification to take full advantage of the benefits offered by additive manufacturing. The ACAMM approach to accelerating qualification and certification is illustrated in Figure 2. Qualification and certification of a part requires confidence that the part was built as planned and with a concentration of defects that does not adversely affect the part's performance. Achieving this throughout a part requires significant spatial control of the process. *In situ* sensors and feedback schemes aid such control.[4] Feedback works best when the input parameters are close to the optimal for the given geometry. This is particularly the case for the high laser speeds involved in metal powder bed fusion where the time constant for the response of the melt pool to changes in power or speed can be relatively slow. Achieving optimized input parameters is referred to as *a priori*[5] or model-based "intelligent feed forward"[3,6] control. Feed forward control has yet to be demonstrated but is now part of the ACAMM project for Fiscal Year 2016. To provide physics-based support to feed forward, ACAMM has developed High-Performance Computing models of the process at the scale of the part and at the scale of the powder (see Figure 3). To tie these together, ACAMM is applying data mining and uncertainty analysis methods, taking advantage of what has been developed for stockpile stewardship.

When the ACAMM team was looking for an external reviewer for their proposal, they identified Professor Joe Beaman of the UT Austin because laser powder

"This is certainly required to have predictive models for the various processes to enable the performance of manufactured parts to be predicted. To feed into the model, a much better understanding of the basic physics of the systems is required as is accurate baseline data to optimize results."

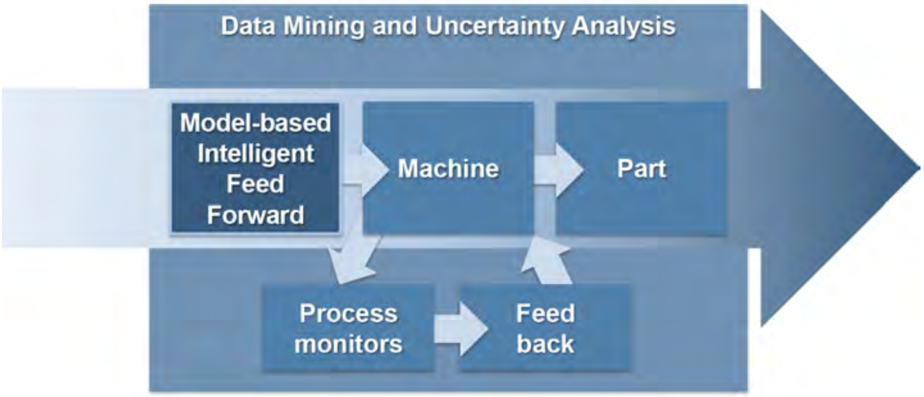

Figure 2. Schematic of the methodology used by ACAMM to accelerate the qualification of additively manufactured parts.

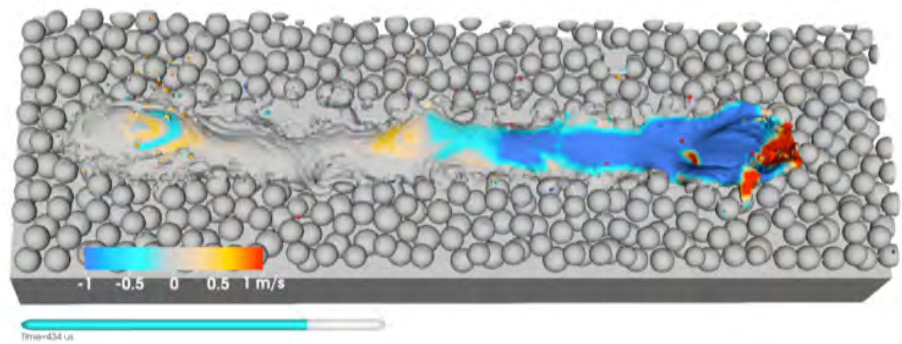

Figure 3. A computer code (ALE3D) simulation of the melting of 316L stainless steel powder by a laser beam. The image is colored by the direction of the flow of the liquid metal: red is flowing to the right and blue is flowing to the left. This is a unique simulation of its type in additive manufacturing research as it includes effects that have not been considered before: the details of the absorption of the laser light and the profound effect of "recoil pressure" as the metal rapid evaporates and exerts a force on the liquid causing it to splash forward (red) and flow to the rear (blue). The simulation takes advantage of LLNL's high performance computing resources.

bed fusion additive manufacturing, the focus of ACAMM, was first developed at the UT Austin by Beaman and Deckard around 1986. The partnership of Beaman and Deckard became the first student/faculty-owned entrepreneurial enterprise spun out from the university, and spawned the additive manufacturing industry. A brief history is documented at https://www.me.utexas.edu/news/news/selective-laser-sintering-birth-of-an-industry. Beaman served on the ACAMM review committee and provided valuable feedback to the project plan.

ACAMM staff participated in the Solid Freeform Fabrication Conference in 2013 (1 paper, 24th annual meeting), 2014 (2 papers, 25th annual meeting), and 2015 (5 papers, 26th annual meeting) held at UT Austin. During the last three years ACAMM has matured to be highly recognized throughout the metal additive manufacturing community. In fact, the UT Austin is now using LLNL's high-fidelity additive manufacturing modeling results to obtain a significantly better understanding of the process that they developed. Even more importantly, they intend to use the results of these models to better control the process.

Recently, Beaman contacted ACAMM to inform them that he is actively putting together a National Science Foundation Engineering Research Center proposal in additive manufacturing and asked to create a formal relationship with the ACAMM group at LLNL.

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Explosive Elasticity by D.E. Hooks, C.A. Bolme, K.J. Ramos, M.J. Cawkwell (Los Alamos National Laboratory)

Explosives get squeezed routinely, loaded mechanically in assembly, and impacted suddenly in accidents or in use. To predict their behaviors we have to know their response to the squeeze—that starts with the fundamental property of elasticity—and it has a big impact: in explosives, there are serious consequences, and we usually need to know for sure what will happen! Figure 1 is an example photograph of an explosive responding to an impact. Our ability to predict these high-consequence outcomes are founded in models based upon our knowledge of the fundamental properties of the materials. It seems simple enough to understand elasticity, but our explosives are incredibly complicated composites, made of even more complicated crystalline explosive constituents. Through academic collaborations and state of the art advances in crystal growth and measurement techniques, we've been able to make some of these first measurements of these critical materials properties over about the last 10 years.

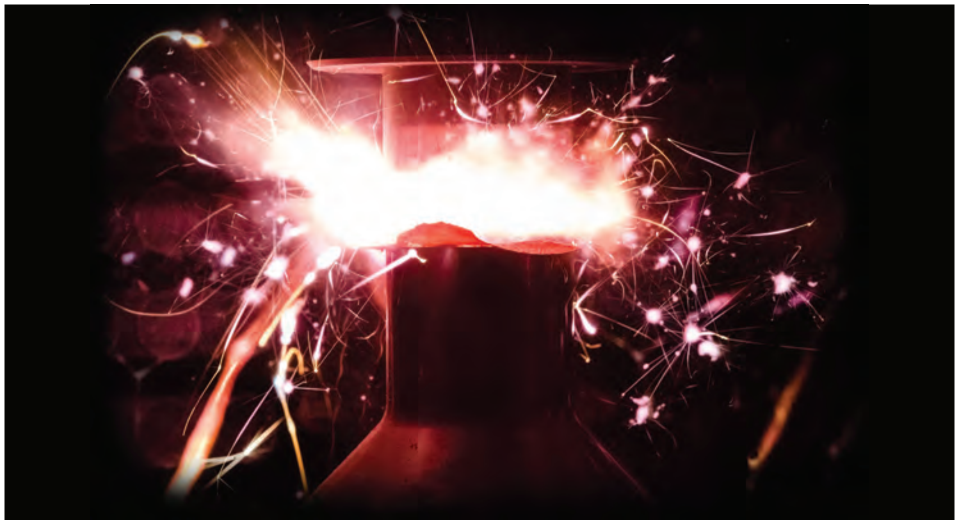

Figure 1. Explosives are designed to explode, as in this response to an impact. Many kinds of explosives response – wanted or unwanted- can result from mechanical stimuli to the explosive material. Predicting the outcome for each explosive to each kind of stimulus is critically important to their function and safety. Measuring the elastic properties is a starting point to predicting safety and performance characteristics for an explosive material. (Photo credit: Daniel Preston)

Working with multiple academic collaborators, researchers from Los Alamos National Laboratory (LANL) have provided some of the first measurements of elastic parameters for key explosives. The issues that needed to be solved to enable these measurements included developing ways to produce the necessary samples and coming up with methods to make measurements in these very fragile, very complicated materials. While the first measurements were exciting, over time, and using multiple techniques, we found that we got different answers—by a lot!

The core sample preparation took place at LANL's unique High Explosive Crystal Laboratory, which has the capability to grow and prepare large, highly precise, and very well characterized crystals of explosive materials to represent the crystals used in engineered explosives. Figure 2 shows an example crystal. Elasticity measurements were performed at LANL using the resonant ultrasound technique, invented at LANL, and the Brillouin spectroscopy technique. Reaching out to some of the best experimentalists and inventors of other techniques, the best of the best of the latest techniques were applied to LANL samples. Researchers from the Massachusetts Institute of Technology and Washington State University performed novel measurements using stimulated scattering techniques and investigated the frequency dependencies of the measurements to compare directly with other measurements. A student from the University of Nebraska came to LANL as a postdoctoral researcher to set up a new Brillouin spectroscopy apparatus, to complement the system that has been a core part of the Nebraska laboratory for years. In ongoing work, LANL and Northwestern University staff are working to understand the effects of temperature, pressure, and other variables on the measurements.

Figure 2. The unique High Explosives Crystal Laboratory at LANL creates and provides samples for critical property measurements for these materials. Shown is a crystal about the size of a golf ball illuminated by laser light—representative of some of the laser techniques used to measure elasticity for this study. (Photo credit: Ethan Frogget)

Ultimately, all of these results could be compared systematically to determine the source of discrepancies between different results, and to provide accurate numbers, with precise errors, for use in modeling tools for the prediction of explosive properties and behaviors. All of this was only possible because of strong science programs and academic collaborations formed and sustained over more than a decade. The predictive models, grounded in the new data, and an ongoing science and collaboration effort are key, since some explosives still remain out of reach of the latest developments in measurement science!

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Quantitative Planetary Science and Improving the Precision of Measurements for Materials in the Stockpile Stewardship Program

by Thomas R. Mattsson[a], Seth Root[a], Raymond W. Lemke[a], Dawn G. Flicker[a], and Richard G. Kraus[b] (Sandia National Laboratories)

When an iron meteor hits the earth, be it in the future or billions of years ago during the formation of the solar system, does it plow into the ground as a bullet, splatter as a drop of rain hitting a windshield, or vaporize into a cloud of iron to return to earth as iron rain as shown in Figure 1?

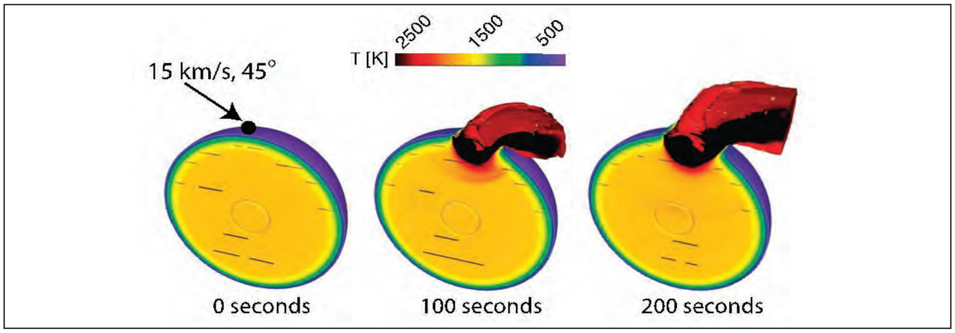

Figure 1. A meteor hitting earth sending a cloud of vaporized iron into the atmosphere, thus spreading iron across the surface. A scenario previously considered impossible, but with the data from new experiments on Sandia's Z machine showing a lower vaporization threshold for iron, instead emerging as a likely explanation of the distribution of iron across the planet.

Finding the answer to this fundamental question in planetary science occupied a team of scientists from Sandia National Laboratories (SNL), Harvard University, University of California, Davis (UC Davis), and Lawrence Livermore National Laboratory (LLNL) over the last four years within the Z Fundamental Science Program (ZFSP). ZFSP is a vehicle for collaborations between scientists at Sandia National Laboratories and several universities that was launched with a call for proposals in 2010 and has had dedicated time on Z since then. The research opportunities at Sandia's Z-machine[1] attract scientists across the world and the interactions with outside collaborators in turn benefit the Stockpile Stewardship Program, Sandia's main mission.

Sandia's Z machine is the world's largest and most powerful pulsed-power machine.[1] Z stores electrical energy in large capacitor banks and utilizes stages of pulse-shaping components to produce up to 80 trillion watts of electrical power; 4-5 times more than the instantaneous power generating capacity of all the power plants in the world combined. This electrical power produces a short current pulse that drives the experiment on Z.

The experimental setup—called platform—developed in the SNL/Harvard/UC Davis/LLNL collaboration on planetary science is shown in Figure 2. In these experiments, the large current from Z is exploited as a source of pressure to drive material to very high pressures. The new platform introduced a thicker flyer plate than previous dynamic material experiments on Z and was developed as a so-called "reverse impact" experiment to study impact vaporization of iron.

In the process of studying impact vaporization relevant to planetary impacts, the team also developed an experimental technique to determine the entropy gain during shock compression, or the amount of heating that occurs from the rapid compression by the shock wave. Just like shock temperatures, we have almost no data on the entropy of materials at high pressure and the type of data that can be obtained with this new technique will provide extremely sensitive tests of our most advanced theoretical methods for calculating material properties and equations of state.

The team's first study was recently completed and demonstrated that shock-induced vaporization will have far-reaching implications on the development of the early solar system.[2] Rick Kraus, who was lead designer of the experiments, graduated from Harvard University with a PhD in 2013, became a Lawrence Fellow at LLNL, and is now a staff scientist at LLNL.

In addition to the scientific achievements, ZFSP illustrates how partnerships with scientists at universities and other institutions bring multiple advantages for the Department of Energy/National Nuclear Security Administration (DOE/NNSA): Graduate students trained in research areas of key importance to the national laboratories; new creative ideas for experimental techniques and diagnostics that have already been adapted in the NNSA Science Campaigns; and scientists at the national laboratories using their unique talents and expertise to address some of the great outstanding questions in fundamental physics.

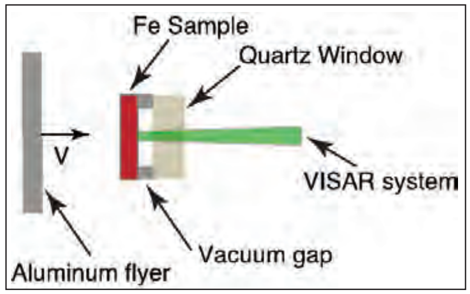

Figure 2. Schematic setup of the reverse shock experiment on Z using the target design developed within the Earth Science collaboration. The Al flyer hits the iron sample at a velocity around 25 km/s (about 55,000 mph), generating a very strong shock in the iron sample. The shock wave travels through the iron and as it reaches the vacuum gap between the iron and the window, the iron begins to decompress and vaporize. The vaporizing iron stagnates against the quartz window, and because the equation of state of quartz is so well known, the density of the vaporizing iron could be accurately determined.

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[2]R.G. Kraus et al., "Shock Thermo-dynamics of Iron and Impact Vaporization of Planetesimal Cores," Nature Geoscience, DOI: 10.1038/NGEO2369, 2015.

[a]Pulsed Power Sciences Center, Sandia National Laboratories, Albuquerque, NM

[b]HED-Shock Physics Group, Lawrence Livermore National Laboratory, Livermore, CA

The Dynamic Compression Sector: A New User Facility for Dynamic Compression Science

by Brian Jensen ✦ Los Alamos National Laboratory (bjjensen@lanl.gov)

The Dynamic Compression Sector (DCS) is a new user facility, funded by the U.S. Department of Energy (DOE) National Nuclear Security Administration (NNSA), which couples dynamic compression platforms to a dedicated x-ray beam line at the Advanced Photon Source (APS). The DCS was established through a partnership between Washington State University (WSU) and the APS, and is driven by the scientific need to examine time-dependent changes at the microscopic scales in materials subjected to dynamic loading conditions—a major theme central to the DOE/NNSA Stockpile Stewardship Program. To address this need, DCS will provide x-ray diagnostics, such as x-ray diffraction (XRD) and x-ray phase contrast imaging, to obtain new in-situ, real-time data that access the atomistic length scales directly. Such data will reveal a wealth of new information about the dynamic processes governing the response of materials at extreme conditions.

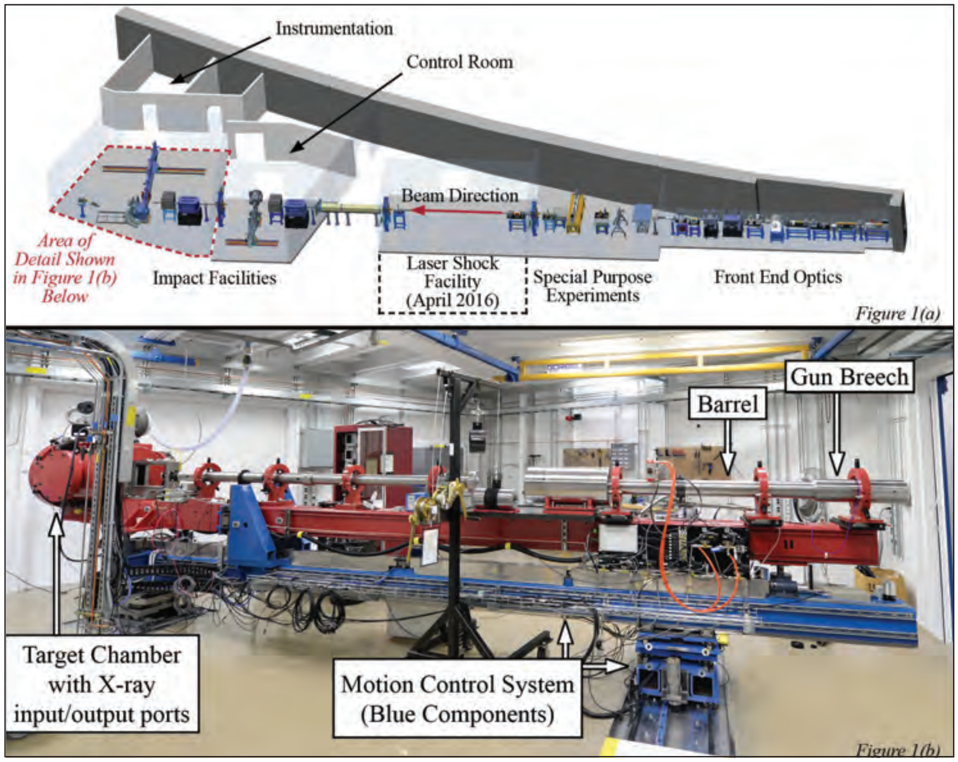


Figure 1(a): DCS Sector Layout. Figure 1(b): WSU's 2-stage powder gun capable of reaching projectile velocities in excess of 5 km/s. Projectiles accelerate down the barrel and impact samples located in the target chamber. The motion control system (shown as blue components) allows for precise alignment of the entire gun system and samples within the x-ray beam for XRD and Imaging experiments.

Central to the capabilities at the DCS are a variety of compression drivers that can be used to study different length and time scales in dynamically compressed materials. Multiple gas and powder guns (single stage gas/powder guns and a 2-stage powder gun) can achieve projectile velocities in excess of 5.5 km/s, and a 100-Joule, 351 nm laser with temporal pulse shaping capabilities that will provide peak stresses above 350 GPa (Spring 2016). A photograph of the 2-stage gas gun is shown in Figure 1. Briefly, projectiles accelerate down the barrel and impact samples to generate well-defined shock wave loading in samples with peak states into the Mbar range. These impact facilities along with a laser shock capability currently in development, are located in three experimental hutches along the x-ray beam at Sector 35 of the APS (Figure 1a). A fourth experimental hutch allows for more prototypical or special experimental campaigns, and includes detonation vessels, Hopkinson bar, and mobile gas guns. All loading platforms are equipped with motion control systems to allow for precise remote positioning of impact samples within the x-ray beam, and diagnosed simultaneously using a full suite of traditional shock wave diagnostics, including photonic Doppler velocimetry. A Lab Office Module includes office space and laboratory space for target fabrication, detector setup and testing, and other experimental support capabilities.

Since late 2014, the DCS has been in a commissioning phase where the impact systems along with essential beamline components (x-ray mirrors, millisecond shutters, high-heat load choppers, beam stops, revolver undulators, etc.) have been brought into operation systematically in preparation for user operations. During this time, WSU and its partners and collaborators (APS, NNSA and Department of Defense Laboratories, academic institutions, etc.) have performed a wide range of experiments. Because of these collaborative efforts, DCS has already seen significant success in obtaining new x-ray data during dynamic loading including small angle x-ray scattering measurements of explosive products during detonation, XRD measurements in explosives and metals, and x-ray imaging to examine the response of Additively Manufactured materials, to name a few. In 2016, the DCS will be available for regular user experiments with a percentage of experimental time available through the General User Proposals system. Inquiries about accessing the DCS should be directed to WSU (Principal Investigator: Yogendra Gupta) and the DCS management team. Contact information can be found on the DCS website (www.dcs-aps.wsu.edu).

Grants and Cooperative Agreements

Stewardship Science Academic Programs

Stewardship Science Academic Alliances

High Energy Density Physics

Cornell University
Bruce Kusse and David Hammer
Center for Pulsed-Power-Driven High Energy Density Plasmas

Ohio State University
Douglass Schumacher / Richard Freeman
High Energy Density Physics Program at the Scarlet Laser Facility

University of California, Los Angeles
Christoph Niemann
Development of First-Principles Experimental Methods to Determine the Physical Properties of Matter Under Extreme Conditions

University of Michigan
Karl Krushelnick
Relativistic Laser Plasma Interaction at the University of Michigan

University of Nevada, Reno
Aaron Covington
Investigations of High Energy Density Plasmas at the Nevada Terawatt Facility and Beyond

University of Nevada, Reno
Alla Safronova
Radiation from High Energy Density Pulsed Power Plasmas and Applications

University of Texas at Austin
Todd Ditmire
University of Texas Center for High Energy Density Science

Low Energy Nuclear Science

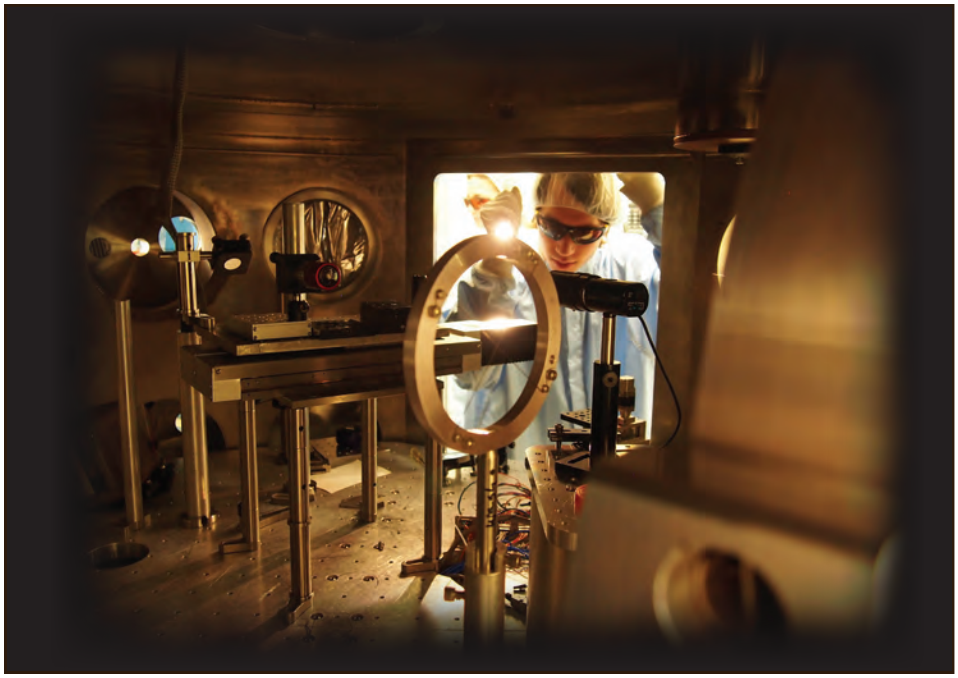
Colorado School of Mines
Uwe Greife
High Precision Fission Studies with the NIFFTE Fission Time Projection Chamber

Duke University
Calvin Howell
Photo-Fission Product Yields of Special Nuclear Materials

Duke University
Werner Tornow
Neutron-Induced Fission Studies and Reactions on Special Nuclear Materials

Indiana University
Romualdo deSouza
Development of a High-Resolution Position Sensitive MCP-PMT Detector

Michigan State University
Paul Mantica
Pulsed Laser Techniques Applied to Rare Isotopes



The Texas Petawatt Laser high intensity target chamber from behind the final mirror.

Michigan State University
Walter Loveland
The Energy Release in the Neutron Induced Fission of ^{233}U, ^{235}U, and ^{239}Pu

Michigan State University
William Lynch
Asymmetric Nuclear Matter Under Extreme Conditions

Michigan State University
Witold Nazarewicz
Microscopic Description of the Fission Process

Mississippi State University
Anatoli Afanasjev
Microscopic Description of Fission in a Relativistic Framework

Ohio University
Carl Brune
Studies in Low Energy Nuclear Science

Rensselaer Polytechnic Institute
Yaron Danon
Experiments with Neutron Induced Reactions

Rutgers University
Jolie Cizewski
Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science

Texas A&M University
Robert Tribble
Developing Surrogate Reaction Techniques to Determine Neutron Capture Rates

University of Kentucky
Michael Kovash
Measurements of Low Energy Neutrons from Neutron-Induced Fission

University of Kentucky
Steven Yates
Elastic and Inelastic Neutron Scattering Differential Cross Sections on Iron, Silicon, and Carbon

University of Massachusetts Lowell
Partha Chowdhury
Nuclear Science with a C7LYC Array (SCANS)

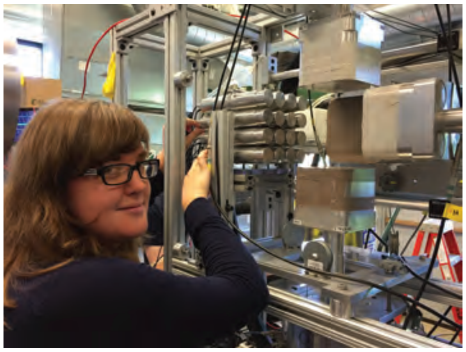
University of Richmond
Con Beausang
Stewardship Science at the University of Richmond

University of Tennessee
Robert Gryzwacz
New High Resolution Neutron Detector for the Studies of Exotic Nuclei (NEXT)

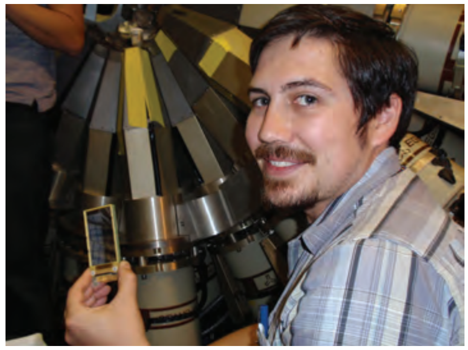
Properties of Materials Under Extreme Conditions

Arizona State University
Pedro Peralta
Formulation and Validation of Anisotropic Models for Growth and Coalescence of Spall Damage in Crystalline Materials

Carnegie Institution of Washington
Russell Hemley
Carnegie/DOE Alliance Center: A Center of Excellence for High Pressure Science and Technology



UMass Lowell post-doctoral research associate Gemma Wilson with the NNSA-SSAA funded SCANS (Small C7LYC Array for Neutron Spectroscopy) set up for measuring beta-delayed neutrons at the CARIBU (Californium Rare Isotope Breeder Unit) facility at Argonne National Lab.



David Walter, Ph.D. student from Rutgers University, with one of the position-sensitive silicon-strip charged particle detectors that are part of the Oak Ridge Rutgers University Barrel Array (ORRUBA) that was coupled to the Gammasphere array of germanium gamma-ray detectors. Charged particles were measured in coincidence with gamma rays following nuclear reactions induced by heavy beams to further our understanding of nuclear structure, astrophysics and applications for stewardship science.

Carnegie Mellon University
Robert Suter
Towards Optimal Processing of Additive Manufactured Metals for High Strain Rate Properties

Case Western Reserve University
Vikas Prakash
Dynamic Shearing Resistance of Metals Under Extreme Conditions

Florida State University
Stanley Tozer
Electron Interactions in Actinides and Related Systems Under Extreme Conditions

Georgia Tech
Devesh Ranjan
Detailed Measurements of Turbulent Rayleigh-Taylor Mixing at Large Atwood Numbers

Harvard University
Isaac Silvera
Pressing for Metallic Hydrogen

Lehigh University
Arindam Banerjee
The Effects of Strength and De-Mixing in Buoyancy (Rayleigh-Taylor) Driven Turbulence

Stanford University
Mark Cappelli
Ultra-High Speed Neutral Plasma Jets and Their Interactions with Materials Generating Extreme Conditions

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Baosheng Li
Thermodynamic and Mechanical Properties of SSP Materials from Simultaneous Ultrasonic and X-ray Studies at High Pressure and Temperature

Texas Tech University
Hongxing Jiang
Fast Neutron Spectrometry, Dosimetry, and Directionality Monitoring Using Semiconductor Thin Film Detector Arrays

University of Alabama at Birmingham
Yogesh Vohra
Studies on Rare Earth Metals and Alloys Under Extreme Conditions in Support of the Stockpile Stewardship Program

University of Arizona
Jeffrey Jacobs
An Experimental Study of the Turbulent Development of Rayleigh-Taylor and Richtmyer-Meshkov Instabilities

University of California, Davis
Richard Scalettar
Spectroscopic and Nuclear Magnetic Resonance Studies of Screening in Compressed Novel Magnets: Rare Earth and Fe-based Compounds

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New Multimodal Characterization of Additive Structures for Extreme Environments

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Novel d- and f- Electron Materials Under Extreme Conditions of Pressure, Temperature and Magnetic Field

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Viscous Plastic Flow, Dislocation Velocities, and Amorphization at Extreme Pressures and Strain-Rates

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High Pressure Science and Engineering Center

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Behavior of Ni-Nb-Zr Amorphous Alloy Gas Permeation Membrane Ribbons at Extreme Conditions

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Quantification of Normal and Oblique Shock-Driven Phase Interaction and Transition to Turbulence in Media with Multiscale Density Interfaces

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Riccardo Bonazza
Investigation of the Turbulent Mixing in a Twice-Shocked Interface

University of Wisconsin, Madison
Zhenqiang Ma
Membrane Enabled Hard X-ray Imager (MEHXI)

Washington State University
Yogendra Gupta
Institute for Shock Physics

Radiochemistry

Clemson University
Timothy DeVol
Robust Extractive Scintillating Resin and Adsorptive Membranes for Plutonium Isotopic Analyses of Aqueous Media

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Kenneth Gregorich
Development of Methodologies for Actinide Separations and Preparation of Actinide Targets Using Polymer Assisted Deposition

University of Tennessee
Howard Hall
University of Tennessee Radiochemistry Center of Excellence

Washington State University
Nathalie Wall
Determination of Thermodynamic and Kinetic Parameters for Complexation of Tc(IV) with F-, Cl-, Br-, I-, SO42- and PO43-, acetate, citrate and EDTA

Eugene Vinitsky, a student from the California Institute of Technology and a participant in Carnegie's Summer Scholars Program, prepares a diamond anvil cell for measurements of the Raman spectra of BaReH9 at high pressure. Vinitsky's stay at Carnegie was supported by the Carnegie-DOE Alliance Center. He is now a graduate student in Physics at the University of California-Santa Barbara.

Other

California Institute of Technology
Paul Dimotakis
A New Computational Fluid Dynamics Framework for Multi-Physics Simulations

Carnegie Institution of Washington
Guoyin Shen
High Pressure Collaborative Access Team (HPCAT) Operations

Washington State University
Yogendra Gupta
Dynamic Compression Sector (DCS) Development at the Advanced Photon Source

High Energy Density Laboratory Plasmas

Cornell University
John Greenly
Magnetized High Energy Density Plasma Flows Drive By Skin Effects

Harvard University
Stein Jacobsen
From Z to Planets: Phase II

Massachusetts Institute of Technology
Richard Petrasso
Studying Hydrodynamics, Kinetic/multi-ion Effects, and Charged-Particle Stopping in HED Plasmas and ICF Implosions at OMEGA, OMEGA-EP, and at the NIF

Polymath Research, Inc.
Bedros Afeyan
Continuation of Statistical Nonlinear Optics of High Energy Density Plasmas: The Physics of Multiple Crossing Laser Beams

Princeton University
Nathaniel Fisch
Fundamental Issues in the Interaction of Intense Lasers with Plasma

Johns Hopkins University
Dan Stutman
Development of Talbot-Lau Phase-Contrast X-ray Diagnostics for High Energy Density Laboratory Plasmas

University of California, Los Angeles
Warren Mori
Continuation of the Application of Parallel Kinetic Simulations to Laser and Electron Transport Through High Energy Density Laboratory Plasmas

University of California, Los Angeles
Chand Joshi
Development of a Broadband (40-80 KV), Directional X-ray Source Platform for Radiography of HEDP Targets

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R. Paul Drake
Center for Laser Experimental Astrophysics Research

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Alla Safronova
Line Emission from High-Z Multiple Ionized Ions Influenced by Dielectronic Recombination and Polarization

National Laser Users' Facility

General Atomics
Mingsheng Wei
Hot Electron Scaling in Long Pulse Laser Plasma Interaction Relevant to Shock Ignition

Massachusetts Institute of Technology
Richard Petrasso
Explorations of Inertial-Confinement Fusion, High-Energy-Density Physics, and Laboratory Astrophysics

Princeton University
Amitava Bhattacharjee
Dynamics of Magnetic Reconnection and Instabilities of Current Sheets in High-Energy-Density Plasmas

Princeton University
Thomas Duffy
Dynamic Compression of Earth and Planetary Materials Using the Omega Laser

Princeton University
Anatoly Spitkovsky
Generation of Collisionless Shocks in Laser-Produced Plasmas

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Raymond Jeanloz
Exploring the Quantum Mechanics of Dense Matter

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Farhat Beg
Fast Electron Energy Coupling and Transport in Warm Dense Plasmas

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Experimental Astrophysics on the Omega Laser

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Louise Willingale
High-energy Electron Beam Acceleration from Underdense Plasma Using OMEGA-EP

University of Michigan
Karl Krushelnick
X-ray Measurements of Laser-Driven Relativistic Magnetic Reconnection Using OMEGA-EP

William Marsh Rice University
E.P. Liang
Creation of Magnetized Jet Using a Hollow Ring of Laser Beams

William Marsh Rice University
Patrick Hartigan
Astrophysical Dynamics in the Laboratory: Mach Stems and Magnetized Shocks

Predictive Science Academic Alliance Program II

Stanford University
Gianluca Iaccarino
Predictive Simulations of Particle-Laden Turbulence in a Radiation Environment

Texas A&M University
Jim Morel
Center for Exascale Radiation Transport

The University of Utah
Philip J. Smith
Carbon Capture Multidisciplinary Simulation Center

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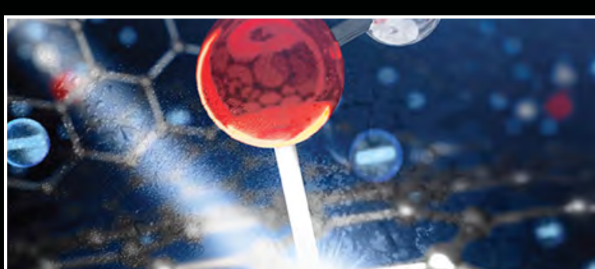

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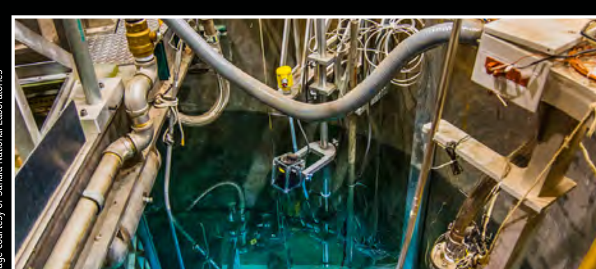

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