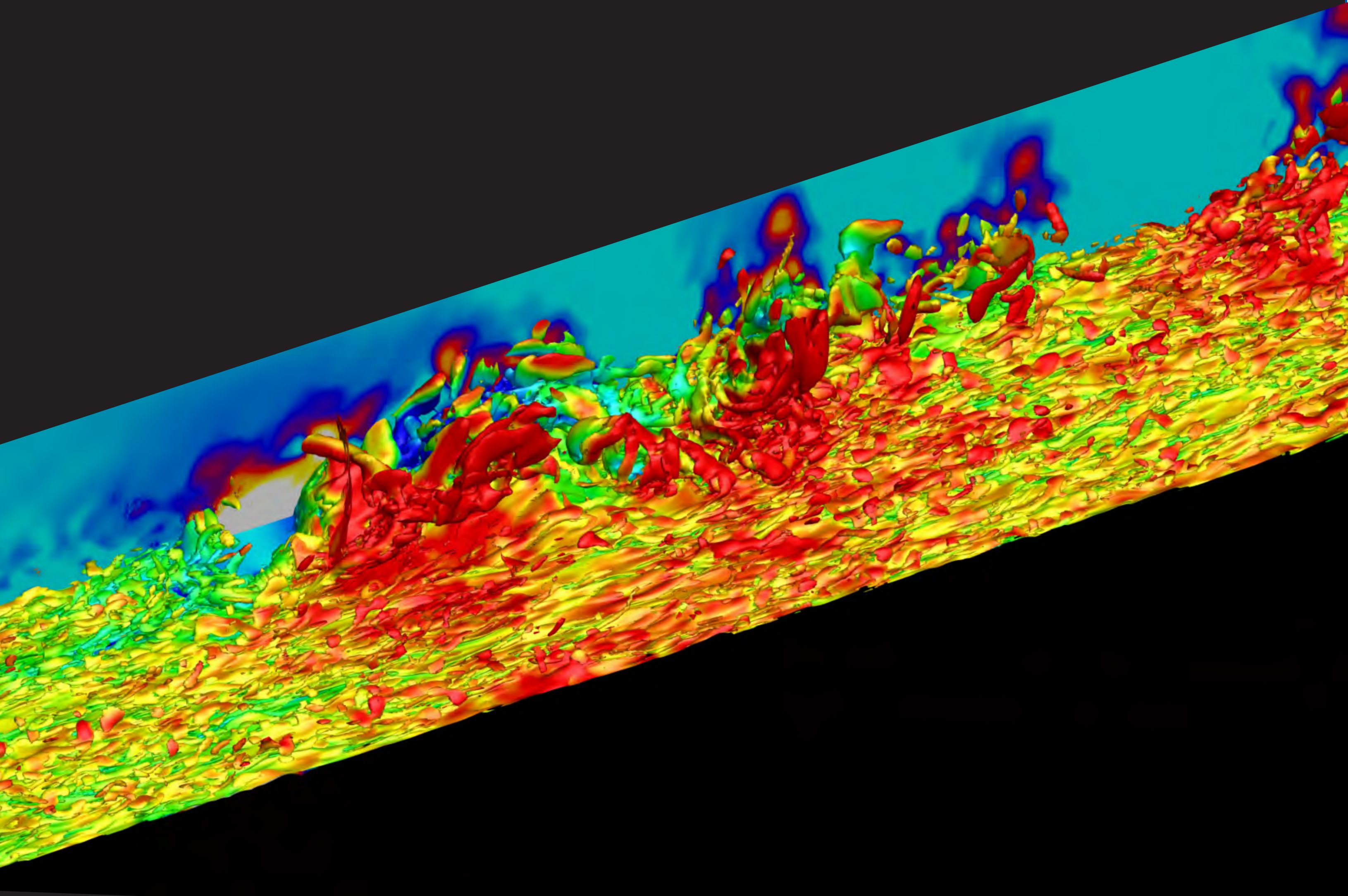
DOE/NA-0020

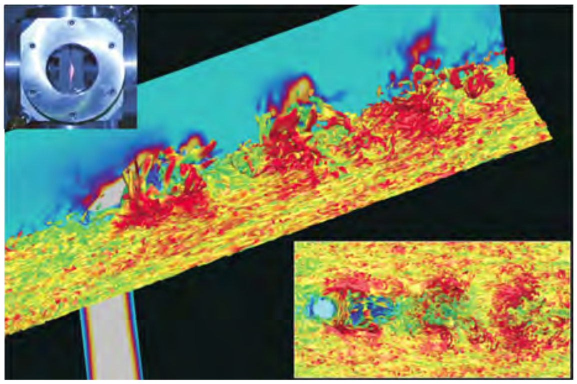
2014
Stewardship Science Academic Programs Annual

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



National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY



On the Cover

Direct numerical simulation of a hydrogen jet injected from a wall into a turbulent boundary layer. Isosurfaces of vorticity magnitude are colored by the local streamwise velocity. The lower-right inset shows a top-down view of the simulation while the upper-left inset shows an experimental image of an arc discharge plasma in a combustion chamber.

— Simulation courtesy of the Center for Exascale Simulation of Plasma-Coupled Combustion at the University of Illinois at Urbana-Champaign (See page 25.)

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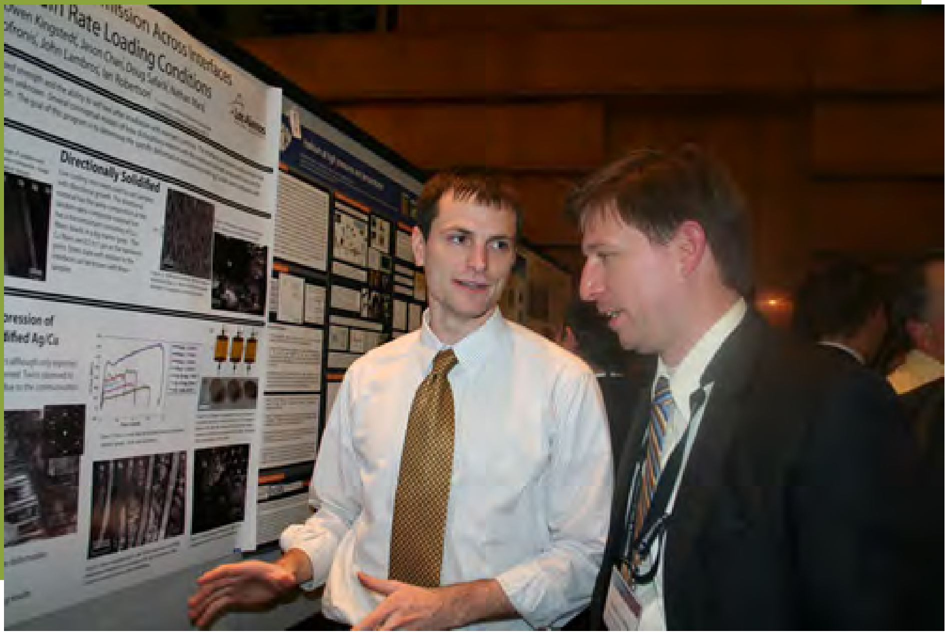

A highlight of the annual Stewardship Science Academic Programs (SSAP) Symposium is the poster session during which the cutting-edge research funded by the SSAP is featured. Above, Dr. Keith LeChien (right), Stewardship Science Academic Alliances Program Manager, and another attendee review one of the research posters.

National Nuclear Security Administration

Mission First...Through Teamwork

Maintaining the Capabilities to Ensure a Safe, Secure, and Effective Nuclear Deterrent

I'm grateful for this opportunity to communicate to you—the next generation of nuclear security stewards. This year, we are faced with many new challenges as well as an increasing need to be agile and responsive to a diverse set of important and exciting national security issues.

The primary mission of the National Nuclear Security Administration (NNSA) is to ensure a safe, secure, and effective nuclear deterrent and to maintain the capabilities needed to do so. Over the last two decades, we have conducted the nuclear weapons program without needing to perform underground nuclear weapons testing. Today, we remain diligently focused on this mission and are grateful for the many former participants from the Stewardship Science Academic Programs who have chosen a career with the NNSA national laboratories. They continue to be 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, other friends, and the world at large safe. Nuclear deterrence has been shown to work, but deterrence needs to be constantly employed for continued success. World-class, state-of-the-art science and technology is a key ingredient to maintaining the effectiveness of our deterrent and, thus, the quality of our lives and that of future generations. Additionally, the skills, capabilities, and facilities put into place for the stockpile stewardship mission serve many other national security missions as well, such as supporting the U.S. Department of Defense, Homeland Security, and the Intelligence Community. While key aspects of nuclear weapons work is, and needs to be, appropriately classified, it is based upon solid science and engineering. Throughout the pages of this *Stewardship Science Academic Programs Annual*, the value of the people contributing to this technical work and the value of the work itself are self-evident.

This Annual is not only intended for the Stewardship Science Academic Programs participants and future participants, but it is a statement to the Nation as well, attesting to the value of these activities not only to the NNSA but also to both the common defense and the general welfare of our Nation.

Dr. Keith LeChien

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

CONTENTS

2014 Stewardship Science Academic Programs Annual

NNSA Office of Research, Development, Test, and Evaluation

Acting Assistant Deputy Administrator for Research, Development, Test, and Evaluation
Keith LeChien

Program Manager, Stewardship Science Academic Alliances
Keith LeChien

Program Manager, High Energy Density Laboratory Plasmas
Kirk Levedahl

Program Manager, National Laser Users' Facility
Lois Buitano

Program Manager, Predictive Science Academic Alliance Program
Lucille Gentry

Publication Editors
Terri Stone, Millicent Mischo

Technical Editors
Mike Kreisler, Chris Werner, Alan Wootton

Designers
Millicent Mischo, Terri Stone

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. For more information, visit www.nnsa.energy.gov/stockpilestewardship.

Please submit comments to:

Terri Stone
terri.stone@nnsa.doe.gov

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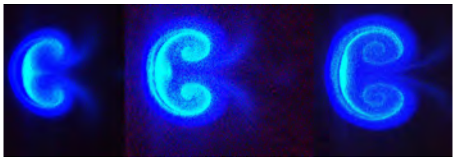
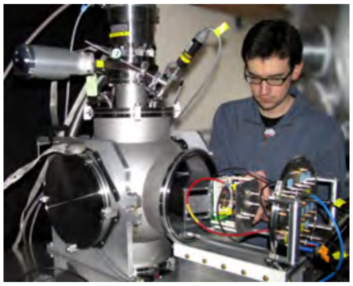

7


10

Overview

Research

Stewardship Science Academic Alliances

Properties of Materials Under Extreme Conditions

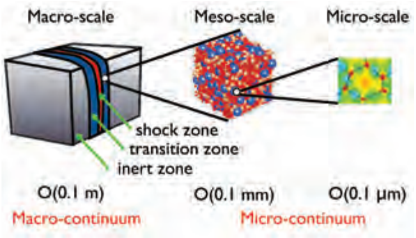
Low Energy Nuclear Science/ Radiochemistry

High Energy Density Physics

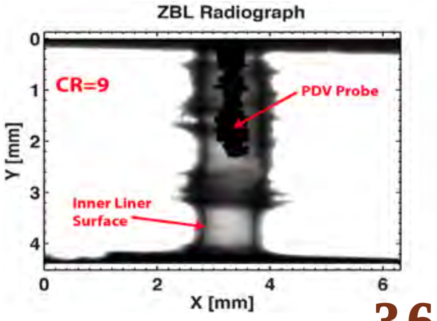
High Energy Density Laboratory Plasmas Physics

National Laser Users' Facility

13



25



36

Predictive Science Academic Alliance Program

Dynamic Compression Sector

High Pressure Collaborative Access Team

Radiation from High Energy Density Plasmas Workshop

National Laboratory Innovation

Students

Alumni

Current Students

List of Grants and Cooperative Agreements

Stewardship Science Academic Programs

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

The National Nuclear Security Administration's (NNSA) Stockpile Stewardship Program guarantees the safety, reliability and effectiveness of the nation's nuclear arsenal. This includes supporting research and development necessary to execute this mission, as well as ensuring the continued existence of the highly skilled and highly regarded scientific and technical workforce at the nuclear weapons national laboratories. NNSA invests in university-based programs through grants and cooperative agreements under the Stewardship Science Academic Programs (SSAP) in areas of science that have special relevance to the nuclear weapons mission. These are fields of research that receive little or no funding from other government agencies or private entities, such as the U.S. Department of Energy's (DOE) Office of Science, the National Science Foundation, the National Aeronautics and Space Administration, U.S. Department of Defense, etc. We invest in this for two primary purposes: (i) Developing the next generation's highly trained technical workforce in a world without nuclear testing, and (ii) to ensure there is a strong community of technical peers throughout the country external to the national laboratories that is capable of providing peer review, scientific competition and to generally strengthen the basic fields of research important to NNSA. These academic programs within SSAP follow, and this *Stewardship Science Academic Programs Annual* highlights a few of the grants and cooperative agreements within the programs.

Stewardship Science Academic Alliances (SSAA) Program

This program emphasizes those areas of fundamental research and development that are relevant to the Stockpile Stewardship Program mission, underfunded by other federal agencies, and for which there is a recruiting need at the NNSA National Laboratories. The goal of the Program is to support advanced experimental activities in the fields of materials under extreme conditions and hydrodynamics; low energy nuclear science; radiochemistry; and high energy density physics.

High Energy Density Laboratory Plasmas (HEDLP) Program

This program is a joint effort with NNSA's Office of Inertial Confinement Fusion and DOE's Office of Science. The areas emphasized in this program are high energy density (HED) hydrodynamics, radiation-dominated dynamics and material properties, magnetized HED plasma physics, nonlinear optics of plasmas and laser-plasma interactions, relativistic HED plasmas and intense beam physics, 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 most important laser systems, OMEGA and OMEGA EP, are accessible to a broad community of academic and industrial research interests, for use as a tool 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.

Predictive Science Academic Alliance Program (PSAAP)

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.

Graduate Fellowship Programs

Also included as elements of the SSAP, but not highlighted in this Annual, are two programs for outstanding graduate students—the Stewardship Science Graduate Fellowship (SSGF) Program and the Computational Science Graduate Fellowship (CSGF) Program, the latter of which is jointly supported with DOE's Office of Science. These Fellowship Programs provide excellent benefits and opportunities to students pursuing PhDs in areas of interest to stockpile stewardship. For more information about these Fellowship Programs, visit http://www.krellinst.org/fellowships.

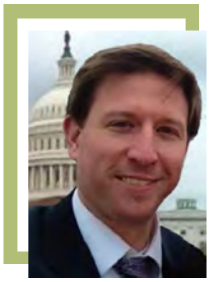
Stewardship Science Academic Programs at a Glance*

- Supports hundreds of faculty members, researchers, postdoctoral researchers, graduate students, and undergraduate students.
- Over 150 SSAP-supported students have found employment at the NNSA laboratories.
- More than 5,000 peer reviewed articles have been published.
- Supports the U.S. scientific community by funding research projects at universities that conduct fundamental science and technology research that is of relevance to the Nation's Stockpile Stewardship Program.
- Provides opportunities for intellectual challenge and collaboration by promoting scientific interactions between the academic community and scientists at the NNSA laboratories.
- Develops and maintains a long-term recruiting pipeline to the NNSA laboratories by increasing the visibility of the NNSA scientific activities to U.S. academic communities.
- CSGF currently supports 75 students.
- SSGF currently supports 21 students.

* 2012 Statistics

Dr. Keith LeChien, Program Manager
Stewardship Science Academic Alliances

Q&As



> *"As a result of NNSA supporting the SSAA, hundreds of individuals, including graduate students, research faculty, and professors, have either pursued careers at NNSA's national laboratories or developed professional relationships that have spawned new research efforts. Several of those students have been nominated and some have won the President's Early Career Award for Scientists and Engineers, a very prestigious annual award. "*

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Why does NNSA need an academic alliance program?

Most Americans do not often think about the nuclear weapons complex, or recognize that the U.S. has not conducted a nuclear test in over 20 years. They do not realize that within little more than a decade, there will be no one working at a national laboratory that has ever tested a nuclear weapon. Today, those that work within the U.S. Nuclear Security Enterprise (NSE), other nuclear nations, and adversaries that aspire to become nuclear states, know that it is the skilled workforce that truly underpins nuclear deterrence, and the U.S. knows that it is critical to ensure this workforce is capable, motivated and dedicated to executing the NSE mission.

The Nation will support a nuclear deterrent in perpetuity, and it is the National Nuclear Security Administration (NNSA) that is responsible for ensuring a safe, secure and effective nuclear deterrent. Stockpile stewardship-based science provides the strategic stability of U.S. nuclear deterrence.

Why does NNSA support the disciplines that it does?

The academic topic areas supported by NNSA are areas of special relevance to the nuclear weapons mission. In most cases, these are fields of research that receive little or no funding by other government agencies or private entities, such as DOE's Office of Science, the National Science Foundation, the National Aeronautics and Space Administration, the Department of Defense, etc.

Why support development of an external community of technical peers?

It is essential to create a network of intellectual peers external to the nuclear security enterprise to provide independent scientific review of journal manuscripts and milestone accomplishments within the science-based Stockpile Stewardship Program. Academic researchers collaborate with national laboratory researchers for the general advancement of science, technology, engineering, mathematics and computation. A healthy external academic community also challenges our laboratories technically, thus raising the bar through competition, a critical component for world leading science programs.

Has SSAA been successful?

As a result of NNSA supporting the SSAA, hundreds of individuals, including graduate students, research faculty, and professors, have either pursued careers at NNSA's national laboratories or developed professional relationships that have spawned new research efforts. Several of those students have been nominated and some have won the President's Early Career Award for Scientists and Engineers, a very prestigious annual award. Hundreds more have joined academia, pursued careers at other government laboratories or within private industry. With the support of the NNSA, the programs' participants have produced thousands of peer reviewed publications, many in highly prestigious international journals.

When is the next call for proposals for the SSAA Program?

We expect the next Funding Opportunity Announcement (FOA) to be posted on grants.gov in May 2014 with awards in May 2015. This next FOA will be for grants only in the areas of Properties of Materials Under Extreme Conditions and/or Hydrodynamics, Low Energy Nuclear Science, and Radiochemistry (we expect a FOA for the HEDLP program will be released around the same time). A call for Center proposals (or cooperative agreements) is expected in Spring/Summer 2016 with awards in 2017.

I have an idea on how to improve NNSA's academic programs. How do I communicate it?

NNSA is constantly working to improve the quality of its program and therefore of the opportunities for program participants. Please contact Terri Stone at terri.stone@nnsa.doe.gov to submit your ideas!

Carnegie-DOE Alliance Center: An Academic Partner Update

Carnegie Institution of Washington
PI: Russell J. Hemley, rhemley@ciw.edu; Program Coordinator: Stephen A. Gramsch, sgramsch@ciw.edu

Now in its eleventh year, the Carnegie-DOE Alliance Center (CDAC) is pursuing some new initiatives in its research program. At its recent review, CDAC introduced four new academic partners, whose expertise extends the scientific breadth of the Center into new areas of the study of matter at extreme conditions relevant to stockpile stewardship. Currently, CDAC supports 17 graduate students in 14 academic partner groups, which represent some of the leading high pressure research groups in the country. Since its inception in 2003, 32 students have earned their PhD degree with CDAC support, and three of these students currently hold permanent staff positions at the National Nuclear Security Administration laboratories.

Figure 1. CDAC Academic Partners. Top row, left to right: James Schilling (Washington University in St. Louis), David Cahill (University of Illinois), Choong-shik Yoo (Washington State University), Abby Kavner (University of California, Los Angeles), and Brent Fultz California Institute of Technology). Middle row: Dana Dlott (University of Illinois), Premyslaw Dera (University of Hawai'i), Eva Zurek (SUNY-University at Buffalo), Hans-Rudolf Wenk (University of California, Berkeley), and Raymond Jeanloz (University of California, Berkeley). Bottom row: Lowell Miyagi (University of Utah), Kanani Lee (Yale University), Yogesh Vohra (University of Alabama-Birmingham), and Steven Jacobsen (Northwestern University).

A significant new direction for CDAC is the addition of a theoretical chemist to the group of academic partners. Professor Eva Zurek studies the electronic structures of solids at high pressures with the goal of predicting the stable structures of systems with unusual stoichiometries. Her work in the CDAC program will initially focus on the electronic structure of boron carbide, a material that is under consideration for the ablator used at the National Ignition Facility (NIF) for ignition experiments. Professor Zurek will use an evolutionary algorithm (EA) to predict stable structures of boron carbide over a wide pressure range relevant to conditions that will be reached at NIF. Such EA methods typically begin with random structures, followed by optimization and the creation of “child” structures, which then are evaluated on the basis of their fitness (according to their enthalpy, for example) to evolve toward more stable structures. In cases where reliable experimental data is either extremely difficult or impossible to obtain due to the target pressure range or the challenges in handling the material itself, computational studies provide valuable information and guidance toward further experiments. Investigations will also address the outstanding physical properties of boron carbide, such as its hardness, thermodynamic stability, and strength at low density. Ongoing collaborations with scientists at Lawrence Livermore National Laboratory (LLNL) will play an integral role in the research program.

The way in which mineral physics is carried out today, with a materials science focus and the use of advanced computational methods and state-of-the-art high pressure spectroscopic and diffraction techniques, provides excellent preparation for work in the area of stockpile stewardship. Development of techniques for the study of matter at extreme conditions has been a cornerstone of the CDAC program since its inception, and new capabilities have emerged regularly along with the scientific breakthroughs that have been enabled by new laboratory techniques. Professor Lowell Miyagi continues this tradition with his work on radial diffraction measurements of texture (preferred orientation of crystallites), lattice strains and deformation at high pressures and temperatures in the diamond anvil cell (DAC). The DAC used in radial diffraction geometry is currently the only high pressure deformation device which can achieve pressures of several hundred GPa, equivalent to the entire pressure range in the Earth. In the past, the major limitation to DAC deformation

> ***“A significant new direction for CDAC is the addition of a theoretical chemist to the group of academic partners. Professor Eva Zurek studies the electronic structures of solids at high pressures with the goal of predicting the stable structures of systems with unusual stoichiometries.”***

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experiments was the diffculty in carrying out deformation experiments at simultaneous high pressure and temperature. As a consequence, nearly all DAC deformation experiments have been done at room temperature. From the scientific standpoint, extrapolation of these results to planetary interiors where materials deform at high pressure and temperature is problematic. Professor Miyagi will extend these techniques to address the deformation behavior of two-phase mixtures at high pressures and temperatures in the DAC, which has important applications to stockpile stewardship as well as to the study of the Earth’s deep interior.

Professor Choong-shik Yoo has been a pioneer in the recent development and application of the dynamic diamond anvil cell (*d*-DAC). The *d*-DAC incorporates a straightforward addition of piezo-electric actuators to the conventional DAC, to produce a fast (< ms) pressure jump (> 1 GPa) at static high pressures. The magnitude, frequency, and rates of compression and decompression can be precisely tailored, allowing detailed studies of transition dynamics over a wide range (10^{-2} to 10^4 GPa/s). In addition, the *d*-DAC is capable of modulating the lattice of a crystalline material by as much as a few percent of an interatomic distance at pressures where the compression energy is comparable to strong chemical bonds. It is feasible then, that compression in the *d*-DAC can facilitate chemical bonding between solid materials with highly mismatched lattices or between chemical species with a low probability of reaction. In his work in the CDAC program, Professor Yoo will be studying two fundamental, but counteracting effects of pressure on nanoparticles—decreasing the domain size (enhancing surface/interface effects) and increasing interatomic interactions (favoring coagulation/bulk effects). Strong pressure modulation and dynamic shear will alter the size and symmetry of grains and the interfacial (or intergrain) structures. Understanding how nanoparticles manifest these pressure-induced changes of their stabilities, local structures, microstructures, and electronic properties is a critical issue for developing nanoscale electronic devices and their applications.

Single crystal x-ray diffraction provides the most detailed information possible on the structure of materials. Until recently, however, the maximum pressure possible in single crystal experiment was about 10 GPa, which is usually not sufficient to produce molecular strains significant enough to be reliably measured, or to reach the kind of conditions that are required to induce solid-state reactions such as polymerization. The development of synchrotron-based methods for single-crystal x-ray diffraction, led in part by Professor Premyslaw Dera over the past decade, has enabled an increase in the accessible pressure range by more than an order of magnitude, which can produce very significant molecular strains. Professor Dera will use single crystal diffraction experiments as part of a combination of characterization techniques that will include diffraction, total x-ray scattering, and Raman and optical spectroscopy. Total x-ray scattering, first introduced in the 1930s and used to generate pair distribution functions for amorphous materials, has received renewed interest with the development of advanced detectors capable of recording high energy x-ray data at high momentum transfer, which can provide information on disorder in crystalline materials. This unique combination of techniques will be applied to the study of energetic materials and their decomposition products at high pressure to develop an increased understanding of detonation processes.

Professor Raymond Jeanloz has returned as a CDAC partner and brings to the Center a wealth of expertise in the study of materials at extreme conditions. In partnership with CDAC Steering Committee member G.W. “Rip” Collins (LLNL), Professor Jeanloz has been involved in basic science experiments on NIF. Along with CDAC Director Russell Hemley, the University of California Berkeley-LLNL collaboration was awarded time for the study of hydrogen at terapascal pressures. Within CDAC, Professor Jeanloz will be studying how the thermodynamic properties of amorphous materials are related to synthesis methods, and how the elastic properties of crystalline materials change upon pressure-induced amorphization.

Pressing for Metallic Hydrogen

Lyman Laboratory for Physics, Harvard University
PI: Isaac F. Silvera, silvera@physics.harvard.edu

Our research program at Harvard University is focused on producing metallic hydrogen (MH) in the laboratory at high pressure. We have a decades-long relationship with the National Nuclear Security Administration (NNSA) national laboratories, where three former PhD students are employed in high-pressure research areas. Support under the Stewardship Science Academic Alliances (SSAA) program, established three years ago, is currently providing support for a student and a postdoctoral fellow.

Support from the SSAA program has enabled us to pursue our research goals, important for physics and for the NNSA program of understanding the properties of hydrogen and its isotopes under high-pressure, high-temperature conditions.

There are two pathways to MH:
1) quasi-isothermal compression of solid molecular hydrogen to multi-megabar pressures until the molecules dissociate to form atomic metallic hydrogen, and 2) heating high pressure hydrogen above the melting line until liquid molecular hydrogen dissociates to liquid metallic atomic hydrogen. A theoretical/experimental phase diagram of hydrogen is shown in Figure 1. We have prepared experiments for the former pathway, but current efforts are focused on the latter. The high temperature transition is predicted to be a first-order liquid-liquid phase transition and is called the plasma phase transition (PPT). Theoretical predictions for this phase line are shown in Figure 1 by the blue lines with the negative slope (showing the range of various predictions). The melting line of hydrogen has a maximum with a negative slope at higher pressures that was experimentally established a few years ago. This line is predicted to go to absolute zero Kelvin with increasing pressure so that hydrogen may be an atomic liquid at megabar pressures and T = 0 K. The PPT line is expected to merge with the melting line so that at higher pressures hydrogen is predicted to melt from a solid molecular to a liquid atomic form.

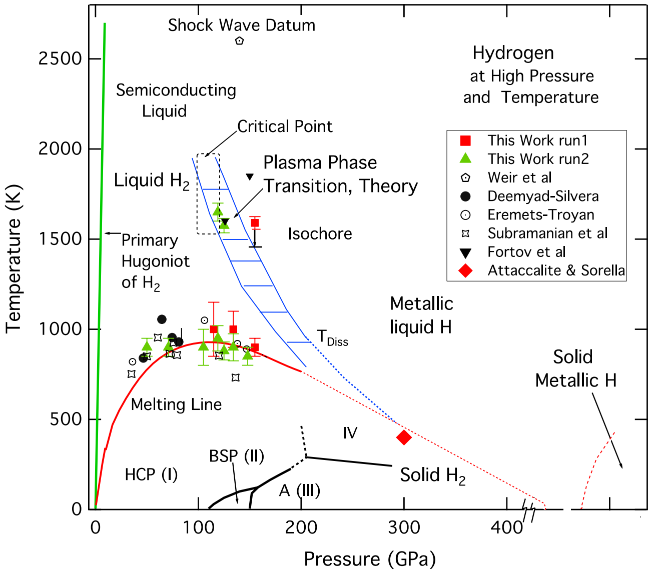

Figure 1. The P-T phase diagram of hydrogen showing both experimental results and theoretical predictions. Measurements were at pressures up to 150 GPa and temperatures up to 2,000 K; the pressure range is currently being increased.

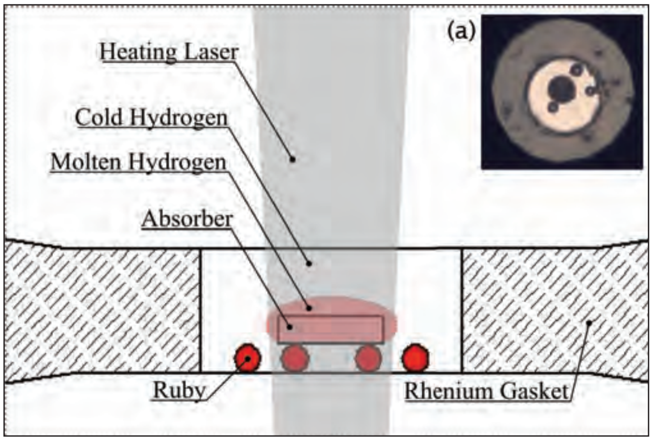

Figure 2. Opposing diamonds (not shown) press on the gasket in a DAC showing the absorber that is heated by a pulsed laser, and ruby balls for pressure measurement. The inset (a) is a back illuminated birds-eye view of the gasket hole before loading with hydrogen, showing the absorber (large dark disc, diameter ~20 microns) and 3 ruby balls.

To study the high-pressure region of the phase diagram, samples are compressed to megabar pressures in a diamond anvil cell (DAC) and high temperatures are achieved using pulsed-laser heating (see Figure 2). In this project, we have succeeded in using pulsed laser heating to explore the high pressure and high temperature (P,T) region of the phase diagram. We extended the melting line measurements to the highest pressures yet achieved and have found evidence of a phase transition that overlaps the theoretical predictions for the PPT. The published data are shown in Figure 1. Our current goal is to show that this phase is metallic; recent experiments of the transmission and reflection of hydrogen at temperatures at and above the observed phase transition provide evidence of changes in the optical properties and are being pursued in a continuation of this grant.

In the lower temperature region, our earlier work determined phase lines for the orientationally ordered molecular phases II and III in hydrogen and its isotopes (see Figure 1). Recent activities by other groups have found a new phase (i.e., phase IV) at even higher pressures. A DAC and optical system to study this region in the infrared are essentially ready and efforts are underway to achieve extreme high pressures at lower temperatures. The diamond anvils that are mounted have had surface defects removed by reactive ion etching and are protected from hydrogen diffusion into the diamond (which leads to failure of the diamonds at room temperature and above) by coating the surface with alumina, which acts as a diffusion barrier.

Shock Interaction with Multiphase Matter: Unraveling the Puzzles

The University of New Mexico
PIs: Peter Vorobieff, kalmoth@unm.edu and C. Randall Truman, truman@unm.edu

The shock tube laboratory at the University of New Mexico (UNM) was established in 2008 with the main goal to study shock interaction with multiphase media. It has been sponsored by the National Nuclear Security Administration (NNSA) since 2010. Since then, two students have received their Master of Science (MS) degrees, and two have been awarded doctorates—one working on a collaborative project with Los Alamos National Laboratory (LANL). In 2014-2015, we anticipate graduation of four more MS Students and one PhD student. It is noteworthy that the graduates of our program have a 100% record of successful entry into the high-tech workforce, including NNSA national laboratories. We also benefit from collaboration with national laboratories (LANL in particular) and local high-tech companies, including Applied Research Associates, the company that develops and maintains the SHAMRC hydrocode for the U.S. government.

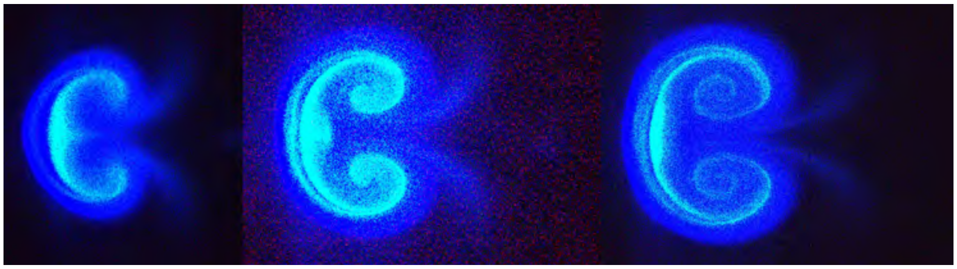

Figure 1. Mosaic of experimental images showing laser-induced fluorescence in planar cross-sections of a Mach 1.7 shock-accelerated SF_6 column. Flow direction is from left to right, vertical image extent is 16 mm, timings after shock arrival are 50, 100, and 150 μs.

Figure 2. UNM Shock Tube Team. Left to right: Professor C.R. Truman, D. Olmstead (PhD student), John Vigil (undergraduate), C. Corbin (MS student), P. Wayne (MS student) T. Bernard (MS student), and Professor P. Vorobieff.

The problem of shock interaction with multiphase media has attracted considerable recent attention because of its multiple applications, from weapons applications to astrophysics. Of specific interest in weapons physics is the behavior of the fluid instability, such as the Richtmyer-Meshkov instability, at interfaces between gases and fluids of different densities as they mix and become turbulent after impact by a shock wave. Here, it is important not just to understand what and why it is happening in the flow, but to provide high-quality quantitative data that can validate hydrocodes—data that will challenge the accuracy of numerical modeling over a wide range of spatial and temporal scales. This challenges experimentalists to develop accurate diagnostic techniques to obtain the relevant quantitative data.

Sometimes, the latter challenge leads to unexpected and important results. Since the 1990s, small particles or droplets were used as tracers to study shock-accelerated flows. It was known that their tracking fidelity is limited. Until recently, it was not appreciated that injection of the "tracer" itself can lead to average density fluctuations, resulting in vortex formation. In numerical simulation, that means that the code must correctly take into account compressible interaction between the particle/droplet and the surrounding gas. Analysis of these findings, originally obtained in our laboratory in 2011, also led to our most recent observation driven by close interaction between modeling and experiment. We studied shock acceleration of a jet of heavy gas carrying micron-sized liquid droplets. Numerical modeling showed features in the flow unseen by illuminating these droplets. A careful investigation of the flow using two diagnostics concurrently—one that traces the droplets and one that visualizes fluorescence in the surrounding gaseous jet material (see Figure 1)—revealed a subtle interaction between the gaseous and the liquid phases that caused decoupling. As the result, one of the most prominent high-speed features of the shock-driven flow (a heavy-gas spike forming due to shock focusing) does not entrain any droplets, and would be invisible to experimentalists relying solely on droplets as tracers for diagnostics. Thus, the data were reconciled with numerical predictions, and an important hydrocode, SHAMRC, was successfully validated. Presently, we are working on adding the capability to accurately measure the size distribution of the non-gaseous phase of the flow, which will lead to further refinement of the benchmark data.

Radiochemistry Center of Excellence

University of Tennessee - Knoxville

PI: Dr. Howard Hall, howard.hall@utk.edu

In 2013, the Stewardship Science Academic Alliances (SSAA) program established the Radiochemistry (Radchem) Center of Excellence at the University of Tennessee - Knoxville (UT). Radiochemistry and nuclear chemistry are key scientific areas that support a number of National Nuclear Security Administration (NNSA) mission areas. "Nuclear chemists and radiochemists play important roles in complex and critical NNSA functions, such as interpreting the performance of nuclear explosives from post-detonation debris, investigating the subtleties of the behavior of nuclear materials, determining nuclear reaction cross-sections, and analyzing materials for radioactive signatures that support international treaties and agreements," noted Professor Howard Hall, UT's Principal Investigator of the Center.

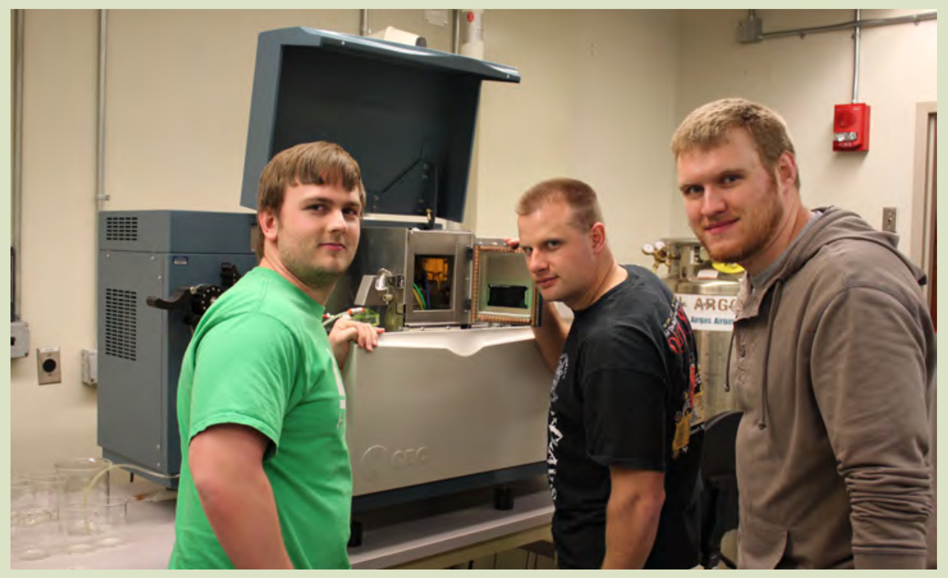

Figure 1. UT graduate students Joshua Chandler, Captain Joshua Molgaard (U.S. Army), and Matt Cook working on the UT inductively coupled plasma–time of flight mass spectrometer, which is used to analyze gas-phase separations.

Hall, a radiochemist, spent much of his career at Lawrence Livermore National Laboratory (LLNL) before joining the faculty in the Nuclear Engineering Department at UT in 2009. "One of the most exciting things about the Radchem Center is the opportunity to build deeper ties with the NNSA laboratories and position graduate students to meet their future needs. Our faculty has extensive experience with NNSA and DOE —approximately 70 person-years of experience at LLNL, LANL [Los Alamos National Laboratory], and LBNL [Lawrence Berkeley National Laboratory]—and that helps us target the fundamental science that underpins NNSA's capabilities," he said.

The UT Radchem Center involves faculty and students in nuclear engineering, chemistry, chemical engineering, materials science, and UT's new interdisciplinary PhD program in energy science and engineering. In addition to students directly supported under the Center, students supported through other means are also being influenced by the work of the Radchem Center. For example, U.S. Army officers pursuing advanced degrees under the auspices of the Army's advanced education programs are participating in Radchem Center research (see Figure 1), and one of UT's senior graduate students just began a National Nuclear Forensics Graduate Fellowship program at LANL to complete his dissertation in actinide measurements by mass spectrometry.

The graduate students that the Radchem Center is educating will be sorely needed within the NNSA complex in the near future. In 2012, a National Academies of Science and National Research Council committee reported:

> *...a sizable percentage of the nation's experts in nuclear and radiochemistry at national laboratories and universities is nearing retirement. For example, data collected from national laboratories...show that there are currently about 950 career employees with nuclear and radiochemistry related skills, about 10% of whom are at or nearing retirement age (60+ years), and more than half of these have a PhD. The projected demand for PhD-level nuclear and radiochemistry experts (i.e., those with nuclear and radiochemistry degrees and those in jobs that involve nuclear and radiochemistry) at the national laboratories is estimated to be about 223 over the next 5 years.*
>
> — Committee on Assuring a Future U.S.-Based Nuclear and Radiochemistry Expertise, National Academies of Science and National Research Council, 2012

The UT Radchem Center is organized into a set of two major and two minor research thrusts, each selected to develop new scientific understanding in areas of strategic interest and to develop student expertise and interests that overlap with NNSA needs. Those thrust areas are advanced radiochemical separations, radiochemical probes for physical phenomena, nuclear cross-sections, and bulk actinide oxide materials processing and behavior. A description of each area follows.

Advanced Radiochemical Separations

The goal is to improve the specificity, timeliness, detection limits, and/or operational suitability of radiochemical separations. Radiochemical separations

> *"Nuclear chemists and radiochemists play important roles in complex and critical NNSA functions, such as interpreting the performance of nuclear explosives from post-detonation debris, investigating the subtleties of the behavior of nuclear materials, determining nuclear reaction cross-sections, and analyzing materials for radioactive signatures that support international treaties and agreements."*

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ultimately underlie all NNSA applications of radiochemistry. This work focuses primarily on exploiting gas-phase chemistry to develop and improve separations, with a particular emphasis on faster and higher specificity separations.

UT's early work in this area focused on developing the instrument and detection capability to investigate these gas-phase separations and elucidate their controlling thermodynamic parameters. Some recent work on modeling this process (see Garrison, Hanson, and Hall, J Radioanal Nucl Chem 291:885-894, 2012) indicates substantial improvements in both specificity and timeliness are possible. A key research objective is to better constrain the thermodynamic data regarding the interaction of the gas-phase species with the separation column substrate; current data is sparse and occasionally contradictory.

Radiochemical Probes For Physical Phenomena

Another major research thrust is using 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 NNSA.

Positron Emission Tomography (PET) produces a three-dimensional (3D) distribution of positron-electron annihilations within the image volume and is well developed for medical diagnostics. Volume resolution of three microliters is achieved with current preclinical micro-PET imaging equipment. Time-resolved 3D activity field development has also been measured for slow-moving flows. Positron emission particle tracking techniques developed in the United Kingdom resolved a 40 MBq particle position to 100 microns every two milliseconds. Extrapolation of this performance to more modern scanners using the same particle activity allows location every 0.2 milliseconds, which is comparable to the speed of current optical tracking techniques. Escalation of particle activity in conjunction with the steady improvement in count rate, sensitivity, and spatial resolution of commercial PET scanners makes them competitive instruments for particle tracking in Lagrangian turbulence measurements.

A common radiopharmaceutical isotope, ^{18}F, was chosen as the particle activating agent. In determining that ^{18}F would most likely yield the optimal tracking capability, the proximity of the nuclear engineering department to the University of Tennessee Medical Center was paramount, as their facilities include a Siemens Eclipse cyclotron (routinely used to produce the nuclide), radiochemical facilities, an expert isotope production staff, and a PET scanner that can be used for preliminary studies. In addition, ^{18}F possesses properties well suited for particle tracking, such as a half life (109.77 min) that is long enough to allow for a reasonable time to activate the particles without an excess of the nuclide decaying, but still short enough to ensure a high flux of 511 keV annihilation photons.

Nuclear Cross-Sections

The UT Radchem Center is also supporting a small effort in improving the fundamental understanding of relevant nuclear reactions, particularly neutron-induced reactions such as (n,xn) reactions, through a variety of means, including high-resolution measurements using inverse kinematics. This approach, if successful, will provide a capability with broad applicability to neutron induced reactions. The Radchem Center is also collaborating with another SSAA center, the Rutgers-led Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science, in aligning the UT approach to neutron-induced measurements with other SSAA activities.

Bulk Actinide Oxide Materials Processing and Behavior

The other small effort supported under the Radchem Center is 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) will focus on computational materials science coupled with experiments to assess new materials synthesis and formulation options for better performance.

One exciting development that occurred in the first few months of the UT program is the development of a new graduate curriculum in nuclear and radiochemistry. The Chemistry Department and the Nuclear Engineering Department are collaborating on implementing a new graduate certificate in Radiochemistry that should begin accepting students in fall 2014. This work, prompted by the UT Radchem Center award, will nicely complement the existing Nuclear Security graduate certificate offered.

Development of a High-Resolution Position Sensitive Microchannel Plate Detector

Indiana University
PI: Romualdo T. deSouza, desouza@indiana.edu

Detection of single electrons, ions, and photons with sub-millimeter position sensitivity in two dimensions is of considerable interest to both fundamental and applied science. Imaging plays an important role in applications ranging from the resonance spectroscopy of loosely bound radioactive nuclei to the detection of sensitive nuclear materials at border crossings. In 2013, the Stockpile Stewardship Academic Alliances (SSAA) program began funding the development of a position-sensitive microchannel plate (MCP) detector capable of detecting an electron with sub-millimeter precision while providing sub-nanosecond time resolution. The detector would also be capable of resolving two simultaneous electrons incident on its active area. Since Indiana University began collaborating with SSAA in 2013, one graduate student and one postdoctoral researcher have joined the group and are supported by the program.

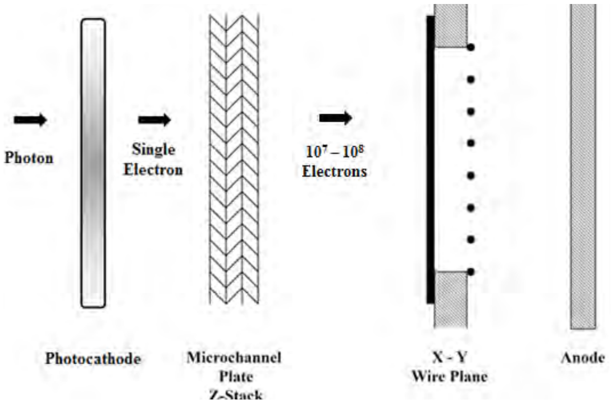

Figure 1. Conceptual diagram of the proposed detector.

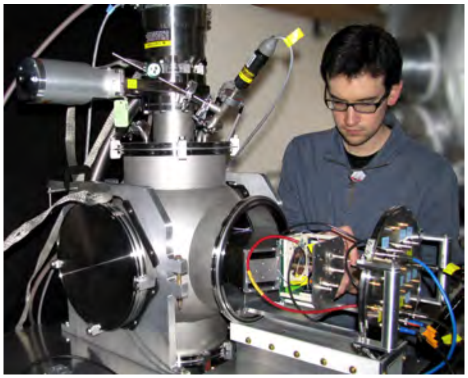

Figure 2. Postdoctoral researcher Eric Richardson inserts a detector into the new vacuum test station.

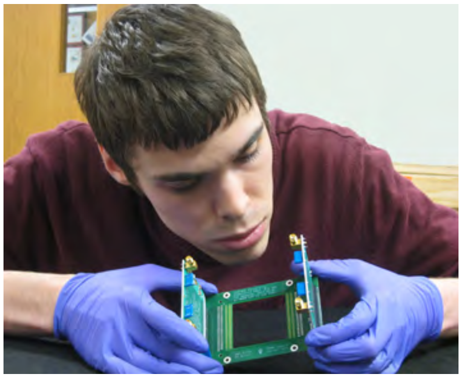

Figure 3. Graduate student Blake Wiggins inspects the second generation sense wire and delay boards.

SSAA funding has been critical in the development of this new detector. The student and postdoctoral researcher have gained valuable experience in computer-aided mechanical design, electronics, and high speed data acquisition. They are engaged in thinking at a fundamental level about the underlying physical phenomena and ramifications on the detector design and signal processing.

The overall concept of the detector is illustrated in Figure 1. A single electron incident on the surface of a Z-stack microchannel plate is amplified to a pulse of 10^7 or 10^8 electrons. This electron pulse with defined spatial and temporal characteristics is accelerated and passes through a harp of parallel wires mounted on a printed circuit board. As the electron pulse passes the wire plane, it induces a signal on the wires of the plane. Readout of this induced signal provides position information on the location of the electron pulse. By orienting a second wire harp with wires oriented orthogonally to the first harp, two-dimensional position information is obtained. After passing the two wire planes, electrons are collected on a metal anode behind the grids, providing a timing signal with sub-nanosecond time resolution.

To avoid reading out each sense wire in a sense wire plane independently, a delay line is utilized. Using this approach, the time difference of the signal arriving at the two ends of the delay line encodes the position of the induced signal. The number of signals to be processed is dramatically reduced also minimizing the electronics required. This reduction allows the use of high-speed digitizers and subsequent detailed signal analysis.

During the past year, we have designed, constructed, and commissioned a vacuum test station (see Figure 2), which provides an efficient means of testing the detector. We have characterized the performance of the first generation design which provides a position resolution of 466 μm for a single electron.[1] A small wire winding machine has also been constructed, enabling the efficient fabrication of the precision sense wire planes. Recently, we have designed a second generation system. This new design, as seen in Figure 3, provides independent readout of the odd and even wires in a sense wire plane. Readout of the odd and even wires for a single sense wire plane by two independent delay lines allows a differential measurement of the electron pulse as it passes by two wires. Simulations predict that this differential measurement should improve the position resolution. In the new design, the sense wire plane and delay boards are separated to achieve a more compact geometry. Final construction and characterization of this new system is underway.

Reference

[1] R.T. deSouza, Z.Q. Gosser, and S. Hudan, Rev. Sci. Instrum. 83, 053305, 2012.

Photo-Induced Precision Cross-Section Measurements of Actinide Nuclei Using Photon Beams

Duke University and the Triangle Universities Nuclear Laboratory
PIs: Calvin R. Howell, howell@tunl.duke.edu and Werner Tornow, tornow@tunl.duke.edu

Figure 1. A 3D rendering (left) of the experimental setup used for the NRF measurements and a photograph (right) of the setup with Brent Fallin, one of the graduate students in the collaboration. High-purity Germanium detectors are placed around the target to determine the γ-ray emission pattern.

Systems to assay the isotopes in materials remotely will use both passive radiation detection and beam-based technologies (neutron and/or gamma-ray (γ-ray) beams). This project will contribute to the databases used in γ-ray beam-based technologies and educate physicists in areas relevant to national nuclear security. Cross-section measurements are being made at the Triangle Universities Nuclear Laboratory (TUNL) on actinide nuclei for two types of γ-ray induced reactions, nuclear resonance fluorescence (NRF), denoted as (γ, γ'), and photo-neutron emission (γ, n). These data also provide nuclear structure information. The team consists of three graduate students, two postdoctoral researchers, and two faculty members supported in part by this grant. "This project provides graduate students and postdocs opportunities to conduct nuclear structure studies at the γ-ray intensity frontier using polarized beams. They develop expertise in high-resolution γ-ray spectroscopy, γ-ray activation measurements, neutron detection, and particle counting data acquisition. They are involved in concept development, experiment design and implementation, data analysis, interpretation, and dissemination of results," said Principal Investigator Calvin Howell.

The measurements use the TUNL's High Intensity Gamma-ray Source. New NRF measurements were made on ^{240}Pu and tests were conducted on ^{233}U. The beam is produced by Compton backscattering of photons from electrons inside the optical cavity of a free-electron laser in an electron storage ring. The γ-ray beams are linearly polarized and have an energy spread of about 5% full width at half maximum (fwhm) and a time structure with 300 ps fwhm wide pulses separated by 180 ns. The time structure enables rejection of backgrounds from the radioactivity of the sample, natural radiation in the room and cosmic radiation.

The NRF can locate and characterize nuclear states excited by dipole and quadrupole γ-ray transitions from the ground state. The approach is to survey dipole transitions over an energy range using a Bremsstrahlung-produced γ-ray beam followed by measurements at specific energies with a linearly polarized γ-ray beam with a narrow energy width. The latter measurements have higher sensitivity and provide determinations of the type of transition, electric or magnetic, using the linear polarization of the beam. Measurements were performed between 1.95 and 2.95 MeV in 0.10-MeV steps. The experimental setup is shown in Figure 1. Examples of energy spectra (backgrounds subtracted) of γ-rays detected at $\theta = 90°$ in the horizontal (blue) and vertical (red) detectors for the NRF measurements on ^{240}Pu are shown in Figure 2. The NRF process is indicated in the schematic energy level diagram of ^{240}Pu in Figure 2. The nucleus is excited from the ground state ($J^\pi = 0^+$) to either a 1^+ state by an electric dipole (E1) transition or a 1^- state by a magnetic dipole (M1) transition. The γ-ray absorption is represented in the diagram by the red arrow. The excited nucleus decays by the emission of γ-rays with an azimuthal angular dependence characteristic of the type of electromagnetic transition (E1 or M1). The asymmetry in the number of γ-rays detected in the horizontal detectors versus those in the vertical detectors provides the determination of the transition type and gives the parity of the excited state. For example, for M1 transitions, all γ-rays will be emitted in the direction of the horizontal detectors, as is the case for the states with excitation energies of 2,566 and 2,578 keV shown in Figure 2. These measurements confirmed the nine excited states observed by Quiter et al.[1] Also, we discovered two additional J=1 states, one at 2,444 keV and the other at 2,834 keV. All observed states were determined to have spin and parity of $J^\pi = 1^-$. Analysis of the data is continuing.

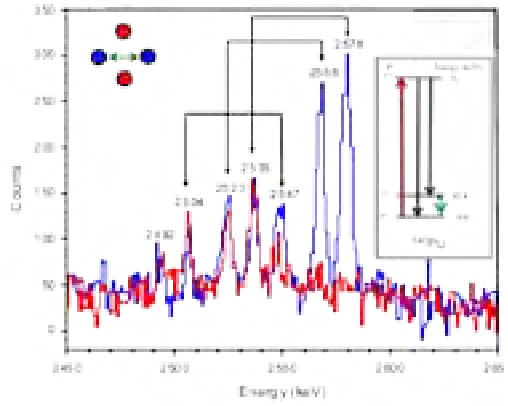

Figure 2. The measured energy spectra (background subtracted) of γ-rays detected at $\theta = 90°$ in the horizontal (blue) and vertical (red) detectors for NRF on ^{240}Pu using a γ-ray beam with centroid energy of 2.55 MeV. The insert is a schematic of the energy level diagram indicating the NRF technique applied to ^{240}Pu.

Reference

[1] B.J. Quiter et al., Phys. Rev. C 86, 034307, 2012.

The Center for High Energy Density Science at the University of Texas

University of Texas at Austin
PI: Todd Ditmire, tditmire@physics.utexas.edu

Introduction

The Center for High Energy Density Science (CHEDS) is an Academic Alliances-funded Center of Excellence at the University of Texas at Austin (UT). It was established in 2003 under the leadership of Professor Todd Ditmire in the Physics Department and now includes half a dozen UT faculty and nearly 40 students, postdoctoral researchers and staff scientists performing experimental research in high energy density plasma physics. The research mission of CHEDS is to execute experiments, supported by theory, on various properties and dynamics of plasmas and materials in the high energy density (HED) regime. CHEDS has traditionally focused on the use of high intensity ultrafast lasers for the creation and probing of HED plasmas, although we also perform experiments on various long pulse laser and pulsed power experimental facilities throughout the National Nuclear Security Administration (NNSA) complex. The principal goal of CHEDS is to train graduate students in the methods of experimental HED research, including how to lead and execute experiments on large-scale HED machines. CHEDS research tends to focus on three main thrusts: measuring the state properties of dense plasmas, shock and blast wave physics, and production of intense particle and photon sources through high field laser-matter interactions.

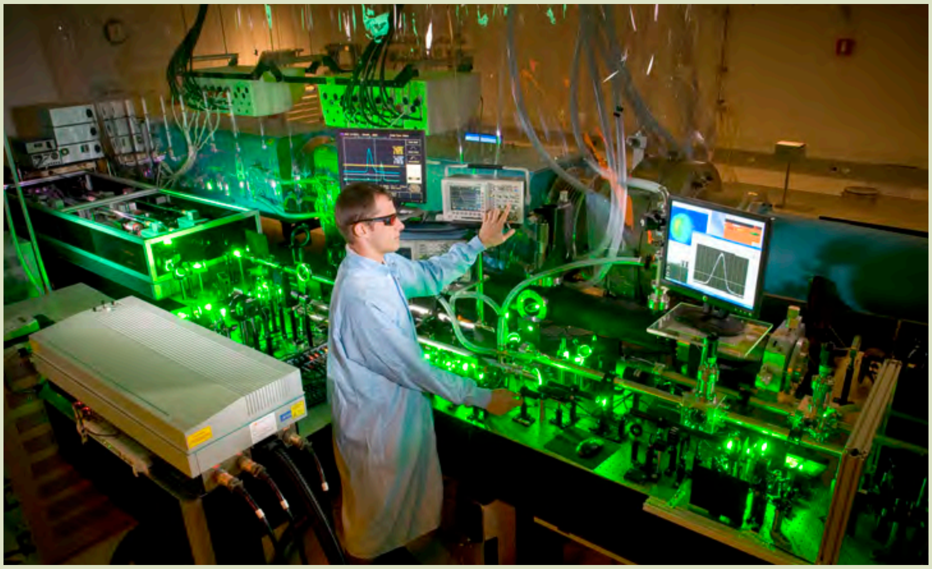

Figure 1. The Texas Petawatt Laser amplifier bay during Petawatt operations.

The Texas Petawatt Laser

On the UT campus in Austin, CHEDS operates a number of high peak power lasers to support its experimental research program, including multi-terawatt Ti:sapphire and Nd:glass lasers. The showpiece facility of our Center is the Texas Petawatt Laser (TPW) shown in Figure 1. This machine, which reached 1 PW (10^{15} W) of peak power in 2008, is presently the highest peak power laser in the United States and among the highest power lasers in the world. CHEDS staff and students constructed this laser using surplus amplifiers from the Lawrence Livermore National Laboratory (LLNL) NOVA laser and executed the project in close collaboration with scientists from LLNL. The parameters of the TPW are unique; the laser produces pulses with energy above 150 J with pulse duration under 150 fs, using special broadband "mixed Nd:glass" technology developed at UT. This laser, although it produces energy only 0.01% of the energy of the National Ignition Facility (NIF), yields peak power twice that of NIF because of the extremely short pulse duration. This enables experiments in HED science in very different regimes from those performed on the NNSA's large-scale HED lasers like NIF and Omega. A focused intensity of $>10^{21}$ W/cm^2 is regularly achieved, and 10 times higher intensities should be achieved in 2014 with a planned upgrade of the machine.

The TPW has become not only a critical driver of novel HED science experiments but also an excellent graduate student training facility, where students learn to plan, assemble and lead experiments on a large scale, low repetition-rate facility, preparing them for future experimental work on the NNSA's large HED experimental facilities. After initial trial experiments in late 2009 and 2010, the TPW commenced experimental campaigns under a collaborative user program led by the Texas Petawatt Facility Director Dr. Mike Donovan. Experiments are selected for time on the machine by a peer-review process. Since the beginning of 2011 to the present, the TPW has supported 28 experimental campaigns, each ranging in length from two to eight weeks. During this period, the TPW has operated reliably averaging about 35 weeks of experimental shot days per year. Each operations day yields six to eight full energy petawatt-level shots.

Science Highlights

The TPW has been the driver for a large number of completed and ongoing graduate students' theses projects. There have been a number of salient physics results produced on this machine over the past three years. Here, we can highlight just a few examples.

Recently experiments aimed at measuring the equation of state (EOS) of solid density copper at temperatures of 1 to 50 eV have been performed by recently graduated CHEDS graduate student Sam Feldman in a team led by Dr. Gilliss Dyer. Using the TPW, pulses of MeV protons accelerated from solid targets were used to heat solid density copper. Expansion rate measurements

> *"This laser [Texas Petawatt Laser], although it produces energy only 0.01% of the energy of the National Ignition Facility (NIF), yields peak power twice that of NIF because of the extremely short pulse duration. This enables experiments in HED science in very different regimes from those performed on the NNSA's large-scale HED lasers like NIF and Omega."*

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yielding the EOS from these targets have been compared to the latest Cu EOS models supplied to CHEDS by LLNL and Los Alamos National Laboratory (LANL) staff. One significant aspect of this kind of experiment is that it probes the EOS in a parameter range not accessed by traditional shock Hugoniot measurements. In another campaign recently concluded by student Woosuk Bang (who is about to begin a post-doctoral position at LANL), fusion neutron production from plasmas produced by TPW irradiation of a gas jet of deuterium clusters was examined. Here, a particularly exciting finding resulted from collaboration between CHEDS and students and staff from the Cyclotron Institute at Texas A&M University. By introducing ^{3}He into the cluster target, ion temperatures in excess of 25 keV were measured.

CHEDS has also had considerable success in recent years in the acceleration of particles to high energy in plasmas irradiated by the TPW. In a set of experiments led by faculty member Professor Mike Downer, the TPW was used to create a plasma-wave in a helium gas target, which accelerated bunches of electrons to energies above 2 GeV. This ground-breaking result captured, for a time, the world record in plasma acceleration of electrons. Professor Manuel Hegelich, who recently joined CHEDS and the faculty of the UT Physics Department, has led an experimental campaign on proton acceleration using the TPW. This CHEDS team then utilized these proton beams to generate large fluxes of neutrons. The latest TPW results demonstrate neutron production similar to the LANL Trident experiments. Other past and ongoing CHEDS-led experiments on the TPW include: 1) measurements of high Mach number blast waves in external magnetic fields produced by a 1 MA pulsed power device supplied by Sandia National Laboratories (SNL) in a collaboration between UT and SNL; 2) high power coherent extreme ultraviolet pulse production; and 3) relativistic laser intensity hole boring measurements.

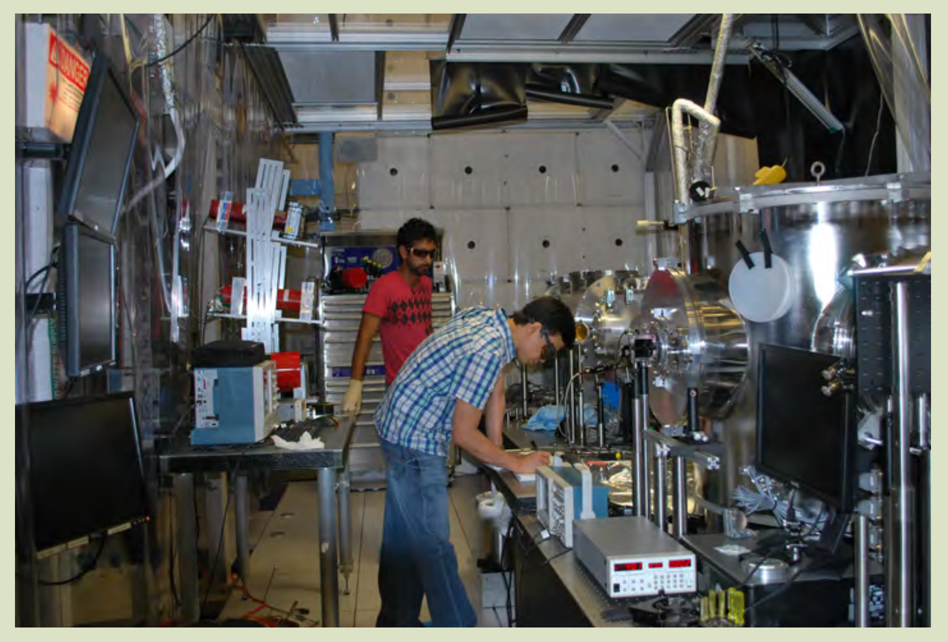


Figure 2. UT students preparing for cluster fusion experiments on Target Chamber 2 at the Texas Petawatt Facility.

Outside Use of the TPW

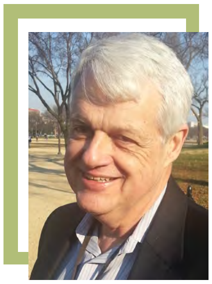
A particularly exciting aspect of the science program on the TPW has been the participation of numerous outside collaborators through the TPW User Program. Since 2010, experimentation on the TPW has included students, postdoctoral researchers and staff from Hebrew University, Los Alamos National Laboratory, Ohio State University, Rice University, and Texas A&M University. For example, CHEDS and Rice University students observed production of large numbers of positrons from gold targets irradiated by petawatt pulses. Future planned experiments will involve students from the University of California San Diego, and Ludwig Maximilian University of Munich, Germany.

Future Upgrade

The capabilities of the TPW continue to improve through various upgrades and diagnostic additions. CHEDS has a major upgrade of the laser planned in 2014 under funding from the Defense Advanced Research Projects Agency in which the temporal pulse contrast will be significantly enhanced though a redesign of the laser front end and relay imaging optical system. This upgrade should yield state-of-the-art temporal contrast. A second upgrade is also planned through funding from the U.S. Air Force Office of Scientific Research, in which an additional deformable mirror and focusing parabolic mirror will be installed to enable focused intensity well above 10^{22} W/cm^2. These upgrades will maintain the TPW as a unique international scientific resource.

Dr. Kirk Levedahl, Program Manager
High Energy Density Laboratory Plasmas

Q&As



What is the High Energy Density Laboratory Plasmas Program?

The High Energy Density Laboratory Plasmas (HEDLP) program is a joint program co-sponsored by the National Nuclear Security Administration (NNSA) and the U.S. Department of Energy Office of Fusion Energy Sciences (OFES) to support and steward basic research in the areas of high energy density physics in support of their respective mission areas. While the OFES program supports national laboratory researchers as well as industry research, the NNSA program is focused on supporting relevant science in the academic community. Although it has separate funding from the balance of the Stewardship Science Academic Alliances (SSAA) program, the NNSA regards its part of the HEDLP program as part of the overall SSAA program.

What is the role of the academic alliance programs in national security?

The NNSA has an enduring mission to support the credibility of our nuclear deterrent as a key component of our national security strategy. Our commitment to these security arrangements is essential to assuring many countries, closely allied, loosely allied or unaligned, to forego their own nuclear weapons development by relying upon the U.S. nuclear umbrella. Should the United States back away from its commitments, a possible outcome is the rapid proliferation of nuclear weapons around the world.

Although the United States has not ratified the Comprehensive Test Ban Treaty, we and the other principal nuclear weapons states observe the ban on nuclear testing. The United States has not tested since 1992, and it is in the national interest to maintain the credibility of our deterrent without further testing and ensure that the ban on testing is internationally accepted. It is also U.S. policy to improve national and international security by seeking mutual agreements to reduce the number and types of weapons in our stockpile.

Assuring credibility of our deterrent with fewer numbers and types challenges our ability to demonstrate the reliability of the remaining systems in the stockpile. This has to be satisfied while observing a second vital concern. If the credibility of our deterrent is critical, equally important is to ensure that not only U.S. weapons, but weapons anywhere in the world, are safe and secure against the accidental or unauthorized release of their potential for destruction or widespread radioactive contamination.

Assuring high reliability and at the same time absolute guarantees of safety in all the complex environments, normal or abnormal, to which a weapon may be subject is a supreme technical challenge. And this must be done without nuclear testing. The stockpile stewardship program seeks to do this by predicting performance in the broadest range of credible scenarios through computational modeling and experimental demonstration where feasible. This is and will remain an enormous scientific challenge requiring our best scientific talent and creativity from a vibrant scientific community. Also, we must understand developments in the international scientific community.

So, the academic alliances program is vital to the success of the NNSA in attracting new scientific talent, maintaining ties to the national and international scientific communities, and assuring that NNSA is maintaining the highest standards of scientific integrity and performance. The mission is too vital not to do so.

Why does NNSA support the disciplines that it does?

The NNSA's academic alliances program supports topical areas that are of special relevance to our mission and which are not well-supported by other government agencies or private industry. NNSA is the dominant U.S. government agency supporting high energy density science through its inertial confinement fusion program which maintains unique facilities, including NIF, Omega, and Z. Everything that happens after a nuclear system goes critical involves high energy density physics. The materials science we support is relevant to the unique materials choices relevant to nuclear weapons or conditions that are not experienced elsewhere. And low energy nuclear science is essential to understanding nuclear processes and radiochemistry vital to the broad range of NNSA missions, including state of the art techniques in instrumentation and measurement just as relevant to nonproliferation as to maintenance of the stockpile.

Why support development of an external community of technical peers?

It is essential to create a network of intellectual peers external to the nuclear security enterprise to provide independent scientific review of journal manuscripts and technical accomplishments within a science-based program. Academic researchers collaborate with national laboratory researchers for the general advancement of science, technology, engineering, mathematics and computation. A healthy external academic community challenges our laboratories technically, raising standards through competition, a critical component for world leading science programs.

I have an idea on how to improve NNSA's academic programs. How do I communicate it?

NNSA cannot succeed without the best ideas we can get and we welcome ideas for improving our program. You can submit your suggestions to Terri Stone at terri.stone@nnsa.doe.gov.

Physics of Pre-Plasma and Mechanisms of Intense Electron Beam Generation by Relativistic Laser Radiation

University of California, San Diego
PI: Sergei Krasheninnikov, skrash@mae.ucsd.edu

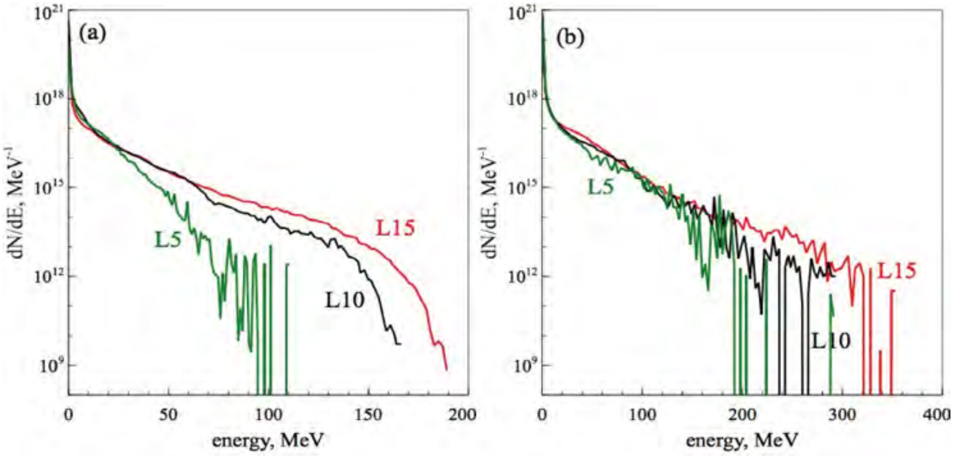


Figure 1. Numerically-simulated time integrated energy spectra of fast electrons passing through the extraction plane and entering the solid target with three different pre-plasma scale lengths (green: L = 5, black: L = 10, and red: L = 15 μm), for laser pulse duration of 1ps (Figure 1a) and 3ps (Figure 1b).

Our current collaboration with the National Nuclear Security Administration—in place for about one year—is focused on the study of the effects of pre-plasma on the generation of intense relativistic electron beams during laser-target interactions. It is a combined experimental and theoretical effort, involving both graduate students and postdoctoral researchers; currently one graduate student and one postdoctoral researcher are funded by the grant.

This grant allows for the thorough development and investigation, both experimental and theoretical, of a new idea proposed by the principal investigator. This is that, during laser–target interactions, a deep potential well can be formed in the pre-plasma and that this potential can play a crucial role in the generation of extremely energetic electron beams. The graduate students and postdoctoral researchers involved will benefit through their participation in a world-class, multi-laboratory scientific team, utilizing world-class experimental and computational facilities.

Laser-target interactions are used to generate beams of electrons. It has been known for some time that long scale-length pre-plasma forms in front of solid targets, and results in an increased electron beam energy.[1-3] However, the physical reasons for this effect were not fully understood. Recently, based on theoretical analysis and computational simulations, it has been demonstrated[4,5] that extremely energetic electrons can be generated through a synergistic effect between the laser-light electric field and the deep potential well formed in the pre-plasma.

To better understand the effect of the pre-plasma on electron beam generation, one-dimensional numerical simulations were performed using the Laser Simulation Plasma (LSP) code. Both the scale-length L and the laser pulse duration were varied in these simulations. The results show that for the short laser pulse (1 ps), the longer scale lengths of the pre-plasma lead to higher mean and maximum energies in the fast electron energy spectra. However, for the longer laser pulse (3 ps), this dependence becomes rather weak. Figure 1 shows time-integrated fast electron energy spectra for three different initial pre-plasma scale lengths, L = 5, 10, and 15 μm, and the two laser-pulse durations 1 ps (Figure 1a) and 3 ps (Figure 1b). For the 1 ps case, Figure 1a shows the shape of the spectrum changes dramatically with L: there is a significant increase in both the fast electron temperature (i.e., high-energy component) and maximum energy as L is increased. However, for the 3 ps pulse length results shown in Figure 1b, the fast electron energy spectra become almost independent of the initial pre-plasma scale-length L. This is explained by a significant thermal expansion of the heated pre-plasma on a multi-picoseconds time scale, which makes the effective scale-length of the pre-plasma independent of its initial value (within the range of L considered). These numerical findings will be validated using two experiments, at both the Texas Petawatt Laser at the University of at Texas at Austin and the Titan Laser at the Lawrence Livermore National Laboratory. In these experiments, the pre-pulse level and laser pulse length will be systematically changed and their effect on electron spectra and temperature will be determined. In addition, the electric field in the pre-plasma will be measured using a proton probe, generated by a short pulse laser.

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Viscous Plastic Flow at Extreme Pressures and Strain Rates

California Institute of Technology
PI: G. Ravichandran, ravi@caltech.edu

Research on viscous plastic flow at extreme pressures and strain rates at the California Institute of Technology (Caltech) is being supported by the National Nuclear Security Administration's High Energy Density Laboratory Plasmas (HEDLP) program. Two graduate students are collaborating with the Lawrence Livermore National Laboratory (LLNL) on this research. In addition, a postdoctoral scholar conducted laser experiments at the University of Rochester Laboratory for Laser Energetics (LLE), and a research scientist and a Stewardship Science Graduate Fellowship Program-supported graduate student performed multiscale modeling of experiments.

The grant from the HEDLP program has enabled the scientists and students at Caltech to participate in advanced laser experiments and multi-scale modeling to understand the behavior of materials at extreme pressures and strain rates. This grant has helped foster collaborations between Caltech and LLNL scientists in the area of high energy density hydrodynamics and warm dense matter.

A fascinating new regime of science, viscous plasticity at ultrahigh pressures well in excess of 100 GPa (1 Mbar) and strain rates in excess of 10^7 s^{-1}, has started to become an experimental reality. The combination of both very high pressures and ultrahigh strain rates makes this frontier regime of material science fascinating, exceedingly challenging, and potentially of very high impact to the world-wide inertial confinement fusion (ICF) and inertial fusion energy (IFE) effort. The goal of the research is to develop the science needed to enable the use of advanced solid-state materials in high-gain capsules for IFE. It is proposed to use material strength at high pressure to limit the development of hydrodynamic instabilities that could limit achieving ICF. Similar to fluid viscosity, strength resists instability development, and the effect of material strength is expected to be significant. Unfortunately, material strength in the ultra-high pressure (TPa) regime has never been measured, and until the recent development of ultra-high pressure shockless compression on laser platforms, such measurements were not even contemplated.

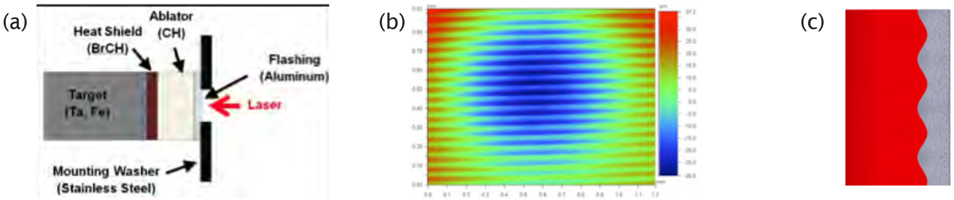


Figure 1. (a) A diagram of the experimental setup for investigating Richtmyer-Meshkov instabilities in metals. (b) A post-shot surface profile measurement of the ripples. Plotted are contours of ripple height in mm. The samples axes are in mm. (c) A computational simulation of Richtmyer-Meshkov instability driven ripple. Ripple spacing is 50 mm and peak to valley height is 10 mm.

Figure 2. Graduate students Zach Sternberger (far left) and Brandon Runnels (far right) discuss the multiscale modeling of Richtmyer-Meshkov instability laser experiments with Professors. G. (Ravi) Ravichandran and Michael Ortiz.

To understand the behavior of materials at extreme conditions of pressure and strain rate, laser driven shock compression experiments (see Figure 1(a)) were conducted on rippled targets of tantalum (Ta) at LLE (see Figure 1(b)) in collaboration with scientists from LLNL. These shock compression experiments explore complimentary regimes of states of matter studied in previous shockless compression Rayleigh-Taylor instability experiments. The precision rippled targets were fabricated by General Atomics (GA) and assembled in a recovery tube. The ablator was subjected to a laser beam from OMEGA, which launched a shock into the rippled target. This resulted in the Richtmyer-Meshkov (RM) instability in Ta causing the growth of the ripples. By comparing the amplitude of the ripples before and after being subjected to the high-pressure shock, a growth factor is computed. Experiments were conducted at various laser energies (pressures) and the corresponding growth factors were computed. Simulations of the ripple growth in Ta (see Figure 1(c)) were performed using a material model for high-strain rate behavior. The growth factors were compared to the simulations, allowing the strength of Ta at high pressures and strain-rates to be inferred. The interaction between experimentalists and computational scientists at Caltech (see Figure 2) and LLNL in studying the hydrodynamic instabilities has advanced the understanding of the role of strength on the RM instability in body centered cubic metals such as Ta.

This multi-institutional collaboration between Caltech, LLNL, and GA has enabled the education and research of graduate students and postdoctoral scholars in the area of high energy density hydrodynamics and associated instabilities. This has provided a unique opportunity for training the next generation of scientists in high energy density physics in national laser facilities and in multiscale modeling of materials under extreme conditions.

Talbot-Lau X-ray Phase-Contrast Diagnostic for High Energy Density Laboratory Plasmas

Johns Hopkins University
PI: Dan Stutman, stutman@pha.jhu.edu

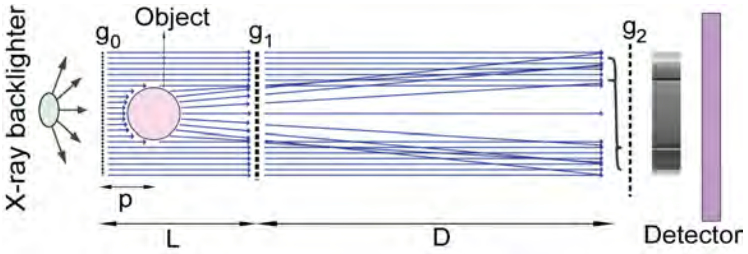


Figure 1. The essential elements of a high magnification Talbot-Lau interferometer; typical L ~25 cm and D ~100 cm.

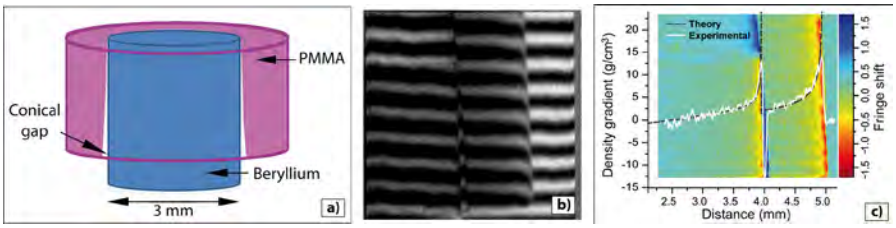


Figure 2. (a) The components of the test object for TL Moiré deflectometry. (b) A Moiré fringe image of the test object at 17 keV mean energy and a magnification of 15. (c) An experimental fringe shift map and density gradient profile of the test object. The theoretical profile computed with an x-ray wave propagation code is also shown, indicating very good agreement with the experiment.

With support from the National Nuclear Security Administration's (NNSA) High Energy Density Laboratory Plasmas (HEDLP) Program, the Plasma Spectroscopy/Diagnostic group at Johns Hopkins University (JHU) is developing a new method for diagnosing density gradients in high energy density (HED) plasmas, namely x-ray phase-contrast imaging with Talbot-Lau (TL) grating interferometers. The TL technique is currently explored for medical radiography of soft tissues in the human body. The method is attractive as an HEDLP diagnostic because it can work with spatially incoherent and polychromatic x-ray backlighters, directly measure electron density gradients without any assumptions about the plasma, and simultaneously measure x-ray refraction, attenuation, and small-angle scatter.

The NNSA grant has enabled us, in the first year, to develop the TL method from that required for medical imaging (low magnification, high x-ray energy, and multiple exposures), to the high magnification, low x-ray energy (<20 keV), and single exposure setup required for a HEDLP diagnostic. The grant is currently supporting a young postdoctoral fellow, while our beginning HEDLP work is eliciting interest among the JHU graduate and undergraduate students, whom we hope to engage in this research.

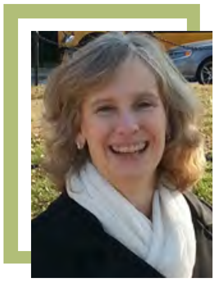
The measurement of electron density gradients in HEDLP is challenging due to the small spatial scales, the short time scales, the large densities/density gradients, and the extreme radiation environment involved. A particularly difficult example is the diagnosis of imploding inertial fusion energy capsules, where the gradients of a sub-millimeter size, multi-material plasma compressed to many times the solid density, need to be characterized with spatial resolution of the order of 10 µm. Attenuation-based x-ray radiography has insufficient contrast for low-Z HED plasmas, because at the x-ray energies needed to penetrate dense plasmas, the attenuation coefficients are small. X-ray refraction or differential phase-contrast offers a stronger contrast mechanism for HEDLP radiography than attenuation, since for low-Z matter, the real part of the complex index of refraction δ, is much larger than the imaginary part, β.

The elements of a high magnification TL grating interferometer are shown in Figure 1. The first grating g_0 serves to convert the spatially incoherent backlighter into a quasi-coherent x-ray source. The second grating g_1 produces through the Talbot effect a micro-periodic fringe pattern at the location of the third grating, g_2. A refracting object placed in the beam shifts this fringe pattern, producing intensity changes behind g_2 proportional to the refraction angle.

The adaptation of the TL technique to a system suitable for a HEDLP diagnostic has been very successful. The laboratory study demonstrates it is possible to achieve high fringe contrast and high refraction angle sensitivity, at the high magnifications needed for high spatial resolution. To enable the refraction, attenuation, and scatter information to be obtained simultaneously from a single x-ray radiograph, we developed a Moiré fringe deflectometry technique using the TL interferometer. Figure 2a shows the test object used, intended to simulate typical density gradients and material interfaces in low-Z HED plasma. It consists of concentric cylinders of acrylic and beryllium, with a small air gap in between. Figure 2b shows the Moiré fringe image of this test object obtained with an 80 µm spot x-ray source of ~17 keV photons, and a magnification of ~15. Clear fringe shifts are seen at the interfaces between the materials, as well as within the bulk materials. The areal density gradient map obtained with a Fourier fringe analysis code, using as a reference the image without the object, shown in Figure 2c. This indicates that using TL Moiré deflectometry, it will be possible to accurately measure density gradients in HED plasmas with high spatial resolution. Future work will extend the TL technique to x-ray energies below 10 keV, study refraction imaging with two-dimensional gratings, and demonstrate phase-contrast imaging with a laser backlighter.

Lois Buitano, Program Manager
National Laser Users' Facility Program

Q&As



What is the National Laser Users' Facility Program?

The National Laser Users' Facility (NLUF) Program provides funding and experimental time on the Omega Laser Facility at the Laboratory for Laser Energetics, University of Rochester, to academic and business researchers. The National Nuclear Security Administration's (NNSA's) Office of Inertial Confinement Fusion funds the facility operations for NLUF, making it possible for researchers to conduct experiments without a direct facility charge. NNSA provides research funds directly to users for experiments in inertial fusion and related scientific areas and funding for target fabrication. All proposals are peer-reviewed by the NLUF Steering Committee (outstanding scientists from universities, industry, and government), which ranks them according to scientific merit. NLUF has had 329 submittals and 176 approved proposals since its founding.

Since 2001, 180 students (including 100 graduate students and postdoctoral researchers) have been funded and more than 700 presentations and publications have resulted from this work. Fifteen of the graduate students have been hired by NNSA national laboratories. A solicitation is held every two years, with $1.6M to support users and about $900K for target support per year. The next solicitation for NLUF proposals will be held early in 2014 for fiscal year 2015 and 2016.

The NLUF Program began in 1979 and is the oldest of the Academic Alliances programs. Some associate the beginning of High Energy Density (HED) Laboratory science with the start of the NLUF Program.

Why do research using lasers?

Since the invention of the laser in 1960, research using lasers has resulted in applications that have changed our lives. Lasers are used in medical applications to kill tumors and perform eye surgery, and in industrial and commercial applications such as laser welding and lithography. The Omega Laser Facility and the National Ignition Facility are high energy and high intensity lasers. They concentrate huge amounts of energy into very small volumes for very short times, creating extreme, high energy density, states of matter—and exciting research opportunities.

What kind of research is being done on the Omega Laser Facility through the NLUF Program?

Experiments have been conducted in inertial confinement fusion, plasma physics, x-ray laser physics, extreme ultraviolet spectroscopy, laboratory astrophysics, planetary science, equation of state measurements and other materials properties in extreme conditions, and instrumentation development.

What new capabilities are available on the Omega Laser Facility?

One new capability available now on OMEGA is the magneto-inertial fusion electrical discharge system (MIFEDS) that enables magnetic fields to be used in HED plasma research. The MIFEDS is a compact pulsed-power system that discharges a capacitor through a set of coils that are wound on a three-dimensional printed mandrel. Field strengths of 10^5 Gauss can be generated as seed fields for experiments and with laser compression they can be increased 500 times. These fields can be used to study many effects, including magnetic reconnection, the process that governs solar flares. A fourth harmonic (260 nm wavelength) probe beam has been recently commissioned on the OMEGA EP laser system. Its first use was to measure the electron density profile in high energy density plasmas. New capabilities are continually being added to the Omega Laser Facility. Many improvements have been as a result of recommendations from the Omega Laser Users Group (OLUG).

What is OLUG?

OLUG was formed by users of the Omega Laser Facility in 2008 to facilitate communication and exchanges among the users of OMEGA, from the users as a group to the facility, and from the users to the broader scientific community. The chair of the OLUG Executive Committee is Dr. R.D. Petrasso of the Massachusetts Institute of Technology. Every year, OLUG organizes an annual 2.5 day workshop, held at the end of April in Rochester, NY. There are two major goals of the workshop: first, to define improvements to the capabilities and operation of the facility that would advance research opportunities for a broad cross-section of the users; this takes the form of Findings and Recommendations that the users generate and then present to the facility management. A second major goal of the workshop is to provide an opportunity for young researchers—students, postdoctoral researchers, and recent PhDs—to present their research in a very interactive yet informal setting. NNSA has provided funding for student/postdoc travel to the workshop. OLUG also meets annually at the Division of Plasma Physics meeting in the fall, to reassess its Findings and Recommendations and to discuss with management progress towards their implementation. Membership is open to anyone that uses or aspires to use the Omega Laser Facility, with currently 340 scientists and students from 35 universities, 27 centers and national labs, and 13 countries.

How does the NLUF Program support Stockpile Stewardship?

NLUF supports the Stockpile Stewardship Program in several ways. It provides a training ground for future stockpile stewards. It engages university and business scientists in research of interest to NNSA, enabling them to provide peer review of NNSA's activities, and it can lead to new platforms and diagnostics that support NNSA's HED needs.

Richtmyer-Meshkov Experiments by the Center for Laser Experimental Astrophysics Research

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

The Center for Laser Experimental Astrophysics Research (CLEAR) at the University of Michigan performs research in high energy density (HED) physics that is also relevant to astrophysics. Our specific focus is the study of phenomena involving shock waves and supersonic flows, and the development of x-ray diagnostics for such studies. Through our research, we train students in science relevant to the National Nuclear Security Administration's (NNSA) mission. The Center and its smaller, precursor research programs have collaborated with NNSA laboratories continuously since 1996. We have seven PhD students pursuing degrees with us. In the past five years, we have graduated eight PhD students. Four of our PhD graduates and one MS graduate have worked at NNSA laboratories. In addition, we involve 15 to 20 undergraduates in our research each year. "The Stewardship Science grant program has enabled us to observe many new phenomena in high energy density systems. The students involved are energized by the connections of our work to astrophysics and by the relevance of their training to inertial confinement fusion," said Professor Drake, the Project Director.

A highlight of the Center's research this year has been the success of experiments to observe novel aspects of the Richtmyer-Meshkov (RM) process, which occurs in any system having shock waves that cross boundaries between materials. A major challenge in understanding shock-driven hydrodynamic instability in HED systems is that the hydrodynamic time scale for these systems (tens of ns) often exceeds the time scale on which HED facilities are capable of supplying them with energy. As a result, experiments often produce continually changing shock conditions, making it difficult to elucidate the effects of the processes at work. A novel experimental platform has been designed at the University of Michigan, taking advantage of the capabilities of the OMEGA-EP laser, to drive and diagnose HED hydrodynamic behavior under steady shock conditions. The first experiment to use this new platform, exploring nonlinear RM dynamics, is discussed here.

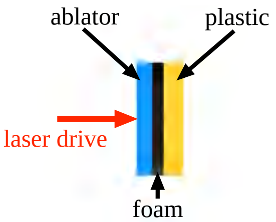


Figure 1. A schematic of the central components of the Richtmyer-Meshkov experiment. The laser irradiates the left edge of the ablator, driving a rightward-propagating shock through the system.

The physical system has as its core components a layer of plastic of density 1.4 g/cm^3 pressed against a layer of carbon foam of lower density, typically 0.05-0.4 g/cm^3. This provides the desired density ratio at the plastic/foam interface. A seed perturbation can be machined at the surface of the plastic at this interface, allowing for precise characterization of the initial conditions from which structure later grows. In the RM experiment, the layers are oriented as shown in Figure 1, with the inclusion of a plastic ablative layer designed to avoid direct laser irradiation of the foam. A dual-mode, sinusoidal perturbation (superposed 50 and 100 μm wavelengths) permits observation of nonlinear mode interaction under the simplest possible conditions.

Two OMEGA-EP beams (351 nm wavelength) irradiate the ablator sequentially, producing an irradiance of roughly 4x10^{13} W/cm^2 for a duration of about 18 ns. This drives a shock into the system, and permits a period of roughly 20 ns during which the system evolves hydrodynamically without experiencing shock-decay effects. This is sufficient to drive RM well into the nonlinear regime. Radiography using the OMEGA-EP Spherical Crystal Imager (SCI) is the primary diagnostic. Figures 2a and 2b show examples of SCI data with and without a seed perturbation.

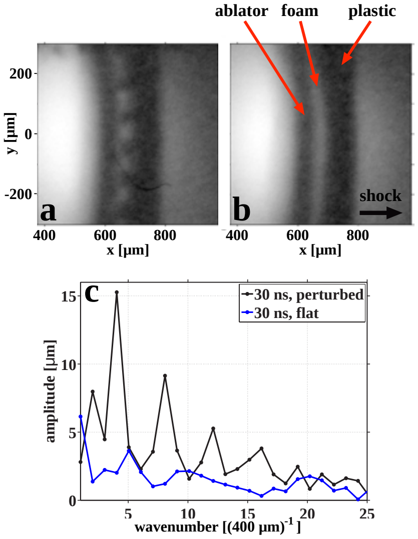


Figure 2. Data and analysis from the RM experiment. Parts (a) and (b) show data from shots with and without the machined seed perturbation, respectively. Both images were taken roughly 13 ns after the shock crosses the foam/plastic interface. Part (c) shows the Fourier transform of the foam/plastic interface contour, demonstrating the growth of the initial modes of wavenumber k=4 and k=8, corresponding to 100 μm and 50 μm wavelengths, respectively, as well as the appearance of harmonic modes k=4+8=12 and k=12+4=16, corresponding to wavelengths of 33 μm and 25 μm, respectively.

The main goal of this experiment is to observe the theoretically predicted coupling of the two initial modes, including both the resulting effect of each mode on the other's growth and the appearance of new, harmonic modes. This is accomplished by Fourier analysis of the interface contour. Figure 2c shows the interface spectra from the data in Figures 2a and 2b, highlighting the growth of RM structure due to the presence of the initial perturbation.

CLEAR is funded through a grant awarded as part of the High Energy Density Laboratory Plasmas Program. Richtmyer-Meshkov experiments on OMEGA and support for the research is provided through an NLUF Program grant.

Journey to the Center of Jupiter: Recreating Jupiter's Core at OMEGA

University of California Berkeley
PI: Raymond Jeanloz, jeanloz@berkeley.edu

To understand the formation and interior evolution of giant planets like Jupiter, Saturn, Uranus, Neptune, and extra-solar bodies, Raymond Jeanloz and his collaborators from Lawrence Livermore National Laboratory (LLNL), Commissariat à l'énergie atomique (CEA), and the Laboratory for Laser Energetics (LLE), University of Rochester, have conducted more than 200 shots on the Omega Laser Facility (at LLE) over the past decade. They have used the National Laser Users' Facility program to develop new techniques coupling static compression with laser-driven shock waves, applying velocimetry and optical pyrometry diagnostics to measure the equations of state and optical properties of planetary materials.[1-4] Increasing the initial density before dynamic compression by pre-compressing the sample in a diamond anvil cell reduces the shock heating and, therefore, accesses uncharted regimes of pressure, density and temperature. This effort has benefited more than eight graduate students and researchers at the University of California, Berkeley, including two current PhD candidates.

The team has been documenting the metallization of hydrogen and helium, as well as the hydrogen-helium mixtures making up giant planets, under the extreme conditions of pressure (several millions of atmospheres (Mbar)) and temperature (several thousand degrees Kelvin) that not only exist deep inside planets, but are also relevant for inertial confinement fusion (ICF) and applied science. Hydrogen and helium fluids metalize at very different conditions, such that over a limited range of pressures and temperatures, the two constituents can separate, with helium sinking toward the center of the planet because of its higher mass. This separation is thought to be an important source of energy inside Saturn, controlling its evolution over the past 4.5 billion years.

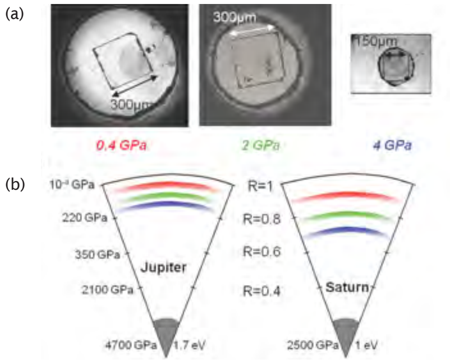


Figure 1. (a) Change in pressure-chamber dimensions within the diamond anvil cell targets, documenting how design improvements over the past years allow higher precompressions than ever. (b) Achieving higher precompression allows studying fluids at pressure-density-temperature conditions relevant for deep regions inside Jupiter and Saturn: the color scale relates the initial pressure to the depth within the planets that can now be recreated using OMEGA.

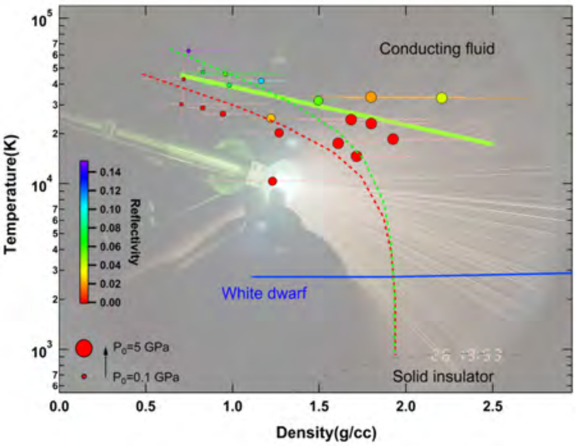


Figure 2. Change in optical reflectivity representative of the metallization (color scale) of warm dense helium as a function of temperature and density. New data for shock-compressed helium up to a final density of 2 g/cc along the Hugoniot, starting at 5 GPa precompression, are reported together with data from 2010 obtained with sample precompressions up to 1.1 GPa.[2-3] Note that the symbol size is proportional to the initial pressure. Preliminary analysis of the new dataset indicates that the metallization density may exceed 5 g/cc (solid green line, guide to the eye), in contrast with previous estimates (dotted lines: Drude model fit to older data).

Ultrafast Doppler velocimetry (VISAR) and streaked optical pyrometry (SOP) yield the pressure-density-temperature equations of state and optical properties of shock-compressed fluids, starting from initial pressures ≥ 5 GPa (50,000 atmospheres). The new measurements in very dense plasmas of hydrogen now approach the degeneracy and correlation conditions of Deuterium/Tritium along the ICF compression path, and do not show a significant density change on metallization (e.g., plasma phase transition). They can be compared with previous explosive-driven compression measurements,[5] with the nature and magnitude of a density jump on metallization being of particular importance for comparisons with theory.

Experiments on pre-compressed helium, combined with earlier measurements,[2-3] reveal a metallization condition above 5 g/cc, in fair agreement with recent *ab-initio* predictions.[6]

Work on methane, water, and nitrogen reveals important changes in chemical bonding as the fluid state is compressed, and is directly applicable to "ice" giants such as Uranus and Neptune. The experimental results support previous suggestions that carbon may be condensing as diamond "hail" deep inside such planets.

Collaborators

Stephanie Brygoo and Paul Loubeyre (CEA, France), Marius Millot (UC Berkeley), Peter M. Celliers, Jon H. Eggert, Sebastien Hamel, J. Ryan Rygg and Gilbert W. Collins (LLNL), and Thomas R. Boehly (LLE).

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Studies of HED Plasmas, Inertial Confinement Fusion Implosions, and Nuclear Science for Astrophysics

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

The High Energy Density Physics (HEDP) Division of the Massachusetts Institute of Technology (MIT) Plasma Science and Fusion Center has participated in the National Laser Users' Facility (NLUF) Program since 1999, performing a wide range of experiments in inertial confinement fusion (ICF) and HEDP at the Omega Laser Facility. During that period, there have been 18 graduate students and 28 undergraduate students involved with the program; four of the graduate students became scientists at the Lawrence Livermore National Laboratory. During 2013, there were seven graduate students, three undergraduate students, and one postdoctoral fellow in the group. Two of the students completed their PhD theses this year: Nareg Sinenian, "Fast-Ion Spectrometry of ICF Implosions and Laser-Foil Experiments at the Omega and MTW Laser Facilities," and Mario J.-E. Manuel, "Rayleigh-Taylor-Induced Electromagnetic Fields in Laser-Produced Plasmas." For this and other work, Mario received a National Aeronautics and Space Administration Einstein Post-Doctoral Fellowship. Two of the other students gave invited talks on this material at the 2013 American Physical Society, Division of Plasma Physics conference. Hans Rinderknecht presented "Observations of Kinetic Effects in Shock-Driven Implosions," and Michael Rosenberg presented "Studies of Asymmetric Magnetic Reconnection Using Laser-Produced Plasmas."All of the students base a large fraction of their research, publications, and thesis content on NLUF experiments at the Omega Laser Facility and on laboratory work at MIT that supports the NLUF experiments (such as the complete updating of an accelerator and the use of that accelerator for developing diagnostic instrumentation). National Nuclear Security Administration support is crucial in enabling this student research, as well as the research and student training carried out by the MIT scientists in the Division.

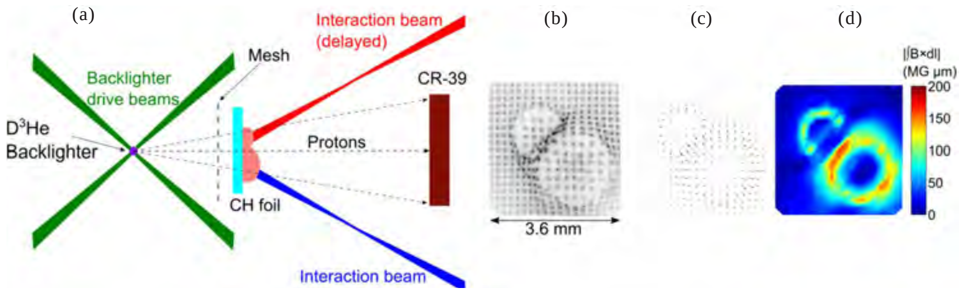

Figure 1. (a) 15-MeV-proton-radiography setup used in asymmetric magnetic reconnection experiments. Two plasma bubbles were formed on a CH foil at two different times by a pair of laser beams that arrived at the foil 0.7 ns apart. From the proton radiograph (b), the displacements of the individual proton beamlets at the imaging detector (c) were used to calculate a map of local field strength (d). Magnetic reconnection resulted in diminished field energy where the two plasma bubbles collided. These results bear on the physics of high-β, driven asymmetric reconnection such as that at the Earth's dayside magnetopause.

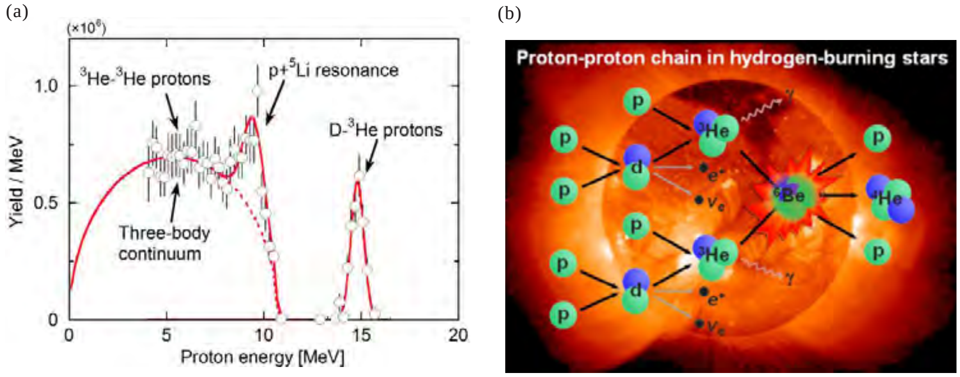

Figure 2. (a) The first preliminary ^{3}He-^{3}He proton spectrum ever obtained using a plasma (OMEGA shot 61252, with a ^{3}He-gas-filled exploding pusher), measured with MIT-developed compact proton spectrometers. Both the three-body continuum and the P+^{5}Li resonance at 9.3 MeV are observed at an average Gamow energy of ~95 keV. This measurement is directly relevant to first-generation, hydrogen-burning Population III stars, which were responsible for the first synthesis of heavy nuclei in the universe. Understanding the evolution of these stars will be critical for calculations of later stellar and galactic dynamics. (b) The proton-proton (pp) chain that took place in Population III stars, at conditions very similar to those in our ^{3}He-^{3}He experiments, also takes place in hydrogen-burning stars like our Sun. These stars were responsible for the first synthesis of heavy nuclei in the universe. Understanding their evolution will be critical for calculations of later stellar and galactic dynamics. These stars will be studied by other groups using the James Webb Space Telescope.

Topics studied this year at the OMEGA and OMEGA-EP lasers and already published include the imaging, identification and measurement of electric and magnetic fields generated in direct- and indirect-drive ICF plasmas and other laser-generated plasmas, and measurement of ICF performance and fusion products. Data acquired in fiscal year 2013 and currently under analysis bear on a range of topics, including magnetic reconnection (see Figure 1), plasma kinetic effects in ICF implosions, the behavior of plasma jets, the stopping of ions in plasmas, cross sections of nuclear reactions relevant to stellar nucleosynthesis (see Figure 2), and development of new diagnostics.

The success and relevance of MIT's NLUF work during the last decade is reflected in the fact that Principal Investigator R. Petrasso received this year's Edward Teller Medal for his division's work in ICF and HEDP. A large fraction of that work was done at the Omega Laser Facility, and much of that was directly sponsored by NLUF.

Generation of Collisionless Shocks in Laser-Produced Plasmas

Princeton University
PI: Anatoly Spitkovsky, anatoly@princeton.edu

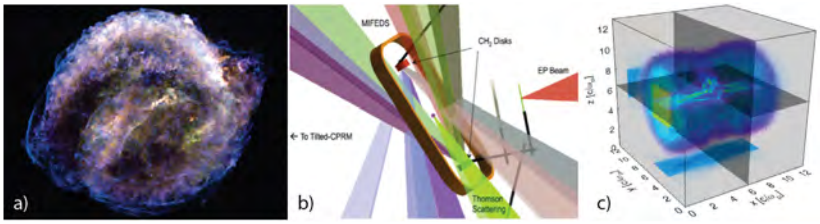

Figure 1. a) X-ray image of Kepler supernova remnant that displays thin blue rims of synchrotron emission from electrons accelerated in the collisionless forward shock driven by the remnant expansion; b) experimental setup for colliding flow interaction at OMEGA; c) visualization of plasma density from 3D PIC simulation of unmagnetized beam interaction, showing flow filamentation at late times.

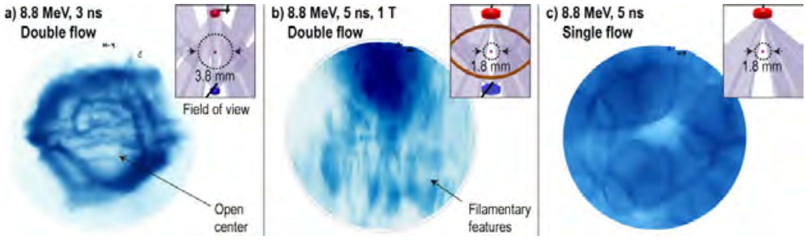

Figure 2. Proton radiography images of interacting a,b) and single flow c), showing the different morphologies of bubbles and filaments obtained as flows interact. Late-time filamentation in counterstreaming flows in b) is indicative of first phases of shock formation through Weibel instability.

This National Laser Users' Facility (NLUF) project studies the creation of collisionless shocks in counter-propagating laser-produced plasmas. Collisionless shocks are very common in astrophysical and space plasmas and occur when the mean free path for Coulomb collisions is large compared to the size of the shock transition. The shock is mediated by collective plasma effects due to interaction between plasma particles and self-generated electromagnetic fields. Collisionless plasma conditions can now be created at OMEGA and OMEGA-EP lasers at the Laboratory for Laser Energetics (LLE), University of Rochester, where laser-driven ablated plasmas propagate at speeds of ~1000 km/s and densities of ~10^{18-19} cm^{-3}. The experiments in this program collide two streams of high-speed plasma and study the formation of shocks as a function of externally applied magnetic field. In collaboration with researchers at Lawrence Livermore National Laboratory and LLE, this project combines experiments with particle-in-cell (PIC) modeling of the flow interaction and diagnostics. The project has supported one Princeton undergraduate student, one graduate student, and one post-doctoral fellow since 2011.

"Shock waves driven by supernova explosions (Figure 1a) accelerate energetic electrons, produce cosmic rays observed on Earth, and can strongly amplify interstellar magnetic fields. How this happens depends on complicated plasma physics of the shock transition, and is not well understood. NLUF support allows us for the first time to study the astrophysical shock formation processes in controlled laboratory conditions and to develop a new platform for laboratory astrophysics with intense lasers," said Dr. Spitkovsky.

The experimental setup is shown in Figure 1b. Nanosecond laser beams ablate CH$_2$ plastic targets 8mm apart, and the resulting high-speed flow interaction is diagnosed with Thomson scattering and proton radiography, using protons provided by OMEGA-EP short-pulse laser. External magnetic fields up to 10 T are applied using a current coil. The experiment and diagnostics are modeled using three-dimensional (3D) PIC simulations (Figure 1c). The theoretical expectation is that at low external fields the shock is mediated by the filamentation (Weibel) instability, while at higher fields magnetic reflection of ions will form the shock. These regimes are representative of the conditions encountered in a range of astrophysical environments, including supernova remnant shocks and solar wind shocks.

Figure 2 shows the proton radiography images of interacting flows obtained at two times during the collision (panels a, b) and a comparison with a single flow (panel c). Electromagnetic fields generated during the interaction deflect probe protons and result in caustic formation in proton images. Colliding flows produce rich morphology of self-organized electromagnetic field structures,[1] including early time bubbles and late time filaments. Modeling with PIC simulations confirms that the observed filaments are consistent with the early stages of shock formation via Weibel instability,[2] thus allowing a direct probe of magnetic field generation in collisionless shocks. Current efforts include varying the strength and geometry of external magnetic field to see the transition to magnetized shocks, and on scaling the experiment for future shots at the National Ignition Facility.

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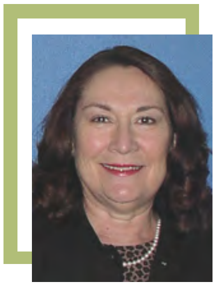
Lucille Gentry, Program Manager
Predictive Science Academic Alliance Program

Q&As



What is 'predictive science'?

Predictive science is the application of verified and validated computational simulations to predict behavior of complex systems where routine experiments are not feasible or are prohibitively expensive. The National Nuclear Security Administration (NNSA) established the Predictive Science Academic Alliance Program (PSAAP) to support fundamental science at universities leading to advances in this emerging field. This is cutting-edge science, blending knowledge from computer simulations, computational science, scientific domains and experiments, and improving our understanding about many types of uncertainties. Predictive Science for PSAAP requires demonstrating science/engineering research resulting in a verified and validated full system predictive simulation.

The PSAAP II Centers will develop science/engineering models and software for large-scale simulations, and methods in emerging disciplines of verification and validation (V&V) and uncertainty quantification (UQ); computer science research will also focus on resolving issues on the path to exascale computing. An overall goal for V&V and UQ is to help scientists make precise statements about their degree of confidence in their simulation-based predictions.

We need predictive science to improve overall understanding, and our ability to respond to "what if" scenarios in areas as diverse as national security (e.g., three-dimensional simulations of observed weapon's aging problems at appropriate resolution), climate change (e.g., hurricane prediction), nuclear energy (e.g., nuclear fuel cycle replacement modeling) and materials science (e.g., design and production of new materials with unique characteristics).

What sort of problems are you trying to solve?

The PSAAP II funds two types of Centers. Multiscale Simulation Centers (MSCs) select an overarching multidiscipline, multiscale science/engineering challenge. The overarching problem for an MSC should advance predictive science (e.g., predict a range of phenomena, over a wide range of space- and time-scales, with improved predictive accuracy and reduced uncertainty) in a multidisciplinary, 3D integrated application, multiscale in space and time and enabled by exascale computing. Overall, the advance may require a combination of progressions in a potentially exascale-enabled piece of science, integration science or UQ science, together with wider use of state-of-the-art V&V techniques.

Each Single Discipline Center (SDC) focuses on scientific advances for a problem or challenge in one discipline that is multiscale (in space and time) and is expected to be enabled by exascale computing. The Center's proposed technical advance must be compelling and significant, and make use of state-of-the-art verification, validation and uncertainty quantification techniques.

Both types of Centers are required to perform work that will contribute to development of effective exascale computational science. While true exascale computing is not likely to be achieved during the timeframe of PSAAP II awards, the Program's computer science emphasis is on resolving issues that are known to arise in reaching towards exascale computing (i.e., next high performance computing paradigm shift to extreme, heterogeneous, multi-core on-node parallelism—and not necessarily to any hardware or system at such scale).

How do the universities know the problem solution is right?

That is what V&V and UQ are all about, and PSAAP Centers must use these tools to demonstrate that their predictive simulation is sufficiently verified and validated to predict behavior of a full system. Appropriate use of UQ assures that predictions are within acceptable error bounds providing confidence in results.

Who is involved in this?

All PSAAP-funded schools are United States academic institutions that grant PhD degrees. When awarded, the cooperative agreements will last five years, with a renewal option for up to three additional years (if DOE/NNSA judges Center's research as making significant progress towards Program goals). This Annual discusses the six PSAAP II Centers on the pages that follow.

If you are successful, will you still need experiments?

In most cases, we will always need experiments. In some instances, experiments on full systems are not possible (for example, underground tests of nuclear weapons are no longer permitted) but there can be experiments on components of systems, and scientific experiments are essential to discovery. Experimental data is essential to validation. Theory, experiments and computational simulation are all critical to advance science and engineering.

How did you get involved in this Program?

My Federal career includes 33 years of managing and reviewing large R&D programs at NNSA laboratories, plants, and sites. I started working with the PSAAP about two years ago from the Albuquerque location of Advanced Simulation and Computing and Institutional Research & Development. My experience and formal education as a Master of Business Administration, enables me to work closely with the laboratories, universities, and Contracts & Procurement Office in Albuquerque. Other responsibilities include management and oversight of Laboratory/Site Directed Research and Development. Working with the many gifted PSAAP individuals is extremely rewarding.

Predictive Science Academic Alliance Program II

University of Florida • University of Illinois at Urbana-Champaign • University of Notre Dame
Stanford University • Texas A&M University • University of Utah

As the result of a Funding Opportunity Announcement released in 2012 by the Advanced Simulation and Computing (ASC) Program in the Office of Defense Programs within the National Nuclear Security Administration (NNSA), ASC has established PSAAP II by selecting six universities to operate research centers focused on demonstrating predictive science in a high-performance-computing environment. Three of the sites will be Multidisciplinary Simulation Centers (MSCs) and three will be Single-Discipline Centers (SDCs) funded at $3.2M and $1.6M, respectively per year for five years. Each Center will solve a problem that advances basic science/engineering and verification & validation (V&V)/uncertainty quantification (UQ), and contributes towards achieving effective extreme-scale computing. The primary difference between the two types of Centers is that MSCs are expected to focus on a multi-disciplinary, integrated problem, while SDCs are required to explore an application in a single discipline.

Following is a discussion of each of the six PSAAP II research centers.

Center for Compressible Multiphase Turbulence

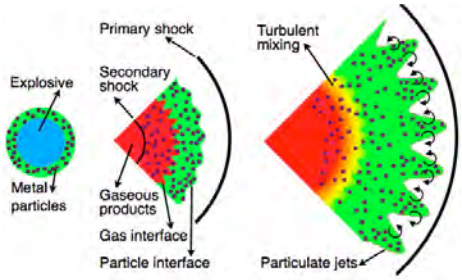
University of Florida

Center Director: S. "Bala" Balachandar, bala1s@ufl.edu

The intellectual objectives of the University of Florida's SDC are threefold: 1) to radically advance the field of compressible multiphase turbulence (CMT) through rigorous first-principle multiscale modeling, 2) to advance 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. We will perform petascale, and work towards exascale simulations of instabilities, turbulence and mixing in particulate-laden flows under conditions of extreme pressure and temperature to investigate fundamental problems of interest to national technological leadership.

CMT is a grand challenge problem that presents a fascinating array of poorly understood transition and turbulent processes. Fully validated exascale simulation is the only path to fundamental breakthroughs in understanding that can lead us out of current empiricism. The Center will pursue a unique multiscale approach that culminates at a signature demonstration problem of explosive dispersal of particles. Simultaneous simulations and experiments at micro, meso and macroscales will allow rigorous uncertainty propagation. The innovative concept of uncertainty budget will be the backbone of the Center and will be used to prioritize the hierarchy of simulations and experiments needed to reduce uncertainty to allow meaningful validation. CMT is characterized by extreme events that are localized in space and time, and we will develop novel techniques for UQ of such rare but critical events.

We will leverage the unique Novo-G facility at the National Science Foundation-supported University of Florida Center for High-Performance Reconfigurable Computing to emulate and evaluate a series of candidate exascale architectures. We will develop an unprecedented capability to behaviorally prototype in hardware a variety of promising forms of next-generation exascale device-level designs at the microscale, node-level architectures at the mesoscale, and communication and system architectures at the macroscale. We will use this capability to conduct experiments with kernels, mini-apps, and skeleton-apps from CMT application and beyond to evaluate promising architectures in terms of performance, energy, reliability, and scalability. For the exascale platforms, we will develop a multi-objective optimized heterogeneous numerical approach that exploits the parallelisms within CMT application and its UQ implementation. •



Schematic of the sequence of events in an explosive dispersion.

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

University of Illinois at Urbana-Champaign

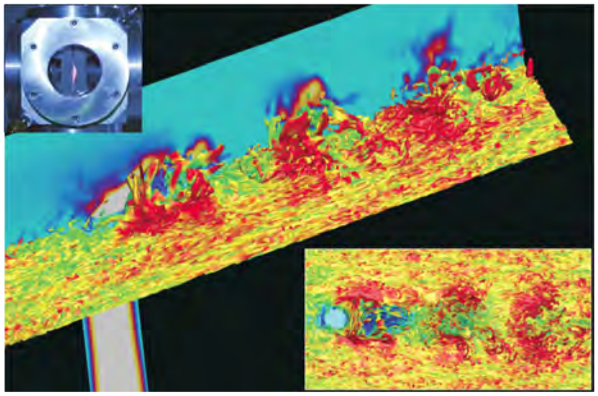
Center Director: William Gropp, wgropp@illinois.edu

XPACC is an MSC in the Parallel Computing Institute at the University of Illinois at Urbana-Champaign. It will use large-scale predictive simulation to advance the science and technology of plasmas to initiate and control turbulent combustion. The target application is a gas-phase fuel jet.

Plasmas offer a unique and untapped means of affecting combustion to boost performance and efficiency. Radicals produced in plasmas short circuit chemical pathways; electric fields affect flame stability via charged species; and plasma joule heating affects both the flow via thermal expansion and chemistry via temperature. Predictions using Bayesian-based UQ will improve understanding of the multi-physics mechanisms and guide alternative uses of plasma actuation. Experiments targeting specific physical mechanisms will be used to calibrate models to provide measures of uncertainty that can be propagated to the principal Quantity of Interest: the ignition threshold.

Each of the physical sub-components of a coupled plasma-combustion system—the flow turbulence, plasma physics, reaction pathways, and electrode aging and electrodynamics—would require petascale computational resources for reliable physics-based predictions. Coupling them across all the important length and time scales to make quality predictions of plasma-coupled combustion demands the co-development of simulation models with tools to harness the heterogeneous architectures of anticipated exascale computing platforms.

The Center will build upon an existing petascale code used at the University of Illinois in a range of flow-physics and multi-physics applications. This code, *PlasComCM*, will be used as an exemplar of modern extreme scale applications. The Center will develop new programming approaches that can be applied to well-structured existing applications that provide portable access to better performance and scalability through data structure and code optimizations for memory efficiency and exploitation of high-throughput computing elements and automatic load balancing to address performance irregularities in compute systems, algorithms, and problems. These and other tools and techniques will be designed to work on applications with similar needs, and the Center will actively engage the community to ensure the success of these performance-oriented programming systems. ●



Ignition of an H2 jet in cross flow by different plasma "forcing" will be a key target of XPACC's prediction. (See also the caption on the inside cover.)

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

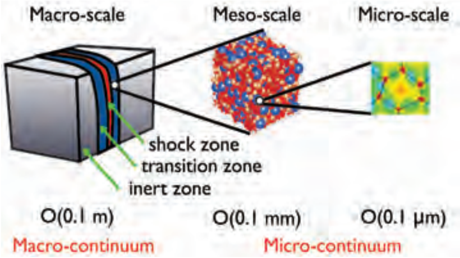
University of Notre Dame

Center Director: Samuel Paolucci, samuel.paolucci.1@nd.edu

The development of controlled microstructures is a primary goal in designing novel materials with unique properties. The main mission of this SDC is to predict shock conditions under which new materials can be synthesized. This processing generates high temperatures and pressures that can lead to the creation of new materials. Such material transformations are governed by a plethora of physical, mechanical, and chemical processes that test our understanding of microstructure-property-relations and our capacity to tune materials at will. The goal of C-SWARM is deployment of verified and validated computational simulations to predict the properties and dynamics of complex systems, with quantified uncertainty.

Heterogeneous reactive materials (HRMs) are one of the best examples of a multiscale problem where exascale computational resources can have a transformative impact. These materials acquire enhanced properties after shock wave processing due to the very large pressures and strain rates they experience. C-SWARM represents a coordinated effort combining multi-resolution simulations, a transformative computational execution model, and experiments to analyze the chemo-thermo-mechanical response of HRMs.

Polydisperse materials with different chemical composition and disparate thermo-mechanical behavior exhibit a complex response that is difficult to capture using conventional theories. To model such materials, C-SWARM employs an adaptive multiscale strategy that solves in adaptive fashion phase-averaged macro-continuum equations using an Eulerian algorithm with constitutive equations locally provided by well-resolved micro-continuum simulations of the multi-phase mixture using a Lagrangian algorithm. The macro- and micro-continuum codes will utilize an advanced execution model, ParalleX. ParalleX enables data-mining of runtime information to dynamically adapt the codes' demands to resource availability. Furthermore, Active System Libraries will be implemented to ensure that the macro- and micro-continuum algorithms can be represented in an effective and hardware-independent fashion.

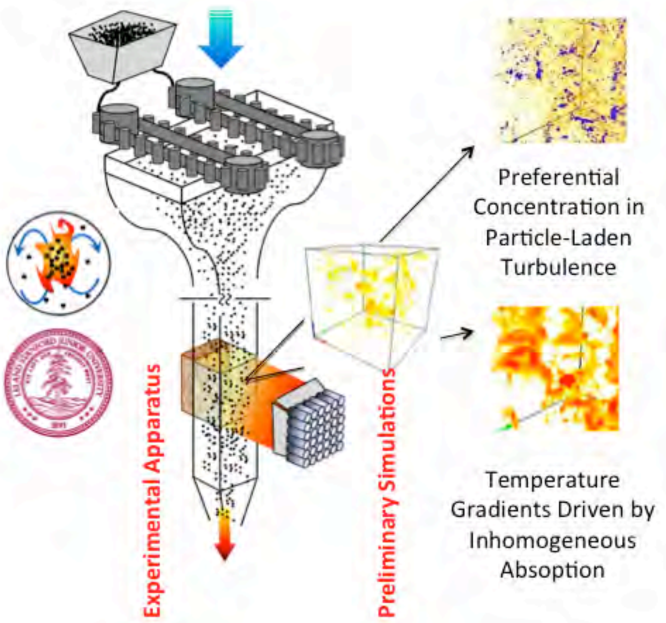


The C-SWARM approach to multi-scale modeling for materials under shock conditions.

The integrated V&V/UQ program provides a platform for computational model verification, validation and propagation of uncertainties. The emphasis of C-SWARM is on quantifying the predictive ability of the multiscale simulations in an efficient manner. A key component of the Center is a series of carefully co-designed experiments and data-driven simulations (with quantified uncertainties) to enable meaningful and rigorous comparison of simulation predictions with experimental results. ●

Predictive Simulations of Particle-laden Turbulence in a Radiation Environment

Stanford University
Center Director: Gianluca Iaccarino, jops@stanford.edu



Schematic of the particle-laden system for the absorption of solar energy.

The Stanford MSC Center's research portfolio blends efforts in computer science, UQ, and computational engineering to tackle a challenging multiphysics problem inspired by methods for harvesting solar energy. Traditional solar-thermal systems use mirrors to concentrate solar radiation on a solid surface and transfer energy to a fluid by conduction and convection. In the proposed system, fine particles suspended within the fluid absorb sunlight and directly transfer heat throughout the fluid volume. This technique might enable higher energy absorption and transfer rates, ultimately increasing the efficiency of the overall system.

The intimate interplay of turbulence, radiation, and particle transport will be explored with high-fidelity simulations to investigate the importance of the coupling effects. A specific regime we will consider is one in which turbulence and particles interact strongly, forming regions of preferential particle concentration and leading to non-uniform absorption of radiative energy and, therefore, to temperature gradients and buoyancy forces in the underlying air carrier.

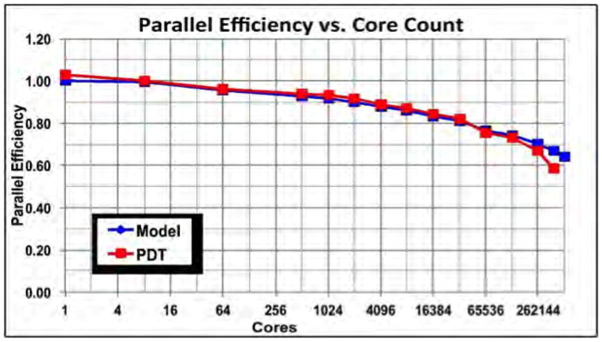
The aim of this project is to develop the methodologies necessary to exploit exascale systems with a comprehensive computer science effort consisting of: (1) innovations in the Liszt domain specific language (DSL) that can handle complex physical modeling and algorithmic challenges; (2) a probabilistic DSL designed to leverage domain expertise, to streamline UQ calculations, and to be interoperable with Liszt; and (3) an embedded resilience component that enables the identification of and recovery from multiple classes of faults. The main objective of the DSL effort is to enable a variety of back-ends to automatically understand data dependencies, to exploit data locality, to extract high levels of parallelism from diverse and heterogeneous architectures, and to incorporate resilience methods.

An important objective of the proposed program is to critically validate the physics-based models and verify the numerical algorithms employed in the simulations. Because of the complex multiphysics nature of the problem and the lack of extensive measurements in the literature, the present proposal includes the design of a dedicated experiment to collect high-quality and detailed data. A critical component of the validation task is the quantification of the uncertainties present in both the experiments and the numerical simulations. ●

Center for Exascale Radiation Transport (CERT)

Texas A&M University
Center Director: Jim Morel, morel@tamu.edu

The focus of this SDC is on the single disciplinary topic of thermal radiation transport (TRT), which is of fundamental importance to NNSA missions. TRT is essential for multiphysics modeling of high energy density physics (HEDP) experiments at a number of NNSA facilities such as the National Ignition Facility at Lawrence Livermore National Laboratory (LLNL). TRT is generally far more computationally expensive than the other physics components in HEDP simulations, chiefly because the transport equation is seven-dimensional. Thus, it is critical to develop efficient algorithms for radiation transport. CERT will develop exascale computer science algorithms and parallel performance models, exascale adaptive algorithms for both improved accuracy and numerical error estimation, multiscale physics models relating to transport in



Weak scaling performance of the latest transport solution algorithm with the predictions of the associated performance model.

embedded voids and small cracks, and exascale multilevel preconditioning techniques. Our computer science research will include the development of methods for fault tolerance and the development of performance models that include the impact of iterative methods on parallel efficiency. The latter will enable us to choose an optimal solution technique based upon characteristics of the problem. The accompanying graph compares the weak scaling performance of our latest transport solution algorithm with the predictions of the associated performance model. It can be seen that our algorithm scales with roughly 60% efficiency from 1 to 384,000 cores of the Sequoia machine at LLNL, and that the performance model agrees very well with the actual performance. CERT will also perform transport experiments with quantified uncertainties for the purposes of validating multiscale models, yielding experimental estimates of our numerical errors, and providing high-fidelity benchmark results to the TRT community. Experiments in the HEDP regime require multiphysics modeling, which makes it difficult to discern the origins of simulation/experiment disagreements. CERT will avoid the need for HEDP experiments by performing surrogate neutron transport experiments, exploiting the strong analogy between thermal radiation transport and neutron transport. The single-physics nature of these experiments enables the use of hierarchical UQ techniques to cleanly differentiate sources of error and uncertainty in a way that is not possible with HEDP experiments. ●

The UQ-Predictive Multidisciplinary Simulation Center for High Efficient Electric Power Generation with Carbon Capture (CCMSC)

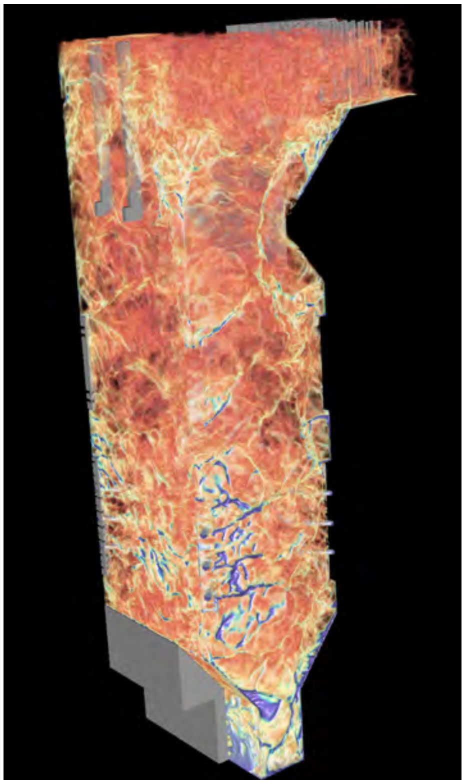
University of Utah

Center Director: Philip J. Smith, Philip.Smith@utah.com

The mission of the MSC is to use exascale UQ-predictive simulation science to rapidly design and deploy a new technology for secure electric energy generation, namely, a high efficiency advanced ultra-supercritical oxy-coal power boiler. 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. We use 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. We extrapolate the uncertainty obtained from the V&V/UQ of the sub-scale, sub-physics analysis to a prediction of the full-scale boiler that is simultaneously consistent with all of the experiments and with all of the validation metrics of our validation hierarchy.

CCMSC starts with an existing proven computational platform (UintahX) and sequentially moves to multi-petaflop and, eventually, exascale computing. We will accomplish this transformation with three software infrastructure components: 1) the exascale runtime system; 2) TASC, a Transparent Abstractions for Scalable Computing, representing a high-level, portable "assembly language" for scientific computation with transparent abstraction by using a sub-Turing, embedded domain-specific language; and 3) the data management and visualization infrastructure for dealing with large data and for connecting that data to the visualization and data analysis components.

The expected impact is a demonstration of using exascale computing with V&V/UQ to more rapidly deploy a new technology for providing low cost, low emission electric power generation. To this end, the CCMSC has established a collaborative agreement with Alstom Power to jointly use this exascale technology to contribute to the design of a new 350 MWe oxy-coal boiler. The exercise of developing the tools for this overarching problem will produce: 1) exascale computing software that will be regularly released through open-source licensing, 2) tools for V&V/UQ for use with other large applications with expensive function evaluations and sparse/expensive experimental data, and 3) new advances in computational fluid dynamics, multiphase reacting flow and radiative heat transfer. ●



A volume rendered image of a CCMSC prediction of an Alstom oxycoal boiler. The image shows local concentrations of the 90 micron coal particles in the boiler. The particles concentrate in local regions due to variation in local Stokes number. The simulation was performed on Titan using 1 million core hours.

The Dynamic Compression Sector at the Advanced Photon Source

Washington State University
PI: Yogendra M. Gupta, ymgupta@wsu.edu

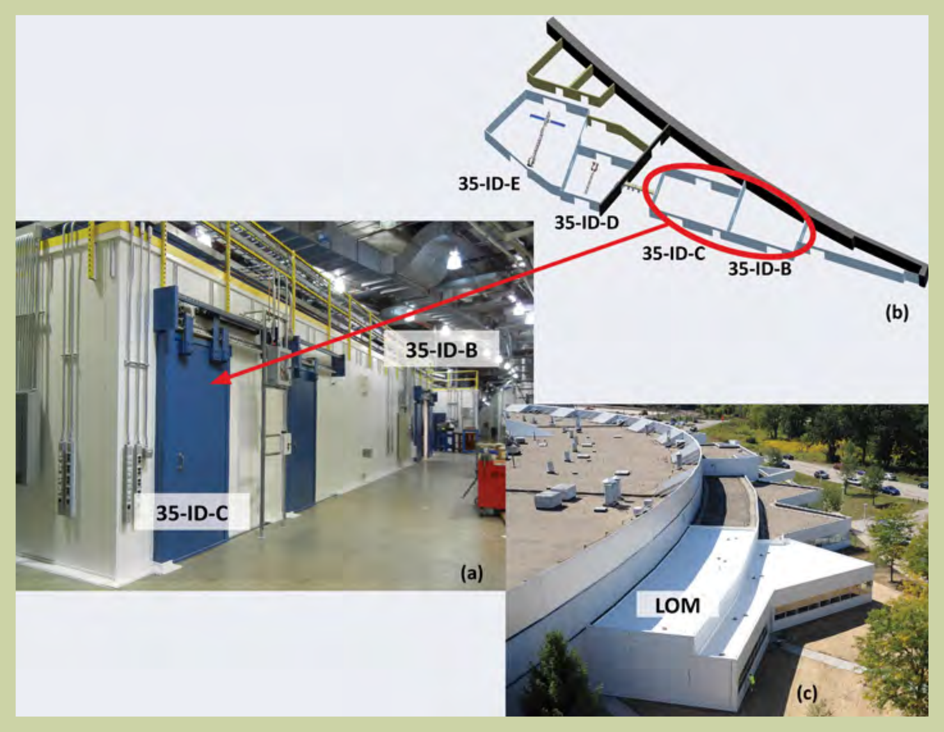


Figure 1. (a) The 35-ID-B and 35-ID-C stations in sector 35. (b) Schematic view of the sector 35 layout. (c) The DCS Laboratory Office Module.

Understanding the real-time, atomistic-level response of materials under extreme dynamic conditions is central to the Stockpile Stewardship Program, to fundamental science frontiers in numerous fields, and to advanced technology. To address this key scientific need, the U.S. Department of Energy/National Nuclear Security Administration (DOE/NNSA) is establishing a first-of-a-kind user facility at the Advanced Photon Source (APS). Washington State University (WSU) is partnering with the APS to establish the Dynamic Compression Sector (DCS), an experimental capability dedicated to time-resolved (~ns resolution), multi-scale measurements in dynamically compressed materials. DOE and NNSA laboratories, and other institutions, are strong collaborators in the DCS development. Experiments at the APS are already conducted by the NNSA laboratories. However, the DCS will provide a unique venue for collaborations in dynamic compression science between students and postdoctoral researchers from WSU and other academic institutions and the national laboratory staff.

DCS will couple a variety of dynamic compression platforms to a state-of-the-art synchrotron beamline, with tunable x-ray energies and time-structures (ns-separated pulses), to obtain x-ray diffraction and imaging measurements simultaneously with continuum measurements to observe time-dependent changes in materials subjected to a broad range of stress amplitudes (~5 GPa to well above 100 GPa) and time-durations (~10 ns to ~1 μs).

Since the publication of the last SSAP Annual, there has been tremendous progress in the development of DCS, a unique user facility dedicated to understanding material dynamics at extreme conditions. Construction of four shielded radiation enclosures (or experimental stations) and a Laboratory Office Module (LOM) have been underway over the past year. These x-ray enclosures, connected sequentially as shown in Figure 1, are nearing completion; commissioning experiments will be performed in 2014. The 35-ID-E and 35-ID-D stations will contain a two-stage light gas gun (2SLGG) and a single-stage gas gun, respectively. These impact launchers will be mounted on motion control systems that allow targets to be precisely aligned to the x-ray beam in both position and angle. The 35-ID-C station will house a laser-shock facility and the 35-ID-B station will be used for special purpose and non-single event experiments. Target diagnostic capabilities, such as laser interferometry to measure particle velocity histories with ns and sub-ns resolution (e.g., Velocity Interferometer System for Any Reflector and Photonic Doppler Velocimetry), will be available in all four stations. The LOM, completed in October 2013, houses the laboratories and infrastructure needed for onsite sample characterization and experimental component fabrication.

X-ray pulses at the APS are produced when a storage-ring electron bunch traverses the periodic magnetic field of an undulator. During the first two APS runs in 2014, the beamline and experimental end station equipment will be tested using 18 mm and 33 mm period undulators. A revolver undulator, a new device that allows switching between two magnetic lattices, with period lengths of 27 mm and 30 mm will be installed during the third APS run in 2014. This revolver undulator will provide nearly continuous spectral coverage with useful x-ray flux from 10 keV to 100 keV. The x-ray beam can be focused for energies up to 35 keV with spot sizes as small as 16(V) by 25(H) μm^2. During a dynamic compression experiment, two types of x-ray measurements will be made: 1) time-resolved, high-spatial-resolution, phase contrast imaging, to obtain a sequence of spatially resolved images, and 2) x-ray diffraction to measure the crystallographic properties. The initial detectors deployed at DCS will record four frames per experiment to provide information about the temporal evolution of the microscopic changes.

Exploring Matter Under Extreme Conditions Using X-ray Synchrotron Radiation

Carnegie Institution of Washington
PIs: Guoyin Shen, gshen@ciw.edu and Russell J. Hemley, rhemley@ciw.edu

The High Pressure Collaborative Access Team (HPCAT) is a frontier synchrotron facility that is optimized for high-pressure studies to advance compression science important to the National Nuclear Security Administration science. HPCAT has played a pioneering role in high-pressure synchrotron techniques enabling many new capabilities. A broad range of static and dynamic pressure conditions together with extreme conditions of temperature, radiation, and deviatoric stress, has been integrated with x-ray diffraction, x-ray scattering and spectroscopy, and x-ray imaging techniques. The integrated HPCAT facility allows for extreme conditions studies in: (1) structural determinations of amorphous, nano-, polycrystalline, single crystal, and microstructures of composite materials, (2) measurements of phonon dynamics, charge dynamics, and electronic and spin states of metals, alloys, oxides, nitrides, hydrides, superconductors, and superhard or other novel materials, and (3) in situ measurements with high spatial resolution (1-3 microns) and high temporal resolution (down to 100 ps). Investigations of structure, equations of state, and electronic and magnetic properties provide critical data for code validation and tests of fundamental theory. The measured "structure-property" correlation helps to establish predictive models for developments of new materials and new applications.

In the past year, 291 individual users performed experiments at HPCAT with 580 separate visits. More than 59% of HPCAT users are graduate students or young postdoctoral scientists, whose involvement provides opportunities for training and professional development.

Highlights of new capabilities and developments at HPCAT in 2013 follow.

Figure 1. More than 290 individual users performed experiments at HPCAT in 2013. Approximately 60% were students and postdoctoral researchers.

Filling the Strain Rate Gap. Capabilities at HPCAT allow us to study materials behavior at various strain rates under dynamic compression or decompression. Both single event loading or unloading and multiple, repetitive ramping events allow the study of materials properties at different strain rates. Through ramp loading, the pressure changes at a rate of 17 TPa per second. This is a step forward filling the strain rate gap between conventional static and dynamic experiments. Compression and decompression can also be controlled for the desired strain rates.

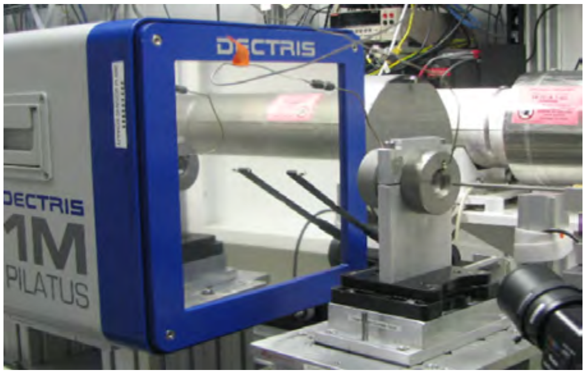


Figure 2. Fast compression/decompression experiments at HPCAT (currently to ~17 TPa per second) bridge the gap between conventional static and dynamic compression.

Megabar Single Crystal Diffraction. A new single crystal diffraction technique has been developed at HPCAT, suitable at megabar pressures. The new method allows obtaining crystallographic orientations of over 100 crystallites at megabar pressures in coarse-grained polycrystalline samples. A few selected crystallites may be tracked using conventional single crystal structural refinement procedures. The new method opens a door for in-situ studies of crystal structures of submicron crystallites in a multiphase polycrystalline sample in a diamond anvil cell. The established technique is particularly useful for studying unquenchable high-pressure phases at extreme conditions.

Polycapillary Optics Improve Signal/Background Ratios. In high-pressure x-ray scattering experiments, we are often limited in pressure and scope by low counting rates. The use of polycapillary optics as an "x-ray objective" in high-pressure x-ray inelastic scattering (IXS) and x-ray emission spectroscopy experiments has been introduced. The polycapillary has a large numeric aperture and a focal spot approaching 20 microns, providing good depth resolution and improving signal/background ratio by an order of magnitude, thus enabling megabar IXS and megabar spectroscopy experiments.

Our new and existing capabilities provide a frontier facility for studying materials behavior at extreme conditions: including quantum critical points revealing the interplay between superconductivity, magnetism and structural disorder; discoveries of new superconductors in metallic and metal oxides; liquid-liquid phase transitions; and strength of iron at Earth core pressures.

Radiation from High Energy Density Plasmas (RHEDP) International Workshop

Radiation from High Energy Density Plasmas Workshop

Organized by: Alla Safronova, alla@unr.edu and Dr. John Giuliani, Naval Research Laboratory, john.giuliani@nrl.navy.mil

The Second International Workshop on Radiation from High Energy Density Plasmas (RHEDP) was held from April 2-5, 2013 in Stateline, Nevada. It was chaired and organized by Professor Alla Safronova from the University of Nevada, Reno (UNR) with the assistance of Dr. John Giuliani from the Naval Research Laboratory (NRL), and some financial support was provided by NNSA. The UNR press release from January 25, 2013, states that "The International workshop is an opportunity to showcase advances made in high energy density plasma research, to highlight the research strength the University currently has in the field, and, just as importantly, to give student researchers an opportunity to network and make connections with scientists from national laboratories." The Workshop hosted 54 attendees, which included 22 students and three postdoctoral researchers (see Figure 1) from four universities (UNR, University of Michigan (UM), University of California, San Diego (UCSD), and Cornell University). Among the senior participants were scientists from NRL, Sandia National Laboratories (SNL), Lawrence Livermore National Laboratory, and Los Alamos National Laboratory (LANL), as well as from two private sector companies (Ecopulse Inc. and Prism Computational Sciences), and faculty from universities. International participants included scientists from the Atomic Weapon Establishment (United Kingdom (UK)), Joint Institute for High Temperatures (Russia), and the Weizmann Institute of Science (Israel).

Figure 1. Students and post-doctoral attendees of RHEDP 2013 International Workshop (April 4, 2013, Stateline, Nevada).

The presentations reflected the recent progress in the RHEDP field particular to z-pinches and laser produced plasmas. Results in basic physics from experiments, diagnostics, theory, and simulation were reported. For z-pinches, some of the important highlights were studies of Doppler and opacity effects in K-shell x-ray sources on the Z Machine at SNL and inclusion of more physical processes in future models; development of radiation sources with planar wire arrays for inertial confinement fusion and HEDP research on the university-scale Zebra generator at UNR and further optimization of the loads and application to lasing; and validation of two-dimensional radiation magnetohydrodynamics code using gas-puff plasma. For laser-produced plasmas, they include experimental studies of emission from solid-density matter heated by a laser-driven proton beam using the TRIDENT laser at LANL; multi-view areal density maps of compressed shells in OMEGA implosions extracted from spectrally resolved images; theoretical studies of spectral and angular distribution of photons produced by the interaction of an extremely intense laser with dense plasma using collisional particle-in-cell simulation and identification of the signature of the radiative damping in future experiments; and the first data on measurements of the spectra from hot, dense aluminium at the Orion laser (UK), including the continuum lowering. Some of the topics, such as characteristic x-ray lines, that have recently been studied in both z-pinch and laser-produced plasmas, were highlighted using experiments on Z, Zebra, and OMEGA at the Laboratory for Laser Energetics, University of Rochester, and require more theoretical and experimental data .

Very positive responses were received from the students about the format of the conference and their interactions with faculty and laboratory scientists. One dedicated discussion panel for students to ask questions to scientists in the field was led by UNR graduate student Michael Weller. A lot of questions were asked, however the most popular question was, "What are some of the main differences and similarities between working in the university setting, the national laboratory setting, and the private sector setting?" Several scientists answered this question: Ronald Gilgenbach (UM) shared his experiences working in all three settings, while Brent Jones (SNL) explained why he chose the national laboratory setting, and finally Igor Golovkin (Prism) provided his experiences working for a private company. Articles detailing sixteen of the selected presentations at RHEDP 2013 will be published during 2014 in a Special Topic Section of the premier plasma physics journal *Physics of Plasmas*.

Materials Under Extreme Environments: Will Additively Manufactured Materials Measure Up?

Lawrence Livermore National Laboratory (LLNL)
Authors: Robert S. Maxwell, maxwell7@llnl.gov, Wayne E. King, Christopher M. Spadaccini, and Melissa Marggraff

The World of Manufacturing Is Changing—Even for the Weapons Complex

The National Nuclear Security Administration (NNSA) has traditionally relied on manufacturing methods that were established a half a century ago and used to create the cold war stockpile. In many cases, these production processes are no longer operational, with many having been mothballed for decades. To complicate things further, raw materials used in original builds are becoming increasingly difficult, if not impossible, to obtain from vendors. Thus, sustaining the legacy, artisanal, manufacturing approaches to component production is becoming increasingly difficult and perhaps unsustainable.

Advanced manufacturing methods, like additive manufacturing (AM), are now being developed and harnessed by global industry to dramatically shorten the concept-development-qualification-deployment cycle. It is becoming increasingly clear that AM may be an attractive solution for modernizing NNSA's manufacturing infrastructure.

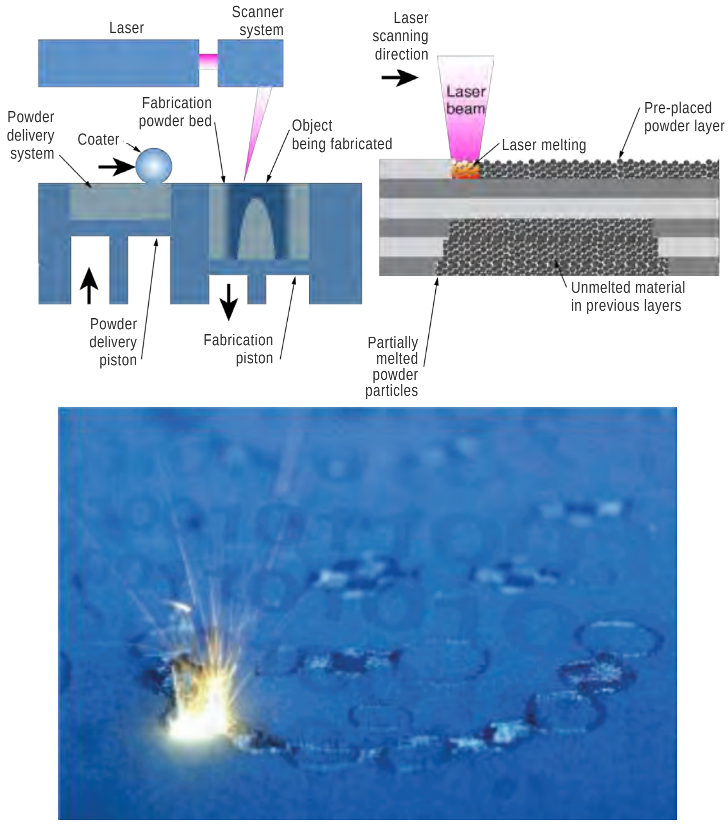


Figure 1. Laser powder bed fusion metal additive manufacturing. In metal powder bed fusion, a layer of metal powder is spread on a powder bed and melted using a laser. When the layer is complete, the fabrication piston moves downward by the thickness of one layer, the delivery piston moves up, and the coater is used to spread the next layer. This process is repeated hundreds to thousands of times until a complete part is fabricated.

AM is a family of highly flexible manufacturing processes by which material is *added* layer by layer in exact compliance with a virtual blue print (see Figure 1). This is in contrast to traditional *subtractive* manufacturing approaches, such as machining, used for the last half century in the Nuclear Security Enterprise. AM can produce structures not manufacturable through subtractive methods, and AM can provide the potential to control structures over a broad range of length scales from atomic to the macroscale. Further, AM is a modern technology for which the infrastructure and workforce will be far more sustainable. International industry has begun to awaken to the vision of *Factories of the Future* harnessing AM to reap the benefits of higher skilled workforces, reduced manufacturing footprints, reduced waste, reduced cost, and reduced time to product.

AM technologies for polymers, ceramics, and metals are now being exploited for low-volume production of specialty and hard-to-find parts in such widely varied industries as aerospace, motorsports, orthopedic implants, and dentistry. In fact, General Electric (GE) is planning to use AM to produce the fuel nozzles for their Leading Edge Aviation Propulsion engine and, by 2020, GE expects to have produced over 100,000 fuel nozzles with AM that will be in flight.

Today, AM is ideally suited to low volume, high value manufacturing, i.e., the post-cold war stockpile, but substantial R&D remains to develop AM for NNSA applications. In fact, Lawrence Livermore National Laboratory (LLNL) is already investigating the viability of applying commercial, as well as developing new, custom AM methods to provide sustainable, rapid, flexible, and tailored manufacturing options for a variety of national security applications. LLNL is actively exploring the range of materials and component types that are amenable to AM, broadening the material diversity, mixing materials in the same fabricated component, and improving resolution and spatial control.

AM Enables the Design of Micro- and Nano-scale Material Architectures with Previously Unachievable Properties as Specified by Mission Need

Material properties are governed by the chemical composition and spatial arrangement of constituent elements at multiple length-scales. This

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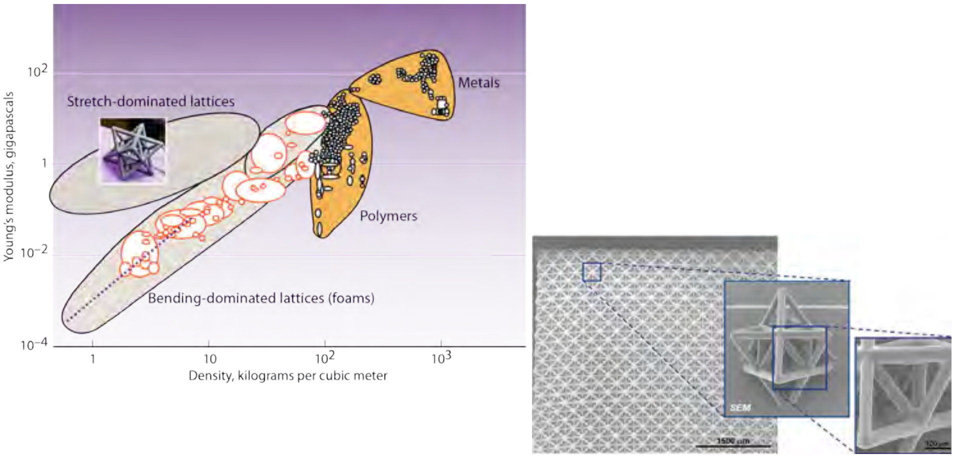

Figure 2. (Top) Material selection chart of stiffness (Young's Modulus) vs. density with the stretch-dominated lattice microarchitecture shown relative to conventional materials. The "stretch-dominated lattice" shown in Figure 2 (right) is an example of a microstructured architecture which leads to previously unobtainable material property combinations; in this case, light-weight, high-stiffness material. This material generated with projection-microstereolithography (PμSL).

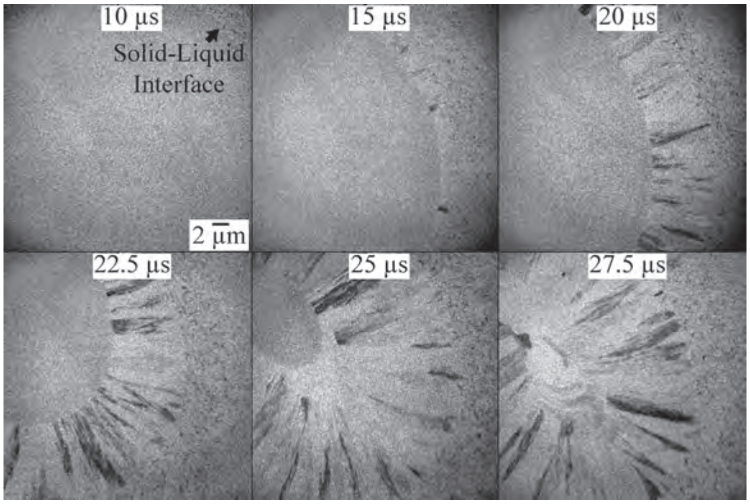

Figure 3. Fifteen-ns-exposure dynamic transmission electron microscopy images recorded at multiple time delays after laser melting of an Al-7 at.% Cu alloy. The melt pool is the featureless area in the middle of the ellipse that shrinks and disappears within 27.5 μs of the pulsed laser-melting event. The black and white contrast that remains reflects the grain structure of the rapidly solidified alloy. We have observed that the resultant microstructure depends critically on the composition and solidification rate of the melt pool.

fundamentally controls a material's properties with respect to each other creating trade-offs when selecting materials for a specific application. This coupling can be visualized in material selection charts as shown in Figure 2 for Young's modulus (E) versus density. The coupling between these properties creates significant unpopulated, yet potentially desirable, design spaces that cannot be accessed using standard synthesis or manufacturing methods. AM has demonstrated numerous advantages over traditional manufacturing and is enabling the creation of arbitrary three-dimensional (3D) multi-material heterogeneous microarchitectures that manifest combinations of properties unattainable previously (see, for example, the stretch dominated lattice, shown in Figure 2).

These New Processes Carry Certification and Qualification Challenges Addressable by Stockpile Stewardship Capabilities

Deploying materials or components in any end-use application can require a lengthy testing and evaluation period over a range of environmental and service conditions. Understanding how novel AM-created structures behave over a wide range of dynamic conditions is crucial if AM components can find enduring national security applications. Building on our base of capabilities developed within the Stockpile Stewardship Program and the Stewardship Science Academic Alliances Program, we can use modeling and simulation to understand and predictively control the connection between manufacturing processes, material structure, material properties, and component performance. As these models mature and are validated by experiment, it may be possible to realize a future where arriving at a qualified component that can be included in a certified system can be done in days or months rather than decades.

For example, many AM processes for metals and ceramics involve rapid melting via short, intense energy deposition followed by rapid solidification of the microstructure.

This must occur while maintaining the overall integrity of the structure. As shown in Figure 3, the results of rapid melting and solidification can have significant impact on material microstructure. Furthermore, multiple studies have shown varying AM processing parameters can have varying effects on material microstructure, as illustrated in Figure 4. Improving our understanding of the influences that determine these structures and how they impact performance in end-use applications will enable the creation of parts with controlled microstructure, potentially producing components with designed anisotropic behavior.

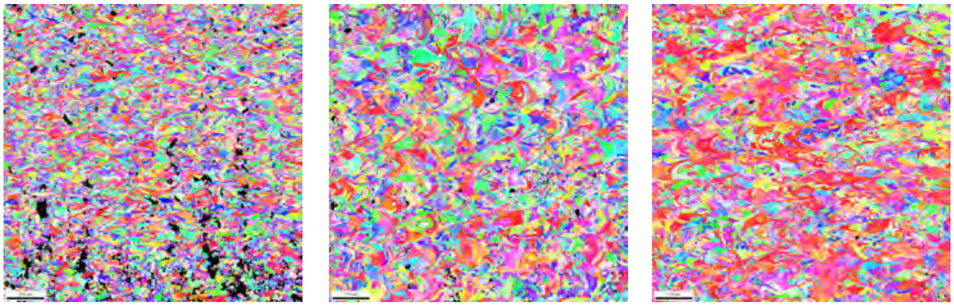

Figure 4. Electron backscatter diffraction study of the effect of power on the microstructure of 316SS produced using metal AM for a laser beam speed of 1,600 mm/s. Grains are colored by orientation. Crystallographic texture is moderate and the grain size is observed to increase with power.

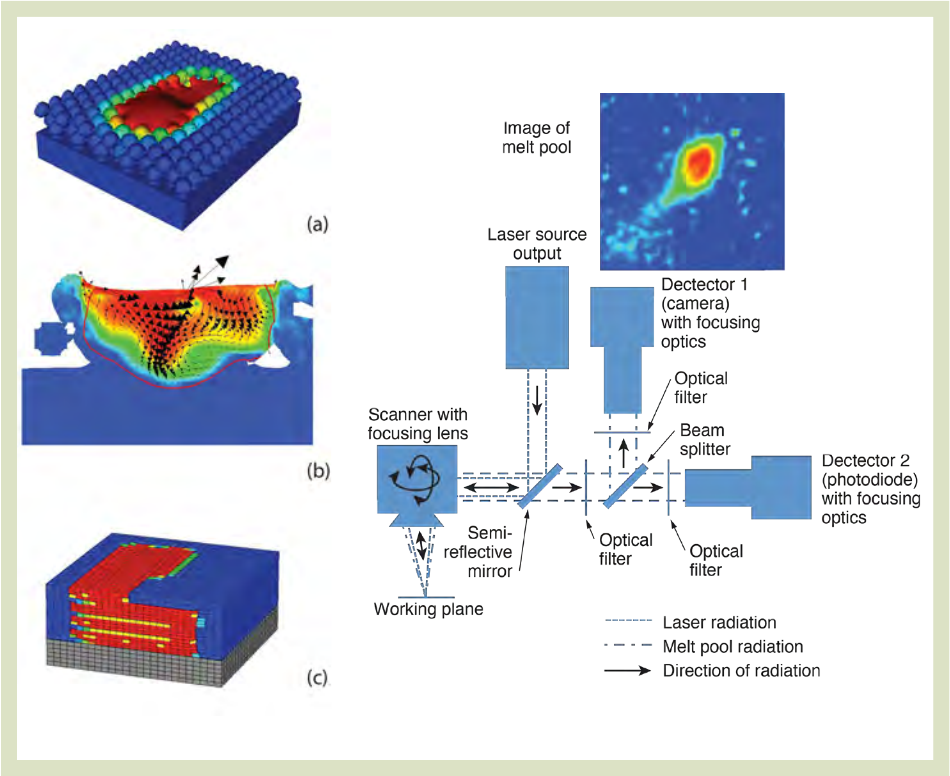

Figure 5. (left) (a-b) Laser melting of a powder layer containing a hexagonal array of 27-micron diameter stainless steel powder particles shortly after the laser was turned off, showing consolidation by surface tension and gravity. The color represents temperature. The molten pool is visible in (a) and the recirculation of the liquid metal is visible through the arrows in the cross section in (b). (c) Thermo-mechanical simulation as the eighth layer of 316L stainless steel powder is formed on a build plate. The model includes melting, consolidation and resulting residual stresses. This configuration leaves a boundary of material (on three sides) in the powder state to examine edge effects. This approach of effective medium modeling is required to reach simulations of part-scale geometry; (right) Real-time melt pool sensor used in LLNL metal AM machines.

Multiple computer modeling techniques exist to optimize various aspects of this problem, but there are significant capability gaps that remain to be filled. Hydrodynamic modeling of 3D flow is challenging; the post-melt flow is not fully turbulent and is largely driven by surface tension effects. The laser or e-beam delivery of energy to the powder can be modeled with ray-tracing techniques, but at lower length scales, the material consolidation process becomes more challenging. Surface oxidation of the powder and the details of the heat flow through the heterogeneous structure and the rapid solidification rate and the effects of capillary forces and wetting, as well as the interaction of thermal gradients with phase transformations and the associated dimensional changes, only serve to compound the complexity of the problem. Ultimately, these local effects take place in the context of a part fabrication, whose local geometry can greatly impact thermal gradients and the resulting temperature time history experienced by the material. Point-wise effects must be efficiently aggregated into predictions of part-scale response such as residual stress and distortion to impact both process development and part design.

As a result, process-aware predictive modeling of direct metal AM processes is still in its infancy. LLNL is applying and modifying multiple computational techniques, including mesoscale codes for phase field and dislocation dynamics, Langevin dynamics for electrophoretic deposition, and macroscale hydrodynamics codes to develop a more integrated, process-aware modeling capability. Much work is still to be done, but some of our early results successfully model the melt pool in metal laser powder bed fusion processing, as shown in Figure 5.

As these models become more robust, they may be combined with still-to-be-developed advanced in-situ process diagnostics (see Figure 5) to measure in real time and at relevant length scales the effects of variable process parameters. Once married, the development of process-aware material codes coupled with feed-forward control

> *"Significant research in AM is occurring throughout the academic, commercial, and national laboratory communities. Through these efforts, our ability to manufacture advanced materials and components will only continue to improve. These tools, when passed to the private sector will enable broader U.S. economic and national security goals. Through effective partnerships and collaborations, the ability to harness these advances to realize the goal of rapid manufacturing with rapid certification may be realized."*

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and feedback loops to self-correct processing on the fly will result in an unprecedented level of control and the precision of material and component fabrication and, thus, the capability to manufacture near-certified components.

AM Can Also Provide a Route to Improved Understanding of Dynamic Performance as a Function of Micro-Structure and Defects

As we have described, materials produced using AM have structure, properties, and performance that can differ from their counterparts manufactured by legacy processes. These differences include surface finish, density, residual stresses, nonequilibrium microstructure, and crystallographic orientation or texture. All these parameters are known to effect dynamic response of materials; however, we are far short of predictive models of the influence of these parameters. In part, this gap in our understanding is due to a general inability to manufacture parts with predetermined and isotropic (or controlled anisotropic) structures. AM processes provide an interesting capability to manufacture test components with controlled microstructure and architecture (see Figure 4), and the inclusion of designed defects. Utilizing AM methods to manufacture and test components with such bespoke structures or bespoke defects will enable a significantly improved predictive capability and enable the capability to tailor dynamic processes through manufacturing. An example of this is shown in Figure 6, where bismuth-tungsten composites are manufactured with either a stainless steel or carbon fiber-based structural support. When subject to dynamic loading at the High Explosives Application Facility at LLNL, significant differences in break up were observed.

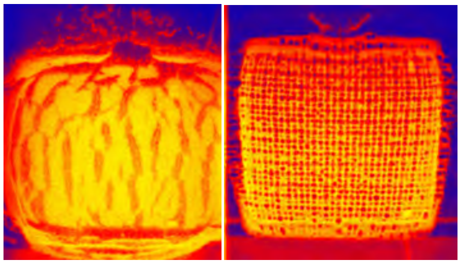


Figure 6. Cylindrical sections of Bi/W composites supported by stainless steel on the left and graphite/epoxy on the right. The behavior of these structures subjected to high explosives loading is captured in these time resolved radiographs. The steel support is seen to fracture and form fragments with the Bi/W flowing into the cracks. Conversely, the graphite epoxy composite imprints the pattern of the graphite fiber fabric on the Bi/W material seen in the radiograph (the carbon is invisible to the x-rays).

With AM, we can conceive of resolving some intriguing open questions about the dynamic performance of materials, including the following:

- Can we decouple strength from ductility?
- How does microstructure control dynamic response?
- How important is surface roughness under dynamic loading?
- Can we build materials with anisotropic dynamic behavior?

Partnerships Are Key

Significant research in AM is occurring throughout the academic, commercial, and national laboratory communities. Through these efforts, our ability to manufacture advanced materials and components will only continue to improve. These tools, when passed to the private sector will enable broader U.S. economic and national security goals. Through effective partnerships and collaborations, the ability to harness these advances to realize the goal of rapid manufacturing with rapid certification may be realized.

Building on our stockpile stewardship capabilities within the NNSA laboratories, plants (Kansas City Plant, Y-12 National Security Complex, and Pantex Plant) and our academic and industry partners, the NNSA Nuclear Security Enterprise already has a significant head start. The more we can understand the connection between manufacturing processes, material structure, material properties, and component performance, the faster we will be able to arrive at qualified materials and components with fewer required final physics, chemistry, and engineering tests. Validated predictive process codes will significantly reduce the amount of Edisonian trial and error "knob turning" involved in legacy manufacturing processes. We may also be able to create a more responsive and sustainable enterprise.

For more information, visit the following websites:

- https://manufacturing.llnl.gov/additive-manufacturing/designer-engineered-materials, and
- https://acamm.llnl.gov.

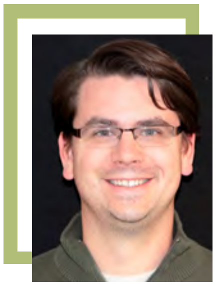
Students Q&As

The National Nuclear Security Administration (NNSA) is responsible for ensuring a safe, secure and effective nuclear deterrent and detecting, securing, and disposing of dangerous nuclear and radiological material, and for related weapons of mass destruction technology and expertise. As part of that mission, NNSA directly funds specialized scientific academic programs, in part to make strategic investments to maintain today's technically sharp workforce and the workforce of tomorrow. To do so, it is essential that NNSA support a strong academic community in science, technology, engineering, mathematics, and computation that not only serves as a future pipeline for the laboratory workforce but also cultivates peers capable of providing strong external review and competition. The Stewardship Science Academic Programs (SSAP) serve this purpose and are crucial to ensuring the next generation workforce for the Nuclear Security Enterprise. One goal of the SSAP is to offer the highest caliber of education and hands-on training and experience to the next generation of scientists and physicists. Working with the top scientists in their fields at the NNSA national laboratories and with SSAP academic partners accomplishes this and helps develop an exceptional pool of professionals to catapult us into the future.

Highlighted in the pages that follow are a few of the many alumni and students that are and have been supported by the SSAP.

Patrick Knapp, Sandia National Laboratories (SNL), pfknapp@sandia.gov

SNL Years: July 2011 to Present • Degree: PhD, Electrical Engineering, 2011
Years in SSAA Program: 2006-2011, Cornell University



During graduate school I was funded by the Stewardship Science Academic Alliances (SSAA) program to study pulsed power driven high energy density physics at the Laboratory of Plasma Studies (LPS) at Cornell University under Professor David Hammer. My graduate work centered around understanding the development of instabilities in wire array z-pinches and understanding the plasma conditions created when large currents (~1 MA) are driven through fine wires. In order to accomplish the former, I developed an x-ray absorption spectroscopy technique using an x-pinch as the x-ray source. This technique was able to measure the charge state in aluminum wire plasma and infer gradients in the conditions.

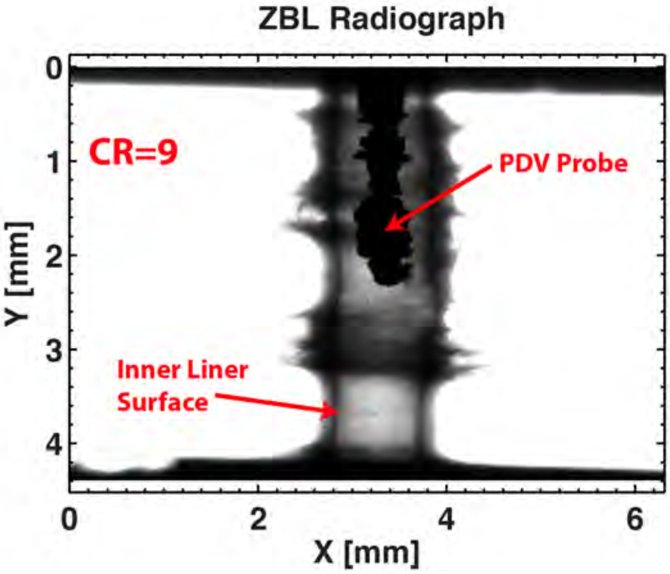


Figure 1. An x-ray radiograph of a deuterium equation of state experiment driven with an imploding liner. This image was captured at a convergence ratio (CR) equal to 9, the highest measured to date on Z. A Photon Doppler Velocimetry probe was used on the liner axis to measure the liner and shock velocities as a function of time. The probe has been destroyed at the time of the measurement.

Through my work in LPS, I was afforded the opportunity to attend a number of conferences and workshops that enabled me to foster relationships with scientists at the national laboratories and other universities. The National Nuclear Security Administration laboratories were always very interested in my presentations, particularly Sandia National Laboratories (SNL), because it was highly relevant to their research, including development of bright x-ray sources and the pursuit of inertial confinement fusion (ICF). This interest and exposure was only possible because the SSAA support at Cornell University allowed me to do research that was relevant to the national laboratories. The relationships I was able to foster during graduate school are the primary reason I am now an employee at SNL.

Working at SNL as an experimentalist on the Z machine provides me with the unique opportunity to explore a wide array of research topics related to pulsed power driven ICF, including nuclear physics, burn in mixed plasmas, compression of matter to high density, plasma instabilities, and radiation physics. This variety of work was a large factor in my decision to work at a national laboratory, and SNL in particular. No other place in the world allows me to do the kind of work that is done on a daily basis on the Z machine. The fast pace and variety of work keeps it interesting every single day. It is a wonderful feeling to know that nearly every single experiment we do is something that no one in the world has done before. This gives us remarkable opportunities to explore, innovate, and discover.

One of the primary goals in our group at SNL is to think of new ways to answer questions that have been plaguing the stockpile stewardship community for years. These long standing questions, like how imploding layers mix, will not be answered with one experiment, or even by a single laboratory, but it is exciting to know that I am already having an impact. Another important and long-term goal is the pursuit of controlled fusion in the laboratory. The promise of pulsed power is an efficient and inexpensive driver for laboratory fusion. It is amazing to be given the opportunity to work in this field, and the Z machine is one of the few places in the world where we can do ICF experiments today that have a strong chance of moving the science and technology forward that will enable fusion as an energy source in the future.

I am so grateful for the opportunity to work in the field of ICF. SNL is a wonderful place to work that offers a unique combination of a wide variety of fast paced work as well as excellent work-life balance. I am confident that I would not have had the opportunity to do what I do now were it not for the SSAA Program and Cornell University.

Amy Lazicki, Lawrence Livermore National Laboratory (LLNL), lazicki1@llnl.gov

LLNL Years: June 2004 to July 2007, September 2010 to Present • Degree: PhD, Properties of Low-Z Solids at High Pressure, 2002
Years in SSAA Program: 2002-2005, University of California, Davis

A Stewardship Science Academic Alliances (SSAA)-funded project at the University of California, Davis that had collaboration with Lawrence Livermore National Laboratory (LLNL) allowed me to do almost all of my graduate research at LLNL, through which I also had access to large-scale facilities such as the Advanced Photon Source and the Advanced Light Source to do experiments. As a graduate student at the laboratory, I made contacts and built relationships that eventually led to my current permanent position at LLNL. I presented posters at the annual Stewardship Science Academic Programs symposia, where I was able to interact with people associated with the National Nuclear Security Administration. These meetings gave me a unique perspective on the work I was doing and one of the scientists I met in this context later offered me a postdoctoral research position. After three years of postdoctoral work, I eventually returned to LLNL, because I really value the depth and breadth of knowledge and the abundance of resources there.

Currently at LLNL, I study the equation of state and phase transitions in materials under dynamic compression. I have primarily been involved in developing an experimental platform to measure x-ray diffraction of solids up to the 10 Mbar pressure regime. Diffraction is a very direct probe of material properties, and the experiment will be critical for understanding materials relevant to the NNSA, as well as to geo- and astrophysics models.

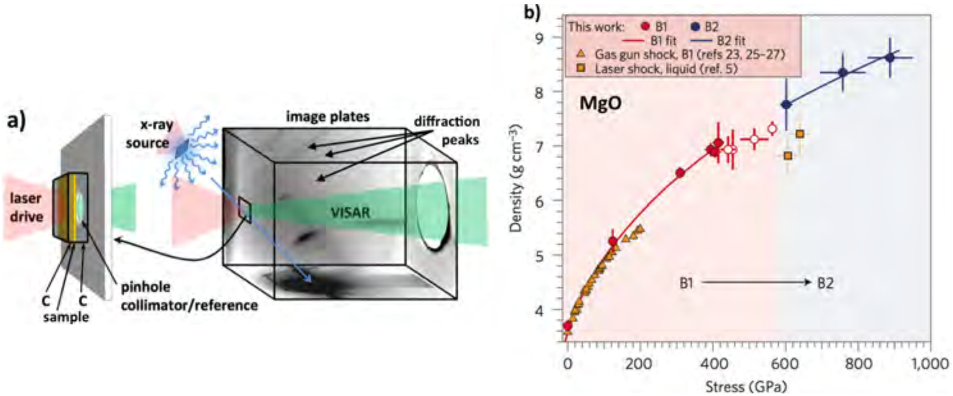


Figure 1. a) Experimental setup: target package consists of 4 μm foil or layer between single crystal diamond plates of 20 μm (ablator) and 40 μm (tamper). The target package is backed by a 300 μm-diameter Ta or Pt pinhole that collimates scattered x-rays and serves as an image plate calibrant. The target package is mounted on a box lined with image plates. Heα x-ray radiation from a laser-ablated 13μm metal foil (incident at 45°) is diffracted by the target and the Debye-Scherrer rings appear as conic sections on the image plates. The back image plate has a hole in it to allow the VISAR diagnostic to probe the rear target surface. b) New experimental results showing the equation of state of solid MgO, now extended to 900 GPA or 9 Mbar.[2]

This effort requires development of a method to compress materials in the solid phase to these unprecedented pressures, which so far can only be done dynamically. We use lasers with shaped pulses to drive our samples to maximum pressure at compression rates on the order of 10^9 s^{-1}. By ramping the pressure up to the maximum within 2-3 ns instead of instantaneously shock compressing it, we are able to retain the solid phase. The diffraction diagnostic then must be able to collect a diffraction pattern on the order of 1 ns, to capture the compressed solid in a quasi-steady-state. Our x-ray source is a 1 ns long burst of helium-alpha radiation from a laser-ablated metal foil. We generally use Fe or Cu (6.9 or 8.3 keV) as our source. The x-rays are scattered off the compressed sample in transmission and registered on image plates lining the inner walls of a box-shaped diagnostic we have developed for use at the Laboratory for Laser Energetics at the University of Rochester in Rochester, New York (see Figure 1a).[1]

We have used this method to study solid tin, tantalum, magnesium oxide, lead, diamond and others to pressures as high as 11 Mbar. We have demonstrated a good agreement with results from static compression methods up to 2 Mbar (the high pressure limit for most diamond anvil cell studies) and have seen evidence for phase transformations not previously accessible experimentally in several cases. The results for MgO are shown in the Figure 1b, where we were able to detect evidence for the long-predicted B1-B2 phase transition near 6 Mbar, and we could establish the stability of this phase up to 9 Mbar.[2] To achieve higher pressures, we are in the process of extending this experimental platform to the National Ignition Facility (NIF). The eventual goal is to reach atomic pressures (tens of Mbars for most elements), the range corresponding to core electron binding energies where physics and chemistry is dominated by core electron interactions. This goal has been identified as one of the basic research directions of the NIF by the NNSA at the 2011 workshop on the Basic Research Directions on User Science.[3]

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[1]J.R. Rygg et al., Powder diffraction from solids in the terapascal regime. Rev. Sci. Instrum. 83, 113904, 2012.

[2]F. Coppari et al., Experimental evidence for a phase transition in magnesium oxide at exoplanet pressures, Nature Geoscience 6, 926-929, 2013.

[3]Report on the National Nuclear Security Administration (NNSA) – Office of Science (SC) Workshop on Basic Research Directions on User Science at the National Ignition Facility.

Tennille Bernard, tenncb10@unm.edu

Degree in Progress: MSc., Mechanical Engineering, The University of New Mexico
Academic Advisor: Peter Vorobieff

Years in the SSAA Program:

2012 to Present

Research Topic:

Observation of the Richtmyer-Meshkov primary instability and secondary instabilities

What are your research responsibilities?

I work in a team consisting of five other students and two professors. I support the experimental collection of data from the shock tube. I assist with troubleshooting the shock tube experimental setup when we need to adjust the conditions of the experiment. Also, I am also working on a submission to the ASME Journal of Fluid Engineering as a lead author and have been a co-author of multiple research papers submitted by the research group.

How have you benefited from the SSAA program?

While the SSAA has provided me with many opportunities, the overall benefit of being a recipient of the program signified the start of a period of confidence and positivity that will inevitably lead to success. Through the SSAA program, I was able to return to pursue a Master's degree without being a burden to my mother, and have all the costs of my degree fully paid.

What has surprised you most about the program?

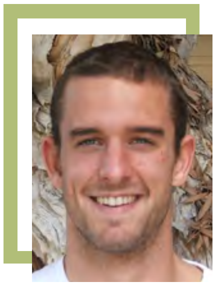
The most surprising thing is that the program offers me opportunities to take my research into the science and engineering community. So far, I have attended two national conferences and increased exposure to the research done by our research group at the University of New Mexico. My attendance at these conferences helped improve the visibility of multi-phase fluid instabilities (and the importance of its application to our lives) and of my university among the scientific and engineering communities.

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

Yes. I got the opportunity to stand up among the experts in the field and share my research at the American Physical Society's Division of Fluid Dynamics conference. I had the opportunity to talk about my research to the people who wrote the papers I used as my references. Funding from the SSAA made it possible. ●

Colin McElroy, cmcelroy@physics.ucsd.edu

Degree in Progress: PhD, Condensed Matter Physics, University of California, San Diego
Academic Advisor: Professor M. Brian Maple



Years in the SSAA Program:

2010 to Present

Research Topic:

Study of new High-T_c iron pnictide materials including single crystal LaFeAsO under extreme conditions (i.e., high magnetic fields, high pressure, low temperature).

What are your research responsibilities?

Our primary focus is the synthesis and characterization of single crystal materials known to exhibit correlated electron phenomena including superconductivity, magnetic order, heavy fermion, and non-fermi liquid behavior. I have been charged with conducting characterization experiments of these materials under applied pressures using several techniques, including designer Diamond Anvil Cells (dDACs) capable of reaching pressures up to 1 Mbar. These experiments allow access to a vast phase space of correlated electron physics for many complex materials we synthesize here in our own lab.

How have you benefitted from the SSAA program?

I have had the chance to conduct fascinating experiments on materials under pressure, allowing me insight into a region of experimental physics capable of shedding some light on otherwise elusive correlated electron phenomena. I have also been given opportunities to travel and share these experiments with colleagues worldwide, which has enriched my education and allowed me to contribute worthy results to the broader research community.

What has surprised you most about the program?

The breadth of experiments covered under the SSAA program is vast and inspiring. To see talks and posters given by students and scientists under the auspices of this program has inspired a sense of collaboration between subspecialties and various areas of interest that will no doubt prove vital to ongoing research.

What do you want students considering the SSAA program to know?

It is extremely important to recognize the context for your research projects within the scientific community. The heavy work-load of any PhD. Program can push that context out of sight, but programs like the SSAA program give a direct line to re-establishing that connection. It is very rewarding to see your research fit into a network of research groups across the country and provide such a fertile foundation for inter-group collaborations.

Did the SSAA program influence your choice of research area and university?

As an undergraduate I became aware of the Maple Laboratory's high-pressure program and the many careers it helped launch. The intricate work involved with the techniques of applied pressure experiments as well as the rich experimental results quickly became a strong motivation for choosing this research program, and that decision has proven to be an excellent one. ●

Cody Parker, parker@phy.ohiou.edu

Degree in Progress: PhD, Nuclear Physics, Ohio University
Academic Advisor: Dr. Carl Brune

Years in the SSAA Program:

2010 to Present

Research Topic:

^{3}H(d,γ)^{5}He/^{3}H(d,n)α Branching Ratio

What are your research responsibilities?

I am a Research Assistant in the Edwards Accelerator Laboratory on the campus of Ohio University. My responsibilities include the operation of the 4.5 MV Tandem van de Graaff Accelerator and assisting in the set-up and diagnostics of many experiments from my research group, as well as outside users. The work done at the lab is primarily in studying reactions that are of interest to the National Ignition Facility, homeland security, nuclear astrophysics, and other applications including materials analysis. I am also involved in general outreach, such as giving tours of the facility to university students and community members.

How have you benefited from the SSAA program?

The SSAA Program has given me the opportunity not only to carry out my research, but to travel to the annual symposia where I have been able to discuss my project with other scientists who are genuinely interested. In addition, it has been rewarding to present my poster as it gave me a chance to practice speaking about my work, as well as network with others. The information sessions from national laboratory representatives are also quite beneficial because it has given me an additional perspective as to what my job opportunities are when I complete my degree. I have also had the opportunity to develop a working relationship with researchers at both Lawrence Livermore National Laboratory and Los Alamos National Laboratory, which has been helpful in my own project.

What has surprised you most about the program?

I was surprised (and excited) to learn about the amount of training opportunities available to students in Low Energy Nuclear Science. However, I was even more surprised by the diversity of the projects supported by the program, which has given me the chance to meet people from outside my area who are all working on common goals, just from different approaches.

What do you want students considering the SSAA program to know?

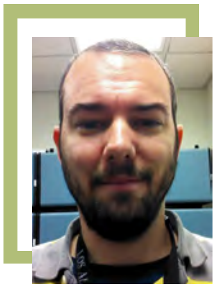
Ohio University has participated in the SSAA Program since 2003. I find it important to know that if a laboratory is doing good work, that there are long-term funding opportunities available, and are likely to sustain students through their time in school. It is important to know that there is financial support available so students can concentrate more on carrying out their research projects.

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

I believe the program has given me the chance to increase my opportunities to work with collaborators from national laboratories that may not have been developed as much otherwise. ●

John William Howard, jwhoward@physics.unlv.edu

Degree in Progress: PhD, Solid State Physics, University of Nevada, Las Vegas
Academic Advisor: Dr. Yusheng Zhao



Years in the SSAA Program:

2007 to Present

Research Topic:

Lithium ion transport in lithium-rich antiperovskite electrolytes

What are your research responsibilities?

To synthesize and characterize lithium-rich antiperovskite materials to be used for battery applications.

How have you benefitted from the SSAA program?

I have been exposed to a large number of great minds and mentors that have significantly accelerated my understanding of science. I have been afforded the luxury of attending several conferences to present my research in a scientific setting. I have access to facilities with state of the art scientific equipment which allows for experiments to be conducted in a timely and elegant fashion.

What has surprised you most about the program?

Meeting many famous scientists I would not have otherwise had the opportunity to has surprised me the most.

What do you want students considering the SSAA program to know?

That your opportunities for success are endless, you are limited only by your own motivation.

Did the SSAA program influence your choice of research area and university?

In a way, yes. My former advisor, the late Dr. Malcolm Nicol, first interested me in high pressure science, and from there my interests coincided with those of the SSAA Program.

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

Absolutely. I have been able to work with some of the greatest minds due to the opportunity provided by the SSAA program. This includes beamline scientists at national laboratories and professors from prestigious universities. ●

Laura Johnson, laj64@cornell.edu

Degree in Progress: PhD, Electrical and Computer Engineering, Cornell University
Academic Advisors: Dr. Dave Hammer and Dr. Stephanie Hansen

Years in the SSAA Program:

2011 to Present

Research Topic:

Applications of the average-atom method of computing atomic absorption spectra and theoretical approaches to computing x-ray Thomson scattering signals

What are your research responsibilities?

During my first couple years, I worked on developing an average-atom code (RadiES) that uses the finite-difference method to numerically solve the Schrödinger equation for a spherically symmetric potential in the self-consistent field approximation. My code allows for various effects such as the ability to account for temperature and density. More recently, I have been working on various theoretical approaches to computing x-ray Thomson scattering signals and would ultimately like to use wave functions produced by my code to compute x-ray Thomson scattering signals. I compare these methods to ongoing x-ray Thomson experiments performed at Cornell's Laboratory of Plasma Studies.

How have you benefitted from the SSAA program?

I am very grateful for the opportunities the SSAA program has provided me. In addition to being able to work with my mentor Dr. Stephanie Hansen from Sandia National Laboratories, it has also allowed me to attend conferences where I have been able to meet and network with other top scientists in my field of research and get wonderful feedback on my research, which has greatly contributed to my professional development. The opportunity to travel to these conferences to present my research has really helped me develop better public speaking skills and confidence in explaining my research to others.

What has surprised you most about the program?

I've been surprised by the flexibility I've had in choosing research topics that fit my unique abilities and interests.

What do you want students considering the SSAA program to know?

There are amazing opportunities and benefits offered by the SSAA Program, including the ability to work with lead scientists, attend international conferences to present research and learn about other on-going research, and the convenience to collaborate with researchers from national laboratories around the country.

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

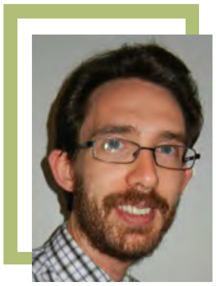
During my time in graduate school, I've had the great opportunity to work closely with Dr. Stephanie Hansen from Sandia National Laboratories. I usually spend a few months of the year working in New Mexico under her guidance. ●

Stanley Paulauskas, spaulaus@utk.edu

Degree in Progress: Nuclear Physics*, The University of Tennessee
Academic Advisor: Robert Grzywacz

Years in the SSAA Program:

2009 to 2013



Research Topic:

Beta-delayed neutron emission and detector development

What are your research responsibilities?

Due to the nature of our research group, my research responsibilities vary greatly. I have primarily worked to develop high resolution timing algorithms for digital electronics. These algorithms provide the time resolutions necessary for the Versatile Array of Neutron Detectors at Low Energy (VANDLE) to measure neutron energies via the time-of-flight technique. One of the goals of VANDLE is to perform beta-delayed neutron spectroscopy of fission fragments. The beta-delayed neutrons from this process are used to determine the Gamow-Teller matrix elements above the neutron separation energy. These matrix elements provide critical inputs to theoretical models, astrophysical calculations, and reactor designs. Currently, I am writing analysis software to determine the matrix elements from the neutron spectra.

How have you benefitted from the SSAA program?

I have been able to work on the VANDLE project from near its inception to its use in physics experiments. This has allowed me to participate in all aspects of the development of a new detector system. My work with digital electronics and timing algorithms provide me with an invaluable tool as many groups in nuclear physics are starting to use digitizers as their primary acquisition systems. My intimate knowledge of such systems meant that obtaining a research position after graduation has not been difficult.

What has surprised you most about the program?

The ability of the program to draw students from many different fields and foster a sense of collaboration.

What do you want students considering the SSAA program to know?

My biggest piece of advice is that one should always consider all of their choices, and choose the option that they will enjoy the most.

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

Yes, I would not have had the opportunity to work with many of my collaborators if the VANDLE project had not been sponsored by the SSAA. ●

* Paulauskas's PhD was conferred in December 2013.

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
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
R. Paul Drake
Richtmyer-Meshkov Experiments by the Center for Laser Experimental Astrophysics Research

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
Z-pinch Research on Radiation, Atomic and Plasma Physics

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
Fission Fragment Distribution Measurements with a Double Arm Time of Flight Spectrometer

Duke University
Calvin Howell
Photo-Induced Precision Cross-Section Measurements of Actinide Nuclei Using Monoenergetic and Polarized Photon Beams

Duke University
Werner Tornow
Fission Product Yields of ^{235}U, ^{238}U, ^{239}Pu and Neutron Induced Reactions on Specific Nuclei

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

North Carolina State University
Gary Mitchell
Cross Section Level Densities and Strength Functions

Ohio University
Carl Brune
Studies in Low Energy Nuclear Science

Rensselaer Polytechnic Institute
Yaron Danon
Measurements of Fission Neutron Distributions and Neutron Cross Section Measurements Using a Lead Slowing-Down Spectrometer

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 Massachusetts, Lowell
Christopher Lister
A Versatile Gamma and Fast Neutron Spectrometer

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

University of Tennessee
Witold Nazarewicz
Microscopic Description of the Fission Process

Properties of Materials Under Extreme Conditions

Arizona State University
Pedro Peralta
Quantification of Local Nucleation and Growth Kinetics of Spall Damage in Metallic Materials: Experiments and Modeling

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

Carnegie Institution of Washington
Guoyin Shen
HPCAT Operations

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

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

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

Texas A&M University
Devesh Ranjan
Detailed Measurements of Turbulent Rayleigh-Taylor Mixing at Large and Small Atwood Numbers

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
High-Z Metal Oxides at High Pressure: Integrated Experiment

University of California, San Diego
M. Brian Maple
Novel d- and f- Electron Materials Under Extreme Conditions of Pressure, Temperature and Magnetic Field

University of California, San Diego
Marc Meyers
Extreme Materials Response in Laser Shock Compression and Release

University of Illinois, Urbana-Champaign
David Ceperley
Quantum Simulations for Dense Matter

University of Michigan
Fuxiang Zhang
Order-Disorder Transition and Small Molecule Incorporation in Pyrochlore Oxides at Extreme Conditions

University of Nevada, Las Vegas
Yusheng Zhao
High Pressure Science and Engineering Center

University of Nevada, Reno
Dhanesh Chandra
Behavior of Ni-Nb-Zr Amorphous Alloy Gas Permeation Membrane Ribbons at Extreme Conditions

University of New Mexico
Peter Vorobieff
Shock-driven Complex Behavior of Multiphase Flow: Dynamics of Particles and Droplets

University of Washington
Evan Abramson
Viscosities at Extreme Densities

University of Wisconsin
Riccardo Bonazza
Investigation of Shock-Induced Turbulent Mixing at a Gas Interface

Washington State University
Yogendra Gupta
Institute for Shock Physics

Radiochemistry

University of California, Berkeley
Heino Nitsche
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

High Energy Density Laboratory Plasmas

California Institute of Technology
Guruswami Ravichandran
Viscous Plastic Flow at Extreme Pressures and Strain Rates

Cornell University
Pierre Gourdain
The Dynamics of High Energy Density Plasmas in Radial Foil Configurations

Cornell University
John Greenly
Experimental and Computational Studies of High Energy Density Plasma Streams Ablated from Fine Wires

Cornell University
David Hammer
Spectroscopic Determination of the Magnetic Fields in Exploding Wire and X-Pinch Plasmas

General Atomics
Michael Farrell
Viscous Plastic Flow at Extreme Pressures and Strain Rates

Harvard University
Stein Jacobsen
From Z to Planets

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

Massachusetts Institute of Technology
Richard Petrasso
HEDLP Studies of Fields, Matter, Transport, Nuclear Physics, and ICF with New Diagnostics at the NIF and OMEGA/OMEGA EP

Princeton University
Szymon Suckewer
Research on Improvement Efficiency and Focussibility of Ultra-Intense Beam of Stimulated Raman Amplifier/Compressor In Plasma Backscattering

Smithsonian Astrophysical Observatory
Guo-Xin Chen
Relativistic Study of X-ray Polarization Spectroscopy for Fusion Plasmas

University of California, Berkeley
Roger Falcone
Design and Fielding of a Highly Efficient Multi-Channel X-ray Spectrometer for Advanced X-ray Scattering Diagnostics

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

University of California, San Diego
Sergei Krasheninnikov
Physics of Pre-plasma and the Mechanisms of Intense Electron Beam Generation by Relativistic Laser Radiation

University of Nevada, Reno
Radu Presura
Single-Crystal X-ray Spectropolarimetry of Z-pinch Plasmas

University of Washington
Uri Shumlak
High Energy Density Z-pinch Plasmas Using Flow Stabilization: ZaP-HD

National Laser Users' Facility

General Atomics
Richard Stephens
Investigation of the Dependence of Fast-Electron Generation and Transport on Laser Pulse-Length and Plasma Material

Massachusetts Institute of Technology
Richard Petrasso
Studies of Laboratory Astrophysics, Inertial Confinement Fusion, and High Energy Density Physics with Nuclear Diagnostics

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

Princeton University
Thomas Duffy
Dynamic Compression of Earth and Planetary Materials Using OMEGA

Princeton University
Hantao Ji
Study of Particle Acceleration and Fine-Scale Structures of Collisionless Magnetic Reconnection Driven by High Energy Petawatt Lasers

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

University of California, Berkeley
Raymond Jeanloz
Journey to the Center of Jupiter, Recreating Jupiter's Core on OMEGA

University of California, San Diego
Farhat Beg
Systematic Study of Fast Electron Energy Deposition in Imploded Plasmas with Enhanced EP Laser Contrast and Intensity

University of California, San Diego
Bin Qiao
Dynamics of High-Energy Proton Beam Focusing and Transition into Solid Targets of Different Materials

University of Michigan
R. Paul Drake
Experimental Astrophysics on the OMEGA Laser

University of Michigan
Louise Willingale
Intense Laser Interactions with Low Density Plasmas Using OMEGA EP

University of Nevada, Reno
Roberto Mancini
X-ray Spectroscopy of Polar Direct-Drive Implosions at OMEGA Using Spectrally-Resolved Imaging

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

Predictive Science Academic Alliance Program

University of Florida
S. Bala Balachandar
Center for Compressible Multiphase Turbulence

University of Illinois at Urbana-Champaign
William Gropp
The Center for Exascale Simulation of Plasma-Coupled Combustion

University of Notre Dame
Samuel Paolucci
Center for Shock Wave-processing of Advanced Reactive Materials

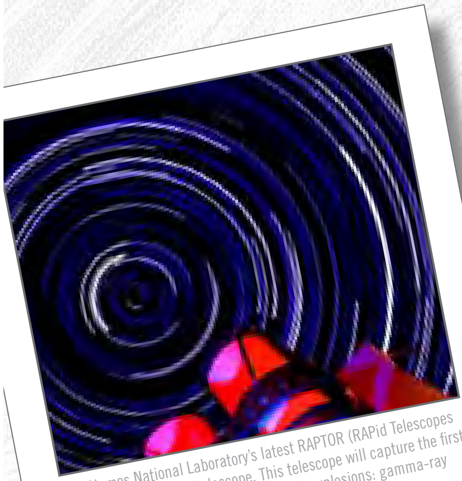
Stanford University
Gianluca Iaccarino
Predictive Simulations of Particle-Laden Turbulence in a Radiation Environment

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

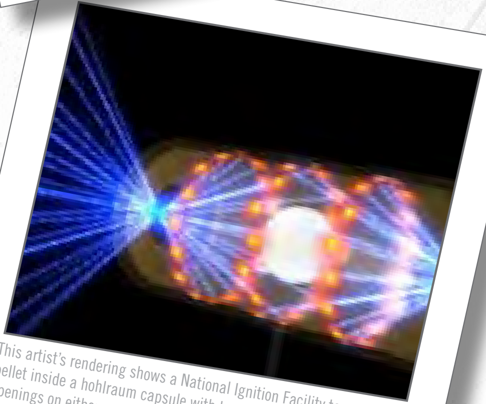
University of Utah
Philip J. Smith
The Uncertainty Quantification-Predictive Multidisciplinary Simulation Center for High Efficiency Electric Power Generation with Carbon Capture

Department of Energy National Nuclear Security Administration

Stewardship Science Graduate Fellowship



Los Alamos National Laboratory's latest RAPTOR (RAPid Telescopes for Optical Response) telescope. This telescope will capture the first color cinematography of nature's largest explosions: gamma-ray bursts.



This artist's rendering shows a National Ignition Facility target pellet inside a hohlraum capsule with laser beams entering through openings on either end. The beams compress and heat the target to the necessary conditions for nuclear fusion to occur. Image courtesy of Lawrence Livermore National Laboratory.

Parabolic trough collectors concentrate the sun's energy on an oil-filled tube running along the focal line of the parabolically shaped trough. Image courtesy of Sandia National Laboratories.

The Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship (DOE NNSA SSGF) program provides outstanding benefits and opportunities to students pursuing a Ph.D. in areas of interest to stewardship science, such as properties of materials under extreme conditions and hydrodynamics, nuclear science, or high energy density physics.

BENEFITS

$36,000 yearly stipend

Payment of full tuition and required fees

$1,000 yearly academic allowance

Annual program review

12-week research practicum

Renewable up to four years

APPLY ONLINE

The DOE NNSA SSGF program is open to senior undergraduates or students in their first or second year of graduate study. Access application materials and additional information at:

www.krellinst.org/ssgf

U.S. DEPARTMENT OF ENERGY

NNSA
National Nuclear Security Administration

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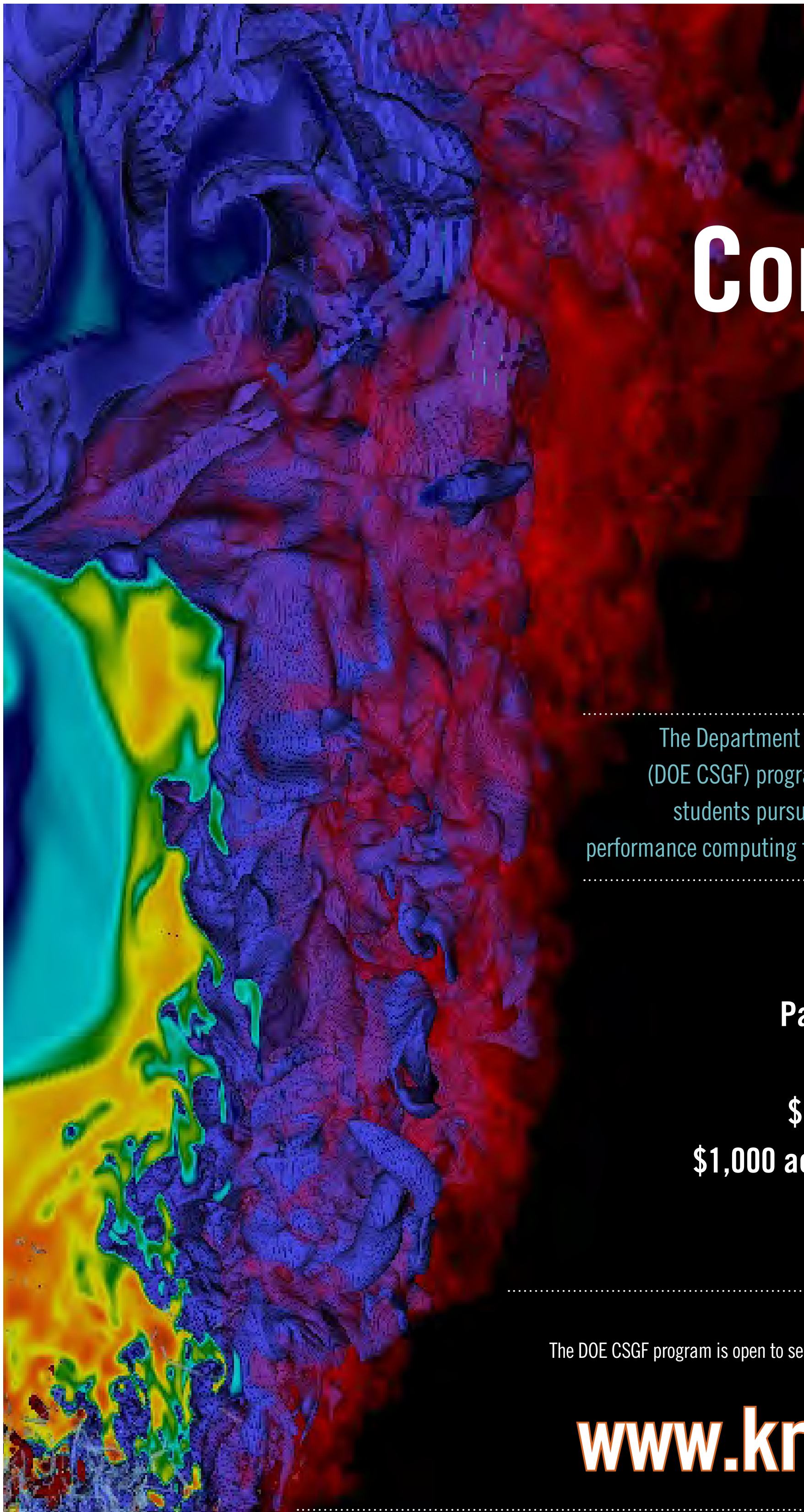
DOE CSGF

Department of Energy

Computational Science Graduate Fellowship



The Department of Energy Computational Science Graduate Fellowship (DOE CSGF) program provides outstanding benefits and opportunities to students pursuing doctoral degrees in fields of study that utilize high performance computing to solve complex problems in science and engineering.

BENEFITS

$36,000 yearly stipend

Payment of full tuition and required fees

Annual program review

$5,000 academic allowance in first year

$1,000 academic allowance each renewed year

12-week research practicum

Renewable up to four years

APPLY ONLINE

The DOE CSGF program is open to senior undergraduates and students in their first year of doctoral study.
Access application materials and additional information at:

www.krellinst.org/csgf

IMAGE: A visualization of a lean hydrogen flame simulation shows three computed fields simultaneously. A bowl-shaped turbulent flame floats over the exit flow from a pipe that is swirling as it moves upward. The gray filaments at the bottom depict regions of high turbulence, the transparent red surface highlights the mixing region between the fuel from the pipe and the air outside, and the purple-to-red zone shows the concentration of nitrogen-based emissions from the flame. Image courtesy of Lawrence Berkeley National Laboratory.

U.S. DEPARTMENT OF ENERGY | Office of Science

NNSA National Nuclear Security Administration

KRELL institute

This equal opportunity program is open to all qualified persons without regard to race, gender, religion, age, physical disability or national origin.

http://www.nnsa.energy.gov/stockpilestewardship

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Comments and Suggestions

The NNSA Office of Research, Development, Test, and Evaluation would like to receive feedback from you. Click the green button to the left to share your comments about the *2014 Stewardship Science Academic Programs Annual*. We also welcome suggestions for future Annuals.


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