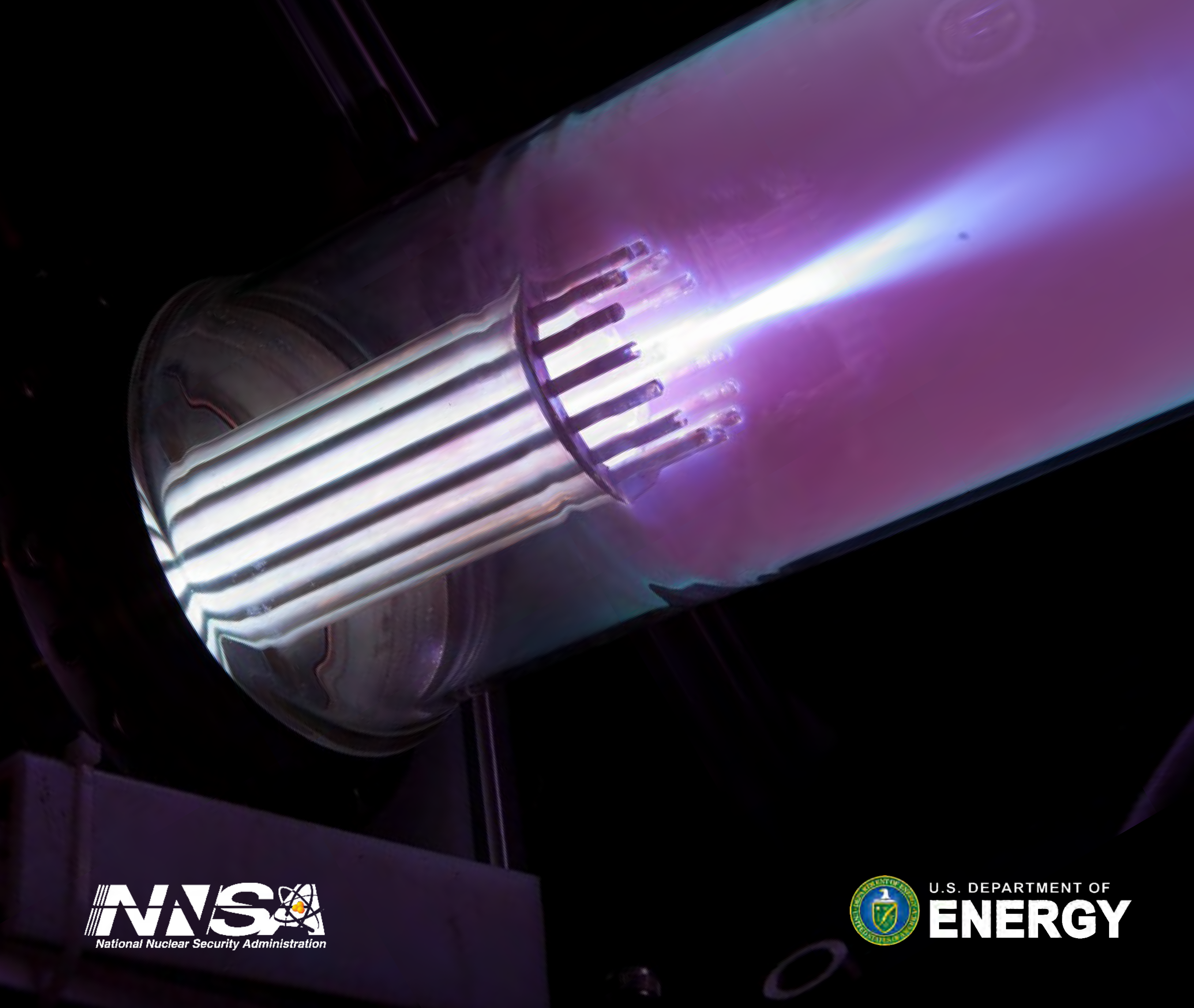
2015
Stewardship Science Academic Programs Annual

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



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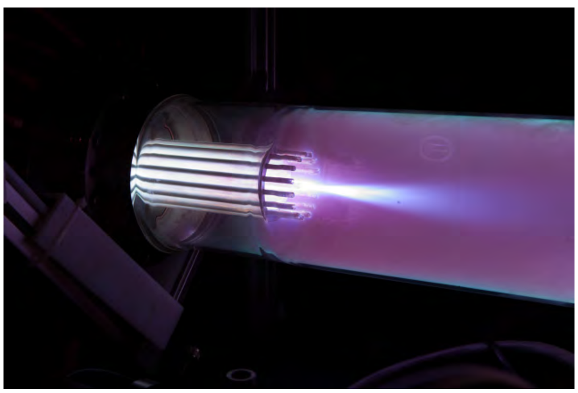

On the Cover

High energy density plasma deflagrations from a coaxial gun form highly concentrated dense plasma jets used to study first-wall fusion reactor science.

— Photo courtesy of Dr. Mark Cappelli, Stanford University (see page 18).

DOE/NA-0027

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National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY

Dr. Donald L. Cook, Deputy Administrator for Defense Programs, NNSA with Dr. Kathleen B. Alexander, Assistant Deputy Administrator for Research, Development, Test, and Evaluation.

NNSA
National Nuclear Security Administration

Mission First...Through Teamwork

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

The Stockpile Stewardship Academic Programs (SSAP) are essential to maintaining a pipeline of professionals to support the technical capabilities that reside at the National Nuclear Security Administration (NNSA) national laboratories, sites, and plants. Since 1992, the United States has observed the moratorium on nuclear testing while significantly decreasing the nuclear arsenal. To accomplish this without nuclear testing, NNSA and its laboratories developed a science-based Stockpile Stewardship Program to maintain and enhance the experimental and computational tools required to ensure the continued safety, security, and reliability of the stockpile. NNSA launched its academic program portfolio more than a decade ago to engage students skilled in specific technical areas of relevance to stockpile stewardship. The success of this program is reflected by the large number of SSAP students choosing to begin their careers at NNSA national laboratories.

What I see at the SSAP Symposium is very exciting—students committed to a future in science, technology, and engineering. By choosing to work in these areas, you are making contributions needed to address the Nation's technological challenges. Through the SSAP, you have the opportunity to take advantage of practicums and other collaborations with staff at the NNSA national laboratories. Some of the successful results of your efforts are presented in this *2015 Stewardship Science Academic Programs Annual*. Congratulations to you for what you have accomplished to date and best wishes for your future.

Dr. Kathleen B. Alexander

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

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

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Published February 2015

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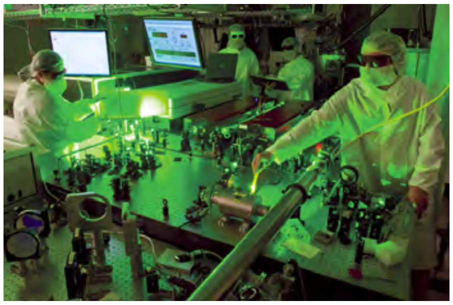

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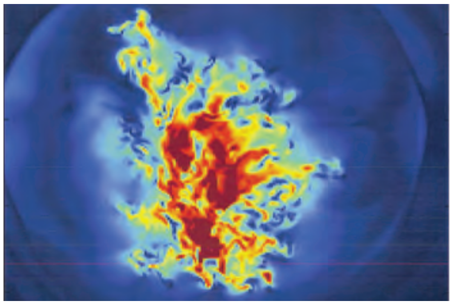

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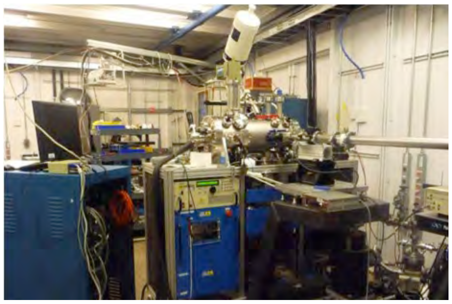
Overview

Research

Stewardship Science Academic Alliances (SSAA)



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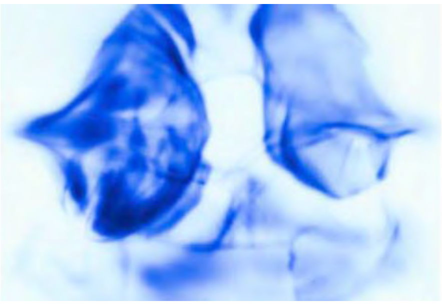

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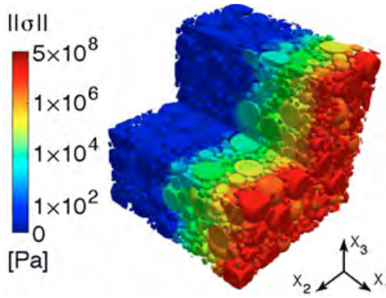

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Stewardship Science Academic Programs

Graduate student Christian Wolowiec, in the laboratory of Professor M. Brian Maple at the University of California, San Diego, attaching electrical leads to a sample of $CeO_{0.5}F_{0.5}BiS_2$ for electrical resistivity measurements under pressure.

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

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

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

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

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

Stewardship Science Academic Alliances (SSAA) Program

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

High Energy Density Laboratory Plasmas (HEDLP) Program

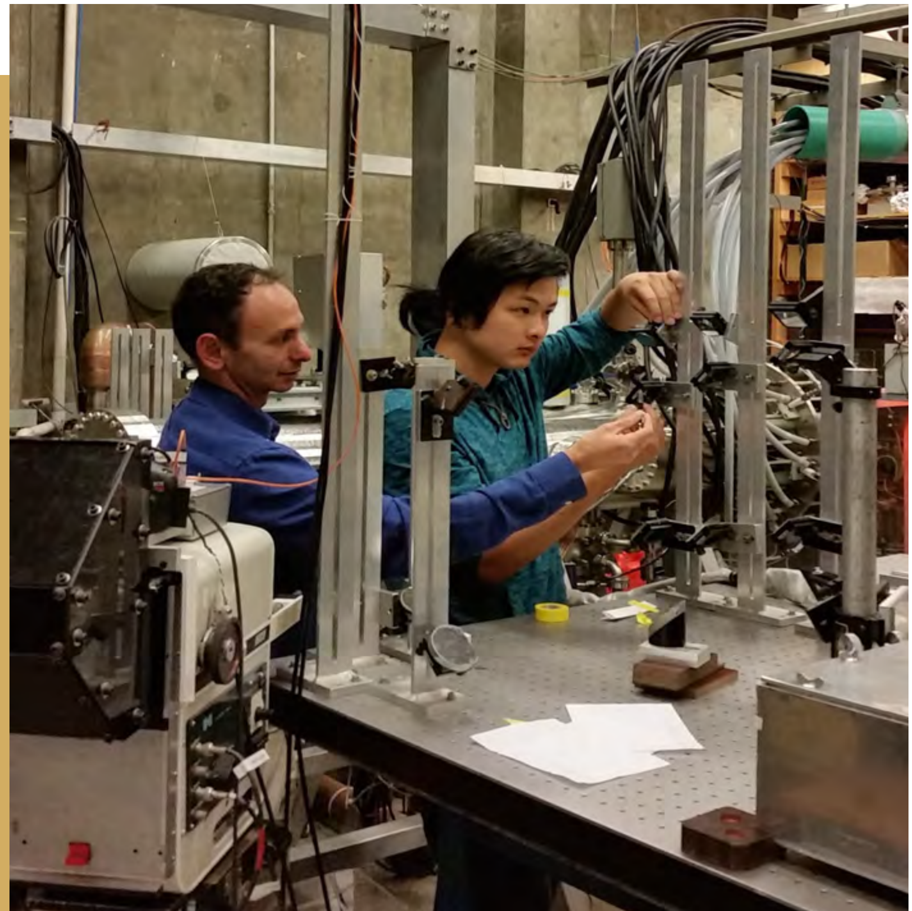
The NNSA's Office of Inertial Confinement Fusion and the DOE's Office of Fusion Energy Sciences established this joint program in 2008. It involves the study of ionized matter in laboratory experiments where the stored energy reaches approximately 100 billion joules per cubic meter (i.e., pressures of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

National Laser Users' Facility (NLUF) Program

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

Predictive Science Academic Alliance Program II (PSAAP II)

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



Professor Uri Shumlak (left) and Bonghan Kim align the multi-chord HeNe interferometer on the ZaP-HD Flow Z-Pinch experiment at the University of Washington.

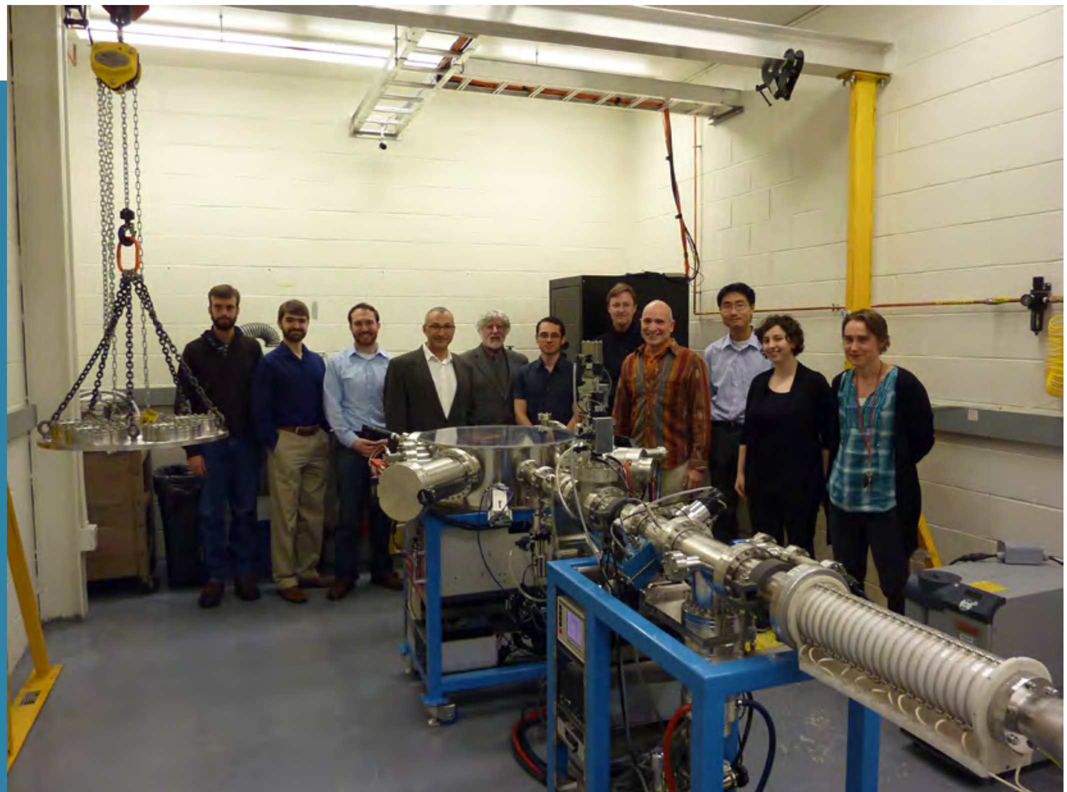
Former SSAP Students Win Prestigious Awards

Researcher **Stephanie Hansen** of Sandia National Laboratories received a 2014 Early Career Research Program award from the DOE's Office of Science. Hansen's winning submission, "Non-Equilibrium Atomic Physics in High Energy Density Material," describes an approach to improve simulation tools used to design high-energy experiments in dense hot plasmas, as well as the diagnostic tools used to interpret data from them. Stephanie participated in the SSAA Program from 2002 to 2003.

Seth Root of Sandia National Laboratories received a 2012 Presidential Early Career Award for Science and Engineering. He was selected for his leading edge research in condensed matter physics. His work on the Z machine is focused on understanding the high-pressure behavior of noble gases cryogenically cooled to an initial liquid state. Seth participated in the SSAA Program from 2002 to 2007.

Physicist **Miguel Morales** of Lawrence Livermore National Laboratory received a 2012 Presidential Early Career Award for Science and Engineering for his leading edge research in condensed matter physics. Using advanced computational techniques such as density functional theory and quantum Monte Carlo, Morales studies materials at extreme pressure and temperature on some of the world's most powerful supercomputers. Miguel participated in the SSGF Program from 2006 to 2010.

Mario J. Manuel received his PhD in Applied Plasma Physics from the Massachusetts Institute of Technology (MIT) Nuclear Science and Engineering Department in 2013. He is the latest Marshall Rosenbluth Outstanding Thesis Award recipient and the first ever from the field of high energy density/inertial confinement fusion physics. Dr. Manuel received the prestigious award on October 29, 2014 for his thesis "Rayleigh-Taylor-Induced Electromagnetic Fields in Laser-Produced Plasmas" through MIT's High Energy Density Division, led by Dr. Richard D. Petrasso of the Plasma Science and Fusion Center. Dr. Manuel's dissertation research focused on the development of a monoenergetic proton radiography system to make the first experimental measurements of magnetic fields induced by Rayleigh-Taylor growth in laser-produced plasmas and was derived entirely out of the NLUF Program.

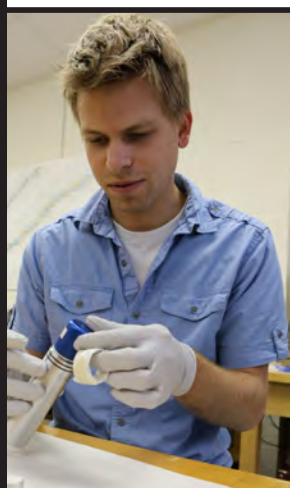


Lawrence Livermore National Laboratory's Deputy Chief Scientist of Inertial Confinement Fusion, Dr. Omar Hurricane (fourth from the left), is shown at the Massachusetts Institute of Technology (MIT) High Energy Density Accelerator Facility with PhD students and physicists, during his visit to the MIT Plasma Science and Fusion Center on December 4, 2014.

Stewardship Science Academic Alliances

Properties of Materials Under Extreme Conditions

High Energy Density Physics



Radiochemistry

Low Energy Nuclear Science

Exploring Matter Under Extreme Conditions Using Pulsed Power

Cornell University

PIs: David A. Hammer (dah5@cornell.edu) and Bruce R. Kusse (brk2@cornell.edu)

Introduction

The Center for Pulsed-Power-Driven High-Energy Density Plasmas at Cornell University studies the dynamics and physical properties of hot dense plasmas produced using ~ 1 MA pulsed power generators. Experiments are supported by extended magnetohydrodynamics (XMHD) computer simulations using the home-grown code, PERSEUS. New diagnostic methods for high energy density (HED) plasmas, such as x-ray Thomson scattering using an x-pinch x-ray source are developed. A principal Center mission is training a new generation of HED research scientists by involving undergraduates as well as doctoral students in Center research projects. About 30 graduate students have completed PhDs at Cornell University and Center partner institutions; Imperial College, London; and the University of Rochester, under Center sponsorship since its inception. Eleven of the 30 are employed at the NNSA national laboratories.

Figure 1. Students, staff, and faculty of the Center for Pulsed-Power-Driven High-Energy Density Plasmas along side of the COBRA experiment chamber.

Several highlights of the work carried out by students and staff scientists during the past year are described in the following paragraphs. Figure 1 shows the facility, students, staff, and faculty.

Gas-puff Z-pinch

Interest in krypton gas puff z-pinches at Sandia National Laboratories (SNL) at >13 keV, high-fluence radiation sources has led to a wave of new experiments on the COBRA (1 MA peak current, 100 ns rise time) pulser at Cornell using a triple coaxial gas-puff valve designed and built for use on COBRA by Center partners at the Weizmann Institute of Science in Israel. The goal at Cornell is to understand the fundamental physics of HED plasmas to optimize their application not only as plasma radiation sources, but also as platforms to study other aspects of HED physics, including magnetohydrodynamic (MHD) instabilities and laboratory plasma astrophysics.

In a gas-puff z-pinch, the neutral gas injection phase, pre-ionization, and gas breakdown physics all play critical roles in assembling the tightly pinched HED plasma column along the nozzle axis, which is the primary radiation source. Growth of disruptive MHD instabilities during the “run-in” phase (as current sweeps material towards the axis) depends strongly on the radial distribution of mass injected by the nozzles.[1] The first step is accurate measurement of neutral density profiles using planar laser-induced fluorescence (PLIF)[2], as shown in Figure 2. The density and thickness of the sheath of accelerated and entrained plasma is measured by laser interferometry, and comparison with neutral density plots yields values of the ionization state immediately prior to the pinch time. Temperature, density, and velocity measurements can be made for both electrons and ions at many points in the plasma from the spectral profiles of high-intensity laser light that is scattered from the plasma electrons by Thomson scattering.

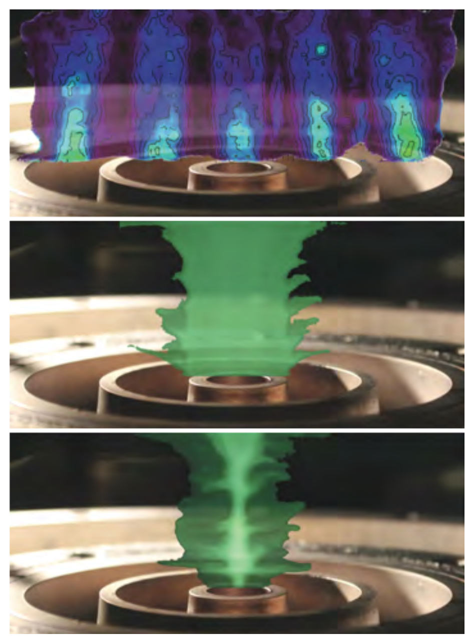


Figure 2. Argon gas injected by the triple-annular nozzle on the COBRA facility (top) is ionized and imploded by 1MA to a tightly pinched column of high energy density plasma (bottom). The growth of trailing ‘spikes’ behind the imploding sheath (middle) is detrimental to the final pinch energy density and x-ray yield, but can be controlled by careful selection of injected gas and radial density profile.

This robust set of diagnostics is beginning to yield an understanding of the growth of MHD instabilities (see Figure 2) and energy transport processes that inhibit formation of a tight pinch and achievement of the brightest possible radiation source. Predictions can be made and tested with both analytical theories and the

PERSEUS code. The role of radiative cooling during the "run-in" phase will be addressed next by careful selection of working gases. Introduction of krypton to the puff has already presented new challenges for experimentalists and collaborators at the Naval Research Laboratory, whose synthetic x-ray emission spectra enable temperature and density measurements at the heart of the pinch.

Upgrades to PERSEUS

PERSEUS was originally developed as a non-relativistic XMHD code. It solves the two-fluid equations, formulated in terms of a generalized Ohm's law (GOL), using a method that captures the expected physics over a wider range of densities than standard MHD. Recently, a numerical scheme called the Discontinuous Galerkin method (DG) for solving the equations has been implemented in the code. It preserves the positivity of the density and pressure in HED plasmas with large density and pressure ranges[3] as well as the divergence-free nature of the magnetic field.[4] Also, it is more accurate for a given amount of computer time in resolving the spatial structure of the plasma than the original version of PERSEUS. The scheme has been used to model magnetized shocks involving the interaction of supersonic/super-Alfvenic flow with obstacles. The Hall term in the GOL is found to be significant in elucidating the physics in magnetic reconnection experiments magnetospheric substorm events, etc. This version of PERSEUS can also be used to study interplanetary physics scaled to laboratory parameters.

Relativistic modeling capabilities are also being incorporated into PERSEUS, enabling it to handle a diverse range of relativistic astrophysical as well as laboratory HED plasma phenomena. Relativistic PERSEUS has simulated laser-plasma interactions and the point x-ray sources that are called hybrid x-pinches. The x-pinch simulations generated relativistic electrons immediately following the intense soft x-ray burst from the x-pinch, consistent with experimental observations of hard x-rays at that moment.[5] Relativistic PERSEUS has also demonstrated it is capable of simulating the penetration of an intense laser (10^{24} W/m^2) into an over-dense gas. The results reproduce relativistic channeling of narrow, collimated magnetized jets. This behavior, seen in experiments, is due to induced transparency, where the laser accelerates electrons to a larger effective mass, increasing the index of refraction and enabling further penetration.[6]

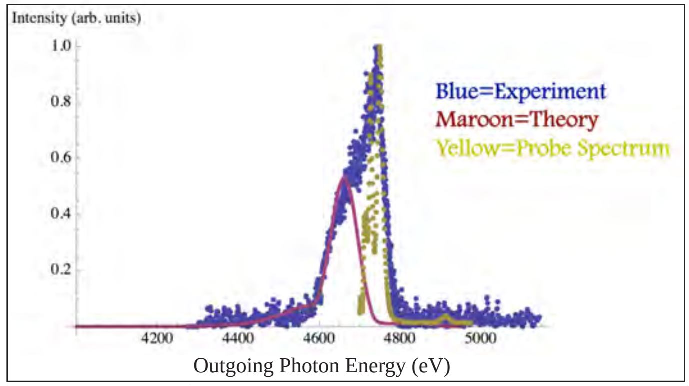


Figure 3. Cold scattering results from 20-μm-thick Al foil. Theoretical fit of scattered spectra made using new in-house model.

Cylindrical Liner Experiments

The Magnetized Liner Inertial Confinement Fusion concept[7] under investigation at SNL uses the ~20 MA Z Machine to implode a cylindrical metal liner to compress and heat preheated, magnetized plasma contained within the liner. Experiments on COBRA investigated the impact a liner's surface structure has on initial plasma formation for both imploding and non-imploding liners.

Cornell has developed liners that consistently initiate with high uniformity for a given current drive, enabling the study of the physics of liner initiation, ablation, and implosion without non-uniform and irreproducible initiation of current flow. These liners are used to study the striation formation observed in experiments on Z.

X-Ray Thomson Scattering (XRTS)

XRTS diagnostics based on laser-plasma x-ray sources created with kilojoule-class lasers probe high densities ($n_e > 10^{21}$ cm^{-3}) and make localized measurements of temperature, density, and ionization state.[8] Hybrid x-pinches are being investigated as an alternative x-ray source for XRTS since they provide short burst durations (10-100 ps), a small source size (~1 μm), and high photon flux (10^{12}-10^{15} photons/sr). The soft x-rays from x-pinches are already used for radiography and absorption spectroscopy.

Initial non-collective XRTS on cold Al using Ti He-alpha (4.75 keV) radiation from a hybrid x-pinch[5] utilized a Bragg optic (Ge400) to focus probe radiation onto the Al sample. A secondary, high efficiency mosaic crystal spectrometer collected scattered photons at backscattering angles of 125-130 degrees and focused them onto image plates. In order to understand the results in detail, a theoretical model that can treat bound-free and free-free scattering processes with a consistent formalism is being developed. It offers a potential improvement over models that enforce an artificial distinction between scattering from bound electrons and free electrons for analyzing the experimental XRTS spectra. This is particularly important for warm dense matter, where valence states are subject to both thermal occupation and pressure ionization. The new model has reproduced XRTS data collected on COBRA (see Figure 3).

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High Energy Density Physics Program at the Scarlet Laser Facility

The Ohio State University

PI: Richard R. Freeman (freeman@physics.osu.edu); Co-PI and Author: Douglass Schumacher (dws@mps.ohio-state.edu)

The High Energy Density Physics (HEDP) group at The Ohio State University is a collaboration of faculty, graduate and undergraduate students, postdoctoral scholars, and technical staff. The group studies HEDP under conditions of short pulse (sub-ps), high intensity (10^{18}-10^{22} W/cm^2) laser excitation. This work focuses on the laser-plasma interaction under these extreme conditions as well as possible applications, including the generation of novel electron, ion, neutron, x-ray and gamma-ray sources. This research features closely intertwined experimental and modeling programs with each used to develop and guide the other. The numerical simulations use particle-in-cell, hydrodynamics and Monte Carlo codes running on supercomputers such as those at the Ohio Supercomputer Center (OSC).

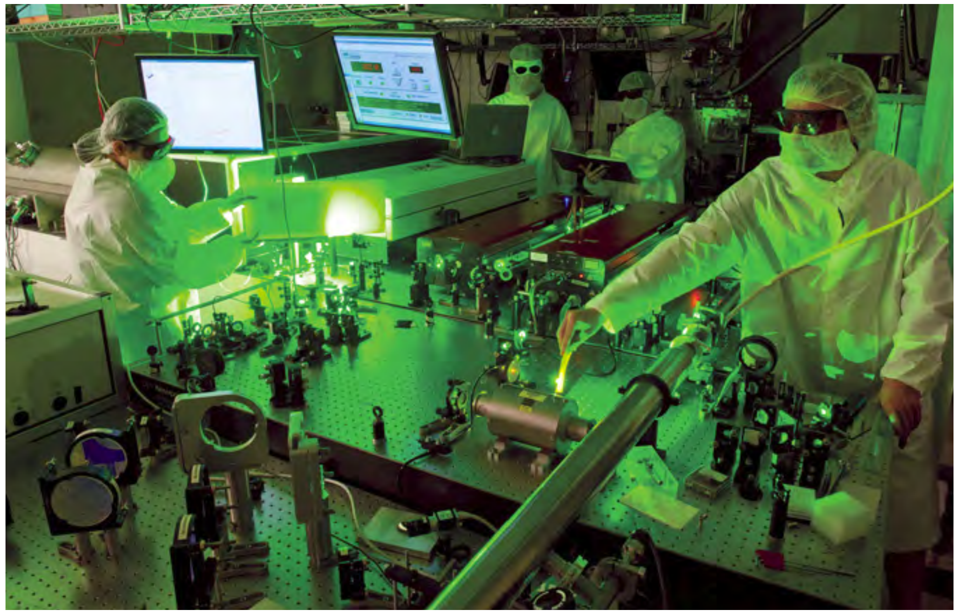

Figure 1. The Scarlet laser bay is maintained at clean room specifications. The seed pulse is generated, shaped and pre-amplified using the systems near the students in the background and the final amplifiers are in the foreground. The compressor and experimental chamber are in a separate room to the right of the figure. The control and data analysis room is on the other side of the wall towards the back. Once the laser is running at least two students are required to run an experiment. Photo: Jo McCulty.

The Scarlet laser (see Figure 1) was constructed primarily with NNSA support and was commissioned in the summer of 2012. It can currently generate 10 J, 30 fs full width at half maximum (FWHM), 800 nm pulses at 1 shot/minute which can be focused to a spot size of 4 µm (FWHM) for an intensity in excess of 10^{21} W/cm^2. The experimental chamber and diagnostics suite were commissioned in 2013 and work is now underway to measure novel forms of the laser plasma interaction, generate secondary radiation, and develop new technology for HEDP experiments. New funding under the SSAP began in 2013 to support this mission, primarily for personnel.

The laser was designed by Professor Enam Chowdhury and professional technical staff and the experimental suite by Professor Kramer Akli, but a substantial portion of the laser was designed and built by graduate and undergraduate students. During the construction and initial testing of this facility, graduate students, with NNSA support, also continued their research using other laser systems around the country. During the 5-year period during which Scarlet was developed, OSU students spent 2.6 person-years onsite at NNSA-supported laboratories, primarily at Lawrence Livermore National Laboratory (LLNL), running experiments. One of these students won a prestigious Lawrence Fellowship from LLNL in 2011. Two recent graduates are now staff at LLNL. The Scarlet facility has only a single technical staff member because so much of the facility operation is under student control. As a result, this research program trains students who can design an experiment with a deep understanding of laser operation and then use state-of-the-art simulation techniques to model the results. Four of the last five graduates were primarily experimentalists that had at least one first authored publication that was primarily based on their own simulations.

Ms. Sheng Jiang, in work supported by NNSA and the Air Force Office of Scientific Research (AFOSR), has performed a combined simulation and experimental study of the use of structured targets. She recently used the particle-in-cell (PIC) simulation code LSP to discover and develop a new way to enhance and control the generation of high energy electrons using solid targets with front surface structure.[1] In contrast to recent efforts that use small scale structures to enhance laser absorption, her approach uses larger structures (many wavelengths) to modify how the laser energy is absorbed. She recently confirmed her findings using Scarlet. She explored a range of structures designed to enhance the high end of the electron energy spectrum using direct laser acceleration. Initial work was performed using two-dimensional (2D) PIC which requires fewer computational resources and then, once promising structures were identified, analysis continued using 3D PIC. Figure 2 shows some of these results. Figure 2a shows a flat target with a plasma profile falling off from solid density roughly approximating a target used with a moderate contrast laser. This was used as a reference target for comparison. Figures 2b and 2c show two targets with front surface structure intended for use with a high contrast laser. Figure 2d shows the predicted electron spectrum using a Scarlet pulse at 5 x 10^{21} W/cm^2. The total yield for all three cases is approximately the same but, above

"Our facility provides a powerful, short pulse laser and excellent computing capability, but all this would count for nothing without our students who surprise us regularly with new findings and ideas. The NNSA SSAP has been vital for supporting these students."

— Richard Freeman, Principal Investigator

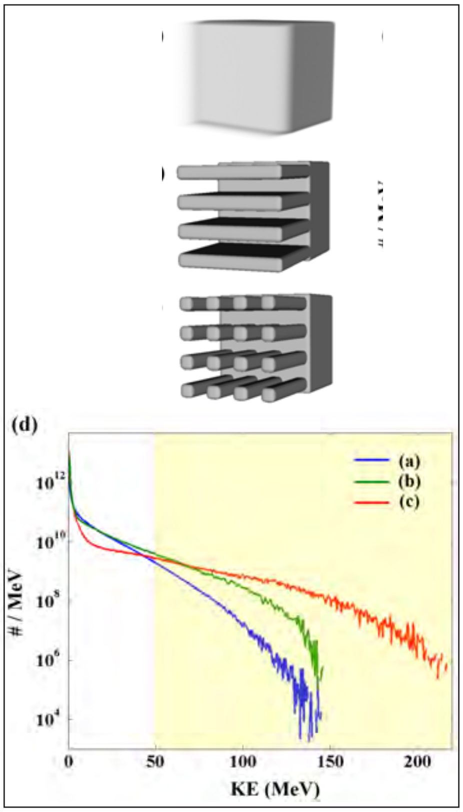

Figure 2. A reference target (a) and two front surface target geometries (b,c) are shown. The modeled electron spectrum generated from a Scarlet laser pulse with peak intensity at 5 x 10^{21} W/cm^2 is also shown (d). The enhancement above 50 MeV is dramatic and highest for the "spikes" structure (c). The spacing between structures is 2 μm and their depth was 10 μm.

50 MeV, the structured targets perform better by an order of magnitude or much more.

Careful analysis of the PIC simulation results included using particle tagging to follow the electron trajectories sorted by final energy and identification of quasi-static electric and magnetic fields due to charge separation, return currents inside the structures and the current of the accelerated electrons themselves. This analysis revealed that these complex elements combined to generate guiding fields in an elegant configuration that

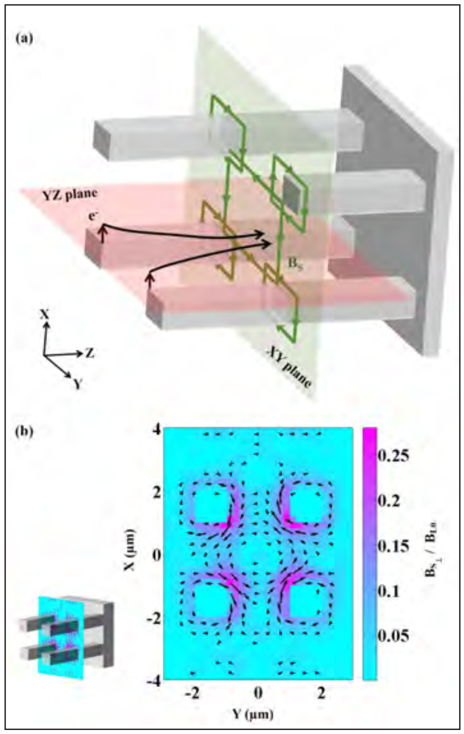

Figure 3. Quasi-static fields play a key role in guiding the energetic electrons and shaping their angular distribution. (a) Schematic of the magnetic fields and typical electron trajectories for the "spikes" target. (b) PIC results at a moment near the peak of the laser pulse.

could dramatically narrow the electron angular distribution. The key figure of merit was the balance between electric and magnetic field effects which was optimal for the "spikes" structured target (see Figures 2c and 3). For this case, the electrons above 50 MeV are in a narrow cone with a divergence angle of roughly 5°. This is superior to the reference which essentially emits over the entire solid angle in the forward direction. This directionality suggests the possibility of future applications, such as the generation of directed gamma rays[2] and differential heating of the target base as a means to guide electron beams. Ms. Jiang was awarded a Best Poster prize for this latter result at the recent Fast Ignition Workshop (2014). Finally, in very recent

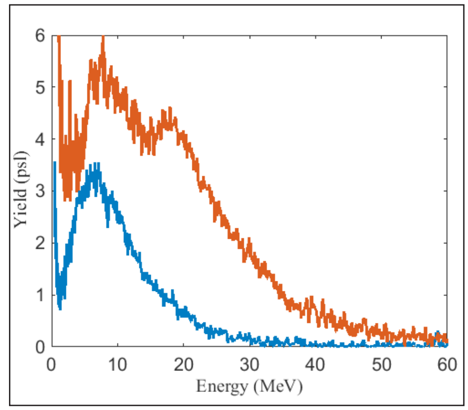

Figure 4. Experimental electron spectrum using a 10^{21} W/cm^2 Scarlet pulse on a flat target (blue) and "spikes" structured target (red). The detector was placed 35° off-axis from the spikes-axis and so the maximum enhancement is likely much larger.

results using targets fabricated by the Lewis Group (California Institute of Technology), the enhancement of the "spikes" target as compared to a flat target was verified using Scarlet (see Figure 4).

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Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science

Rutgers University
PI: Jolie A. Cizewski (cizewski@rutgers.edu)

Low energy nuclear physics helps us to understand fundamental questions such as the origin of the elements in the cosmos. It can also provide solutions to some of the challenging problems facing our Nation by developing passive and active nuclear detection systems for homeland security. Research activities in this field train the next generation of leaders in fundamental research and in applications of low energy nuclear science, from nuclear forensics to homeland security to nuclear energy.

The Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science (RIBSS), established in 2003, has been a leader in low energy nuclear science and in attracting and training early career scientists. The Center is led by Rutgers University as a consortium of scientists from the University of Tennessee-Knoxville, Michigan State University, Colorado School of Mines, Louisiana State University, the University of Notre Dame, Tennessee Technological University, and Oak Ridge and Livermore National Laboratories. The focus has been to use radioactive ion beams of fission fragments and other rare isotopes to study reactions on and structure and decay of atomic nuclei far from stability. Studies with many of these short-lived isotopes can help us understand the origin of the elements. These efforts require new theoretical approaches, new experimental tools, and new rare isotope beams. Realization of these research efforts requires a highly talented team that includes graduate students and postdoctoral scholars. In Fall 2014, seven graduate students and six postdocs are supported at least in part to play important roles in research efforts of the RIBSS Center. They are included in the total of 45 graduate students and 23 postdocs since 2003. In addition, 43 undergraduates have been supported by the Center, with five receiving at least partial support in 2014 from SSAA funds. One of the PhD students and one of the undergraduate summer students received prestigious Stewardship Science Graduate Fellowships. Two current students associated with this project spent eight weeks during 2014 at the NNSA Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL), respectively. Three alumni of the RIBSS Center are staff members at LLNL and two are postdocs at LLNL and LANL. In addition, one alumnus is a staff member at Oak Ridge National Laboratory and two are faculty members at research universities, who, along with their students and postdocs, continue to work with the Center.

Research Highlight: Beta-Decay of Fission Fragments and r-Process Nucleosynthesis

When uranium or another actinide fissions, two fragments are released that are unstable to beta decay. Studying the properties and decay of these fragments has broad implications for understanding the structure of atomic nuclei, informing nuclear reactor science, and helping us to understand how the elements heavier than iron are formed in explosions of stars. Believed to be responsible for the synthesis of half of the elements heavier than iron, the rapid neutron or r-process of nucleosynthesis proceeds through nuclei far from stability, including uranium fission fragments. These nuclei are so unstable that many of them decay by not only emitting a beta particle but also a neutron, and sometimes more than one neutron, as the decay proceeds towards the stable isotopes. To detect these neutrons and understand the details of the decay process and structure properties of these short-lived isotopes, the RIBSS Center has developed the Versatile Array of Neutron Detectors at Low Energy (VANDLE), that was commissioned in Winter 2012 at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL) with studies of the decay of ^{238}U fission fragments.[1] A photograph of VANDLE as deployed during this campaign is displayed in Figure 1.

Figure 2 summarizes the ^{238}U fission fragment beta-delayed neutron studies in the Winter 2012 campaign. Both light (near ^{78}Ni) and heavy (near ^{132}Sn) fission fragments were measured. An example of the results is displayed in Figure 3: the decay of ^{84}Ga where a very rich spectrum from low energy

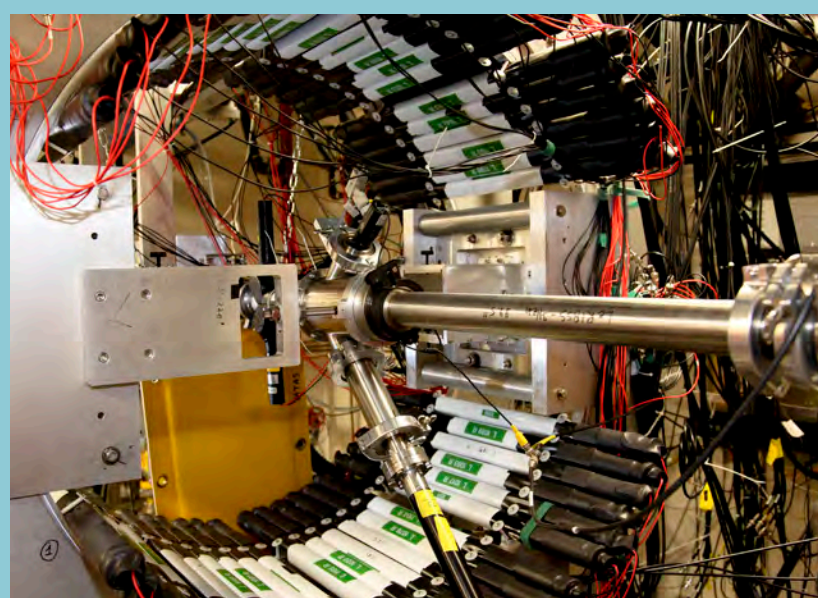

Figure 1. Photograph of the VANDLE set up in the Winter 2012 campaign at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory. The VANDLE bars of plastic with photomultiplier tubes at both ends are wrapped in white to maximize light tightness. Also shown are the mounts for high purity Ge (HPGe) clover gamma-ray detectors. The beam enters from the right to implant radioactive species on a moveable tape in the center where a thin beam pipe at the end of the tape drive is surrounded by two thin beta-particle scintillators. Adopted from Reference 1.

"The SSAA funds have enabled the support of superb graduate students and postdoctoral scholars who are doing frontier research at the interface of nuclear and astrophysics and developing the tools not only to realize current but also future research with radioactive ion beams. They are part of a synergistic collaboration of low energy nuclear scientists at seven universities and two national laboratories and benefit from several opportunities each year to connect with nuclear scientists at Livermore and Los Alamos National Laboratories."

— Jolie A. Cizewski, Principal Investigator

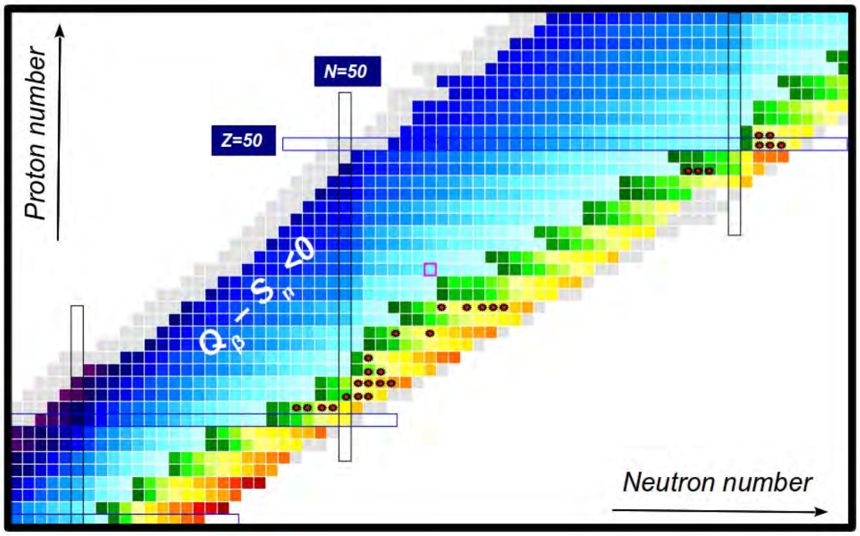

Figure 2. Chart of the nuclei where the colors are a measure of the difference between the energy released in beta decay (Q_{beta}) and the neutron separation energy (S_n). For most nuclei (shades of blue) the Q_{beta} energy is less than the neutron separation energy and therefore no beta-delayed neutrons would be emitted. The red points indicate radioactive ^{238}U fission products where the beta-delayed neutrons were measured in Winter 2012 with VANDLE at HRIBF.

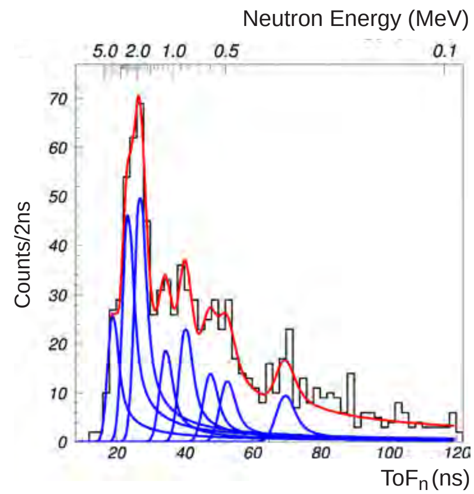

Figure 3. Spectrum of beta-delayed neutrons from ^{84}Ga measured with VANDLE. The x-axis on the bottom is time of flight in nanoseconds; x-axis on the top is neutron energy in MeV. The components of the spectrum (blue) are determined from the response of VANDLE; the red curves are the resulting fitted spectrum. In the present work 84 ± 15% of the decay of ^{84}Ga is observed as beta-delayed neutrons. Adopted from Reference 2.

(<200 keV) to significant observation of relatively high-energy (>5 MeV) neutrons were observed.[2] This spectrum of neutrons emitted from ^{84}Ga is important for reactor and stockpile stewardship interests—such intense yield of high-energy neutrons was not expected. At the same time, this neutron spectrum is confirming the robustness of ^{78}Ni (with 50 neutrons) as a core for configurations in ^{84}Ga. Within a simple model, allowed beta decay can proceed only through the decay of one of the neutrons in the ^{78}Ni core. For the N>50 nuclei, this would lead to population of very highly excited states: as the neutron is transformed to one of the protons outside the Z=28 shell closure, a vacancy in the N=50 core will be produced. This "hole" state can be filled only by the neutron from the next shell, which is separated by about 4 MeV. The evidence for high-energy neutrons is a strong confirmation of this picture, which was further confirmed by theoretical calculations which use ^{56}Ni with 28 protons and 28 neutrons as the core, and allowing only neutrons in the N=28-50 orbitals of the ^{78}Ni core to decay. The agreement between VANDLE data and this model indicates that the N=50 shell closure at ^{78}Ni is indeed robust. The validation of the theory by VANDLE data will enable predictions of nuclear-decay properties to be made, such as lifetime and beta delayed emission branching ratios for the r-process nuclei, which might not be available experimentally. Postdoctoral scholars and graduate students are taking the lead in all aspects of this project, from developing the VANDLE array to analyzing the data to interpreting the results. In particular, this work was part of the PhD dissertation of Stanley Paulauskas from the University of Tennessee.

VANDLE is indeed versatile. It has been deployed in measurements of reaction neutrons with both fast and slower radioactive ion beams for fundamental nuclear physics and astrophysics, as well as in the measurement of neutrons emitted in the interaction of fluorine with alpha particles, motivated by needs for passive interrogation of enriched uranium.

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A Versatile Gamma and Fast Neutron Spectrometer

University of Massachusetts Lowell

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A 16-element array for fast neutron spectroscopy based on the emerging scintillator Cs_2LiYCl_6 (or CLYC) has been developed. This material has dual neutron-gamma detection capabilities, with excellent pulse-shape discrimination between neutrons and gammas, far superior to liquid scintillators.[1] CLYC detectors normally utilize the capture of thermal neutrons on ^{6}Li and detect the energy of the ^{7}Li breakup into an alpha particle and tritium. Thus, standard CLYC detectors have enhanced ^{6}Li isotope concentrations. This current research project has centered on their discovery that CLYC can also detect fast neutrons via the ^{35}Cl(n,p)^{35}S reaction, with about a 10% energy resolution.[2] Such resolution is unusual in neutron spectroscopy, as most neutron scintillators have no energy-measuring capability. In this project, they have fabricated CLYC detectors that are depleted in ^{6}Li, removing the thermal neutron response, and allowing for a clean spectral response to fast neutrons for neutrons from 500 keV to above 10 MeV.[3]

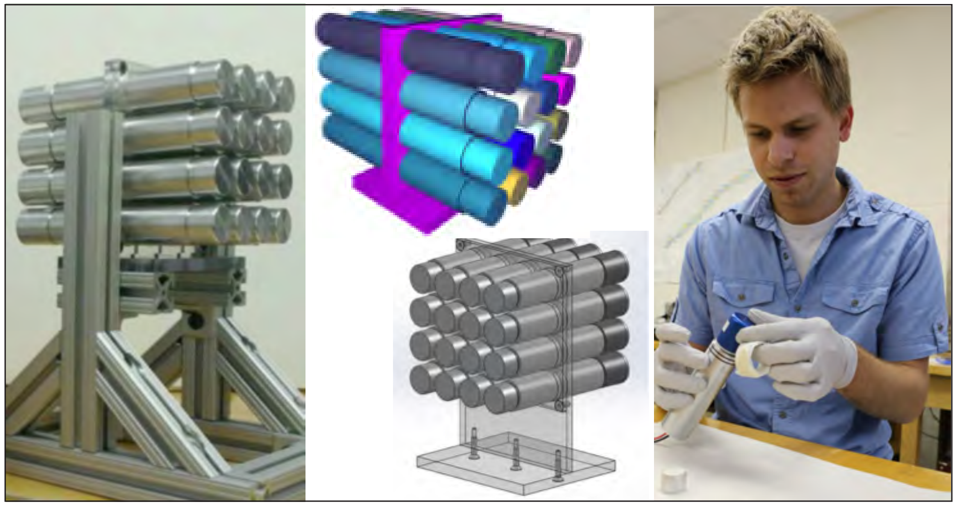

Figure 1. Three views of the 4 X 4 CLYC array for fast neutron spectroscopy (left and center) and a picture of Nate D'Olympia, the lead graduate student, assembling a crystal element (right).

Working with Radiation Monitoring Devices, Inc. of Watertown, Massachusetts, the group at the University of Massachusetts Lowell (UML) has successfully specified, procured, and tested the first ever 16 ^{6}Li-depleted CLYC crystals that have been grown anywhere. The crystals have been assembled into a full detector with an initial 4 x 4 matrix geometry of 1" x 1" crystals (see Figure 1). They have also acquired and commissioned a dedicated VME-based (a computer bus standard) digital data acquisition system with 16-channel capability, and fully characterized the response of all elements with mono-energetic fast neutrons ranging from 500 keV to over 50 MeV. The tests were carried out at three different accelerator facilities that use different reactions to generate neutrons: the in-house 5.5 MV Van de Graaff that uses a ^{7}Li(p,n) reaction to generate 1-3 MeV neutrons, the 7 MV sister accelerator at the University of Kentucky that uses (p,t), (d,d), and (d,t) reactions to generate neutrons up to 23 MeV, and finally the Weapons Neutron Research (WNR) facility at Los Alamos National Laboratory (LANL) to generate a wide spectrum of neutrons to high energies, with time-of-flight techniques for neutron energy determination event-by-event. Monte Carlo simulations have been performed with the MCNP code to model detector response. The results of the simulations have allowed an insight into new nuclear reaction channels that open up at high incident neutron energies.

Two initial physics experiments have been proposed with this array. Both have been successful in obtaining beam time at NNSA national laboratory facilities. One project uses the CARIBU facility at Argonne for measuring beta-delayed neutrons from mass-separated neutron-rich fission fragments from a 1-Curie ^{252}Cf source, where the CLYC array will be integrated with a high-resolution Ge array and a beta-decay tape station which has been commissioned recently by the UML group. The second project is in collaboration with LANL and is an extension of UML test runs there. This latter project is to measure energy-dependent elastic and inelastic neutron scattering cross-sections for ^{56}Fe and ^{238}U at their WNR facility. Three weeks of beam time has been scheduled in early 2015.

The software for multi-parameter event-by-event analysis for the array continues to evolve in complexity. The CLYC work has resulted in an MS degree and PhD dissertation, three *Nuclear Instruments and Methods in Physics Research* papers with a fourth in preparation, the last two fully funded through this grant. The lead student responsible for the bulk of this work, Nathan D'Olympia, has just graduated and moved into industry, and had a choice of several job offers prior to completion of his PhD.

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Development of New Methodologies for Actinide Separations and Preparation of Actinide Targets Using Polymer-Assisted Deposition

University of California, Berkeley

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The University of California, Berkeley Heavy Element and Nuclear Chemistry Group (http://heavyelements.lbl.gov) has been supported by the NNSA for the past eight years to carry out research optimizing chemical separations of actinide elements and developing new production techniques for targets used at heavy-ion accelerators. NNSA has supported this work initially under low energy nuclear science and more recently, radiochemistry. The group performs this work under a strong collaboration with Lawrence Berkeley National Laboratory, allowing the students the unique opportunity of effectively working full-time inside the national laboratory system while pursuing their graduate studies.

The NNSA SSAA radiochemistry grant has supported two postdoctoral researchers, a research specialist, a junior specialist, and the work of two graduate students. After participating in this program, one of the postdoctoral researchers will be continuing at Lawrence Livermore National Laboratory (LLNL) in the Nuclear Forensics Group. A former research specialist has recently begun a position as a Presidential Management Fellow in Washington, DC. The annual SSAP symposium has been particularly instrumental in introducing students to both the staff at various national laboratories as well as the diverse range of projects being done at these institutions. This direct connection between graduate school work and real world applications of national significance has been a significant motivator for the students.

The group has made significant advances recently in the area of solid-phase extractants for lanthanide and actinide separations. Solid-phase extractants composed of a mesoporous (i.e., with pores between 2 and 50 nm) silica support are functionalized with nuclear fuel cycle-relevant organic ligands (see Figure 1). A variety of solid-phase extractant materials have been synthesized within the group and have been successfully tested with both lanthanide and actinide cations. These materials have demonstrated good stability in acidic media and high extraction efficiencies for metals of interest. Also under investigation are the electrochemical interactions of plutonium and other actinides with ordered mesoporous carbon materials, which offer a potential platform for separations that include redox chemistry. An active collaboration is underway with LLNL working to characterize the silica materials using nuclear magnetic resonance spectroscopy, allowing graduate students the opportunity to experience another NNSA laboratory.

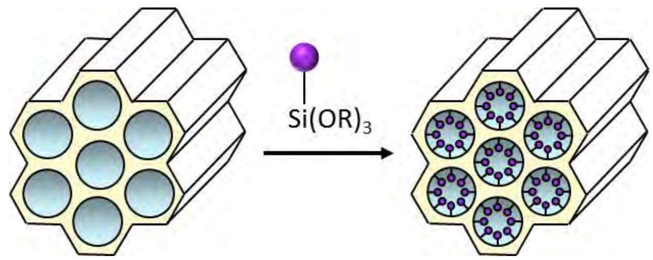

Figure 1. Illustration of the technique for functionalizing ordered mesoporous silica. “OR” is an oxygen to organic moiety (or functional group) bond. Depending on the particular reaction scheme used to bond the silicon hub to the surface, different organic groups are required.

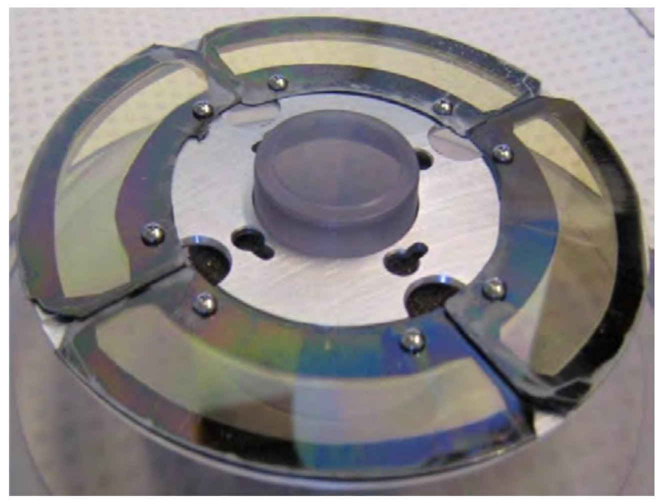

Figure 2. Completed target segments fabricated using polymer assisted deposition, mounted on a target wheel.

The group is also working on improving targets for use in heavy element production for nuclear cross section measurement. Current accelerator technology has evolved towards the use of very high beam currents, requiring large area targets to withstand the energy deposited by the beam. The polymer-assisted deposition target procedure is ideal for producing thick, homogenous and robust targets with low surface roughness (see Figure 2). This technique uses a polymer carrier solution for the actinide cation, which is spin coated onto a thin film backing and then annealed to produce high quality actinide oxide targets. Recent work has focused on three primary objectives: 1) improving 1-micron-thick target backing durability, 2) expanding the technique to a greater number of actinide elements, and 3) miniaturization of the process for use in gloveboxes with higher specific activity radionuclides.

The development of actinide targets and advanced separation materials impacts both the stewardship and the larger nuclear science community. There has been strong interest in this work, as presented through six papers given in the past year at the American Chemical Society National Meeting, the American Nuclear Society International Isotopes Conference, Plutonium Futures, and the Actinide Separations. In addition, in the last year, experimental results from this project were published in the peer-reviewed literature, with several additional manuscripts in preparation.

The UC Berkeley community was saddened by the sudden and unexpected loss of Professor Nitsche in July 2014. For more information, visit: http://chemistry.berkeley.edu/publications/news/2014/heino_nitsche_has_died.php.

Understanding Materials at Extreme Dynamic Compression

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Shock wave experiments subject materials to large compressions, deformations, and high temperatures on very short time scales (ps to µs) resulting in a rich array of time-dependent physical and chemical changes. These experiments are ideal for achieving a fundamental understanding of materials under extreme conditions, and are central to NNSA's Stockpile Stewardship Program (SSP) mission.

Scientific activities at the Institute for Shock Physics (ISP), involving students and researchers from several disciplines (Physics, Chemistry, Materials Science, and Mechanical Engineering), are focused on a continuum-to-atomic scale understanding of a broad range of condensed matter phenomena: structural transformations, deformation and fracture, and chemical reactions.

The shock physics effort at Washington State University (WSU) has a distinguished history of research innovations and educational excellence dating back to the late 1950s. The Institute, established in 1997, supports the SSP mission through the following activities: innovative and exciting research; educating/training the next generation of scientists; and meaningful collaborations with the NNSA national laboratories and other institutions.

Research Highlights

The Institute's research activities emphasize real time, multiscale measurements and provide students and postdoctoral scholars with strong "hands-on" training in shock wave and static high pressure research. Representative research projects follow.

Shock Compression of Diamond Single Crystals

The mechanical and optical anisotropies of diamond crystals were determined by shock compressing Type IIa crystals along the [100], [110], and [111] orientations. Hugoniot elastic limits (HELs) were determined from the measured wave profiles. Unlike isotropic solids, threshold shear stresses along the relevant slip systems are a better measure of the crystal strength (or elastic limit) than the HEL values. Shocked diamond was strongest for compression along [110] and weakest for compression along [111]. The elastic-inelastic response of shocked diamond crystals is complex due to time-dependence and the role of normal stresses. This work provided the first diamond strength determination under well-defined loading conditions. –John Lang, former Physics Graduate Student, Los Alamos National Laboratory

Molecular Response of Multiply Shocked Liquid Nitrogen

Raman spectroscopy measurements under multiple shock compression were used to examine the molecular response of liquid nitrogen at pressures (15-40 GPa) and temperatures (1,800-4,000 K), not accessed previously. Liquid nitrogen temperatures and pressures were determined experimentally to provide the pressure-temperature (P-T) states for multiply shocked liquid nitrogen. By combining the present results with results from previous studies, the liquid nitrogen Raman shifts were determined over a broad P-T region. This comprehensive determination showed that the molecular response of liquid nitrogen is both pressure and temperature dependent, and the P-T dependence of the measured Raman shifts for all available static and shock compression data can be quantified using a single relation. The liquid nitrogen molecular response depended more on temperature than pressure, and is best described by considering three temperature regions: below 1,500 K, 1,500-4,000 K, and above 4,000 K. For the P-T states accessed in the multiple shock compression experiments, liquid nitrogen remains a molecular fluid and becomes a grey body emitter at 40 GPa (~4,000 K). –David Lacina, former postdoc, Air Force Research Laboratory

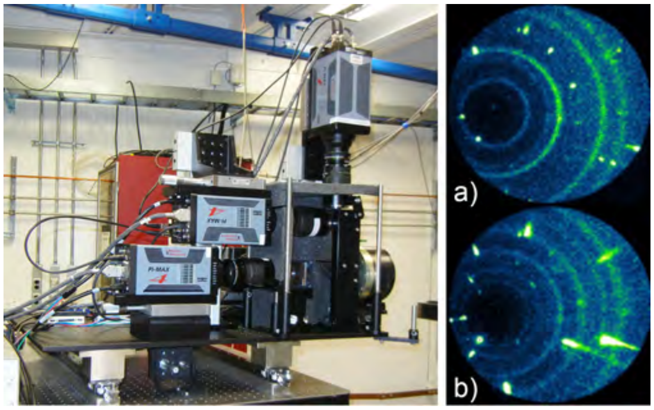

Figure 1. X-ray diffraction (XRD) at the Dynamic Compression Sector (DCS) to examine shocked solids. Polycrystalline Si XRD results shown a) 113 ns after impact, and b) 574 ns after impact.

Real-Time, X-ray Diffraction (XRD) to Examine Shocked Solids

Using a powder gun and a 4-frame x-ray detector, the shock response of several materials was examined at the Dynamic Compression Sector (DCS). XRD measurements on polycrystalline silicon shock compressed to 13 GPa were used to observe the growth of a high-pressure phase (see Figure 1). Measurements on shocked KCl crystals, undergoing the B1 to B2 structural change, provided B2 phase texture information giving new insight into the phase transformation mechanism. Deformation effects at the microstructural level were observed through measurements on shock compressed polycrystalline Al. The DCS experiments demonstrated that multi-frame XRD measurements in dynamically compressed single crystals and polycrystalline solids provide new insights into structural transformations and deformation. –Stefan Turneaure, Senior Scientist

Shock-Induced Elastic-Plastic Deformation of Molybdenum Single Crystals

To examine and understand shock-induced elastic-plastic deformation in BCC metals, molybdenum single crystal samples were shocked to an elastic impact stress of 12.5 GPa along the <100>, <110> and <111> orientations. Measured elastic-plastic wave profiles showed both orientation and time dependence. The elastic wave amplitude decayed rapidly before reaching threshold values of ~5.3 GPa along <111>, and ~3.6 GPa along <100> and <110>. The corresponding resolved shear stresses on the quasi-static {011}<11> and {112}<11> slip systems are comparable to the reported Peierls stress for screw dislocations suggesting that their motion governs plasticity under both quasi-static and shock loading. Preliminary wave propagation calculations suggest that either of the quasi-static slip systems could be operative, and the rapid elastic wave attenuation is likely caused by the regeneration of mobile dislocations above the threshold elastic limit. –Anirban Mandal, Mechanical Engineering Graduate Student

Stability of Molecular Crystals Under High Pressure: Tuning of Hydrogen Bonding by Deuterium Substitution

To gain insight into the role of hydrogen bonding on the structural stability of insensitive HE, Raman measurements were performed on deuterated single crystals of FOX-7 under static compression to 35 GPa. The 4.5 GPa phase transition observed in FOX-7 was unchanged by deuterium substitution. However, deuteration did lift the 2 GPa phase change, and likely introduces a new phase transition around 8 GPa. Pressure shifts of ND2 stretching vibrations indicate that not all deuterium bonds are strengthened upon initial compression. Mixing of modes was suppressed by deuterium substitution. This work demonstrates that deuterium substitution changes the FOX-7 stability by selectively altering the hydrogen bonding related effects. –Yuchuan Tao, Postdoc, and Zbigniew Dreger, Senior Scientist

Figure 2. The ISP 2014 Summer Undergraduate Research Experience: Materials Under Extreme Conditions program provided hands-on participation in dynamic compression and high-pressure research.

Education and Outreach

Interactions with scientists at the NNSA national laboratories provide a valuable research experience for the ISP students and researchers. For example, Peter McClure, a Materials Science graduate student, spent summer 2014 at Los Alamos National Laboratory (LANL). Dr. Ellen Cerreta, a LANL scientist, is co-supervising Peter's PhD research to understand the spall response of Ti single crystals shocked along different crystal orientations. Peter's activities at LANL were focused on learning and using a variety of techniques to examine spalled samples recovered from experiments performed at the ISP. Metallographic sample preparation using chemical etching was performed to reveal the microstructure of the spalled samples. In addition, scanning electron microscopy, optical microscopy, and electron backscatter diffraction techniques were utilized to examine the samples.

Summer Undergraduate Research

The Institute provides research opportunities to undergraduate students in the physical sciences and engineering through the Summer Undergraduate Research Experience: Materials Under Extreme Conditions. The 2014 students (see Figure 2) and research topics included: **David Mildebrath**, University of Alabama: Shock Compression of Aluminum; **Paul Somers**, Missouri University of Science and Technology: Hydrogen Bonding Under Pressure; **Sonal Nanda**, Carnegie Mellon University: Confocal Microscopy of Fluids Under Pressure; **Nathan Briggs**, University of Utah: Mechanical Behavior of Polymer Nanocomposites Under Dynamic Loading.

Figure 3. Dr. James Hawreliak, Associate Professor, has initiated an experimental program to investigate the properties of warm dense matter.

Warm Dense Matter (WDM) Research: New Thrust

Dr. James Hawreliak (see Figure 3), formerly a physicist at the Lawrence Livermore National Laboratory, has recently joined WSU as an Associate Professor. Dr. Hawreliak is initiating an experimental program using the emerging dynamic compression capabilities at x-ray light sources, such as the DCS, to probe materials in the WDM regime. Measuring the continuum or thermodynamic response of WDM, in conjunction with x-ray measurements, will result in the development of theoretical models to predict transport and other physical properties. Dr. Hawreliak is launching a vibrant academic research program for graduate students and postdocs at WSU, including strong collaborations with the NNSA national laboratories.

Mimicking Disruption Events and Fusion Plasma-Wall Interactions Using Coaxial Plasma Guns

Stanford University

PI: Mark Cappelli, Stanford University (cap@stanford.edu); Co-PIs: Laxminarayan Raja and Graeme Henkelman, University of Texas, Austin

Magnetic confinement fusion continues to be challenged by the poorly understood interaction between the energetic hot plasma and material surfaces, particularly following violent disruption of plasma confinement due to instabilities. To better understand these interactions, facilities such as the now-decommissioned co-axial plasma accelerator known as PLADIS[1] generated plasma jets of high energy densities (~20 MJ/m^2) and characterized the ensuing damage to exposed potential reactor wall materials. These previous studies served to provide indication of the extent of damage that can be experienced for a range of overall plasma pulse energy, but provided limited insight into the mechanisms that create the surface damage and how the damage can be traced back to the properties of the plasma jet such as plasma temperature, velocity, and density. The research at Stanford University and at the University of Texas at Austin is aimed at developing a more fundamental understanding of this interaction by combining simulations of the plasma jet and plasma-surface interactions with experimental measurements of plasma properties and materials surface characterization. The project is in its second year of SSAA funding and involves a total of three students and three postdoctoral researchers, mentored by three members of the faculty at the two institutions. According to Professor Mark Cappelli, the principal investigator at Stanford University, "The students on this project bring diverse skills to the table, ranging from experimental plasma physics to computational magneto-fluid dynamics, and to quantum-level ab-initio simulations of surfaces to address a very difficult problem of significance to the fusion community. One benefit to the students is the experience gained by working together as a team of researchers of very diverse disciplinary backgrounds."

The plasma jets (see Figure 1) of speeds approaching 100 km/s are produced by dense coaxial plasma deflagrations during high energy discharges lasting 20-100μs in duration, in a facility similar to that described in Reference 1. Experiments at Stanford[2] include measurements of plasma density, temperature, and velocities, to validate magnetohydrodynamic (MHD) simulations (see Figure 2).[3] While good agreement is generally seen between experiments and simulations at lower discharge energies and inside the coaxial gun, the model predicts a jet profile beyond the gun exit which is qualitatively different from the experimentally observed jet profile—a deficiency associated with the challenges of simulating the transition from the continuum flow within the barrel to the hard vacuum into which the jet exhausts. A novel gas-vacuum interface tracking algorithm is under development to address this challenge and current efforts are towards simulating highly under-expanded gas jets and demonstrating the applicability of the interface tracking algorithm to describe gas jets exhausting into vacuum.

Figure 1. Photograph of the plasma gun operating in a pulsed deflagration mode. A strong concentrated plasma jet stream is seen within a gun diameter of the exit. See cover graphic.

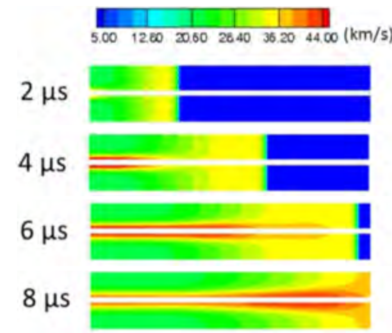

Figure 2. MHD simulations of gun discharge and jet evolution inside the gun barrel. Shown are axial velocity contours at different times.

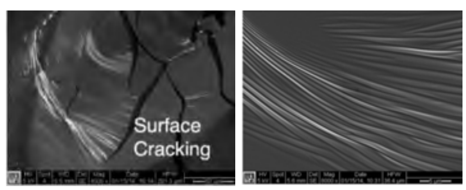

Figure 3. Scanning electron microscope photographs of the surface damage following a single plasma exposure event: (top) surface cracking, (bottom) melting and re-solidification.

Experiments of plasma-material interactions have included studies of deuterium plasma jets of modest (~1 MJ/m^2) energy density impinging on single crystal silicon substrates. Post-exposure analysis of the samples show various features (see Figure 3), including evidence of micro-cracking and regions of surface ripples resulting from melting and re-solidification. It is apparent that even at modest plasma energies interesting and complex features are seen to develop. To complement sample exposure experiments, simulations are also being carried out at the University of Texas of the atomistic interactions of energetic atoms and ions with surfaces. Both molecular dynamics[4] and density functional theory-based ab-initio simulations are being developed to predict atomic level disordering and ablation induced by energetic argon incident onto crystalline silicon surfaces. The atomistic simulations allow the prediction of energy barriers to ablation. The combination of experiments with simulations in this multi-physics research project will help build tools that will enable a better understanding of how materials will perform under extreme conditions associated with high energy plasma-exposure typical of that seen during unanticipated events in fusion systems.

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Behavior of Ni-Nb-Zr Alloy Gas Permeation Membrane Ribbons at Extreme Pressure Condition

University of Nevada, Reno

PI: Dhanesh Chandra (dchandra@unr.edu)

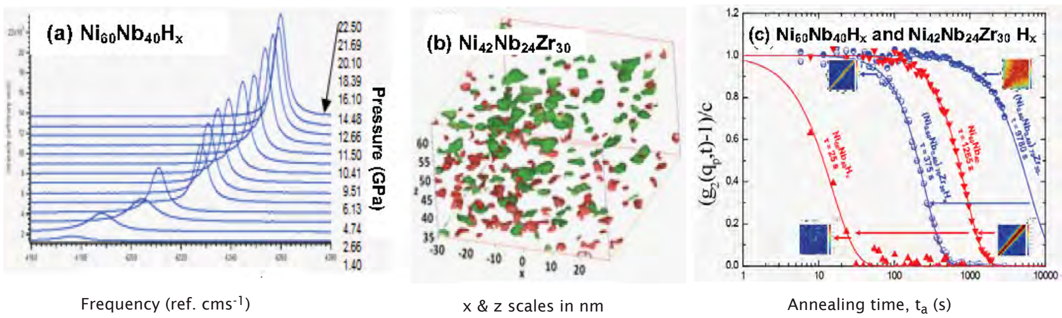

Figure 1(a). Raman Spectra of $Ni_{60}Nb_{40}H_x$ (blue) up to 22.50 GPa. Figure 1(b) 3-D reconstruction of atom tomography on $Ni_{42}Nb_{28}Zr_{30}$ ribbon showing Nb-rich (green) and Zr-rich atom clusters (red); Ni matrix is not shown here for clarity. Figure 1(c) X-ray photon correlation spectroscopy data showing decay of the curve gives quantitative information on the structural relaxation time (τ). At 373K, for $Ni_{60}Nb_{40}$, τ(vacuum) =1,265 sec, with $\tau(H_2)$=25 sec. and for $Ni_{42}Nb_{28}Zr_{30}$, τ(vacuum) = 780 sec, with $\tau(H_2)$ = 375 sec. these indicate ternary alloy have less atom motion than the binary.

The effect of high pressure on local atomic order in glassy metallic alloys is being studied. This study which began in March 2013 will help in technological advances in environmentally sound hydrogen separation/purification processes for power generation, and also conserving strategic reserves of precious metals in the United States. Fundamental research is focused on the phenomenon underlying extreme pressure induced amorphous-to-crystalline phase transitions (with/without H_2), changes in the local atomic order of glassy membranes, newly discovered amorphous-to-amorphous phase transitions (termed as poly-amorphism), lattice/atom dynamics via inelastic neutron scattering, and x-ray photon correlation spectroscopy and atom tomography.

This project was initiated to use novel Ni-Nb-Zr amorphous alloys that are inexpensive membranes to separate H_2 from CO_2 and other gases using water shift reaction of coal-derived syngas. Typically, Pd/Pd-Ag crystalline (commercial) membranes are widely used for this purpose, but Pd is a strategic metal and is very expensive ($31,000/kg) and needs to be replaced with alternate inexpensive metals. These studies are expected to reveal the nature of transitions, potential long-range topological order in these metallic glasses, cluster formation, lattice dynamics, effect of extreme pressure that will potentially allow fabricating an ideal inexpensive alloy membrane with optimum permeation properties. Research is being conducted on understanding the behavior of non-precious $(Ni_{0.6}Nb_{0.4})_{100-x}Zr_x$ (where x = 10, 20, 30), $Ni_{60}Nb_{40}$, $Ni_{60}Nb_{20}Zr_{20}$ and $Ni_{64}Zr_{36}$ amorphous alloys when subjected to hydrogen and also pressure.[1] There are no fundamental experimental studies on what happens inside the glassy materials when hydrogen is introduced in these membranes or effect of pressure. More high pressure studies will be conducted in the near future.

One of the missions at the University of Nevada, Reno is to train students to conduct fundamental science/engineering research. Four graduate and three undergraduate students have worked on this project. Undergraduate students were trained on diamond anvil cell research on the high resolution instrument at Carnegie Institution of Washington, and a graduate student on x-ray neutron inelastic scattering at the National Institute of Science and Technology as well as x-ray photon correlation spectroscopy at the European Synchrotron Radiation Facility.

During the last calendar year, amorphous alloys $(Ni_{0.6}Nb_{0.4})_{100-x}Zr_x$ (x=20, 30) in ribbon form were investigated. Experimental work on these alloys is in progress on extreme pressure studies conducted at the Carnegie Institution of Washington. An example of high pressure diamond anvil cell results on amorphous $Ni_{60}Nb_{40}$ are shown in Raman spectra up to ~22 GPa as shown in Figure 1a. Atom probe tomography results revealed that these membranes were non-homogeneous and were comprised of Zr- and Nb-rich clusters embedded in Ni amorphous matrix.[1] For example, numerous Nb-rich clusters (green) with average composition of $Ni_{31.78}Nb_{46.50}Zr_{21.72}$, and Zr-rich clusters (red) with $Ni_{38.64}Nb_{17.9}Zr_{43.45}$ were found as compared to nominal membrane composition of $Ni_{42}Nb_{28}Zr_{30}$ (see Figure 1b); these were previously not known. These results imply that H-atom sites are inside Zr as well as in Nb-rich polyhedrons. Japanese computational research[2] suggests that there are possibly icosahedron type polyhedrons in these amorphous alloys, in which hydrogen sites exist.

X-ray photon correlation spectroscopy results showed large changes in local atomic order in the binary as compared to ternary alloys, when hydrogen is introduced even at 100 ^oC. This is measured by the relaxation time (τ); smaller the relaxation time, faster the atom motion; Figure 1c shows differences between binary and ternary relaxation times. The two time correlation functions (with blue/brown dots) insets show the drastic changes in atom dynamics. These experiments will be performed after subjecting these materials to extreme pressure. An increased understanding is expected after analysis of the data from inelastic neutron experiments on these hydrogen desorbed alloys.

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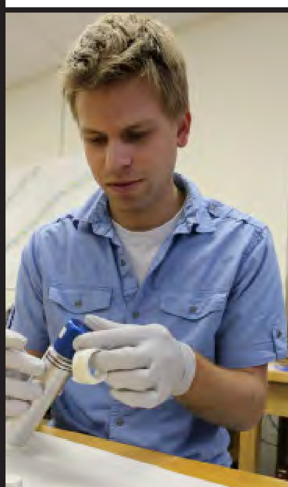
Alumni & Students
Stewardship Science Academic Alliances

Eloisa Zepeda-Alarcon

Austin Stafford

Christopher Prokop

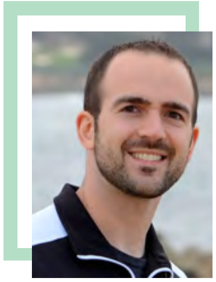


Chris Weber

Matthew Bishop

Kenneth Williamson

Chris Weber, Lawrence Livermore National Laboratory (LLNL), weber30@llnl.gov
Years at LLNL: January 2013 to Present • Degree: PhD, Nuclear Engineering and Engineering Physics, 2012
Years in SSAA Program: 2008-2012, University of Wisconsin



The SSAA Program provided support for my research project during graduate school at the University of Wisconsin. This research was performed at the Wisconsin Shock Tube Laboratory under the advisement of Professor Riccardo Bonazza. My research focused on a hydrodynamic instability that is present in scenarios ranging from inertial confinement fusion (ICF) to supernova. This instability, called the Richtmyer-Meshkov instability, occurs when a shock wave passes through two different densities. I studied the turbulent mixing that can result from this instability.

The support from the SSAA Program allowed me to explore both experimental and computational aspects of this problem. The experimental component involved performing shock tube experiments and used planar-laser imaging. For computational work, I was given access to resources at LLNL, including access to their computing center and hydrodynamics codes. This fostered collaboration with LLNL scientists, led to an onsite summer internship through the High Energy Density Physics summer student program, and helped make connections that led to my current position at LLNL.

My background in hydrodynamics instabilities is useful in my current position as an ICF physicist at the National Ignition Facility (NIF). Here at NIF, there is a focus on understanding the factors that degrade ICF implosion performance and inhibit ignition. Therefore, we continue to model past experiments while designing new, focused physics experiments to test those models. Hydrodynamics and mixing is an important area of concern in ICF implosions. These implosions use a shell of cryogenic deuterium and tritium (DT) surrounded by an ablator material, usually plastic, which is compressed by a factor of 30 to 40 by laser radiation. If the ablator material mixes with the DT during compression, it can radiate away much of the energy needed to achieve ignition. Hydrodynamic instabilities cause perturbations to grow at the interface between these materials and can lead to mixing. Additionally, turbulent effects could pose a problem, as they could convect heat away from the hot central core.

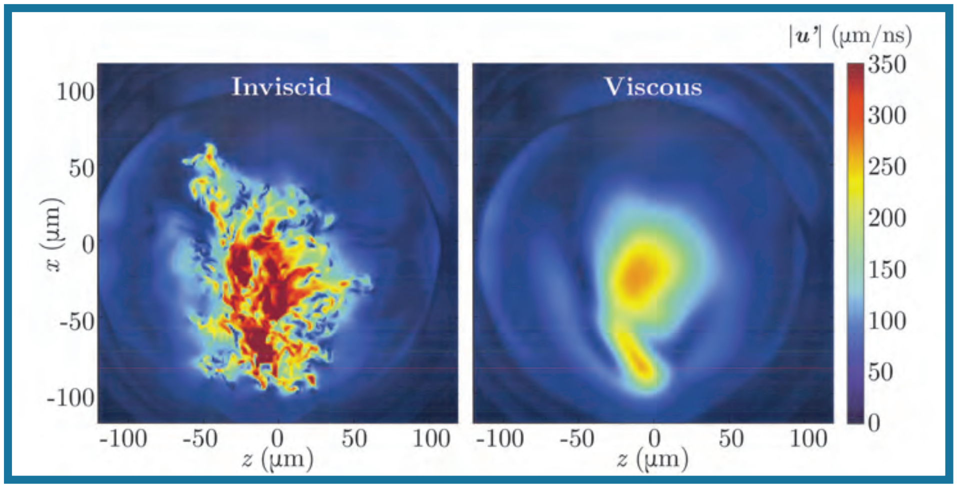


Figure 1. The velocity fluctuations in the center of an ICF implosion, modeled using the Miranda code.[1] At this time the strong inward-going shock wave has reflected from the center and is starting to slow the high density shell. Perturbations in the shock wave leave behind high-velocity and small-scale structures (left). Much of this structure is removed when including the effects of viscous dissipation (right). Figure is reproduced from Reference 2.

Part of my recent work involved modeling these implosions in high-resolution, three-dimensional simulations. Some past simulations raised the concern over turbulent motion in the central hot spot. We found that viscous dissipation needs to be included in our models, as it removes much of the hot-spot turbulent kinetic energy. Viscosity also changes the length scales of the flow, leaving behind only larger-scale structures (see Figure 1). This effect changes what would have been a turbulent flow field into a laminar one. Ultimately, these changes do not significantly alter the global state of the flow, as most of the kinetic energy is in the high-density fuel and not changed by viscosity. But understanding the flow field of the low density hot spot is essential to interpreting diagnostic signature, since neutrons from fusion reactions are Doppler shifted by bulk velocity. Therefore, this result helped limit the motion that we expect in the hot spot while also improving our models.

I feel fortunate to work in such an exciting field and at an eminent laboratory. Here at LLNL, I contribute towards solving grand challenge problems alongside world-class expertise and use state-of-the-art facilities. This opportunity would not have been possible without SSAA supporting graduate research in fields relevant to NNSA.

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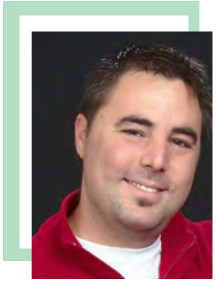
[1]A.W. Cook, "Artificial Fluid Properties for Large-Eddy Simulation of Compressible Turbulent Mixing," Phys. Fluids 19, 055103, 2007.

[2]C.R. Weber et al., "Inhibition of Turbulence in Inertial-Confinement-Fusion Hot Spots by Viscous Dissipation," Phys. Rev. E 89, 053106, 2014.

Kenneth Williamson, Sandia National Laboratories (SNL), kwilli1@sandia.gov
SNL Years: June 2012 to Present • Degree: PhD, Plasma Physics, 2011
Years in SSAA Program: 2004-2011, University of Nevada Reno (UNR)



My undergraduate research was tremendously enjoyable, but the prospect of continuing for six years to earn a PhD was truly daunting. The curriculum at UNR gave me such a broad exposure to the different physical science disciplines that I couldn't choose, let alone commit most of my mid-20s to studying. That's where the SSAA Program helped me, even though I didn't know it at the time. The investment that SSAA made into the hot plasma research at UNR encouraged Professor Victor Kantsyrev to reach out to me just before I received my bachelor's degree in 2003. That was one of the most important conversations of my life. I went on to become a graduate research assistant under his advisement and graduated with my doctorate in 2011.

My graduate work was concerned with radiation source development in high energy density z-pinch plasma. The z-pinch is a technique for generating bursts of high-energy radiation, like x-ray or harder, by driving an array of fine wires into an imploding plasma with a fast pulsed-power generator (typically 0.1 µs to 1 µs rise time, 1 MA to 26 MA peak current). This research gave me the opportunity to perform experiments at z-pinch research facilities such as the 1-MA Zebra generator at UNR, the 1-MA COBRA generator at Cornell University, and at the monstrous 20-MA Z Machine at SNL. I presented my results at numerous conferences across the United States and Europe and interacted with some of the field's best scientists.

After a rewarding year as a postdoctoral research associate at the Plasma Engineering Research Laboratory at Texas A&M, Corpus Christi, I accepted a senior staff position as an experimental plasma physicist in the Radiation and Electrical Sciences department at SNL. Currently, I am the principle investigator on numerous projects across a broad range of high-impact research topics concerning electrical breakdown in aerospace vehicles, system susceptibility to electro-magnetic pulses, nuclear power systems, solar power systems, and our patented electrical oil and gas exploration technology. This blend of cutting edge, diverse, and practically valuable research is what attracted me to SNL. In addition, the sheer concentration of advanced researchers and facilities makes SNL a hot spot for interdisciplinary collaboration and innovation.

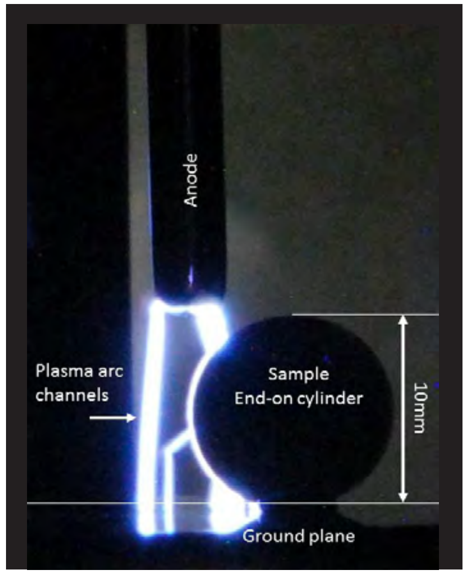


Figure 1. A 10 kVDC rod-plane electrical discharge near a cylindrical rutile sample (seen from the end) within a controlled dry air atmosphere at 600 Torr. The anode-cathode gap is 10 mm, the sample is 10 mm in diameter and is offset 5 mm from the axis. Optical spectroscopy indicates that this plasma is hotter than 25,000 K.

My time is usually split between three or more independent projects, each with its own budget, personnel, and deliverables. One project that I'm leading now, in collaboration with UNR, Texas Tech University, and Voss Scientific, is focused on understanding the fundamental processes leading to electrical breakdown near high-permittivity materials. I was surprised to learn that "sparks" could be so difficult to understand. Figure 1 shows a recent experiment that I performed with my team in our Advanced Component Development Laboratory. It is a time-integrated image of a 10,000-volt electrical discharge between the upper rod anode and the lower ground plane. The high-permittivity cylinder (εr ~ 100) sample is seen from the end. It is made from a special blend of annealed rutile provided to us by our advanced materials collaborators here at SNL. Rutile is a mineral composed primarily of titanium dioxide, TiO_2, and is the most common natural form of TiO_2. The bright multi-channel plasma discharge is seen here "jumping" off the sample halfway through the gap, taking a sharp downward turn, and proceeding to ground in parallel to another plasma channel. Developing a model to understand how this behavior represents the "path of least resistance" may take many more years of study.

The investment that the SSAA Program made into UNR and thus to my education gave me a wonderful opportunity to become a plasma physicist working in industrial and national security research. SNL is an incredible place to work because of our ongoing professional development, solid work-life balance, and strong peer-support structures.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Matthew Bishop, mbishop4@uab.edu

Degree in Progress: PhD, Physical Chemistry, University of Alabama, Birmingham
Academic Advisor: Dr. Yogesh Vohra

SSAA Program:
2013 to Present

Research Topic:
High pressure-temperature phase stability of 1,1-diamino-2,2-dinitroethylene (FOX-7)

What are your research responsibilities?

I am currently enrolled as a PhD student in the Chemistry program and a member of the high pressure group at the University of Alabama at Birmingham. Our research group collaborates with the Shock and Detonation Physics group at Los Alamos National Laboratory (LANL). Part of our team's research involves using diamond anvil cells to investigate the structural stability of high explosives at extreme conditions (high pressure-temperature). Resulting data provides information on the fundamental properties (e.g., structural stability, compressibility, etc.), which can be directly related to the safety, reliability, and performance of energetic materials. The use of synchrotron radiation is critical to probing energetic materials response to extreme conditions. I am responsible for writing proposals for beamtime at the Argonne National Laboratory and the Brookhaven National Laboratory synchrotron sources. The data collected falls to me to analyze and publish; in fact, we are now preparing to submit the first phase diagram of FOX-7 for publication.

How have you benefited from the SSAA program?

The SSAA has enabled me the use of a one-of-a-kind experimental technique with designer diamonds for studies on materials under extreme conditions under the supervision of my advisor, Dr. Yogesh Vohra.

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

In summer 2014, I was given the opportunity to be one of the inaugural speakers at TEDxLANL, an honor that has opened a large array of opportunities that would have not been possible without participating in the SSAA program (http://vimeo.com/askascientist/scientificlinguist).

Have you spent time at one of the national laboratories?

I have spent the last 3 summers at LANL working on my dissertation, but the nature of my research requires me to travel to other national laboratories to use unique experimental techniques. In addition, the vast network of expertise at LANL has provided a multidisciplinary approach to research that has complemented my disciplinary-focused training at the university. The ability to pick up the phone and call an expert in the field when I have a question has provided me with an unparallel research experience. The SSAA has provided an excellent launch pad for my career by providing me a high quality research background at the national laboratories, and the necessary experience to competitively pursue a post-doctoral appointment within the NNSA laboratory network. The SSAA Program network was critical in establishing research collaborations. I am sincerely grateful for all the opportunities SSAA has provided.

Christopher Prokop, prokop@nscl.msu.edu

Degree in Progress: PhD, Nuclear Chemistry, Michigan State University
Academic Advisor: Dr. Sean Liddick

SSAA Program:
2013 to Present

Research Topic:
Beta-decay spectroscopy and digital data acquisition system development

What are your research responsibilities?

My research responsibilities are divided into two main categories. Most of my work is performing beta-decay spectroscopy experiments on neutron-rich nuclei far from beta-stability. The goal of this research is to extract properties of nuclear levels such as energies, lifetimes, branching ratios, and feeding to deduce nuclear structure information and inform theoretical models. I also develop and optimize digital data acquisition systems to obtain high-resolution time and energy extraction from a variety of detectors. These digital data acquisition techniques are then applied during the experiments enhancing the quality of the data.

How have you benefitted from the SSAA program?

The SSAA Program has provided the funding for me to perform research, travel to a variety of meetings and conferences, and be awarded a summer internship at Lawrence Livermore National Laboratory (LLNL). Through my research, I have participated in all aspects of low energy nuclear science experiments such as development of hardware and software, proposal and paper writing, as well as experimental setup, execution, and analysis, all of which has prepared me for postdoctoral positions. Attendance at meetings and conferences has permitted me to network and attend talks by leading researchers in the field enhancing my general understanding and perspective. My summer internship at LLNL, funded by the SSAA Program, broadened my horizons and exposed me to career opportunities and research thrusts at NNSA laboratories.

Have you spent time at one of the national laboratories?

During my internship, I worked with a group performing nuclear forensics research, which is complimentary to the basic science-driven work I perform at the National Superconducting Cyclotron Laboratory. The experience at LLNL gave me an understanding of how the lab operates and what a career there would be like. The contacts I made have opened the door to additional postdoctoral career opportunities as well as further future collaboration.

Austin Stafford, austins@unr.edu

Degree in Progress: PhD, Physics, University of Nevada, Reno
Academic Advisor: Dr. Alla Safronova

SSAA Program:
2010 to Present

Research Topic:
Spectroscopic analysis of plasmas from cylindrical wire arrays and laser produced plasmas

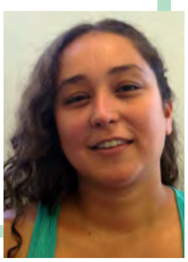
What are your research responsibilities?
My responsibilities primarily involve analyzing K-shell and L-shell x-ray spectra. I use our non-local thermodynamic equilibrium kinetic model to estimate plasma conditions, such as electron temperatures and densities, in the plasma we create. During our experimental campaigns, I am in charge of acquiring the data from the oscilloscopes and processing it quickly so that we can make adjustments for the following experiments. This is most important for adjusting time sensitive diagnostics. Most recently, I have begun preparing my research for publication in peer reviewed journals with one publication earlier this year.

How have you benefited from the SSAA program?
The SSAA program has provided me with an incredible number of opportunities to interact with the high energy density plasma community. The yearly reviews provide a chance to discuss my work with distinguished scientists and at the review from 2013 there was a tour of Sandia National Laboratories. Beyond the reviews, the SSAA program supports me going to international conferences so I can learn about work conducted all over the world. Thanks to the program, I have met people who will be mentors and inspiration in my life for many years.

What do you want students considering SSAA to know?
I would like new graduate students to know how important it is to the Stewardship Science Academic Programs (SSAP) to connect students to professionals in the national laboratories. At each yearly review, the SSAP brings representatives from the NNSA national laboratories so that you can ask questions about their research and responsibilities. At these meetings, students learn how to apply to the laboratories, but more importantly students are directed to professionals working in fields of interest. The SSAP provides opportunities for you to learn about the numerous options available so you will find where you fit best.

Eloisa Zepeda-Alarcon, eloisa@berkeley.edu

Degree in Progress: PhD, Earth and Planetary Science, University of California, Berkeley
Academic Advisor: Dr. Hans-Rudolf Wenk



SSAA Program:
2011 to Present

Research Topic:
High pressure and temperature deformation of $MgSiO_3$ perovskite + MgO aggregates: Experiments with diamond anvil cell and viscoplastic modeling

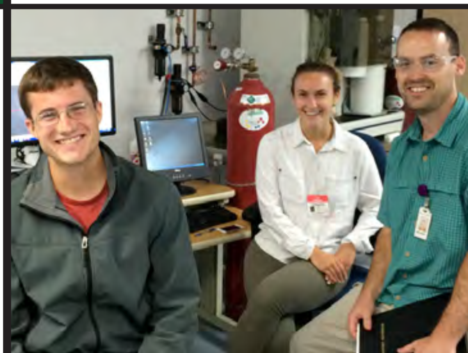
What are your research responsibilities?
As a graduate student researcher at UC Berkeley my main research responsibility is to understand deformation of two-phase aggregates under high pressure and temperature conditions. Specifically, I work with the perovskite + periclase aggregate, which is the main component of the lower mantle of the Earth. To achieve this understanding, I perform experiments with synchrotron radiation to quantify the development of preferred orientation in polycrystalline samples under compression in a diamond anvil cell. The travel related to these experiments is supported by the SSAA Carnegie/DOE Alliance Center. I also perform viscoplastic simulations that provide further insight as to the mechanical processes that occur as these polycrystals deform.

How have you benefitted from the SSAA program?
The benefits I have received from the SSAA program are invaluable. It not only provides full funding for my graduate studies, which gives me the security and peace of mind to pursue my research, but it also provides full support for travel to synchrotron facilities to do the experiments needed for my project. I have also greatly benefited from their summer internship program, which has enriched my career significantly.

Have you spent time at one of the national laboratories?
I spent two months at Los Alamos National Laboratory (LANL) working in the Materials Science in Radiation and Dynamics Extremes group doing viscoplastic modeling of two-phase polycrystals. My experience at LANL opened a whole new avenue in my research and will be an important part of my PhD thesis. I also expect a paper to be published in a peer-reviewed journal from my work at LANL. I did a great deal of networking while in my internship, providing great collaboration possibilities for the future.

What do you want students considering SSAA to know?
The SSAA program provides support for your graduate studies and research in many different ways. Their financial support with travel provides unique opportunities for you to grow as a scientist and perform world-class experiments. The extensive network that this program provides becomes a strong pillar of your career. There is always a new project or collaboration around the corner. Finally, being part of the SSAA program becomes like being a part of a great, knowledgeable, and supporting family.

High Energy Density Laboratory Plasmas



Relativistic X-ray Polarization Spectroscopy

Harvard-Smithsonian Center for Astrophysics

PI: Guo-Xin Chen (gchen@cfa.harvard.edu)

The theoretical x-ray spectroscopy project at the Harvard-Smithsonian Center for Astrophysics (CfA) is supported by an NNSA/HEDLP grant. The CfA is a collaboration of Harvard College Observatory (HCO) and Smithsonian Astrophysical Observatory (SAO) and home to Harvard University's Department of Astronomy. The main goal of the project is to develop relativistic atomic theory at the SAO/CfA suitable for highly accurate calculations of x-ray polarization spectroscopy (XPS). This can then be applied to the analysis of anisotropic velocity distributions of hot electrons and the directionality of high energy density laboratory plasmas (HEDLP), and to plasmas in x-ray astrophysical sources. The long-term goal is to develop a powerful program unifying relativistic atomic theory, relativistic spectroscopy calculations, and practical plasma diagnostics.

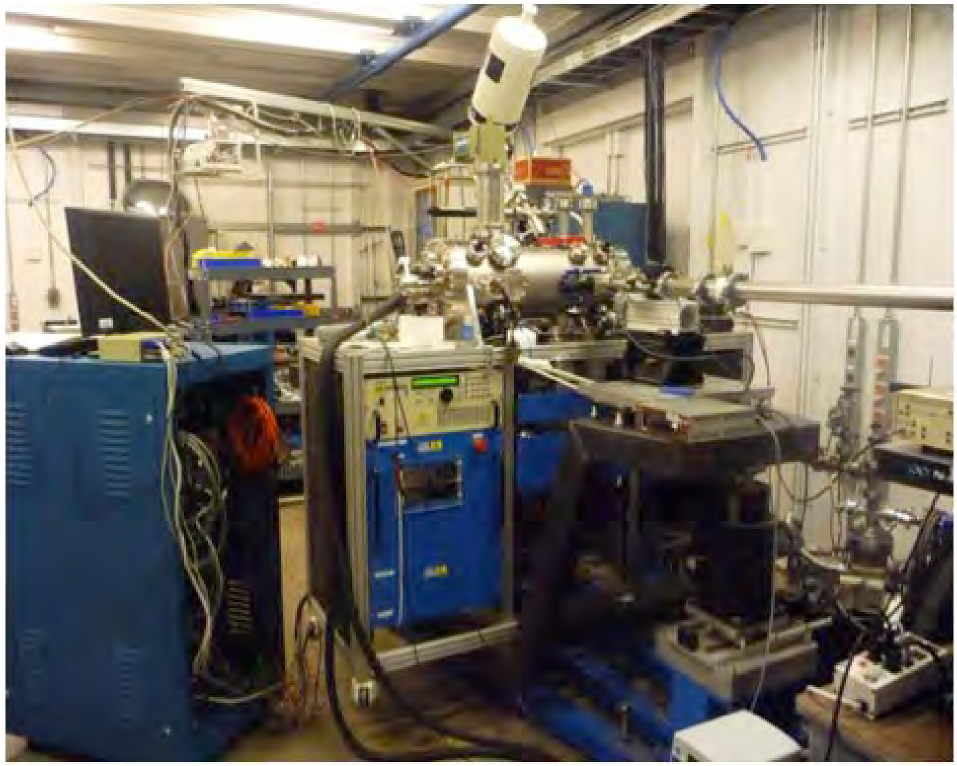


Figure 1. The SAO/CfA Electron Beam Ion Trap (EBIT) Facility.

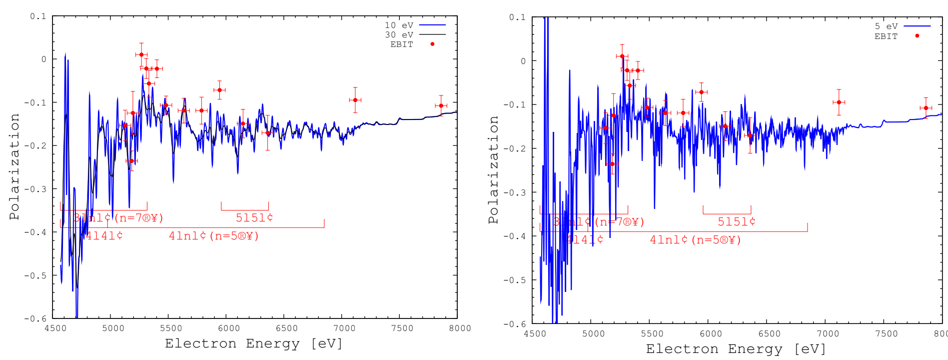


Figure 2. Demonstration of our new resonant polarization spectroscopy (RPS) method. Top - Averaged M2 polarization of Ba^{46+} for EBIT beam width W = 10 eV (blue) and W = 30 eV (black). The filled dots with error bars are polarization observed in the EBIT produced Ba plasma at NIST. Bottom - Averaged M2 polarization of Ba^{46+} for beam width W = 5 eV (blue curve).

X-ray Polarization Spectroscopy (XPS) can provide new insights into the anisotropy of relativistic atomic processes in high energy density plasmas. It can be applied in many areas, including hot laser-produced plasmas, inertial confinement fusion plasmas, magnetic confinement fusion plasmas, and laboratory and cosmic-scale astrophysical plasmas. For example, L-shell tungsten XPS is needed to measure the high x-ray radiation yields in z-pinch and wire array x-pinch experiments, and L-shell gold XPS is needed to diagnose inertial confinement fusion plasmas in hohlraums. Highly accurate techniques have been successfully developed, incorporating complicated resonant structures, to calculate the XPS of high-Z (atomic number), multiply charged complex ions (the semi-relativistic Breit-Pauli R-matrix method and fully relativistic Dirac R-matrix (DRM) method). Using these techniques, it has been shown that the x-ray polarization is a function of both the electron energy and the non-Maxwellian electron distributions. This suggests a new plasma diagnostic, which is called resonant polarization spectroscopy (RPS). For example, a comparison between the results from a sophisticated relativistic calculation of the polarized radiation from in Ba^{46+} (allowing for the complicated resonant structures) and experimental data constrains or even determines the directional beam electron distribution of a laboratory Ba plasma. RPS may be broadly applied to HEDLP for the diagnostics of directional and non-Maxwellian source conditions of laser produced plasmas, inertial confinement fusion plasmas, magnetically confined fusion plasmas, and astrophysical plasmas.

Experimental and Computational Studies of High Energy Density Plasma Streams Ablated from Fine Wires

Cornell University

PI: John Greenly (jbg2@cornell.edu)

Cylindrical arrays of fine wires used to form imploding z-pinches are the world's highest yield pulsed x-ray sources driven by the Z Machine at Sandia National Laboratories (SNL). The research program at Cornell investigates the high energy density (HED) flows of plasma ablated from such wires, both to deepen the understanding of their behavior in imploding z-pinches and to use these flows in other configurations to investigate fundamental physical phenomena in HED plasmas. This research program was initially funded by a Department of Energy/National Science Foundation collaboration, and is now continuing under NNSA sponsorship.

This work is a closely-coupled program of experiments, computer simulations and theory. Experiments are carried out on the COBRA pulsed-power facility in the NNSA Cornell Center for Pulsed-Power Driven High Energy Density Plasmas. Simulations use the PERSEUS extended-magnetohydrodynamic (MHD) code. Matthew Martin, the graduate student who built PERSEUS with co-Principal Investigator Professor Charles Seyler, is now a staff member at SNL in the Z Machine research organization. For her PhD research Xuan Zhao built a faster and less diffusive DG-PERSEUS especially suited to simulating shocks. Several beginning graduate students in the Cornell Center assisted with COBRA experiments this year. Micro-Bdot probes (to measure magnetic fields) developed during this work have been fielded in a number of experiments on the Sandia Z machine this year. A team of Cornell undergraduates were challenged to produce the highest possible magnetic fields on COBRA, > 150 Tesla, to test these probes. NNSA sponsorship has enabled these students to learn about the SNL program and present their work at conferences.

A major focus of this work is on a new regime of HED magnetic reconnection. Reconnection is a fundamental process in plasmas that plays a major role across all scales from tiny z-pinches to controlled fusion plasmas, to the solar corona and up to galactic astrophysical phenomena. Basically, any plasma that has more than a single current channel contains magnetic fields in separate topological regions which constrain the evolution of currents and fields. Reconnection breaks these constraints, resulting in unsteady, impulsive phenomena such as solar flares and the coronal mass ejections that can threaten the U.S. power grid. In many cases, the details of how reconnection is triggered are not fully understood.

This research has used the COBRA pulsed-power machine in a new way to elucidate a fundamental reconnection triggering mechanism. COBRA is used to drive currents in a pair of parallel aluminum wires. The separate wire plasmas store magnetic and thermal energy as the current increases up to its peak of 1 MA in ~ 200 ns. With the right choice of wire mass, this work has demonstrated that reconnection of the fields and outward acceleration of the plasmas occurs exactly and only when the driving voltage is reversed. This generates reversed current at the plasma edges by an inverse skin effect, reducing the magnetic pressure there and driving reconnection that liberates the trapped magnetic energy.

Figure 1 shows images, in extreme ultraviolet (XUV) radiation, of this evolution. The two wires, initially 16 mm apart, are viewed end-on. The first image is during the current rise, the second is just after voltage reversal, and subsequent images are 20, 30 and 70 ns later. Plasma accelerates from both wires toward the center, forming an elongated central reversed current sheet where magnetic fields of the two wires reconnect, and outflows carrying reconnected magnetic fields form to the left and right. The final image shows that shock structures form at obstacles placed in the outflows.

PERSEUS simulations of these magnetized, radiative shocks indicate that the flow is both supersonic and super-Alfvenic, the first time this regime has been observed in the laboratory in HED plasma dominated by magnetic forces. The triggering mechanism may be at work in the solar corona and other reconnection phenomena.

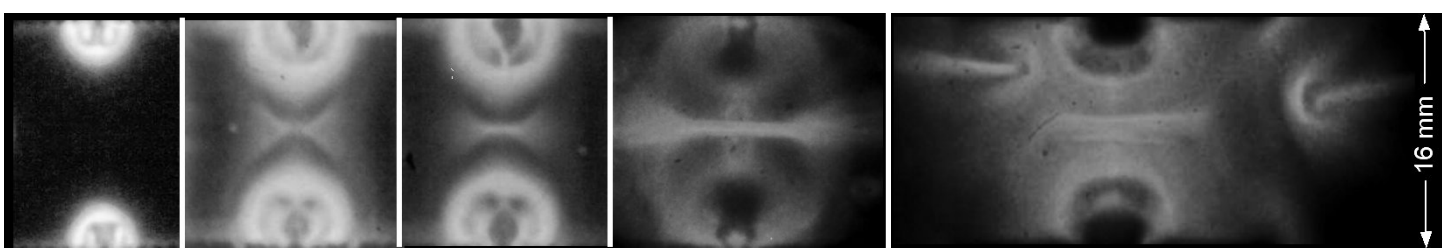


Figure 1. Two-wire reconnection images in XUV radiation, 5 ns exposures. View is end-on, parallel to the axes of the wires seen at the top and bottom of the images, at 100 ns, 230 ns, 250 ns, 260 ns and 300 ns after start of current.

Development of a Single-Crystal X-Ray Spectropolarimeter

University of Nevada, Reno
PI: Radu Presura (presura@unr.edu)

The polarization of the emitted x-rays is a unique diagnostic tool for plasmas with anisotropic distribution functions. In 2012, through the High Energy Density Laboratory Plasmas (HEDLP) program, NNSA began funding the development of a novel spectropolarimeter capable of measuring the polarization degree of x-ray spectral lines using a polarization-splitting crystal. The technique will be used to investigate the anisotropy and its origin in z-pinch plasmas. One postdoctoral researcher and two graduate students have participated in this research, and currently the grant funds one graduate student.

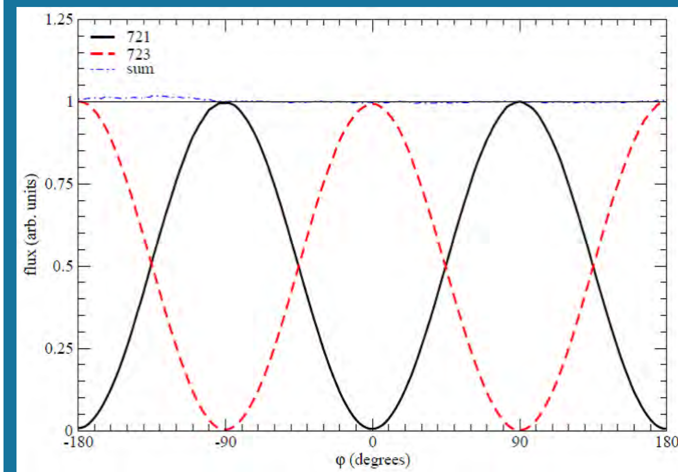


Figure 1. The x-ray flux diffracted from the two polarizing crystal planes as a function of the polarization angle of the incident x-rays (solid and dashed traces). The dash-dot trace represents their sum, showing the very small deviation from the expected unit value.[2]

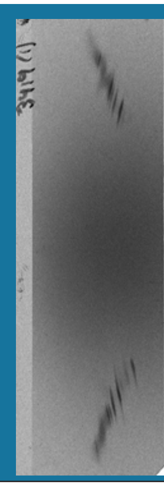


Figure 2. Two spectra produced by the polarizing planes are recorded simultaneously and appear on the film as two mirrored series of lines. The darker region in the center of the image represents higher energy continuum.

Energetic particle acceleration is a common occurrence in z-pinches, resulting in hard x-ray bursts or beam-target fusion reactions. The mechanisms that create the strong electric fields responsible depend on complicated plasma physics of the region where the acceleration occurs, and are not well understood. Insight into these processes can be obtained without perturbing the plasma through polarization-sensitive spectroscopy. This NNSA grant has enabled a collaboration as noted below between researchers with complementary expertise in HEDLP and x-ray spectroscopy, who are making rapid progress in developing a single-crystal x-ray spectropolarimeter and its application to z-pinch plasmas. The students involved appreciate the training they receive by working on world-class facilities and by direct interactions with experts in the field.

When the electron distribution function in a plasma has a preferential direction, it creates a specific population of certain atomic levels, leading to the emission of polarized lines. With proper modeling, the energy and angular distribution of the directional electrons can be determined from polarization measurements. The x-ray spectropolarimeter developed under this grant provides accurate measurements of the polarization degree by using a polarization-splitting crystal.[1] Instead of using the surface plane, as in traditional spectrometers, this technique uses pairs of internal planes that allow, for a certain wavelength, two reflections of an x-ray beam in two directions perpendicular to each other and to the incident beam. The reflected x-rays are linearly polarized in mutually perpendicular directions. This feature assures that the two mutually orthogonal polarization-state intensities of each observed spectral line are emitted simultaneously from the same plasma region.

Quartz crystals, which have this property due to their hexagonal structure, were selected for the instrument. The polarization properties of each crystal were verified with polarized synchrotron x-rays at the Argonne National Laboratory's Advanced Photon Source.[2] Figure 1 illustrates the high polarization contrast measured for one of the crystals. This enables high quality measurements of the polarization degree. An x-ray spectropolarimeter was built and optimized for z-pinch experiments, using a quartz crystal with the spacing of the polarizing planes closely matching several emission lines of highly ionized aluminum. The first measurements were performed on wire array z-pinch plasmas at the Nevada Terawatt Facility of the University of Nevada, Reno (UNR). As an example, Figure 2 shows the pair of polarized spectra recorded for a cylindrical z-pinch.

Collaborators

Nino R. Pereira (Ecopulse, Inc.), Roberto C. Mancini (UNR), and Peter Hakel (Los Alamos National Laboratory)

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As of January 2015, Dr. Paul Neill (paul@unr.edu) will take over as Principal Investigator of this grant. Dr. Presura will be going to work for Voss Scientific, LLC (radup@vosssci.com).

Enabling the Study of Matter in Extreme Conditions with the Flow Z-Pinch

University of Washington, Seattle

PI: Uri Shumlak (shumlak@uw.edu) www.aa.washington.edu/research/ZaP/

The University of Washington ZaP Flow Z-Pinch Project investigates sheared flows as a novel means of stabilizing an otherwise unstable plasma configuration. The resulting long-lived meter-long z-pinch offers a unique and convenient platform to study high energy density (HED) physics.

The z-pinch configuration is a plasma column where axial current creates an azimuthal magnetic field that confines the plasma. Higher current produces a stronger magnetic field, which compresses the plasma column, decreasing its radius and increasing its pressure. Z-pinch plasmas scale to HED (high pressure) through any combination of lower plasma mass or higher pinch current. Traditional z-pinch plasmas suffer from large-scale instabilities that spoil magnetic confinement and terminate plasma lifetime within tens of nanoseconds. These instabilities have limited z-pinch plasma length to centimeters and lifetimes to nanoseconds. The ZaP experiment mitigates these instabilities with sheared flows, which allow for large-scale, long-lived z-pinches that are particularly advantageous for studying HED physics.

Unlike axial magnetic fields, which can also provide stability, axial plasma flows do not restrict the maximum achievable plasma pressure. Theoretical results demonstrate complete stability when the flow shear, i.e., axial velocity variation with radius, exceeds a threshold value. The ZaP research group, which includes five graduate and three undergraduate students, conducts experimental investigations to generate flow-stabilized z-pinch plasmas that are over a meter long and have 50-microsecond lifetimes. Generating a flow z-pinch is accomplished by coupling a coaxial plasma accelerator, which produces and sustains the flowing plasma, with a pinch assembly region where the compressed z-pinch plasma column forms and persists. Figure 1 shows the experimental apparatus.

Making detailed measurements to fully characterize HED plasmas represents a major challenge of experimental plasma physics research. An advantage of using the flow stabilized z-pinch for HED investigation is that its large

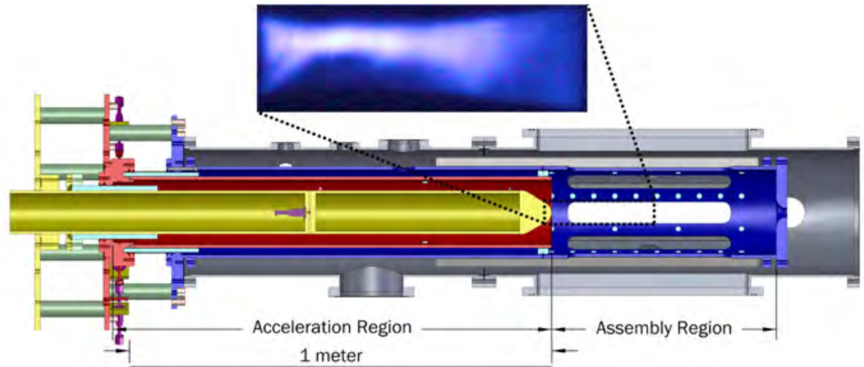


Figure 1. Machine drawing of the ZaP-HD experimental apparatus illustrating the coaxial plasma accelerator coupled to the pinch assembly region in a triaxial electrode configuration. An image from the fast framing camera captures a z-pinch plasma column.

size and long life facilitate detailed measurements. The ZaP Flow Z-pinch is studied using a suite of diagnostics. Plasma stability is monitored by reconstructing the magnetic topology from approximately 100 field probes and by fast framing photography of the pinch plasma. The magnetic structure evolves into a tightly compressed, centered, and stable configuration during a quiescent period. Fast framing photographs taken during the quiescent period show a stable plasma column with well-defined structure. Flow shear is measured using Doppler-shift, imaging spectroscopy of impurity line radiation. Twenty viewing chords integrate plasma emission at different impact parameters. The spectra are simultaneously deconvolved and analyzed to determine profiles of axial velocity, as well as plasma temperature, density, and magnetic field. Figure 2 shows axial velocity measurements.

The flow shear determined from the measured axial velocity profile is compared to the theoretically required flow shear, computed from experimentally measured plasma parameters. Consistent with theoretical predictions, the plasma quiescent period is observed when the experimental flow shear exceeds the theoretically required value. The ZaP group conducts detailed numerical simulations using the Mach2 and NIMROD MHD codes and the WARPX multi-fluid plasma code to complement the experimental effort.

Scaling the flow z-pinch to HED conditions requires separately controlling the plasma accelerator,

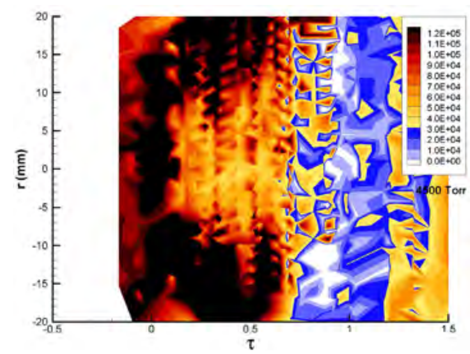


Figure 2. Contours of axial plasma velocity [m/s] as a function of radius and time. At the start of the quiescent period, normalized time τ=0, an initially large and uniform plasma flow develops a shear where the core velocity is lower than the edge velocity. At the end of the quiescent period, τ=1, the flow shear diminishes as the plasma slows.

which dictates the mass in the plasma column, and the pinch current, which compresses the plasma column. Independent control is accomplished in ZaP through separate power supplies and a triaxial electrode configuration. Initial operation demonstrates the concept's ability to produce stable flowing plasmas. Achieving HED conditions requires installing the ZaP configuration onto a larger pulsed power driver, where the compression current is supplied by the driver, and a separate acceleration power supply creates and sustains the z-pinch plasma. The simplicity of the flow z-pinch concept and its ability to produce large-scale, long-lived plasmas facilitates the generation of HED plasmas and enables extensive study of HED physics.

Alumni & Students
High Energy Density Laboratory Plasmas

Rachel Young

David A. Martinez

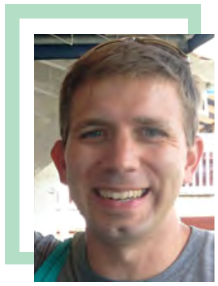
Zachery Sternberger

Eric Harding

Eric Harding (ehardi@sandia.gov)

Years at SNL: July 2010 to Present • Degree: PhD, Applied Physics, 2010

Years in SSAA Program: 2003-2010, University of Michigan



The HEDLP Program together with the Naval Research Laboratory (NRL) supported my graduate studies at the University of Michigan. My thesis research concentrated on generating and understanding the Kelvin-Helmholtz instability in high energy density (HED) plasmas.[1] The support I received from these programs made it possible to focus on my research, as well as travel to numerous conferences and technical workshops. As a result of this travel, I connected with many scientists from various national labs including NRL, Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), and the University of Rochester Laboratory for Laser Energetics (LLE). Many of these scientists are now trusted colleagues and friends upon whose expertise I continue to rely.

Obtaining exposure to the national lab environment is an important aspect of the Stewardship Science Academic Programs, and future candidates can take advantage of many of the labs' expertise. By engaging scientists at the labs, students can acquire further direction on their thesis research and possibly discover ways to increase the impact of their research on the broader HED community. This was the case for my thesis work, and I continue to be appreciative for the support and guidance I received. As a graduate student, my experience at the national labs was rewarding. As I went forward in my career, I wanted direct access to facilities in which I could continue my research of HED plasmas.

In July 2010, I began work as a staff member at SNL. Our group at SNL conducts experiments relevant to HED physics using both a large, pulsed-power device known as the Z Machine and a several kilojoule laser known as Z-Beamlet. With access to these machines, there is an enormous potential for a wide variety of innovative and novel HED experiments. This made SNL a particularly attractive place to work. Now, several years later, I have participated in a range of experiments related to x-ray scattering, inertial confinement fusion (ICF), and high-pressure equation-of-state measurements. In all these experiments, the lab provides the resources to implement new, and in some cases high-risk, target and diagnostic schemes. This type of environment makes the national labs an exciting place to work. In addition, my managers and colleagues here have generously supported my interest in broadening my expertise into areas that were outside my thesis research. In particular, I continue to seek to increase my knowledge of atomic physics as it relates to spectroscopy of HED plasmas. As part of this endeavor, our group has now implemented several new, spherical-crystal based x-ray diagnostics. One of the most exhilarating moments here was when we unexpectedly captured the image shown in Figure 1 with one of these new diagnostics. This thin column of x-ray emission originates from a thermonuclear plasma created by the cylindrical compression of deuterium gas.[2] Participating in these experiments has been tremendously rewarding and I look forward to advancing our understanding of this experiment and hopefully many others.

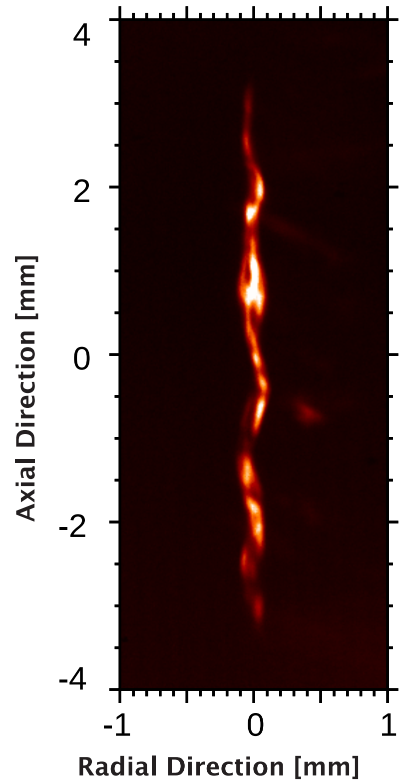


Figure 1. Shown here is an image of the x-rays emitted by an ICF type experiment that was conducted on the Z-machine March 5, 2014. The general ICF concept is known as magnetized liner inertial fusion (MagLIF).[3] A tube (also known as a liner) constructed from beryllium metal is filled with D_2 gas and imploded by the large magnetic pressure created by an electrical current flowing on the exterior of the tube. As the tube converges the gas is heated to thermonuclear conditions producing copious x-rays and neutrons. This particular shot (z2613) produced 10^{12} DD neutrons.

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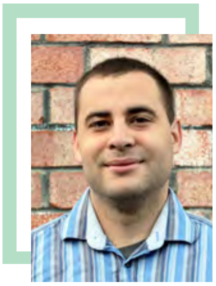
Years at LLNL: 2011 to Present • Degree: PhD, Physics, 2011
Years in SSAA Program: 2006-2011, University of Nevada, Reno



I began my career in high energy density (HED) physics at the University of Nevada, Reno where I studied shear flow stabilization of magnetohydro-dynamic instabilities. This work was performed at the Nevada Terawatt Facility using the 1 MA Z-pinch generator where, under the guidance of Radu Presura, an aluminum conical wire array generated a flow over a conducting stationary plasma. This research, supported by the HEDLP Program, touched on both inertial confinement fusion and laboratory astrophysics, and I desired to continue along this career path at one of the NNSA national laboratories. From attending workshops hosted by the Stewardship Science Academic Programs (SSAP) I knew the NNSA national laboratories were the best place to pursue a career in HED physics as they are on the frontier of science.

I sought employment at Lawrence Livermore National Laboratory (LLNL) because I wanted to perform experiments at the National Ignition Facility (NIF) to investigate hydrodynamic instabilities. I found the laboratory to have an exciting environment because projects were focused on using a multi-disciplinary approach to solving problems of national interest. With the many experts involved, it was simple to discuss new ideas. The most challenging aspect I have found is learning to limit the number of projects I work on: there are numerous opportunities available.

Through LLNL, I was afforded the opportunity to participate not only in programmatic experiments of national security interest but also in discovery science experiments through the NIF Discovery Science program, where, in an international collaboration led by Dr. Alexis Casner, we investigated the ablative Rayleigh Taylor instability.[1] Classically, the Rayleigh Taylor (RT) instability describes the unstable interface between a heavy fluid supported by a light fluid in a gravitational field. In the ablative RT case, the instability is formed from an interface being heated to produce hot, low-density plasma that pushes on cold, dense material. This situation occurs in laboratory inertial confinement fusion (ICF) plasmas such as those generated by the NIF. Our ablative RT instability experiments are designed to investigate the fundamental physics involved, in particular, the transition from the linear to the non-linear regime and then on to the turbulent regime. The experiment utilizes a 180 eV hohlraum radiation source (see Figure 1) to ablatively drive a plastic sample with a known pre-imposed perturbation for 12 ns. This allows the RT instability to reach the deeply non-linear regime where the dynamics are governed by a self-similar process resulting in an "inverse cascade" in which small structure perturbations coalesce into longer wavelength modulations through a "bubble merger" process.[2] Understanding this fundamental process will give us better models for mix and turbulence,[3] important for inertial confinement fusion[4] and laboratory astrophysics.[5]

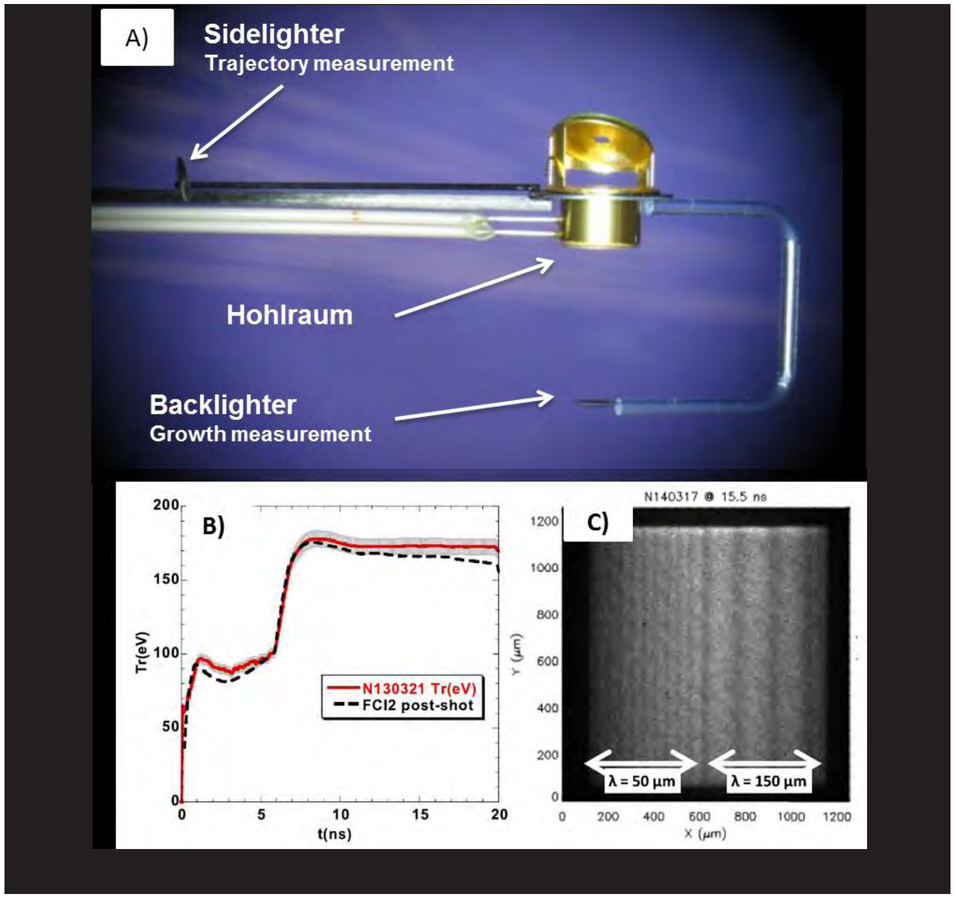


Figure 1: A) experimental setup showing a 5mm diameter hohlraum with attached backlighters. B) Radiation temperature measured from the hohlraum. C) Modulation growth from the RT instability at 15.5ns.[1]

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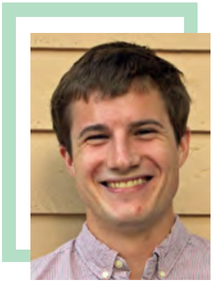
Zachary Sternberger (zsternberger@gmail.com)

Degree in Progress: PhD, Aeronautics, California Institute of Technology
Academic Advisor: Dr. Guruswami Ravichandran



SSAA Program:
2013 to Present

Research Topic:
Viscous plastic flow at extreme pressures and strain rates

What are your research responsibilities?

In the summer, I participated in an experiment at the Jupiter Laser Facility to test the growth of coined ripples on tantalum targets under Richtmyer-Mehskov and Rayleigh-Taylor instabilities. With collaborators at General Atomics, I have been analyzing our samples from this experiment. I will also simulate the experiments using a hydro code.

How have you benefited from the SSAP?

My PhD studies are currently funded by a grant from the NNSA. The SSAP also provides additional opportunities to see and learn about related research projects. The SSAP conference gave me the opportunity to see the range of topics important to the NNSA and to meet the students working on these topics.

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

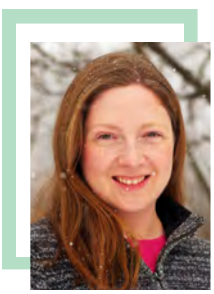
An important component of my PhD experience is the opportunity to learn from collaborators. Working on our group's most recent experiment, I was in contact with researchers from Lawrence Livermore National Laboratory, General Atomics, the University of California, San Diego, and Caltech. I had questions at every point in the preparation, execution, and analysis of the experiment. Our collaborators answered my questions and always provided me with something new to consider. I would have been unable to confidently work on the experiment without their guidance. The collaboration on the project has also deepened my understanding the role of a researcher, both in industry and at a national lab.

Have you spent time at one of the national laboratories?

My month at the Jupiter Laser Facility is the highlight of my PhD studies so far. The hands on work at Janus gave me a much more tangible understanding of the experiment. I learned about many concepts leading up to the experiment, but it took running an experiment to internalize the concepts. The month was also a fantastic insight into what work is like at a national lab.

Rachel Young (rpyoung@umich.edu)

Degree in Progress: PhD, Applied Physics, University of Michigan
Academic Advisors: Drs. R. Paul Drake and Carolyn Kuranz



SSAA Program:
2009 to Present

Research Topic:
Experimental astrophysics, scaled experiments of accretion on young stars

What are your research responsibilities?

Experimental astrophysics involves scaling high energy density physics experiments to study astrophysical phenomena. I research accretion shocks on the surface of young stars—essentially "baby Suns" growing at the center of an accretion disk. By conducting scaled experiments of these shocks at the OMEGA laser at the University of Rochester Laboratory of Laser Energetic (LLE), we hope to gain an understanding of their structure. This will enable the scientific community to better calculate accretion rates and thereby test theories about star formation.

As a graduate student primary investigator for a "shot day" (a day of experiments), I'm responsible for everything from the initial conceptual planning to the eventual data analysis. The planning might begin a year or more before the actual shot day. From there, we move onto target design and fabrication and planning the flow of experiments for the actual shot day. After our experiments are complete, we might spend several months analyzing data.

How have you benefitted from the HEDLP program?

The HEDLP Program is essential to my work. Funding pays for everything from my tuitions to my travel. Also, the conversations I have had with other scientists at the annual Stewardship Science Academic Programs Symposium have improved my research.

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

As a veteran of the nuclear navy, I was eager to continue serving my country while furthering my education by earning a PhD. I was attracted to stewardship science because of the overlap between astrophysics (my first love) and national defense.

How has the HEDLP Program been beneficial to your research?

Without the support of the HEDLP Program, I would not have had the opportunity to be a graduate student primary investigator at OMEGA. I feel I have gained immensely from that, not just because of the science I have learned, but because of the unparalleled leadership opportunity. We grad student PIs are not just responsible for planning the experiments; we are trusted with running the shot day: we give the scientific briefs to LLE staff, we work with the control room staff and we make adjustments to the shot plan. It is a real world experience that I don't think many graduate students get and I am extremely grateful to have had it.

National Laser Users' Facility

Dynamic Compression of Earth and Planetary Materials at OMEGA

Princeton University

PI: Thomas Duffy (duffy@princeton.edu)

The SSAP-sponsored research program at Princeton University is a collaboration between Princeton University and scientists at Lawrence Livermore National Laboratory (LLNL). The focus of the research is on understanding the structure and properties of geological materials at ultrahigh pressure conditions. These studies enable a better constraining of the composition, structure, and evolution of planets, both within and outside our solar system.[1] With support from the National Laser Users' Facility (NLUF) Program, the OMEGA laser is used to dynamically compress materials to as high as 10 megabar (1 terapascal) pressure, far beyond that achievable with more traditional laboratory techniques. In addition to geological materials, there is an effort to understand key materials that are important for high-pressure science and technology. There has been funding by the NLUF Program since 2011, and the project has provided support for graduate student, Jue Wang (PhD 2014), and current postdoctoral fellow, June Wicks.

The OMEGA laser is used to drive a compression wave through the material under study. By controlling the shape and duration of the laser pulse, either shock or ramp compression can be produced. Additional OMEGA laser beams are used to generate a nanosecond x-ray pulse, allowing the recording of an x-ray diffraction pattern from the compressed material.[2] The experimental observable in diffraction experiments is the interplanar spacing (*d*-spacing) which is directly related to the crystalline structure and density.

Wüstite, FeO, is an endmember component of ferropericlase, an expected major component in the mantles of super-Earth extra-solar planets. FeO is also important as a potential core component for the Earth and super-Earths. The determination of the structure, oxidation state, and nature of the bonding of wüstite will help constrain the equation of state of FeO at multimegabar pressure and high temperatures, which is a fundamental step for building reliable models for the evolution of Earth and other planets.

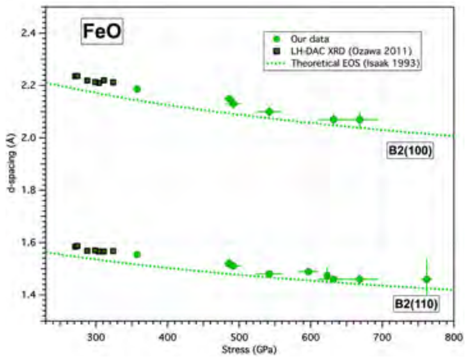


Figure 1. Experimentally determined interatomic *d*-spacings for iron oxide as a function of pressure as obtained in our ramp-compression experiments at OMEGA. Circles represent OMEGA data and they are compared with static compression experiments (squares) and theoretical simulations (dashed line). Our OMEGA results show that the B2 phase of FeO is stable at least up to 750 GPa, conditions relevant to the deep mantle or core of a super-Earth planet.

In this work, the structure and compressibility of FeO up to 7.5 Mbar (750 GPa) has been determined (see Figure 1). FeO shows a complex polymorphism below 200 GPa and experimental data[3] on its structure and density exist only up to 300 GPa. In experimental campaigns at OMEGA, FeO was ramp-compressed from 350-750 GPa and the high-pressure polymorph was measured in a totally unexplored pressure regime. The measured *d*-spacings show that the stable structure in this pressure regime is the B2 (cesium chloride) phase, which has not previously been studied experimentally to such high pressure. These data allow determination of the stress-density relation for B2-FeO and its equation of state and will provide an experimental benchmark for theoretical simulations.[4]

Molybdenum (Mo) is a technologically important transition metal that is widely used as a component and standard in static and dynamic compression experiments. However, significant unanswered questions and unresolved discrepancies remain about the high pressure-temperature behavior of this fundamental material.[5,6] Laser-compression experiments were carried out on Mo to as high as 1,050 GPa using x-ray diffraction as a diagnostic.

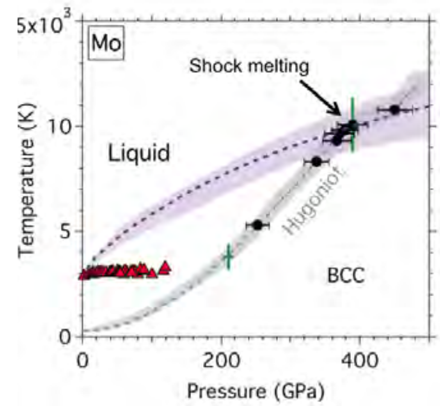


Figure 2. Phase diagram of Mo. Black circles represent experimentally measured shock pressures at OMEGA. The grey and purple dashed lines show the calculated Hugoniot temperatures and melting curve for Mo. Our OMEGA results are consistent with theoretical calculations that melting begins on the Hugoniot near 390 GPa and require a steeper melting curve than suggested from diamond anvil cell data (red triangles).

These results provide the first direct experimental determination of the crystal structure of Mo at these extreme conditions, in which the body centered cubic (BCC) structure remains stable until shock melting occurs at 390 GPa and under ramp loading the BCC structure is stable until 1,050 GPa. These results constrain the phase stability, melting curve, and equation of state of Mo to unprecedented levels of compression.

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Magnetic Reconnection Between Colliding Magnetized Plasma Plumes

Princeton University

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The researchers have developed and conducted experiments on the OMEGA EP laser at the University of Rochester's Laboratory for Laser Energetics to study the phenomenon of magnetic reconnection.[1] Magnetic reconnection occurs when regions of opposite directed magnetic fields in a plasma interact and relax to a lower-energy state; it is an essential plasma physics process in many systems which governs the storage and explosive release of magnetic energy in systems such as the Earth's magnetosphere, solar flares, and also magnetic fusion devices. The energy thus liberated can produce heat, flows, and can enable the acceleration of a large number of particles to relativistic energies. The researchers have been supported by the National Laser Users' Facility Program for two years, and the grant presently supports one postdoctoral scholar at Princeton University.

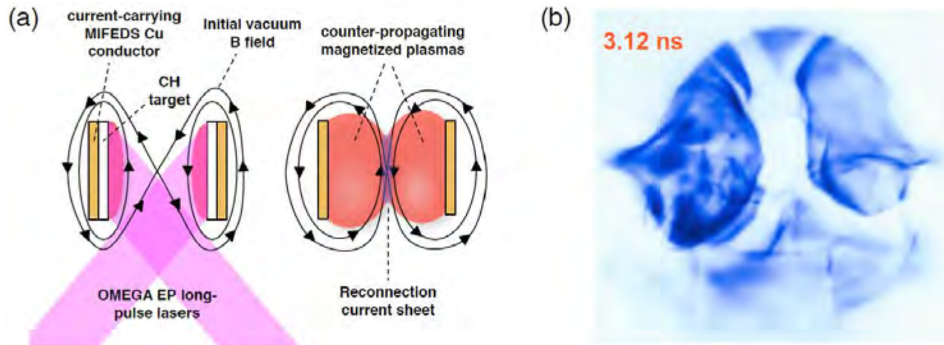

Figure 1. (a) Diagram of the experimental setup. During the experiment, an external magnetic field was first created by a pulse of electric current flowing along conductors mounted behind each target, and the region was then pre-filled with a tenuous background plasma. Two laser-driven expanding plasma plumes then sweep up this magnetic field into a pair of magnetized "ribbons" which collide and drive reconnection of the magnetic field. (b) Proton-radiography image of the colliding plumes. Light areas are regions of strong magnetic field.

Recent experiments have demonstrated how magnetic reconnection can occur and be studied in laser-produced plasmas, using the enormous (10-100 T) magnetic fields which can be self-generated in the laser plasma interaction.[2-4] Interestingly, despite the primary motivation of studying reconnection to learn about astrophysics, the research may have fusion application as well; the self-generated magnetic fields may also play roles in controlling the heat transport in coronal plasmas and in inertial confinement fusion hohlraums,[5] and recent magnetized implosions on OMEGA have demonstrated improvement in fusion performance with externally applied fields of order 10 T, subsequently compressed to thousands of T.[6]

In a new set of reconnection experiments conducted on OMEGA EP, the researchers used an externally applied magnetic field of order 10 T as the seed field for reconnection. With an externally applied field, the fields undergoing reconnection are under experimental control, so it is possible to conduct experiments with variable fields and topologies. In the first experiment, the researchers conducted the "zero field" case, in which the plumes can interpenetrate and drive the Weibel instability,[7] which also has very interesting applications to particle acceleration in astrophysics as a mechanism to produce collisionless shocks in the blast waves of astrophysical explosions.

The researchers have now successfully *magnetized* the counter-propagating plasmas and observed reconnection of the fields as the plumes collided.[8] Figure 1 shows the experimental setup and an example proton radiography image of the collision and interaction of the magnetized plasmas. The results are qualitatively different from the unmagnetized case and show the formation of a pair of magnetized "ribbons" propagating toward one another. The ribbons are regions of strong magnetic field, swept up and compressed to about 30 T, which shows up on the film as white "voids" where the magnetic fields are strong enough to steer the diagnostic proton beam off-film. The successful formation of the pair of ribbons is non-trivial: it was found that it was essential to add a third, "background" plasma source, triggered before the blowoff from the two primary targets, to fill the experimental volume with a diffuse low density plasma. The two magnetized ribbons collide at the mid-plane, generating bubble-like structures as the regions of oppositely magnetized plasmas interact and drive reconnection of the magnetic fields.

Future experiments will use these newly developed tools to study particle acceleration, one of the most important possible astrophysical consequences of reconnection.

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Magnetic Reconnection Experiments in Laser-Driven High Energy Density Plasmas

Princeton University

PI: Hantao Ji (hji@pppl.gov)

Magnetic reconnection is a ubiquitous process to dissipate magnetic energy in astrophysical, space, and laboratory plasmas through breaking and reconnecting magnetic field lines. This National Laser Users' Facility (NLUF) project focuses on developing a platform for magnetically driven reconnection in laser-driven high energy density plasmas and studying important physics such as particle accelerations during the reconnection process. Led by Professor Hantao Ji, the program brings together a creative team that is comprised of theorist, experimentalist, and astrophysicists from Princeton University, the University of Rochester Laboratory for Laser Energetics, and the Princeton Plasma Physics Laboratory. The group designs and carries out experiments with astrophysical importance, benchmarking particle-in-cell (PIC) and magnetohydrodynamic (MHD) simulations, and applies the results to astrophysical scenarios. The program has trained a graduate student at the University of Rochester and supported a postdoctoral fellow at Princeton University.

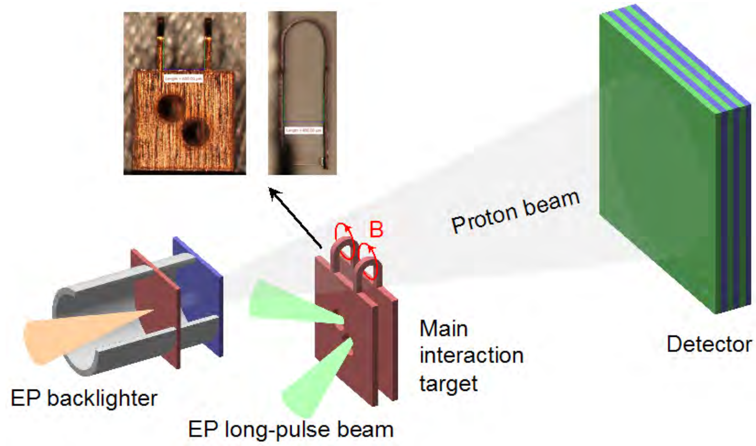

Figure 1. Experimental setup for the recent reconnection experiments at OMEGA EP based on a novel field generation technique. The main target is comprised of two copper plates connected with two wires. Target parameters are well characterized before the experiment, as shown in the pictures taken for the actual target. Two OMEGA EP long-pulse beams pass through the holes on the first plate to reach the second plate where hot electrons are released to charge up the first plate and form electric currents through the coils. Energetic protons generated by the OMEGA EP short-pulse beam are used to probe the reconnection process.

Figure 1 shows the experimental setup for the most recent reconnection experiments on the OMEGA EP Laser System based on a novel field generation technique. The main interaction target is comprised of two parallel copper plates, connected with two copper wires. Two OMEGA EP 2.5-kJ, 1-ns laser pulses pass through the laser entrance holes on the front plate and are focused on the back foil, generating a beam of superthermal hot electrons. The hot electrons stream onto the front plate and build up an electrical potential between the plates. This, in turn, drives large currents in both wires and creates magnetic reconnection because anti-parallel magnetic field lines exist in the middle plane. Ultrafast proton radiography was utilized to probe the reconnection process at various times with high spatial and temporal resolutions. To characterize the magnetic field generation around the wire, targets with double plates connected with a single wire were also used.

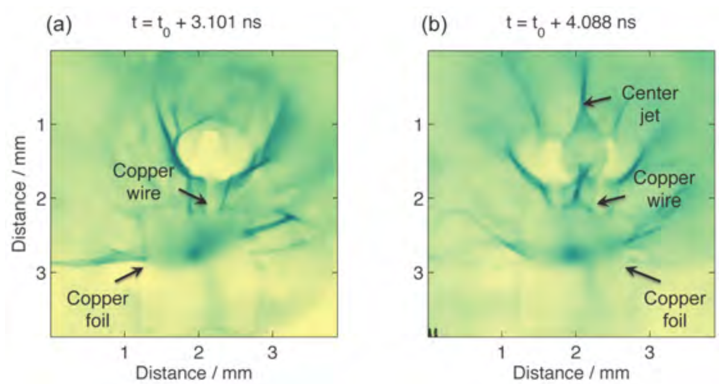

Figure 2. Panel (a) shows a proton radiograph of a single wire case where the light bubble is caused by magnetic fields around the wire deflecting incident protons. Panel (b) shows a proton image for the two-wire case.

The experimental results are shown in Figure 2. Panel (a) is an example proton image for the single wire case, taken at $t = t_0 + 3.101$ ns for 20 MeV protons, where t_0 is the arrival time of the long-pulse drive beams at the copper foil surface. The image is high quality, showing the location of the copper plate and the wire. In particular, a light bubble is formed, when incident protons are deflected by the azimuthal magnetic field around the wire. The results show ~500 Tesla magnetic fields at a distance of 40 μm from the wire surface. Energetically, the generated magnetic energy by the coil is on the order of 1% of the total energy of two incidental lasers. Panel (b) shows an example proton image for the two-wire case, taken at $t = t_0 + 4.088$ ns for 20 MeV protons. Besides the features of copper plate and copper wire, two light bubbles and a jet-like feature in the center are observed. Detailed analysis on the cause of the jet is underway. The significance of these experiments is the accurate measurement of magnetic fields generated by the coil target scheme and demonstration of an external magnetic filed source on OMEGA EP. Current efforts built on these results include driving axisymmetric reconnection to study efficient particle acceleration and use the OMEGA EP high-energy pettwatt lasers to study energetic asymmetric reconnection processes.

Dynamics of High-Energy Proton Beam Focusing and Transition into Solid Targets of Different Materials

University of California, San Diego (UCSD)

PI: B. Qiao (bqiao@ucsd.edu)

The Proton Dynamics National Laser Users' Facility Project, led by UCSD, studied proton generation in the regime of a kilojoule multi-ps laser driver. High-current applications, such as isochoric heating, are suited to this regime, but the focusing and transport of such high-current beams in warm solid materials has not been explored. One student and one postdoc were partially supported by the project starting in FY 2013; the postdoctoral scholar received training and facility experience. "The project has been a great benefit to us by allowing our work to be extended to a new regime using the outstanding resources and expertise at the Laboratory for Laser Energetics [University of Rochester]. It has also developed two diagnostic techniques that are being used by ourselves and others in future experiments," stated Dr. Qiao.

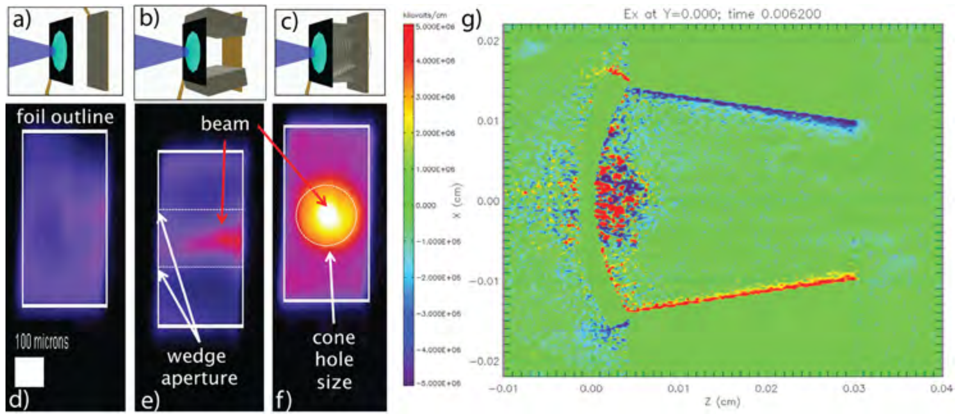

Figure 1. Three target types (a-c) used in the OMEGA EP experiment, showing heating by a focused beam as indicated by the emission profiles of 8.048 keV Cu Kα (d-f). Comparison of the signals shows that the total Cu Kα yield increased for the targets with structure, indicating a highly divergent source from the free case. The cone focused the beam, resulting in a 100 μm FWHM emission region. (g) LSP simulation plot of the transverse electric field E_x at time t=6.2 ps for a cone target.

A curved diamond-like carbon target was shot with OMEGA EP Backlighter Single Beam (1,250 J in 10 ps) to focus protons into a copper (Cu) foil. The Cu Kα (8.048 keV) emission was imaged with the Spherical Crystal Imager, as shown in Figure 1(d-f) for three target types (a-c). For the case of freestanding, separated foils, the Cu K-α signal was weak and diffuse over the entire Cu foil. This confirmed that the inherently diverging electron beam from the interaction contributed minimally to the Cu K-α signal at this standoff distance. However, for the case in which the gap was filled by a wedged structure, (b), signal was increased on the wedge center plane (e). The emission was greatest in the center, not at the edges of the wedge connection vertices, and no signal enhancement was observed in the region directly in contact with the wedge walls. This suggests that the signal was due to *focused*, freestreaming particles within the vacuum gap rather than particles transporting through the wedge. For the case with a cone filling the gap (c,f), the effect was even clearer, with 8x higher peak signal than the freestanding case. These data indicate focusing of the beam in one dimension by the wedge and in two dimensions by the cone. This effect has been studied in detail by the group using a sub-ps laser[1] and particle-in-cell (PIC) simulations,[2,3] while this result demonstrates that structures are effective for focusing in the kilojoule, multi-ps regime.

Two-dimensional PIC simulations have been conducted to further study the accelerating and focusing dynamics relevant to the OMEGA EP experiment. In the freestanding case, protons are initially focused due to the curvature of the target. However, a significant fraction of them diverge away. In the case with a cone, a strong focusing field is observed to persist along the inner cone surface (see Figure 1g) with strength comparable to the field from the curved target, confining protons and increasing their density. The simulated Cu K-α yields are being calculated for comparison to the experiment.

The proton and ion spectra were also measured, continuously for energies down to 0.4 MeV, using a Thomson parabola spectrometer in-line with the axis of the curved target. The cone cases showed similar spectra to the free cases except for reduced signal above 10 MeV for the cone cases. This is in agreement with our understanding of electron escape from the target electrons that escape the target into the cone and bring about quicker weakening of the accelerating sheath, reducing the highest energy but not the charge.

The peak beam current is estimated to be 4 x 10^9 A/cm^2. This density is sufficient to heat the metal foils locally to warm dense matter, which models predict can cause self-modified beam transport. Our PIC codes predict that the stopping range can be measurably changed as beam densities increase from 10^9 to 10^{10} A/cm^2, but thicker transport layers may be necessary.

Co-Investigators

C. McGuffey, J. Kim, F.N. Beg, UCSD; M.S. Wei, P. Fitzsimmons, M. Evans, R.B. Stephens, General Atomics; J. Fuchs, S.N. Chen, Laboratoire d'Utilisation des Lasers Intenses, France; P.M. Nilson, D. Canning, D. Mastrosimone, University of Rochester Laboratory for Laser Energetics; M.E. Foord and H.S. McLean, Lawrence Livermore National Laboratory.

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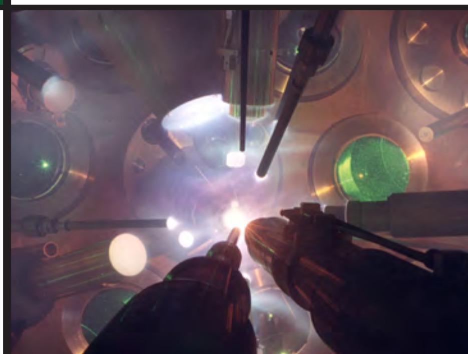
Alumni & Students
National Laser Users' Facility

JONATHAN PEEBLES

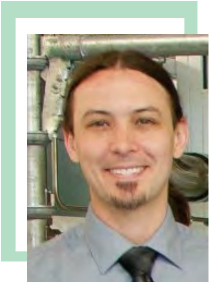
LESLIE WELSER-SHERRILL



L. CHARLIE JARROTT

DANIEL CASEY

Daniel Casey (casey21@llnl.gov)
Years at LLNL: September 2012 to Present • Degree: PhD, Applied Plasma Physics, 2012
Years in NLUF Program: 2005-2011, Massachusetts Institute of Technology



The National Lasers Users' Facility (NLUF) program helped fund my PhD research at the Massachusetts Institute of Technology in the High Energy Density Physics division led by Dr. Richard Petrasso. My thesis research centered around the commissioning and first uses of the Magnetic Recoil Spectrometer (MRS)[1,2] diagnostic at the OMEGA laser facility and the National Ignition Facility (NIF). The MRS measures the deuterium-tritium neutron spectrum from inertial confinement fusion (ICF) implosions and has become an integral part in the quest for ignition by providing crucial metrics for overall performance such as the total yield, the areal-density, and the ion temperature. The experience of bringing a diagnostic like MRS to OMEGA and NIF has helped me to prepare for the complexities of doing experiments on these giant facilities.

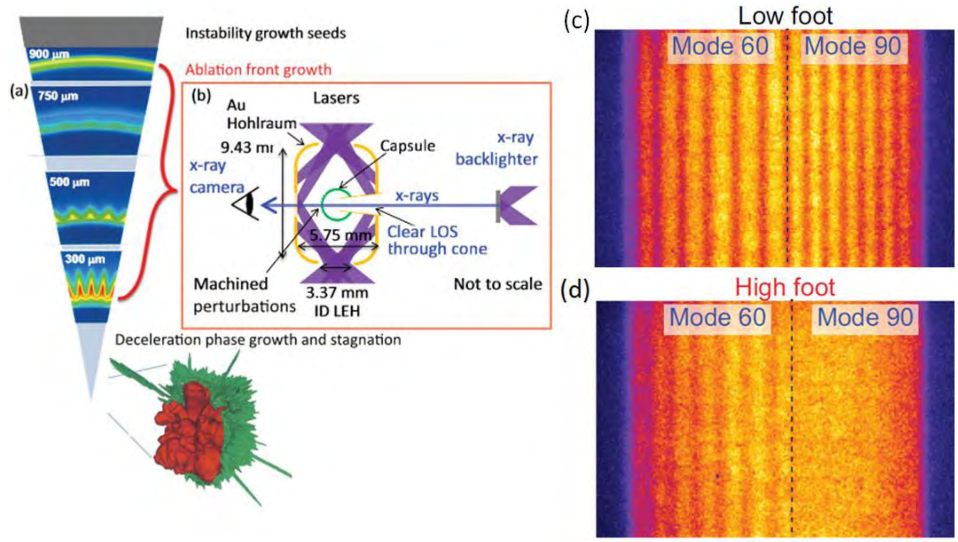


Figure 1. a) Schematic diagram of instability growth at several different radii (i.e., snapshots in time) showing density contours simulated by the hydrodynamic code HYDRA. Also shown (bottom) is a simulated stagnated hot spot illustrating the consequences of instability growth. b) Schematic of an indirectly driven hydrogrowth radiography target. The capsules are machined with sinusoidal perturbations and backlit using a vanadium foil x-ray backlighter. c) Slit image radiograph of side-by-side, preimposed, single-mode ripples of Legendre modes l = 60 and 90, for the low-foot pulse, which corresponds to an imploded radius of R=613 µm or convergence ratio (R0/R) of ~1.8. d) Also shown is a slit image radiograph, driven with the high-foot pulse, for the same side-by-side modes and convergence ratio. The high-foot drive results in reduced growth for both preimposed modes when compared to low foot.

After graduating, I came to Lawrence Livermore National Laboratory (LLNL) and have become involved in several exciting experimental efforts at the NIF. In one experiment, capsules with preimposed defects are x-ray radiographed in-flight to quantify the amount of unstable growth. ICF implosions are affected by the Raleigh-Taylor (RT) instability during the acceleration and deceleration phases. If left unabated, these instabilities can destroy the capsule inflight and significantly degrade implosion performance. Testing our understanding of the RT instability is therefore essential to making progress toward ignition. Furthermore, the high-foot drive was developed in the wake of the ignition campaign to help reduce unstable growth compared to the low-foot drive used during the ignition campaign. Figure 1 shows the results of these radiography experiments that compare the low-foot and high-foot drive, which experimentally demonstrated during the acceleration phase of the implosion, that the high-foot drive is more stable.[3] These experiments may explain the lower observed mix and significantly higher implosion performance of the high foot[4] and are helping to suggest new directions for the ICF program.

The NLUF Program provided support for me to attend conferences such as the Annual Meeting of the American Physical Society Division of Plasmas Physics, which enabled me to make important connections that helped me find a job and continue to aid my career.

When I was in high school, I read about massive fusion experiments in *National Geographic* and dreamed about what that experience might be like. Now, I can describe that experience firsthand. I love working at NIF because it is a unique national resource where exciting cutting edge research is regularly conducted, and every day brings a new adventure. I am especially grateful for my experiences in graduate school, for the support provided by the NLUF Program, and for the preparation and networking that have brought me to LLNL!

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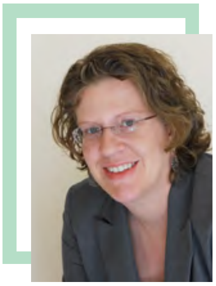
[4]O.A. Hurricane et al., Nature 506, 343, 2014.

Leslie Welser-Sherrill (lwelser@lanl.gov)
Years at LANL: 2006 to Present • Degree: PhD, Physics, 2006
Years in NLUF Program: 2000-2006, University of Nevada, Reno



As a graduate student at the University of Nevada, Reno, I was funded to work with Professor Roberto C. Mancini through a National Laser Users' Facility (NLUF) grant. My dissertation focused on the spectroscopic determination of temperature, density, and mix spatial profiles in inertial confinement fusion (ICF) implosions. The NLUF program gave me the opportunity to travel to the OMEGA laser facility at the University of Rochester to assist in conducting NLUF-funded experiments. This experience was undoubtedly one of the most important aspects of my graduate school career, since it connected me directly with the world of experimental physics. Not only did it broaden the scope of my knowledge base as a theorist, but it also colored my perception of how science should be accomplished. I am now a proponent of theorists being intimately involved in the experiments they help design.

Due to NLUF funding, I was also able to attend a number of conferences where I presented my research and met many scientists with whom I now collaborate. Through these connections, I became a graduate research assistant at both Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL), and worked on a variety of projects that extended the scope of my doctoral work. At graduation, I was awarded the Graduate Scholar Award by the University of Nevada Regents. After receiving my PhD, I returned to LANL in 2006 for my postdoc, and was converted to a staff position two years later. One of the many benefits of working at a national laboratory like LANL is the ability to be involved in both theoretical and experimental programs for a wide variety of scientific projects.

As a new staff member at LANL, I spent time studying mix in high energy density physics experiments, which culminated in a successful multi-year experimental campaign to study variable density mix layer behavior when subjected to strong shocks or shear (L. Welser-Sherrill et al., High Ener. Dens. Phys. 9, 2013). These situations can arise in ICF capsules, as shock waves traverse capsule defects and initiate mix between shell and fuel materials.

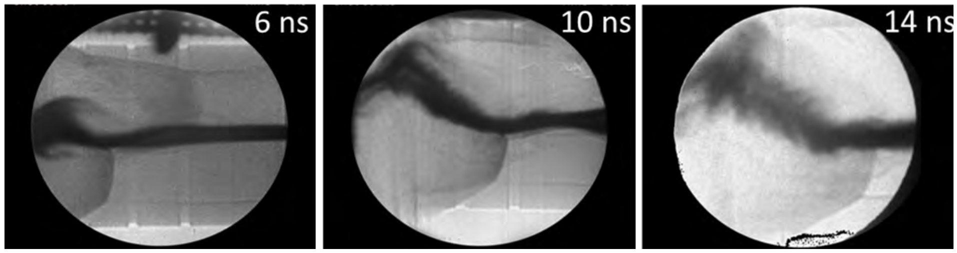


Figure 1. In the shear experiment, radiography captures the developing turbulent mix layer edge-on, with the Be tube visible at top and bottom, and the black representing the Al plate separating two hemi-cylinders with two different densities of foam. In the first frame, at 6 ns, the shock has impacted from the left, and can be seen moving at different velocities in the upper and lower halves of the cylinder due to the different foam densities. The shear feature at left still maintains its structure. In the second frame, at 10 ns, the shock has already passed through the upper half cylinder, but is still visible in the lower half. At this time the shear feature is getting more diffuse and is beginning to become turbulent. By the last frame, at 14 ns, the feature has achieved fully developed turbulent mixing.

Our reshock experiment studied the Richtmyer-Meshkov-driven process of shocking and reshocking mix layers. The first laser-driven shock impacted a plastic ablator on one end of a millimeter-scale Be tube filled with low-density foam, and drove a shock through a thin aluminum (Al) tracer disk. The Al mix layer was then reshocked by a laser-drive from the opposite end of the tube, and experienced a compression due to the counter-propagating shock, after which the layer continued to grow. Radiographic data provided a measure of the mix width across the Al layer, and the results were compared to the widths extracted from simulated radiographs.

The shear experiment investigated shear-driven growth of a mix layer. In this experiment, a Be tube was filled with half-cylinders of low-density and high-density foam. The two regions were separated by a thin Al plate. A single laser-driven shock from one side of the tube initiated hydrodynamic motion and produced a shear layer, which developed temporally and became more turbulent. The area of the shear feature was extracted as a function of time from both the radiographic data and the simulated radiographs. The figure demonstrates the progression of the turbulent shear layer over a period of 8 nanoseconds.

The reshock and shear experiments have proven to be extremely useful in mix model validation efforts. Together, these experiments are answering some of the questions about physical mixing processes as they occur in ICF implosions.

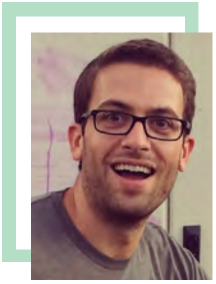
I now work in a division responsible for nuclear weapons physics and stockpile stewardship. Over the past four years, I have worked closely with code developers, in conjunction with Verification & Validation and NNSA Science Campaign efforts, to develop new capabilities in modeling primaries. I am now the Primary Verification & Validation Project Leader for the Advanced Simulation and Computing Program.

L. Charlie Jarrott (ljarrott@ucsd.edu)

Degree in Progress: PhD, Engineering Physics, University of California, San Diego
Academic Advisor: Dr. Farhat Beg

SSAA Program:
2011 to Present

Research Topic:
Fast electron transport and spatial energy deposition in fast ignition plasmas



What are your research responsibilities?

I designed a working platform for characterizing the spatial energy deposition of fast electrons in fast ignition plasmas. I analyzed the spatial and spectral diagnostic data, looking at copper (Cu) K-shell radiation produced from MeV electrons transporting through a Cu-doped fast ignition assembled fuel. Finally, I modeled the fast electron spatial energy deposition using a hybrid-particle-in-cell transport code to better understand the experimental results.

How have you benefited from the NLUF program?

I am very grateful for the opportunities that the NLUF program has provided me. The collaborations that I have developed while visiting facilities and conferences have proved to be invaluable in my research progress. In addition, the high exposure of my research at conferences has given me a great chance at securing work after my PhD. And, the friendships that I have developed within the program have made my time in graduate school one of the best experiences of my life.

The Stewardship Science Academic Programs (SSAP) give students an opportunity to not only be successful within their research, but also afterwards. It is all too easy for students to slip through the cracks and be forgotten en route to their degree. Within SSAP, students and their research are always the focal point where they can demonstrate their competence and prove themselves to the scientific community. The SSAP is also fun! While working in the NLUF Program, I have traveled around the world performing cutting edge research at amazing facilities with amazing scientists.

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

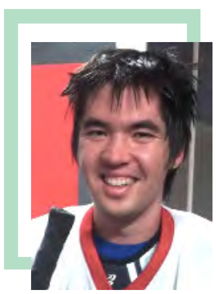
Absolutely. When faced with the option of a low exposure, under-funded field of research versus the exact opposite, the choice was quite simple. As an undergraduate, I first learned about the inertial confinement fusion concept listening to a seminar from a scientist at Lawrence Livermore National Laboratory. From that point on, I focused my graduate school search on universities that were heavily involved in laser-driven fusion research.

Jonathan Peebles (jpeebles@ucsd.edu)

Degree in Progress: PhD, Engineering Sciences, University of California, San Diego
Academic Advisor: Dr. Farhat Beg

SSAA Program:
2012 to Present

Research Topic:
Laser-plasma interaction and subsequent electron generation and transport



What are your research responsibilities?

My responsibilities include planning, carrying out and analyzing data from laser plasma interaction experiments on high intensity laser systems. Specifically, I'm looking into the impact that laser pre-pulse has on generating high energy electrons. In addition, I help implement and analyze data from bremsstrahlung spectrometers, a versatile diagnostic fielded on several different types of experiments, including positron production, x-ray backlighting, and shock ignition.

How have you benefitted from the NLUF Program?

The NLUF Program has opened opportunities for me to participate directly in experiments on the OMEGA EP laser at the University of Rochester, one of the premier high intensity laser facilities in the United States. These experiments have not only provided excellent data, but have also informed me on how to carry out future experiments on other laser facilities. In addition, the NLUF Program generated many new avenues of collaboration for me with researchers and students from General Atomics, Lawrence Livermore National Laboratory (LLNL), the University of Rochester, and the University of Michigan, which has allowed me to branch outside of my thesis topic to participate in more fields of research. Furthermore, events such as the SSAP Symposium and OMEGA Laser Facility Users Group annual meeting have provided me a venue to meet researchers in similar fields to my own, enabling further cooperation for future experiments.

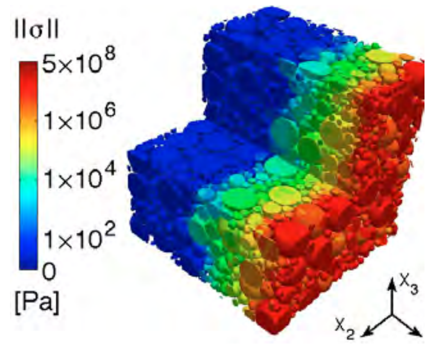
What do you want students considering the NLUF Program to know?

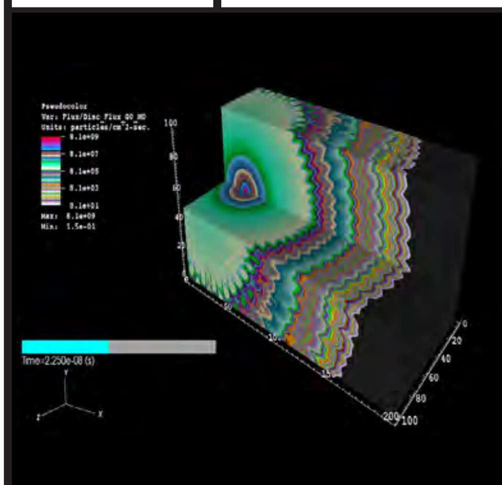
The most important thing that I've learned from the NLUF Program is how incredibly interconnected various research groups are, even if they are researching very different topics. The NLUF Program gives a great opportunity to make initial connections with other researchers and students forming the basis of long-term collaborations. While it's easy as a student to concentrate on your thesis and field of work, it's extremely valuable to have the broad base of knowledge and experience gained by making these connections.

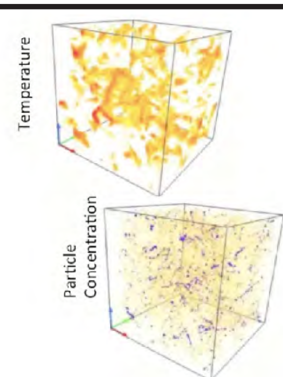
Have you spent time at one of the national laboratories?

I've spent almost half a year at LLNL, both as a summer intern and participant on several experiments at the Jupiter Laser Facility (JLF). The benefits gained from understanding and working in the national laboratory environment cannot be understated, and the JLF is an excellent place to gain hands-on knowledge of nearly every aspect of performing experiments at a laser facility. I also recently lead an experiment on the laser at JLF which produced data that will go directly towards my thesis.

Predictive Science Academic Alliance Program II







Predictive Simulations of Particle-Laden Turbulence in a Radiation Environment

Stanford University

PI: Gianluca Iaccarino, jops@stanford.edu; Co-PI: Ali Mani (alimani@stanford.edu)

In 2013, the National Nuclear Security Administration (NNSA) selected Stanford University as one of the new centers of excellence in predictive science. Stanford was named as one of three Multidisciplinary Simulation Centers, under NNSA's Predictive Science Academic Alliance Program II (PSAAP II).

The project, "Predictive Simulations of Particle-Laden Turbulence in a Radiation Environment," focuses on the effect of radiation on particle motion in a turbulent airflow. This is a poorly understood physical process that can open new opportunities for efficiency gains in solar thermal receivers with applications in energy conversion and chemical splitting in hydrogen production plants. The objective in such systems is to achieve high temperatures with minimal losses to the environment. Conventional solar-receivers collect focused sunlight primarily via a solid surface, which then conductively heats a target fluid (see Figure 1). One main drawback is that achieving high mean temperature in the fluid requires local heating of the solid surface to even higher temperatures, which can result in significant radiation losses.

Particle-based receivers remedy this issue by allowing more uniform and volumetric absorption of radiation by the working fluid. Given most fluids are transparent to radiation, absorbing particles are needed to intercept high-energy solar rays and allow local transfer to the fluid mixture. However, the three-way coupled physics of particle transport, fluid dynamics, and radiation presents extraordinary challenges. For example, fluid motion in such systems naturally involves turbulence, and while turbulence helps global mixing of mass and heat, it induces preferential concentration of particles: local turbulent vortices can centrifuge out particles to zones of local shear, and lead to heating non-uniformities and reduction of the overall efficiency. Additionally, temperature inhomogeneity leads to local fluid expansion altering the turbulence structures. Insights into design and optimization of such systems require careful investigations of the physical

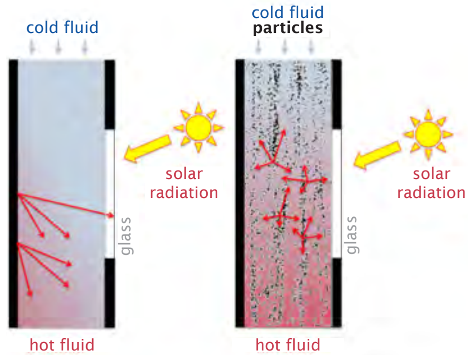


Figure 1. Heating of a mixture via a conventional receiver (left) and a particle-based receiver (right).

interactions between particle, radiation transport, and fluid turbulence.

The Stanford PSAAP II Center is carrying out simulations at an unprecedented level of fidelity by accessing the largest supercomputers in the United States. A snapshot of one of the Center's high-resolution simulation is reported in Figure 2. The red spots in the temperature map represent local high-temperature air plumes generated by high radiation absorption, while the blue spots in the particle concentration plot show instantaneous preferential accumulation of solid particles driven by air turbulence. Such calculations will help develop and ultimately demonstrate predictive science on next-generation exascale systems—computers that can perform a trillion floating-point operations per second—expected to become available in 2020. The current trend in supercomputer systems is to increase the number of computing cores and, as a consequence, this leads to massive data movement across extensive networks. Moreover, diverse and specialized computing units (CPUs, GPUs, and other accelerators) and multiple memory banks with different performance will coexist creating a truly complex hardware and network system. Achieving high performance requires new programming models that enable computational scientists to develop algorithms and software tools without intimate knowledge of the underlying architecture details. A key feature of the Center is the strong partnership between computational and computer scientists. Domain Specific Languages such as

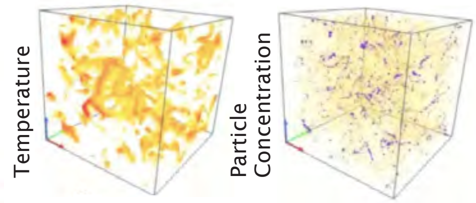


Figure 2. Instantaneous snapshot from direct numerical simulation of radiation-induced turbulence in a particle-laden fluid.

Stanford's developed Liszt are the key ingredient to enable computer programs to identify and recover from faults while providing flexibility in data management and efficiency in mapping simulation algorithms on the most appropriate computing units.

The project will also concentrate on uncertainty analysis, allowing researchers to quantify errors and uncertainties in the simulations and, therefore, to determine how much confidence can be placed in the results. A dedicated experimental campaign will be undertaken alongside the computational work to help understand and identify these uncertainties and to provide overall validation data to assess the predictive ability of the physical models and soft-ware tools developed within the project.

Broad interdisciplinary knowledge spanning energy systems, fluid dynamics, radiation physics, and multiphase flow systems is required to tackle Stanford's PSAAP problem. The project provides opportunities for collaborations with the NNSA national laboratories and, in addition, the research activities also impact the graduate curriculum at Stanford with the introduction of new courses on multiphase flow and radiation modeling. Further impact on the simulation technology across computer science, numerical analysis, and statistical sciences is also anticipated.

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

Center for Exascale Radiation Transport

Texas A&M University

PI: Jim Morel (morel@tamu.edu)

The Center for Exascale Radiation Transport (CERT) is led by Texas A&M University with the University of Colorado and Simon Fraser University as partners. CERT research includes development of exascale algorithms for thermal radiation propagation in the high energy density physics (HEDP) regime, general purpose exascale computer-science algorithms, numerical methods and subgrid models for radiation propagation, and experiments that test computational predictions and associated uncertainty quantification. The CERT project has been funded since March 2014, but five faculty members on their team have worked on either one or both of the PSAAP projects associated with the PECOS Center at the University of Texas and the CRASH Center at the University of Michigan. Furthermore, seven faculty members on the CERT team have a decades-long history of collaborations with NNSA laboratories. They have collectively sent many graduates to NNSA laboratories as postdoctoral fellows or staff members. Last year, CERT faculty had three PhD graduates hired at NNSA national laboratories as either postdoctoral fellows or staff members.

Professor Jim Morel, Director of CERT and Project Principal Investigator, states, “The SSAP funding for CERT has enabled our faculty and students to engage in an integrated research program with resources sufficient to vastly improve the predictive capability of thermal radiation propagation calculations for NNSA applications, and to broaden our existing collaborations with NNSA laboratory staff.”

Currently, exascale computers are being developed to perform 10^{18} (one quintillion) operations per second. These computers have the potential to be nearly 50 times faster than the fastest currently existing computers. However, computing on exascale machines will present new challenges relative to current machines, due to the need to drastically reduce both energy consumption per processor and RAM per processor. Another challenge is that computational errors may routinely occur during calculations with far greater frequency than they currently occur. In addition, the cost of moving data relative to the cost of computing with data will dramatically increase.

Thermal radiation propagation is of primary importance to a variety of NNSA programs including those associated with the National Ignition Facility at Lawrence Livermore National Laboratory, the Z Machine at Sandia National Laboratories, and many aspects of stockpile stewardship. Simulations of HEDP experiments involve many types of physics. Thermal radiation propagation calculations are a primary component of such simulations and generally consume far more computational resources than any other type of physics calculations. Thus, efficient HEDP simulations demand efficient radiation propagation calculations. CERT researchers recently developed a new model of parallel performance for radiation propagation algorithms that is enabling them to pinpoint and eliminate bottlenecks in their algorithms. Radiation propagation calculations using approximately 500,000 processors with a speedup of roughly 300,000 relative to computing on a single processor have been performed recently. A unique aspect of the CERT project is the use of neutron experiments as a surrogate for thermal radiation experiments in the HEDP regime. This approach will enable CERT researchers to experimentally determine both the errors in the numerical simulations of experiments and the sources of those numerical errors via hierarchical Uncertainty Quantification methods. The information obtained from the neutron experiments will be equally relevant to both neutron propagation calculations and thermal radiation propagation calculations. This type of information could not be obtained from radiation experiments in the HEDP regime because many types of physics would be required to model the experiments, but only propagation physics is needed to model the neutron experiments.

Figure 1 shows predicted solutions for one of the simpler CERT propagation problems.

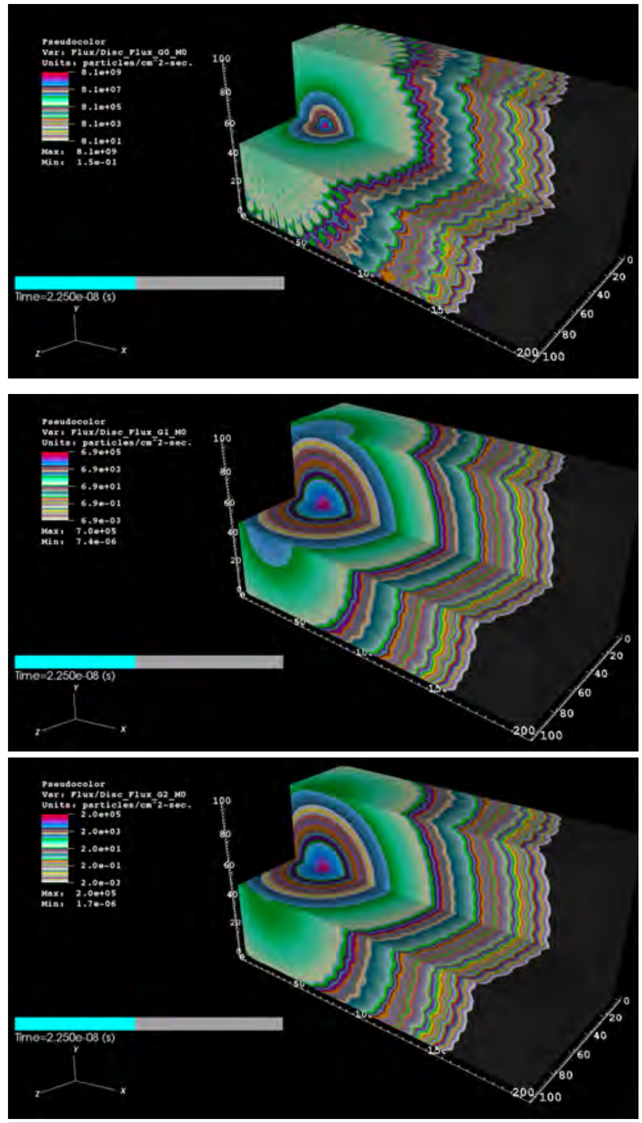


Figure 1. Predicted radiation intensity contours in a typical CERT problem. Top, center, and bottom are high-energy, medium-energy, and low-energy radiation, respectively.

Center for Compressible Multiphase Turbulence

University of Florida, Gainesville

PI: S. Balachandar (bala1s@ufl.edu); Technical Manager: T.L. Jackson (tlj@ufl.edu)

The overarching goals of the Center for Compressible Multiphase Turbulence (CCMT) are threefold:

- to radically advance the field of compressible multiphase turbulence (CMT) through rigorous first-principle multiscale modeling;
- to advance very large-scale predictive simulation science on present and near-future platforms;
- and to advance a co-design strategy that combines exascale emulation with a novel energy-constrained numerical approach.

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

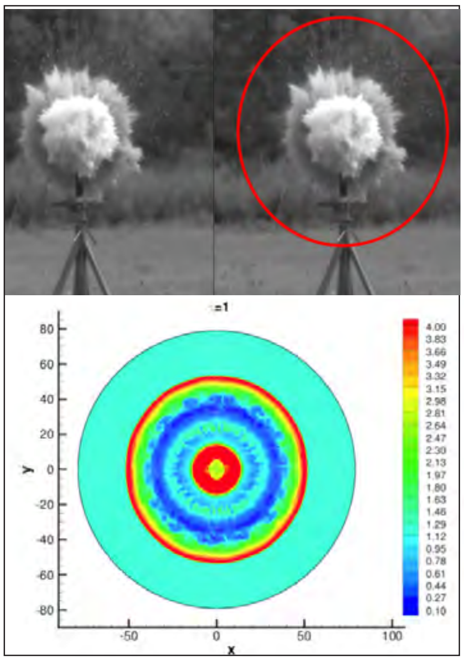


Figure 1. Experiment (top) and simulation (bottom) at early times of a cylindrical charge with inert particles.

Professor S. Balachandar notes that the Stewardship Science Academic Programs has brought international attention to the University of Florida, recognizes their commitment to high-speed computing on current and near-future platforms, and engages students from a wide spectrum of research interests to work together in tackling some of the world's most difficult problems. Most noteworthy, new classes and course materials are being developed in response to the program.

The chosen CMT demonstration problem for the initial phase of the research activities is an explosive dispersal of solid particles that consists of a detonator connected to a charge, which runs across the length of a cylinder filled with iron powder. The mid-section of the cylinder is occupied by a matrix enclosing a cloud of inert spherical glass particles. The computations aim at simulating the evolution of the mid-section of the cylinder. See Figure 1 for preliminary simulations. The state-of-the-art simulations of this problem at the micro-, meso-, and macroscales, along with companion validation-quality experiments will allow us to better understand the fundamental physics of compressible multiphase turbulence and translate this understanding to a rigorous multiscale modeling and simulation approach that can impact a wide variety of problems of national and societal importance. Uncertainty reduction is a key goal of the Center and it will drive micro- and mesoscale-informed model development, apart from error reduction in both experimental and numerical approaches. The uncertainty budget will drive the overall development of models, software, simulation, and calibration/validation experiments.

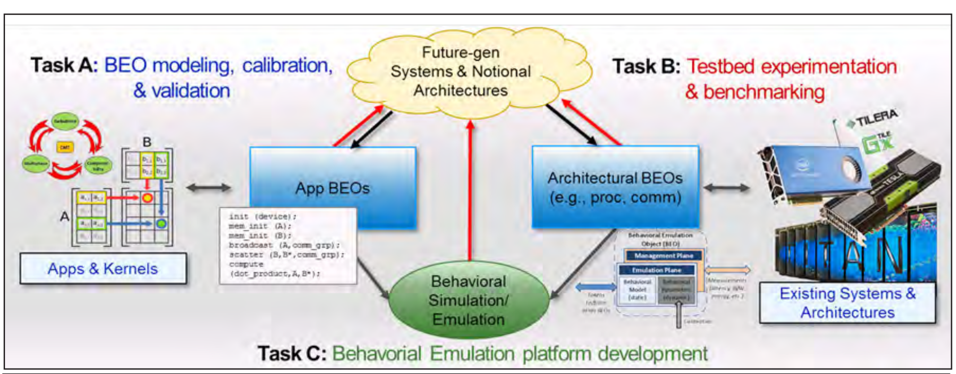


Figure 2. Concept diagram for Exascale emulation for future-generation systems. Task A is behavioral.

Shown in Figure 2 is a concept diagram of the exascale emulation project within CCMT. It is based on a coarse-grained simulation approach that is analogous to rapid virtual prototyping. Exascale emulation will provide an accurate first-order approximation for performing design-space exploration on extreme-scale, future-generation systems before (and complemented by) time-consuming detailed simulation/emulation. As shown in the figure, the project is divided into three major tasks. Task A is Behavioral Emulation Object (BEO) modeling, calibration, and validation of application kernels (App BEOs) and systems (architectural BEOs). A BEO is a model that is used as a surrogate of the real (existing) or notional (future) application or architecture. Task B is testbed experimentation and benchmarking used to calibrate and validate the developed models (BEOs). Task C is development of the behavioral emulation platforms. Currently, the exascale group is exploring the use and development of three platform types: discrete-event simulator, a symmetric multiprocessing simulator on many-core computer, and hardware emulator on a reconfigurable computer.

Faculty

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

University Partners

R. Adrian (Arizona State University), J. Zhang (Florida Institute of Technology), P. Fischer (University of Illinois at Urbana-Champaign)

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

University of Illinois at Urbana-Champaign

PI: William Gropp (wgropp@illinois.edu); Co-Author: Jonathan Freund (jbfreund@illinois.edu)

The Center for Exascale Simulation of Plasma-Coupled Combustion (XPACC) is a new Predictive Science Academic Alliance Program (PSAAP II) Multidisciplinary Simulation Center at the University of Illinois in its first six months of operation. The Center uses large-scale computing to enable predictive simulation that advances the science and technology of plasmas to initiate and control turbulent combustion. The target application is a gas-phase fuel jet, which requires novel computational approaches that utilize extreme-scale computing. The Center funds 20 PhD-level student projects, most of whom will spend a 10-week internship at an NNSA national laboratory.

“At Illinois, PSAAP II has created a core of activity in computational predictive science, where faculty and students from diverse disciplines pursue joint scientific goals and develop new capabilities in extreme-scale computing,” said William Gropp.

Plasmas offer a unique and untapped means of affecting combustion to boost performance and efficiency. Chemistry produced in plasmas can short-circuit the standard reactions; electric fields in the charged gas can undermine the flame stability; and the heating due to resistance of the plasma can impact both the flow and the chemistry. Predictions that include Bayesian-based analysis of the uncertainty in the calculation will maximize the utility of the simulations; low-dimensional, physics-targeted experiments will be used to identify physics and calibrate models for the principal Quantity of Interest: the sustained ignition threshold.

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

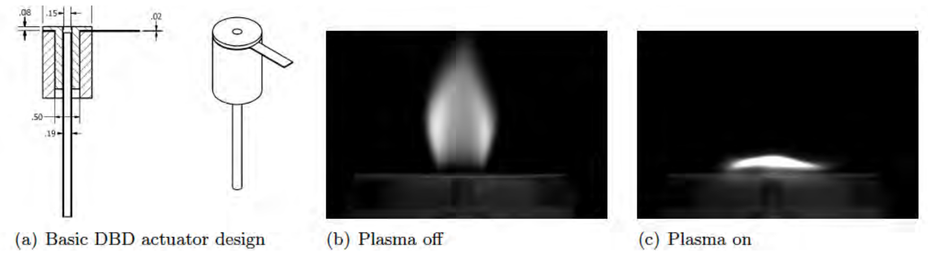


Figure 1. The DBD plasma showing an order-one effect on an H_2 flame in a model, physics-targeted configuration.

The Center builds upon an existing petascale code, PlasComCM, and pursues new programming approaches that provide portable access to better performance and scalability through data structure and code optimizations for memory efficiency, exploitation of high-throughput computing elements, and automatic load balancing. Along with other tools and techniques, these will be designed to work on applications with similar needs, and the Center will actively engage the community to ensure their broad utility.

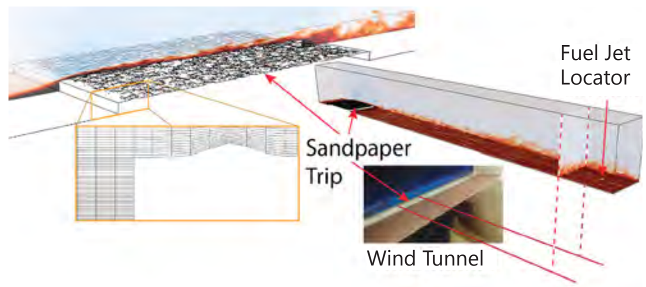


Figure 2. 3D inert turbulence resolved simulation of the wind tunnel, including a geometric realistic representation of the sandpaper turbulence trip. Upper left: cross-section near the inlet that shows the flow crossing over a piece of #40 sandpaper, which is used to initiate turbulence. Image just below: the computational mesh at the beginning of the sandpaper. To the right: a wind tunnel section, starting at the inlet before the sandpaper and ending a little after the location of the fuel jet (which is not used in this simulation). Below that (lower right): photo showing where this cross section sits in the wind tunnel—this shows that the computation (upper right) is for the center of the flow, well away from the sides of the wind tunnel.

A co-designed experiment-simulation plan is a key part of the principal predictive science goal. An annular dielectric barrier discharge (DBD) plasma actuator has been demonstrated to directly influence a hydrogen jet flame in a reduced model configuration (see Figure 1). When placed in a turbulent cross flow, the role of this actuator is to sustain ignition. Similar reduced, physics-targeted configurations have been developed to enable advanced bench-top diagnostics to identify mechanisms and calibrate models. The full system will couple the actuator, a spark ignition system, and the fuel jet into a turbulent boundary layer (see Figure 2).

Simulations are progressing along two paths. A two-dimensional (2D) model has been developed to integrate first-generation models for the plasma, chemical kinetics, and flow. At the same time, a large turbulent 3D boundary layer simulation will match the upstream measurements from the Illinois wind tunnel. Inflow conditions are anticipated to be particularly important, so a realistic sandpaper trip is explicitly represented as shown in Figure 2.

PlasComCM has been subjected to detailed analysis in preparation for the transforms that will enable it to achieve high sustained performance on emerging machines. In addition to an optimization that doubled its performance and improved memory management, it has been analyzed with the Illinois tools VectorSeeker, AMPI (via ROSE), and Triolet. To facilitate analysis and subsequent transforms, representative pieces of the code termed codelets have been developed to highlight key features of the full application—a similar approach to development has been successful at NNSA national laboratories.

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

University of Notre Dame

PI, Director: Samuel Paolucci (paolucci@nd.edu); Co-Director: Karel Matouš (kmatous@nd.edu)

The goal of the C-SWARM Single-Discipline Center is to predict the behavior of heterogeneous materials, specifically the dynamics of their shock induced chemo-thermo-mechanical transformations and resulting material properties. The C-SWARM research is devoted to the development of a parallel multiscale and multiphysics computational framework for predictive science using models that are verified and validated (V&V) with uncertainty quantification (UQ). Such research resonates well with the mission of the NNSA national laboratories. Through adaptive exascale simulations, C-SWARM's goals are to predict conditions for the synthesis of novel materials and provide prognoses of non-equilibrium structures that will form under shock wave processing. In particular, researchers at C-SWARM plan to identify conditions under which they can synthesize cubic boron nitride (c-BN). c-BN is not found in nature and therefore can only be produced synthetically. The hardness of c-BN is inferior only to diamond, but its thermal and chemical stability are superior. Because of these properties, c-BN surpasses diamond in high temperature mechanical applications. Shock synthesis of c-BN enabled by exascale predictive computations with V&V/UQ would be a significant scientific achievement. During the first seven months of work, the C-SWARM is supporting seven U.S. graduate PhD students.

"Working on such a complex multidisciplinary problem would not have happened without the sustained support from NNSA," said Samuel Paolucci, Professor of Aerospace and Mechanical Engineering and the project's director. "Our students and research staff benefit greatly from working on a difficult problem that requires an interdisciplinary approach in conjunction with high-performance computing," he added.

To model such materials, C-SWARM employs an adaptive multiscale and multi-time strategy that solves in adaptive fashion macro-continuum equations using an Eulerian algorithm with constitutive equations locally provided by well-resolved micro-

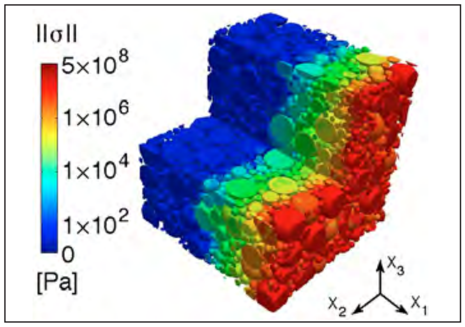


Figure 1. Shock propagation in the heterogeneous hyper-elastic material. Effective stress field after t = 1.1 nanoseconds in a material sample of aluminum (Al) and nickel (Ni) particles with diameters of 100 microns (Ni), 50 and 25 microns (Al). A material sample of 1 mm x 1 mm x 1 mm is impacted by strike velocity of 100 m/s in the negative x1 direction. Number of computational cells is ~18 million and simulation was performed on 1,024 computing cores at C-SWARM using the micro-continuum solver, PGFem3D. The cut portion of the cube is removed to see inside. The Ni particles are spheres of 100 microns in diameter. Disks (two-dimesional (2D) objects) are created once the spherical particles (3D objects) are cut.

continuum simulations using a Lagrangian algorithm (see Figure 1). C-SWARM takes advantage of the instantaneous localization knowledge of those regions where detailed simulations are necessary. In the last calendar year, researchers of the Computational Physics team have focused on establishing data-driven material modeling concepts, enhancing micro- and macro-continuum solvers, and developing enabling software technologies.

The macro- and micro-continuum codes will utilize an advanced execution model, ParalleX, and its execution runtime system HPX. ParalleX/HPX enables data mining of runtime information to dynamically adapt the codes' demands to resource availability. Furthermore, Active System Libraries (ASLib) will be developed to ensure that the macro- and micro-continuum algorithms can be represented in an effective and hardware-independent fashion (see Figure 2). In the last calendar year, researchers of the Computer Science team have focused on the analysis of existing MPI-based codes, advancing the development of HPX, delineation of the software stack,

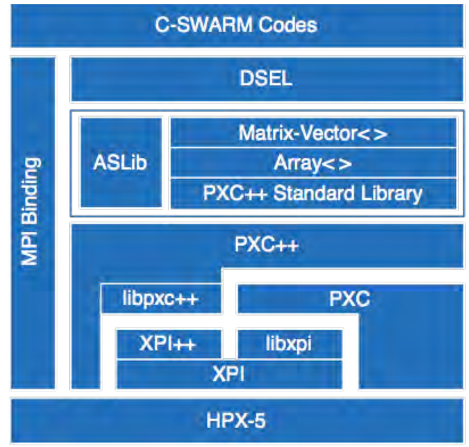


Figure 2. C-SWARM software stack showing different layers of software being develop as part of the C-SWARM project. The top layer are C-SWARM scientific codes. Under the C-SWARM scientific codes is a layer of advanced software libraries and programing languages. Under this layers is a layer of libraries related to runtime system (HPX). The last layer is the runtime system HPX-5 that is being developed and used to run the parallel exascale applications.

and formulating a Domain-specific embedded language (DSeL).

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. The key component is a series of carefully co-designed experiments and data-driven simulations (with quantified uncertainties) to enable meaningful and rigorous comparisons of simulation predictions with experimental results. In the last calendar year, researchers of the Experimental Physics team have focused on code verification, materials characterization and calibration of material data, as well as on validation experiments, and micro-, micro- to macro-, and macroscale tests.

On the educational side, research performed in C-SWARM provides a unique setting for the multidisciplinary education of students, postdoctoral scholars, and research staff to join the workforce in critically important areas of national importance.

The Uncertainty Quantification-Predictive Multidisciplinary Simulation Center (CCMSC) for High Efficiency Electric Power Generation with Carbon Capture

The University of Utah

PI: Professor Philip J. Smith (philip.smith@utah.edu)

In February 2014, DOE/National Nuclear Security Administration funded the creation of the Carbon-Capture Multidisciplinary Simulation Center (CCMSC). The goal of the center is to use exascale simulation, validation and uncertainty quantification (V/UQ) tools for design, risk assessment, and deployment of a new low-cost, electric power energy technology with carbon capture: namely, a high efficiency advanced ultra-supercritical 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. Since its inception, the Center has provided financial support, research, and educational opportunities to eighteen graduate students and one undergraduate student. Over this past summer two of these supported students participated in internships at Los Alamos National Laboratory and Sandia National Laboratories.

Professor Philip Smith, the CCMSC Principal Investigator said, "The significant financial commitment of DOE and the three universities of this multidisciplinary center demonstrates a deep commitment to the development of new energy solutions, the predictive science field, and the simulation science based workforce of the future."

The CCMSC is organized into three teams: the Exascale Team, the Predictive Science/Physics Team, and the V/UQ Team. The center is building on an existing proven computational platform (UintahX) developed under previous DOE/NNSA funding and sequentially moving to multipetaflop and eventually exascale computing. CCMSC uses extreme computing and 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. The V/UQ from the subscale, subphysics analysis is used to bridge the four levels or scales to a final prediction of a full-scale utility power boiler. This validation and prediction process is constrained so that the final prediction is consistent with all of the experiments and with all of the validation metrics of the validation hierarchy simultaneously.

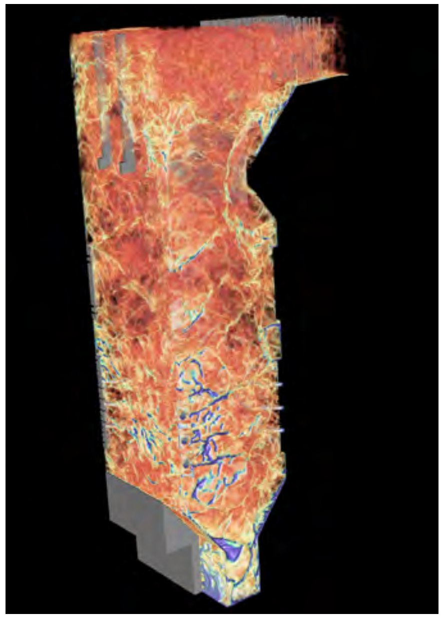


Figure 1. Volume rendered image of the concentration of the larger (80 micron) particles in the Alstom 50 MW pilot scale oxy-coal boiler. The simulation was performed using CCMSC tools running on Titan from Oak Ridge National Laboratory. The visualization was performed using volume rendering tools developed by the CCMSC visualization team and running in VisIt from Lawrence Livermore National Laboratory.

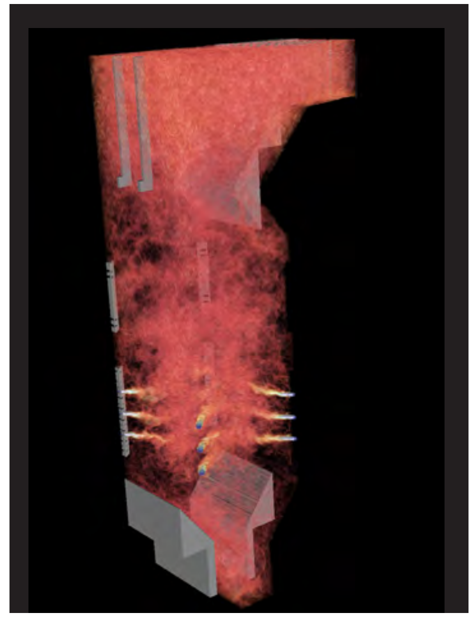


Figure 2. Volume rendered image of the concentration of the smaller (20 micron) particles in the Alstom 50 MW pilot scale oxy-coal boiler. The simulation and visualization details are the same as those specified in the Figure 1 caption.

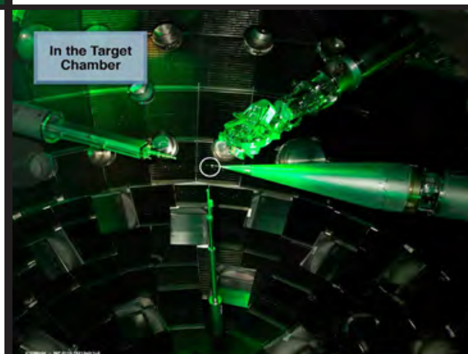
The expected impact is a demonstration of V/UQ predictive exascale computing to more rapidly deploy low-cost, low-emission electric power generation to meet the growing energy needs of the United States. and the world. To this end, the CCMSC has established a collaborative agreement with Alstom Power to jointly use this technology to help design a new 350 MWe oxy-coal boiler. Alstom has contributed experimental data for validation. These data were taken from Alstom's 50 MW pilot-scale facility. Figure 1 shows a volume rendered image of the concentration of the largest particles (~80 microns in diameter) from a simulation of this pilot-scale boiler.

For comparison, Figure 2 shows the concentration of some of the smaller particles (~20 microns in diameter) from the same simulation. This computation was performed with the center simulation tools being run on Titan, the Oak Ridge National Laboratory computing facility. The image was produced using volume rendering tools developed by the Center and integrated into VisIt (LLNL visualization software). The faculty, staff, and students working on this project are delivering: 1) exascale computing software that is regularly released through open-source licensing, 2) tools for V/UQ for use with other large applications with expensive function evaluations and sparse/expensive experimental data, and 3) new advances in computer science, software engineering, computational fluid dynamics, multiphase reacting flow and radiative heat transfer. The students participating in this program represent a new generation of professionals educated and experienced in exascale predictive science applied to multiscale, multiphysics, multidisciplinary energy problems.

Alumnus & Students
Stewardship Science Graduate Fellowship

JUAN MANFREDI

MAREENA ROBINSON

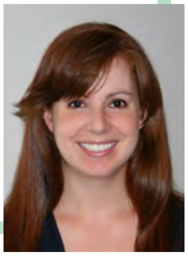


SAMANTHA LAWRENCE

BENJAMIN GALLOWAY

LAURA BERZAK HOPKINS

Laura Berzak Hopkins, Lawrence Livermore National Laboratory (LLNL), hopkins31@llnl.gov
Years at LLNL: June 2012 to Present • Degree: PhD, Plasma Physics, 2010
Years in SSAA Program: 2006-2010, Princeton University



As a design physicist at Lawrence Livermore National Laboratory (LLNL), my work focuses on laser and target design for indirect-drive inertial confinement fusion (ICF) experiments on the National Ignition Facility (NIF). The NIF is an incredibly unique facility, the world's largest and most energetic laser, spanning a broad mission space from national security to fundamental science to energy security research.

For me, the SSGF was a critical opportunity to expand my scientific knowledge, experience, and contacts. As a graduate student, it can be difficult to see potential career paths outside of your direct line of research; the SSGF opens eyes and opens doors to the ongoing research and dedicated scientists at the NNSA national laboratories.

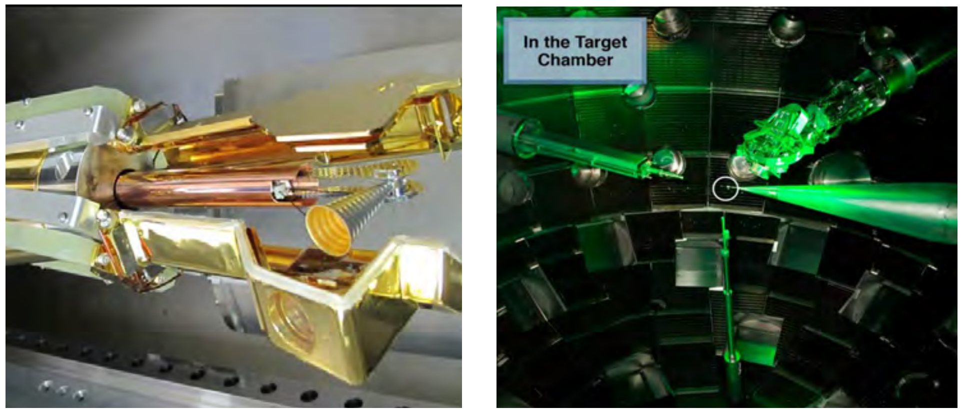


Figure 1. Target assembly for a shock-timing target held in place by the cryogenic cooling target positioner system (left image). View inside the NIF chamber of a target inserted on the positioner system as well as several diagnostic arms (right image).

In ICF research, millimeter-scale capsules are imploded in nanosecond timescales, bringing the contents of the capsule to high density, temperature, and pressure. Often, the contents of the capsule are deuterium and tritium, which fuse and release helium as well as large amounts of energy. Understanding and efficiently controlling this process is the ultimate goal of fusion research. With indirect-drive ICF, the fuel-filled capsules are placed at the center of a high-Z, cylindrical radiation enclosure ('hohlraum'); NIF's 192 laser beams are fired into each end of the hohlraum forming an x-ray radiation bath which implodes the capsule, producing fusion reactions.

The position of design physicist (or 'designer') at NIF occupies a unique niche in research space—connecting computational scientists, experimentalists, and theorists. Design work requires utilizing massively parallel radiation hydrodynamics simulations to explore high energy density physics theory and questions. With these questions in mind, a designer decides upon capsule and hohlraum materials and dimensions, as well as the laser power and energy to be fired. Based on designers' preshot simulations, experimentalists appropriately filter and time the necessary diagnostics, and after an experiment is fielded, data is collected, analyzed, and interpreted by the team. The complexity and scale of the system can be seen in Figure 1. Then, the process begins again, building upon the new understanding that was developed through the most recent experiment. Being a designer on NIF is electrifying work, work that could only occur at the scale of a national laboratory and that always presents new challenges—computational, experimental, and theoretical. Because of this, I have found that my research provides an unparalleled opportunity to develop a broad range of knowledge across many fields of physics. This is only made possible through being part of such a large and integrated facility and interacting with the scientific experts at LLNL on topics from laser optics damage to radiochemistry to shock physics.

My work as a graduate student, and Stewardship Science Graduate Fellow (SSGF), was also in fusion research, but in magnetic fusion energy (MFE). My dissertation was experimentally focused and involved the design and development of an extensive set of magnetic diagnostics as well as a start-up technique for a medium-scale spherical tokamak with large internal, conducting shells. When I completed my PhD and before heading to LLNL, I stepped away from research for two years to serve as a scientific advisor in the U.S. Congress, through the American Physical Society Congressional Fellowship.

For me, the SSGF was a critical opportunity to expand my scientific knowledge, experience, and contacts. As a graduate student, it can be difficult to see potential career paths outside of your direct line of research; the SSGF opens eyes and opens doors to the ongoing research and dedicated scientists at the NNSA national laboratories. National laboratories, like LLNL, provide the opportunity to pursue 'big science' and 'science in service of the Nation'. I've found this combination to be a unique and inspiring fit to my background in plasma physics and MFE as well as my passion for connecting science, politics, and policy. The SSGF was an important contributor to finding this path, and I appreciate staying involved, now as an alumni, to share my excitement with the next generation of fellows.

Benjamin Galloway, benjamin.r.galloway@colorado.edu

Degree in Progress: PhD, Atomic, Molecular, and Optical Physics, University of Colorado
Academic Advisor: Dr. Margaret Murnane

SSGF Program:
2013 to Present

Research Topic:
Optimization of High Harmonic Generation Sources for Measurement of Warm Dense Plasmas

What are your research responsibilities?

At the University of Colorado (CU), I am a member of the Kapteyn-Murnane group, a team that is making huge progress in the field of high harmonic generation (HHG). Similar to synchrotrons or free electron lasers (FELs), HHG sources can produce pulsed, laser-like radiation in the extreme ultraviolet and soft x-ray regions of the light spectrum. Currently, synchrotrons and FELs can produce brighter and higher energy radiation, but tabletop HHG sources have the advantages of reduced size and cost. My research goals consist of investigating novel generation schemes to improve HHG flux and photon energy. These advances will help make HHG a more capable alternative to FELs and synchrotrons at a fraction of their costs. Additionally, I plan to use HHG to probe warm, dense plasma in an attempt to improve theories for this elusive state of matter. To achieve these goals, I perform various electrodynamic simulations modeling HHG, and I contribute to HHG experiments in the laboratory to characterize, improve, and utilize this cutting-edge light source.

How have you benefited from the SSGF Program?

Aside from the excellent financial benefits of the program, being a fellow has helped me connect with high-profile scientists around the world, and it has allowed me to contribute to groundbreaking research at Lawrence Livermore National Laboratory. The 12-week practicum at the national laboratory may be the best opportunity I have had to advance my career and develop working relationships with highly influential researchers. Such relationships are difficult to come by at this stage in my career, but the fellowship made the introductions for me and gave me a chance to demonstrate my aptitude to potential employers and collaborators.

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

When I applied for SSGF, I was already a member of my research group at CU, and I was initially uncertain that my research area really pertained to what NNSA was seeking. A little digging revealed to me several intriguing applications of HHG in high energy density physics. While applying, I found direction in which to take my research; a direction that I chose, not one that was forced on me.

Samantha Lawrence, lawren13@purdue.edu

Degree in Progress: PhD, Materials Science and Engineering, Purdue University
Academic Advisor: Dr. David Bahr

SSGF Program:
2012 to Present

Research Topic:
Assessing coupled mechanical behavior and environmental degradation at submicron scales

What are your research responsibilities?

My research addresses materials performance in extreme conditions. My research objectives include: quantifying relationships between structure and mechanical properties in sub-micron volumes of materials; determining changes in performance of engineering alloys when exposed to harsh processing or service conditions; and predicting and controlling the microstructural response of materials to perform reliably in harsh environments. My research will enhance the ability to manufacture components for service in high-performance, extreme environments. I combine multiple experimental techniques such as nanoindentation, high-resolution electron microscopy, and electron and x-ray diffraction to interrogate crystal orientation and interface effects on mechanical response of metal systems, fracture and corrosion resistance of nanosecond-pulsed laser-fabricated oxide markings on steel and titanium components, and hydrogen degradation of nickel alloys.

How have you benefitted from the SSGF Program?

The SSGF program has had a profound impact on my graduate career. The fellowship has obvious advantages, including tuition, fees, and a competitive stipend, but I have found other unique benefits throughout my fellowship experience. The annual research allowance provided me the means to travel internationally twice as a graduate student—to a conference and to conduct research—opportunities which may not have been possible otherwise. Also, the SSGF Annual Program Review provides an ideal forum for understanding my research in the broader context of stewardship science, which can encourage collaboration across disciplines.

Have you spent time in one of the NNSA national laboratories?

The SSGF research practicum provides an excellent opportunity for developing collaborations. I have participated in two practicums. At Sandia National Laboratories (SNL) in California, I studied hydrogen effects on materials using a high-pressure, high-temperature gas phase charging system unique to SNL CA. This experience ultimately led to collaboration with researchers at Aalto University in Finland, which I subsequently visited using my academic allowance. At SNL New Mexico, I engaged in novel laser-processing research to develop robust oxide coatings for tamper-evident markings on metal components. Through my practicum experiences at SNL and interactions with the SSGF community, I have refined my career goals and built a strong network of collaborators across multiple national laboratories and universities.

Juan Manfredi, manfredi@nscl.msu.edu

Degree in Progress: PhD, Nuclear Physics, Michigan State University
Academic Advisor: Dr. Betty Tsang

SSGF Program:
2013 to Present

Research Topic:
Exotic fission barriers

What are your research responsibilities?

I'm involved in all aspects of running rare isotope beam nuclear physics experiments at the National Superconducting Cyclotron Laboratory (NSCL), in particular using the High Resolution Array (HiRA). My responsibilities include detector maintenance, setup, and testing. I also work on data acquisition, data analysis, and vacuum systems. In my spare time, I give tours of the lab to visiting groups (e.g., high school students, professional organizations, student organizations, etc.) and I serve as the Graduate Recruitment Coordinator for both the NSCL and the Physics Department.

How have you benefited from the SSGF Program?

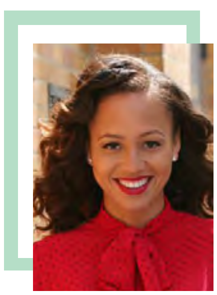
Aside from multiple years of funding, I've received three key benefits from the SSGF. First, I was offered a 12-week summer practicum at the DOE laboratory of my choice. I spent last summer working at Lawrence Livermore National Laboratory (LLNL) with Rob Hoffman and Peter Anninos on neutron star simulations. I used this opportunity to not only experience new physics, but also to experience the national laboratory working environment. The second benefit I've received through SSGF is the community of fellows. Finally, the fellowship has encouraged me to practice my communication skills. I've presented three posters in one year as a fellow and written an essay about my proposed thesis research that won the annual SSGF Essay Slam.

Have you spent time at one of the NNSA national laboratories?

I worked on neutron star calculations at LLNL last summer. I picked this project so that I could use my background in nuclear physics to learn about a new problem. Also, this was my first experience focusing full-time on theoretical calculations. But perhaps the most valuable takeaway from my summer at LLNL was the exposure to the scientific diversity of the national laboratory research environment. Graduate school requires intense focus on a single topic, and that can lead to narrow mindedness. Spending time at a laboratory that not only features a diversity of research but actively encourages interdisciplinary collaboration was invigorating.

Mareena Robinson Snowden, mrobin@mit.edu

Degree in Progress: PhD, Nuclear Science and Engineering, Massachusetts Institute of Technology
Academic Advisor: Dr. Richard Lanza



SSGF Program:
2012 to Present

Research Topic:
Development of radiation detection technology for verification in future warhead dismantlement treaties

What are your research responsibilities?

I am researching the possibility of using passive detection to verify the presence and type of treaty-limited warheads in future warhead dismantlement treaties between nuclear weapon states. Based on simplified, open source representations of nuclear warheads, my research activities include understanding the radiation emissions generated by interactions inside the various layers of the weapon, as well as developing approaches to best measure them. Through Monte-Carlo particle (MCNP) simulations I have identified signatures of the warhead, which I aim to passively detect and quantify using the intrinsic neutron and gamma emissions. Most recently, I have investigated the feasibility of using high-energy gammas produced by thermal neutron capture and inelastic scatter reactions to determine the amount of high explosives contained in a warhead. This mass, coupled with the amount of fissile material present, may be a used to determine the presence of a warhead, and more ambitiously to distinguish between possible types. In addition to simulations, I conduct experimental research using radiation detectors and mock warhead materials to infer the real-world obstacles to detecting and identifying treaty-limited weapons.

How have you benefitted from the SSGF Program?

The much-needed financial support the program provides allows me the freedom to explore ideas that I am passionate about. The blueprint of the program, complete with summer practicum experiences and annual conferences with senior researchers, has allowed me to seamlessly migrate from my very narrow dissertation research during the school year to a more broad discussion on the implications of our research. Although these discussions, which take place during the SSGF poster sessions or graduate fellow talks, allow me to continually add to my knowledge and make informed decisions about my next steps as a researcher. Although these experiences are not unique to SSGF, the program has afforded me easier access to these opportunities.

What do you want students considering the SSGF Program to know?

A successful application is as much about expressing your passion for the field and the skillset you have acquired through your past research experiences as it is about the caliber of your undergraduate and graduate grades. Graduate research is a unique academic experience where you have the privilege to 'think' for a living; however this privilege is not without much demand and obligation. Expressing an understanding of the potential impacts and implications of your research in your application is a valuable way to speak beyond the numbers. Take the time to understand who you are as a researcher and build this clarity throughout your time as an SSGF fellow.

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NNSA National Laboratories

Sandia National Laboratories

Lawrence Livermore National Laboratory

Los Alamos NATIONAL LABORATORY

A "NIFFTE" University-Lab Partnership

Lawrence Livermore National Laboratory (LLNL)

by Jennifer L. Klay (California Polytechnic State University)

The Neutron Induced Fission Fragment Tracking Experiment (NIFFTE) collaboration has been working diligently for the past six years to develop a novel device to measure cross-sections for neutron-induced nuclear fission of the major actinides to unprecedented precision. A joint venture between two NNSA-funded laboratory groups, i.e., Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL), and university partners, the collaboration is working on completing the measurement of ^{239}Pu/^{235}U and ^{238}U/^{235}U cross-section ratios with data collected at LANL's Los Alamos Neutron Science Center (LANSCE) Weapons Neutron Research 90-Left flight path.

Since the beginning of the project, collaboration between the laboratories and universities has been critical to the project's success. According to Mike Heffner, project leader at LLNL, the experiment would not be where it is today without the contributions of the university groups.

"For example, Oregon State University has provided all of our targets, including thin-backed segmented ^{239}Pu, ^{238}U, and ^{235}U targets that will allow us to make simultaneous measurements."

While the laboratories focused on the design and development of the hardware for the fission time projection chamber (fissionTPC), the software for both data acquisition and offline reconstruction and analysis were pioneered by collaborators and students at two undergraduate institutions: Abilene Christian University, led by Rusty Towell, and California Polytechnic State University, San Luis Obispo (Cal Poly), led by Jennifer Klay.

"This enabled us to acquire and analyze engineering data from spontaneous fission sources and in-beam prototyping early on to help clarify the technical challenges so we could revise the hardware design to meet them," said Heffner.

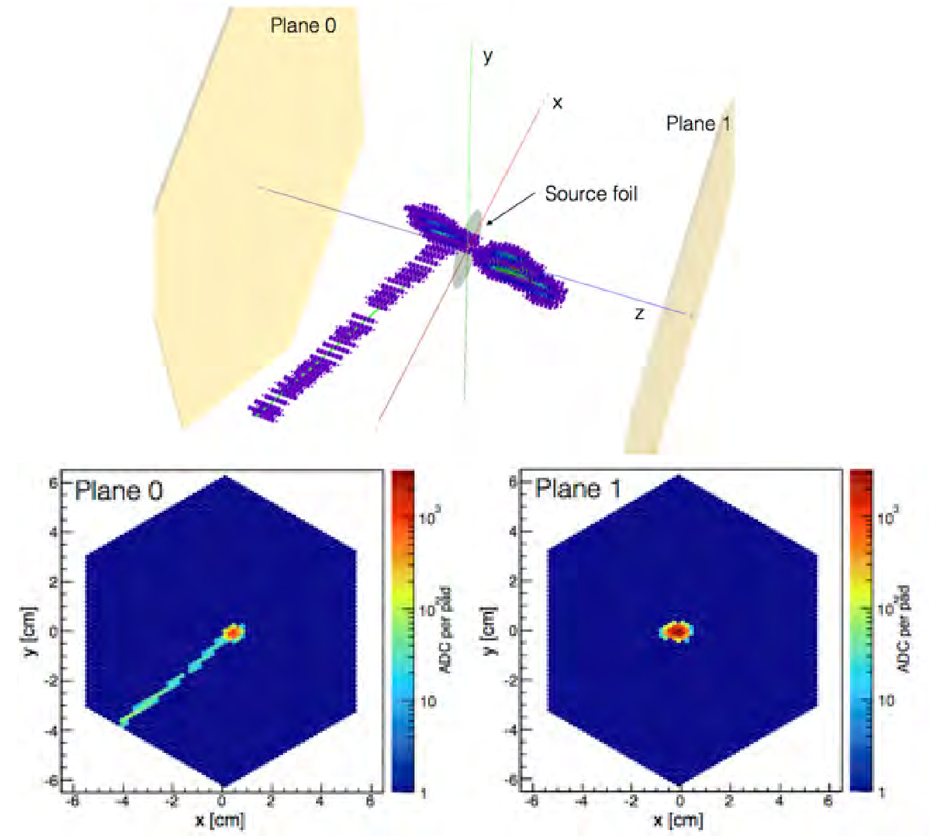

Figure 1. An example of the 3D reconstruction of an alpha-accompanied fission event in the dual volumes of the NIFFTE time projection chamber. The top image shows the fragments emitted from the source foil while the bottom panels display the 2D projected ionization on the readout planes.

The fissionTPC design is based on technology that has been in wide use in high energy particle physics for over 30 years, but which has only recently been adapted to low energy nuclear physics applications. The detector's design allows for full three-dimensional (3D) reconstruction of charged particle trajectories in its gas-filled volume. An example of a fission event reconstructed in the fissionTPC is shown in Figure 1. A first technical paper detailing the design and performance of the detector with spontaneous fission targets and actinide targets in neutron beams at the LANSCE was published in May 2014 in the journal Nuclear Instruments and Methods.[1] Two papers documenting the development of actinide targets for NIFFTE have also been published.[2,3]

The chief advantage of the fission TPC over traditional ionization chamber measurements of fission cross-sections is that the systematic uncertainties in those measurements can be investigated and minimized by directly observing the count rate, total kinetic energy vs. emission angle, and fragment emission vs. incident neutron energy in the fissionTPC. Furthermore, the fissionTPC data can be analyzed in full or in "ionization chamber mode" using software cuts to demonstrate what a comparable ionization chamber would measure for the same exact interactions. The collaboration is focusing initially on the major actinide cross-sections ^{235}U, ^{238}U, and ^{239}Pu, but is also interested in pursuing other novel measurements with the device.

"The experiment would not be where it is today without the contributions of the university groups."

— Mike Heffner, LLNL

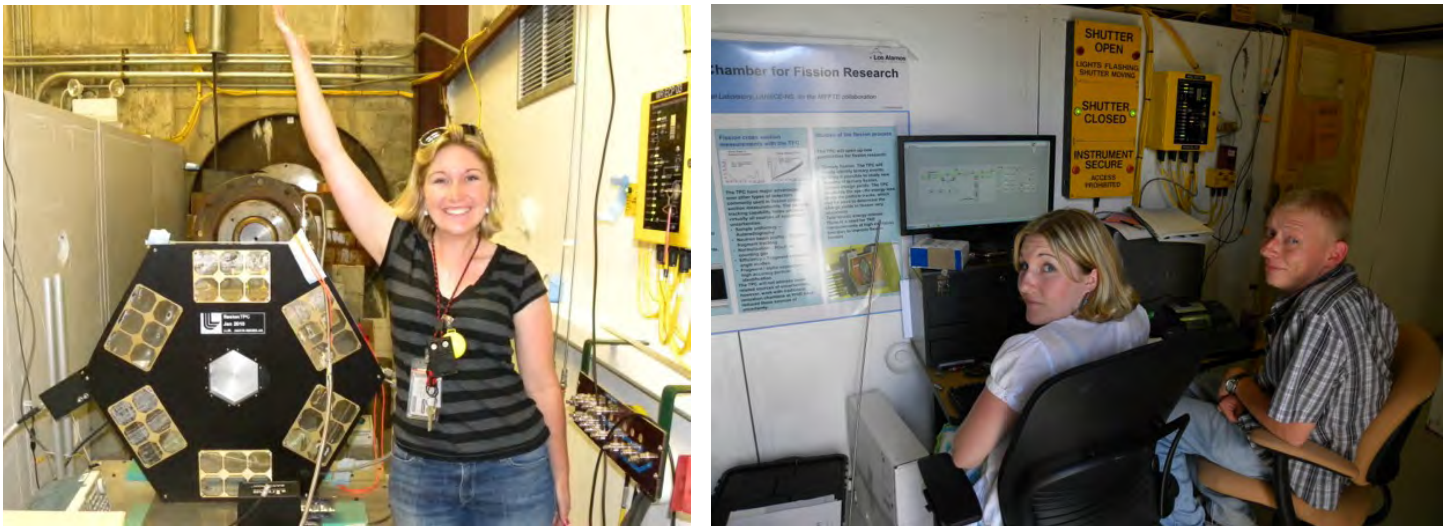

Figure 2. Colorado School of Mines graduate student Dana Duke with the prototype fissionTPC in the 90-Left flight path in 2010 (left). Dana Duke and LLNL postdoc Lucas Snyder at the NIFFTE gas control station in the 90-Left flight path in 2010 (right).

The detector's complex gas control system was designed and constructed by NIFFTE collaborators at the Colorado School of Mines (CSM), under the direction of Uwe Greife. Several graduate students at CSM have worked on NIFFTE, including Lucas Snyder, who completed his dissertation on the alpha to spontaneous fission ratio in ^{252}Cf in 2012 before joining Heffner's group as a postdoctoral researcher at LLNL. Dana Duke, a CSM graduate student currently stationed at LANL, started her involvement with NIFFTE as an undergraduate at Cal Poly. She worked on data analysis and spent two summers as an intern at LANL, working with LANL's Fredrik Tovesson and CSM's Lucas Snyder on the NIFFTE gas system before graduating and joining the Greife group at CSM to continue her research with NIFFTE. Dana and Luke are shown with the detector and at the gas-control station in the 90-Left flight path in 2010 in Figure 2.

University involvement in the project was originally supported through funding from both NNSA and DOE nuclear energy programs but in recent years has been funded exclusively through NNSA laboratory-university subcontracts. Over the course of the project, more than 25 undergraduates and 10 graduate students have contributed to the success of the experiment. Many of these have proceeded to graduate school or postdoctoral positions in nuclear science.

The joint laboratory-university partnership on the NIFFTE project is providing a stimulating experimental environment for students to mature as highly trained nuclear scientists. These young scientists may ultimately become the future leaders of stewardship science at NNSA labs and beyond.

Reference

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[3]W. Loveland and J.D. Baker, "Target Preparation for the Fission TPC," Journal of Radioanalytical and Nuclear Chemistry 282, 2, 361-363, 2009.

Energy Dependence of Fission Product Yields for ^{239}Pu, ^{235}U, and ^{238}U

Los Alamos National Laboratory (LANL)

by Matthew Gooden (M.E. Gooden)*

Fission is undergoing a renaissance of interest as both new theoretical and experimental efforts are underway to obtain more precise fission cross section measurements; study fission yields and correlations of prompt fission gamma-rays and neutrons; and, as highlighted in this report, determine the energy dependence of fission product yields.

For the Stockpile Stewardship Program, the fission yield is an important performance metric. During the nearly 50-year nuclear testing program, fission product yields provided the primary diagnostic for determining the fission yield of a device. In the underground testing environment, due to its relatively long half-life, low volatility, actinide similarity, and minimal chemical fractionation, ^{147}Nd became the most utilized fission product for obtaining fission yield information. This necessitated an accurate knowledge of the number of times this isotope was produced per fission, i.e., its fission product yield (FPY).

For high-yield fission products, such as ^{147}Nd, the fission product yield was generally assumed to be independent of incident neutron energy; however, recently published data[1-3] indicate that the FPY for ^{147}Nd increases in the 0.2 to 1.9 MeV neutron energy region by 3.2% to 4.7% per MeV depending on what data set was used in the analysis. This is a significant finding that can impact the deduced fission yield. Given this importance, we are pursuing a complete, high-precision, self-consistent study of the energy dependence of fission product yields using mono-energetic neutron beams with the goal of providing accurate (<2% relative uncertainty) information on the energy dependent fission product yields covering neutron energies from thermal to 16 MeV.

The irradiation setup is shown in Figure 1. A dual fission chamber is used to count the number of fissions taking place in thin (10-100 micrograms) reference foils during the course of a neutron irradiation. A thick (200-400 micrograms) target placed between the reference foils is activated and then gamma counted for a period of two months to quantitatively extract the yields of characteristic gamma-rays from the specific isotopes of interest. Both the reference foils and the thick target are made of similar, isotope-enriched and chemically purified materials of ^{239}Pu, ^{235}U, or ^{238}U. The number of fissions occurring in the thick target is accurately determined by scaling the number of fissions measured in each fission chamber by their mass and solid angle acceptance relative to the thick target. Using standard activation analysis methods, the yield of each fission product is measured. The FPY for each fission product is then obtained by dividing the yield for each fission product by the total number of fissions in the target.

Mono-energetic neutrons are produced at the 10 MV FN Tandem accelerator at the Triangle Universities Nuclear Laboratory (TUNL) on the campus of Duke University. Several different reactions, as listed in Table 1, have been used to produce neutrons of

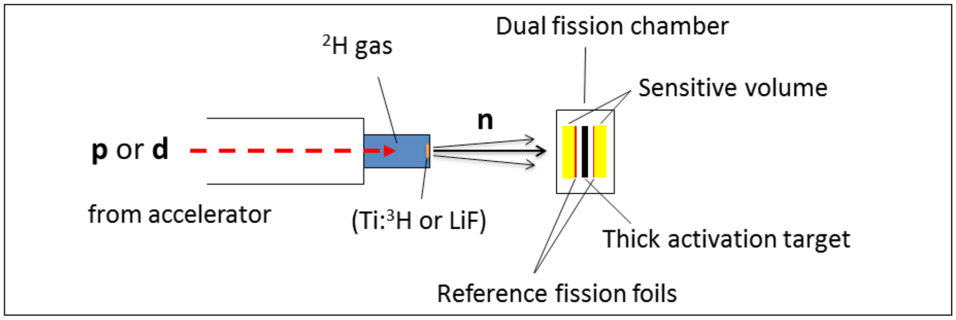

Figure 1. Schematic of the irradiation setup. Neutrons are produced using a deuteron beam on a D2 gas target (blue), without gas by protons or deuterons on a tritiated titanium foil or by protons on a lithium fluoride target. The various neutron production reactions are given in Table 1. See text for a description of the fission chamber.

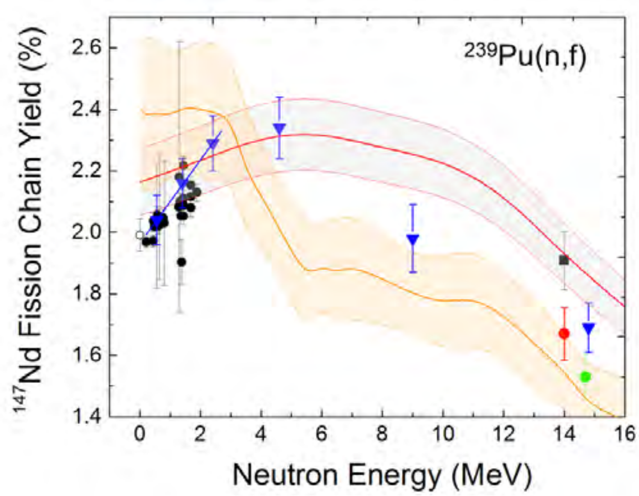

Figure 2. The energy dependence of ^{147}Nd fission product yield from ^{239}Pu is shown from thermal to 14.8 MeV. TUNL data are indicated by blue triangles with a fit line through the three lowest energies; the open data point is the ENDF/B-VII.1 thermal value; the black circles are the data of Selby[1]; the black square, red, and green data points at 14-14.7 MeV are those of MacInnes,[8] Nethaway,[8] and Laurec,[9] respectively. The red line and uncertainty band are the predictions of Lestone,[6] and the orange line and shaded area are calculated using the GEF code.[7]

Table 1. Reactions Used to Produce Mono-Energetic Neutrons at the Triangle Universities Nuclear Laboratory Facility

Reaction	Neutron Energy (MeV)	Typical Flux on Target (n/cm^2-s)
^{7}Li(p,n)	0.025 - 0.65	6 x 10^6
^{3}H(p,n)	1.4 – 3.6*	9 x 10^6
^{2}H(d,n)	4.6 – 14.5*	8 x 10^6 – 3 x 10^7
^{3}H(d,n)	14.8	5 x 10^6

* Off-energy neutrons are produced with increasing intensity above ~2 and 5.5 MeV, respectively, for these two reactions.

different energies. Typical beam currents were 1.5-2 μA for deuterons and 3-4 μA for protons. To obtain good counting statistics at these fluxes, target irradiations were done for three to seven days. More details about the dual fission chamber and these neutron sources and their backgrounds can be found in Reference 4.

To date, we have measured 12 to 15 high-yield fission products for ^{239}Pu, ^{235}U, and ^{238}U at several different neutron energies (0.6, 1.4, 2.4, 4.6, 9, and 14.8 MeV). Approximately 2,000 hours of beam time have been used for these irradiations and the activated targets have been counted nearly continuously over the last three years. This is a large dataset that cannot be presented in detail here (see reference 5), but for illustrative purposes, we highlight this work in Figure 2 by presenting preliminary results for ^{147}Nd (half life t1/2=10.98 d, Eγ=531.0 keV) from the neutron-induced fission of ^{239}Pu. These data show a significant increase in the FPY for ^{147}Nd at low energies. Fitting our three lowest data points (0.6, 1.4, and 2.4 MeV) to a line, we obtain a slope of (7.1 +/- 2.1) %/MeV. This slope is larger than those determined from previous data by Chadwick and Thompson, but given the large uncertainties, they are not statistically inconsistent.

At higher energies, we see that the FPY for ^{147} Nd turns over and decreases. This trend is predicted by the calculations of Lestone,[6] but the estimates of the GEF code[7] shows a flat FPY dependence below 3.5 MeV followed by a sharp decrease at higher energies. To better define the FPY energy dependence, we have recently performed a measurement at 3.5 MeV (in analysis) and are planning to make additional measurements between 4.6 and 14.8 MeV at TUNL as well as a thermal energy measurement at the Massachusetts Institute of Technology Nuclear Reactor Laboratory.

At the important 14.8 MeV neutron energy, our ^{147}Nd FPY is in good agreement with Nethaway,[8] but 2.3 σ below the value presented by MacInnes[8] and 2 σ larger than the value of Laurec.[9] Our new measurement helps resolve this long-standing difference between these measurements. Compared to the FPY at 2.4 MeV, the FPY has decreased by 26% at 14.8 MeV. This general trend is expected since the FPYs for fission products in the valley region (A~110-128) and the high-/low-mass wings increase with increasing excitation energy in the fissioning system. In order to maintain the sum of all fission products to be 200%/fission, it is necessary for the higher yield "peak" products such as ^{147}Nd to decrease in relative yield.

Not only do these new results have important applied interest, the FPY increases observed at low-energies are providing valuable fundamental information about the various fission paths, microscopic shell structure and pairing effects that are in delicate balance at energies near or just above the fission barrier. Additional measurements will be performed to better define these dependences and provide benchmarks for emerging new theoretical models addressing these fundamental fission issues.

References

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[4]C. Bhatia et al., Nucl. Instrum. Meth. Phys. Res. A 757, 7, 2014.

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[6]J. Lestone, Nucl. Data Sheets 112, 3120, 2011.

[7]K-H. Schmidt, Europhy. Lett. 83, 32001, 2008; GEF v2.2, 2013.

[8]M. MacInnes et al., Nucl. Data Sheets 112, 3135, 2011.

[9]J. Laurec et al., Nucl. Data Sheets 111, 2965, 2010.

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Fundamental Science on the Sandia National Laboratories' Z Machine—Stellar Physics, Planetary Science, and Radiation Dominated Plasmas in the Laboratory

Sandia National Laboratories (SNL)

by Thomas R. Mattsson, Gregory A. Rochau, and Dawn G. Flicker (SNL)

The conditions created on SNL's Z machine are literally out of this world. On Z, scientists duplicate and analyze states of matter otherwise found in such exotic locales of the universe as the photosphere of a white dwarf star, a meteor impacting Mars, the radiation heated accretion disk surrounding a black hole, the deep interiors of Jupiter, Saturn, Neptune, and thousands of exo-planets, or the boundary layer inside the sun where convection replaces radiation in transporting energy from the core to the corona. The creation of large enough pieces of out-of-this-world matter for long enough time to enable its careful study is what makes Z unique; it is the driving force behind the collaborations between scientists at SNL and several universities and institutions within the Z Fundamental Science Program (ZFSP).

While collaboration between scientists at SNL and other institutions is not new, ZFSP was an important development that resulted in dedicated experimental time on Z for fundamental science, new collaborations, a growing community of users, and impactful scientific discoveries. Following workshops in 2009 and 2010, ZFSP was launched with a call for proposals in 2010, and dedicated experimental time has been allocated on Z since then. Over the course of the program, more than 40 dedicated experiments have been done together with an additional 40 'ride-along' experiments—non-interfering add-ons to experiments dedicated for stockpile stewardship science. The program has 20 experiment days on Z allocated for calendar year 2015 and a new call for proposals will be issued in June 2015 for experiments to be executed in 2016 and beyond. The sixth workshop in the series "Fundamental Science with Pulsed Power" is planned for July 19-22, 2015 in Albuquerque, New Mexico and we invite participation from researchers in the many fields of science that can be pursued on Z.

SNL's Z machine is the world's largest and most powerful pulsed-power machine.[1] Z stores electrical energy in large capacitor banks and utilizes several stages of pulse-shaping components to produce up to 80 trillion watts of electrical power; 4-5 times more than the instantaneous power generating capacity of all the power plants in the world combined. This electrical power produces a short current pulse that energizes several different experiment configurations (platforms) on Z, each with a distinct purpose.

In studying the properties of the sun, a large team including scientists from Sandia, The Ohio State University, University of Nevada, Reno, Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), the French Commissariat à l'énergie atomique (CEA), and Prism Computational Sciences, use a z-pinch platform designed to emit very strong x-ray radiation (see Figure 1). The radiation heats a sample of iron to temperatures in excess of the 2.2 million degrees found in the solar interior to study the absorption of x-rays in the associated iron plasma. This research has brought new profound insights into the behavior of matter under these extreme conditions and could partially explain a large discrepancy in the measured and modeled structure of the Sun.[2]

In combination with the iron experiment, two other types of experiments are conducted using the same Z x-ray platform. In a collaboration with the University of Texas at Austin, the x-ray radiation is used to heat hydrogen plasma in a large gas cavity, shown in Figure 2, to the conditions existing in the atmospheres of white dwarf stars; the oldest stars in the universe.[3] The optical emission and absorption spectra from this controlled plasma is used to calibrate models for determining the ages of objects in our galaxy. Ross Falcon, the graduate student leading this research, recently completed a PhD from the University of

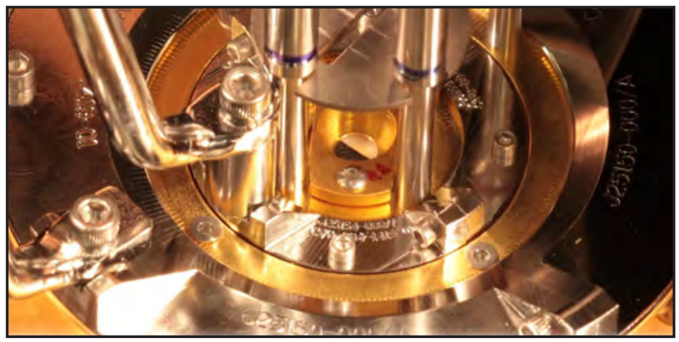

Figure 1. Platform for measuring the x-ray absorption of iron at conditions of the convection/radiation boundary in the sun. A z-pinch located below the brass ring creates intense x-ray radiation that heats the two half-moon-shaped samples in the center.

Figure 2. Gas cavity for measuring the optical properties of white dwarf stars. Ross Falcon graduated in 2014 from UT-Austin with a PhD in Astronomy and is now a postdoctoral researcher at Sandia.

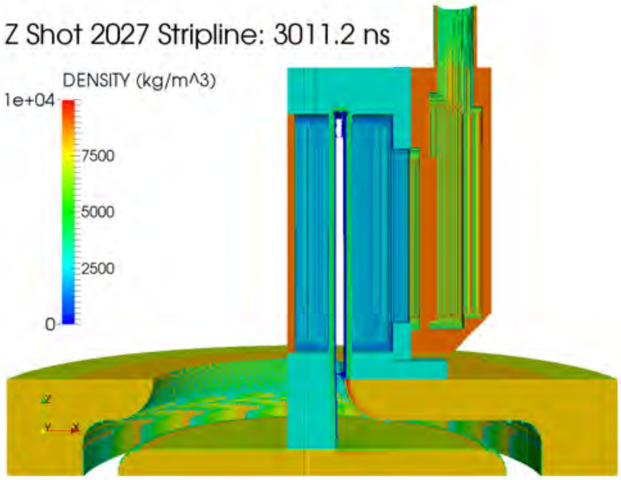

Figure 3. Z Shot 2027 Stripline: 3011.2 ns. Magnetohydrodynamics simulation in 3-dimensions of an high-velocity flyer plate impact experiment. The flyer plate travels faster than 30 km/s (67,000 mph) when it hits the sample. The simulations were done by Sandia scientist Tom Haill using the Sandia code ALEGRA on the Cielo supercomputer located at LANL.

Texas at Austin based on the work and is now a postdoctoral researcher at SNL. In another collaboration with the University of Nevada, Reno, University of West Virginia, and LLNL, the strong x-ray radiation on Z is used to heat a sample of neon or silicon to achieve states of matter where radiation is a dominant factor in determining the ionization.[4] The x-ray emission and absorption spectra from this 'photoionized' plasma is used to benchmark models describing the processes in the accretion disks around black holes.

A different kind of platform is used to study materials under strong dynamic compression. In these experiments, the large current is exploited as a source of pressure to drive material to very high pressures. A computer model of a flyer plate experiment is shown in Figure 3. These experiments are carefully simulated and optimized using large and complex codes running on some of the biggest and fastest computers in the world. In collaboration with the University of Rostock in Germany, the team used flyer plates to study properties of water under the conditions of giant gas planets like Neptune, concluding that water is less compressible under these conditions than previously thought.[5] A collaboration led from Harvard University and the University of California, Davis, instead uses flyer plates to study properties of the materials constituting earth-like planets, e.g., iron and magnesium silicates. The team's first study was recently completed and demonstrated that shock-induced vaporization will have far-reaching implications on the development of the early solar system.[6] Rick Kraus who was lead designer of the experiments, graduated last year from Harvard University with a PhD and is now a Lawrence Fellow at LLNL.

The ZFSP has already yielded more than 15 peer reviewed published publications, including one published in *Nature*, one accepted for publication in *Nature Geoscience*, one in *Physical Review Letters*, three articles in *Physics of Plasmas*, and two in *Physical Review*. Several manuscripts with very exciting discoveries are presently in review. Five postdoctoral scholars have been involved in the program as well as several graduate students, two of which have graduated with PhDs and are now working at NNSA national laboratories.

The ZFSP involves scientists from a large number of international institutions, including the University of Texas at Austin, Harvard University, University of California, Davis, University of West Virginia, Ohio State University, University of Nevada, Reno, University of Rostock, LANL, LLNL, and CEA. In addition to the scientific achievements, ZFSP illustrates how partnerships with scientists at universities and other institutions bring multiple advantages for DOE and NNSA:

- Graduate students trained in research areas of key importance to the national laboratories;
- New creative ideas for experimental techniques and diagnostics that have already been adapted in the NNSA Science Campaigns; and
- Scientists at the national laboratories using their unique talents and expertise to address some of the great outstanding questions in fundamental physics.

We are very pleased with the first five years of the Fundamental Science Program on the Z-machine and excited about the prospects for the future.

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

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

University of Nevada, Reno
Alla Safronova
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

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

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Cross Section Level Densities and Strength Functions

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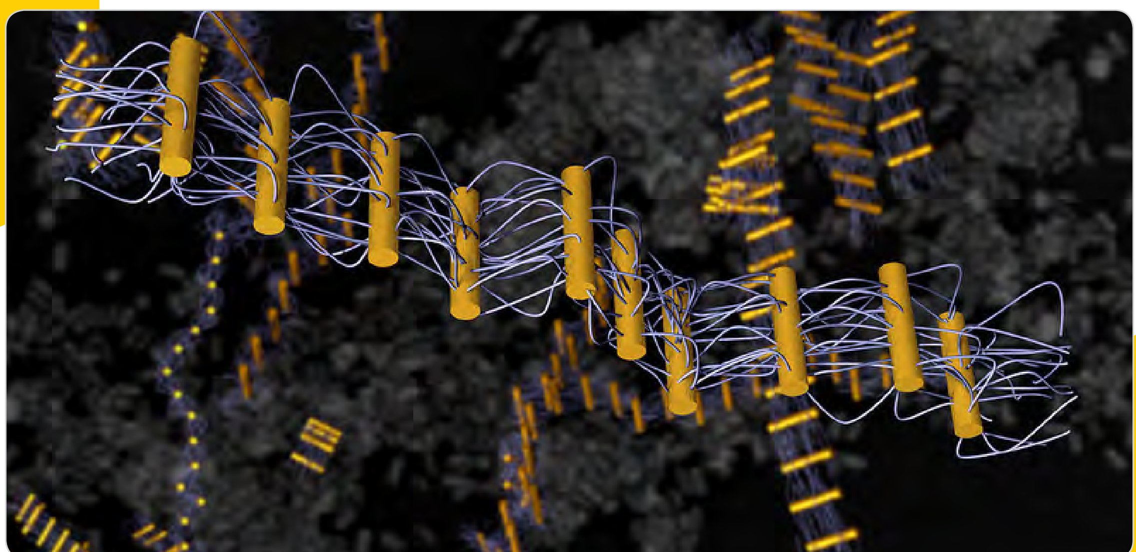

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