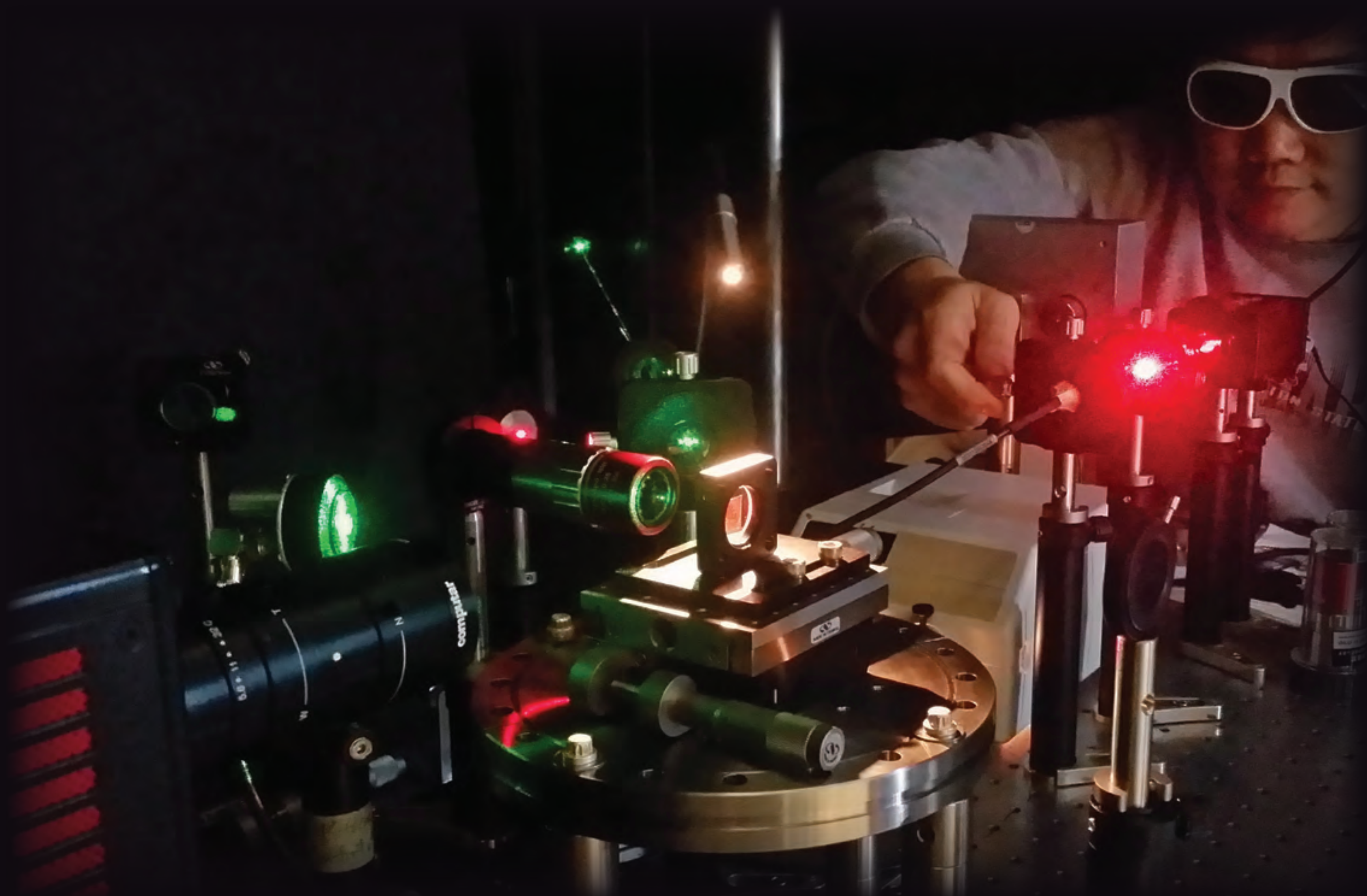
DOE/NA-0079

2019 Stewardship Science Academic Programs Annual

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



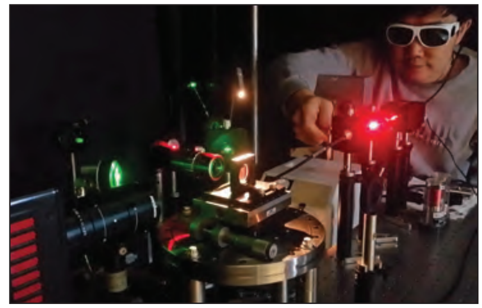
NNSA
National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY

On the Cover

Dr. Jinhyuk Lim, postdoctoral scientist at Washington State University, is setting up a time-resolved Raman spectroscopy experiment to investigate the chemistry of dense planetary mixtures under extreme conditions, in support of the National Nuclear Security Administration Stewardship Science Academic Alliances program.

— Image courtesy of Dr. Choong-Shik Yoo, Washington State University



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2019 Stewardship Science Academic Programs Annual

NNSA Office of Research, Development, Test, and Evaluation

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

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Published February 2019

"The Stockpile Stewardship Academic Programs (SSAP) allow DOE/NNSA to seed the academic pipeline of talent and provide access to world-class computing power and experimental facilities to train the next generation of stockpile stewards. The return on investment in the SSAP has been significant for DOE/NNSA with much of the best talent choosing to join the DOE/NNSA national laboratories as permanent staff or remaining in academia to foster the development of future generations of stewards."

— Dr. Kathleen B. Alexander
Assistant Deputy Administrator
for Research, Development, Test, and Evaluation

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

The National Nuclear Security Administration (NNSA) is tasked with ensuring a safe, secure, and effective nuclear deterrent. Since the end of nuclear testing in 1992, we have accomplished this mission through the expert use of experimental science, engineering, and computational capabilities. This expertise allows us to model the performance of nuclear weapons and to evaluate changes that may occur to weapon performance as the life of a weapon system is extended beyond its original design lifetime, materials age, or changes are made (e.g., material substitutions are made or changes occur in manufacturing processes) that cause the weapon to differ from its original design. The Office of Research, Development, Test, and Evaluation (RDT&E) directs these experimental science, engineering, and computational activities that make it possible to evaluate weapon performance without testing.

To accomplish this mission requires world-class, state-of-the-art computing power, experimental facilities, and the best minds in the Nation trained in science and engineering disciplines. The Stockpile Stewardship Academic Programs (SSAP) allow the Department of Energy (DOE)/NNSA to seed the academic pipeline of talent and provide access to world-class computing power and experimental facilities to train the next generation of stockpile stewards. The return on investment in the SSAP has been significant for DOE/NNSA with much of the best talent choosing to join the DOE/NNSA national laboratories as permanent staff or remaining in academia to foster the development of future generations of stewards.

Work conducted in support of stockpile stewardship is exciting and cutting-edge. It includes areas such as materials science studies to understand the fundamental properties of key materials and how these materials are affected by the pressure and temperature conditions experienced in a nuclear event. Another exciting area is the use of lasers to achieve plasma conditions in laboratory experiments to understand how engineered systems are affected under these intense, plasma conditions and how various components of the systems interact. Work also is conducted in the design and engineering of one-of-a-kind, state-of-the-art diagnostics that allow data to be collected from these experiments. The design and engineering of these diagnostics are amazing achievements and entire fields of study unto themselves. These are only a few examples of the exciting work that occurs at the national security laboratories through RDT&E.

World-class, state-of-the-art theoretical, computational, and experimental science and technology are key to maintaining the effectiveness of our Nation's nuclear deterrent. The high quality of work performed under the SSAP is reflected in this 2019 Stewardship Science Academic Programs Annual. Inside you will find highlights of the newly awarded Centers of Excellence which form a core of the SSAP both for training and developing students and for the research and diagnostics development that directly benefits the weapons' program. Also featured are the students and alumni of the SSAP who write in their own words about their research and about their perspective on the SSAP and the opportunities provided. The work presented in this annual, however, represents only a small window into the outstanding work provided by SSAP.

To all of you, I extend my congratulations on a job well done and best wishes for continued future successes.

Dr. Kathleen B. Alexander

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

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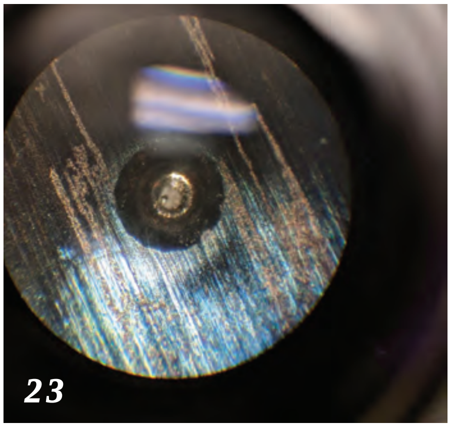

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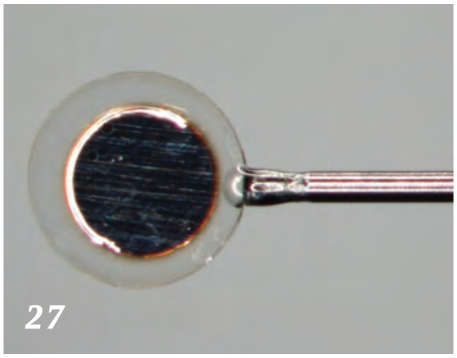

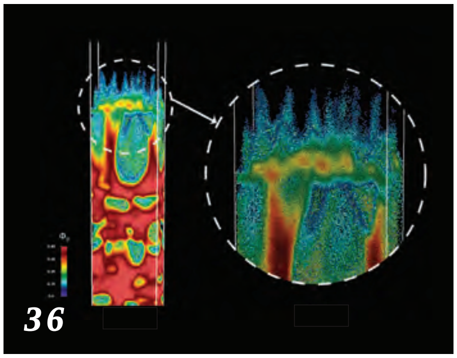

Students

Predictive Science Academic Alliance Program II (PSAAP II)

Alumnus

Stewardship Science Graduate Fellowship (SSGF)

Alumnus

Students

Grants and Cooperative Agreements

Stewardship Science Academic Programs

— Our Future Stockpile Stewards

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

In this 2019 SSAP Annual, some of the outstanding work performed under the SSAP during the past year is highlighted. The SSAP includes the following academic 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).

Travis Volz examines a target in the impact laboratory of the Institute for Shock Physics at Washington State University. See page 32 for more information.

The 2018-2019 SSGF and LRGF Classes. Front row, left to right: Michael Wadas, University of Michigan; Olivia Pardo, California Institute of Technology; Raspberry Simpson, Massachusetts Institute of Technology; Travis Voorhees*, Georgia Institute of Technology. Back row: William Riedel*, Stanford University; Drew Morrill, University of Colorado, Boulder; Stephanie Miller*, University of Michigan; Chad Ummel, Rutgers University; and Sergio Pineda Flores, University of California, Berkeley. *Denotes LRGF Program*

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.

DOE/NNSA Fellowship Programs

The SSAP also includes the Stewardship Science Graduate Fellowship (SSGF) Program, Laboratory Residency Graduate Fellowship (LRGF), and Computational Science Graduate Fellowship (CSGF) Program (jointly sponsored with the U.S. Department of Energy's (DOE's) Office of Science). These three programs support PhD students in areas of interest to stockpile stewardship. SSGF and CSGF provide a yearly stipend, tuition fees, and an academic allowance. The LRGF extends that to at least two longer practicums and encourages fellows to pursue their thesis research in collaboration with lab scientists. This Annual highlights an alumnus and four students from the SSGF Program (see pages 42-44). 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 DOE/NNSA Centers of Excellence and/or 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.

> *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.*
>
> — *Dr. Kathleen B. Alexander*
> Assistant Deputy Administrator
> for Research, Development, Test, and Evaluation

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 in which 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 potentially is applicable to a variety of applications, from nuclear weapons effects to efficient manufacturing, global economics, and 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.

Stewardship Science Academic Alliances

Multi-University Center of Excellence for Pulsed-Power-Driven High Energy Density Science

Cornell University ✦ PIs: Dr. Bruce Kusse (brk2@cornell.edu) and David Hammer (dah5@cornell.edu)

One of our Center tasks is to develop new diagnostics for high energy density physics (HEDP). The high temperatures and densities of HEDP and short time scales of the experiments present serious diagnostic challenges. During last year, three Center partners, Imperial College, Weizmann Institute of Science, and Cornell University, made progress with new diagnostic techniques for measuring temperatures, densities, and magnetic fields in HEDP plasmas.

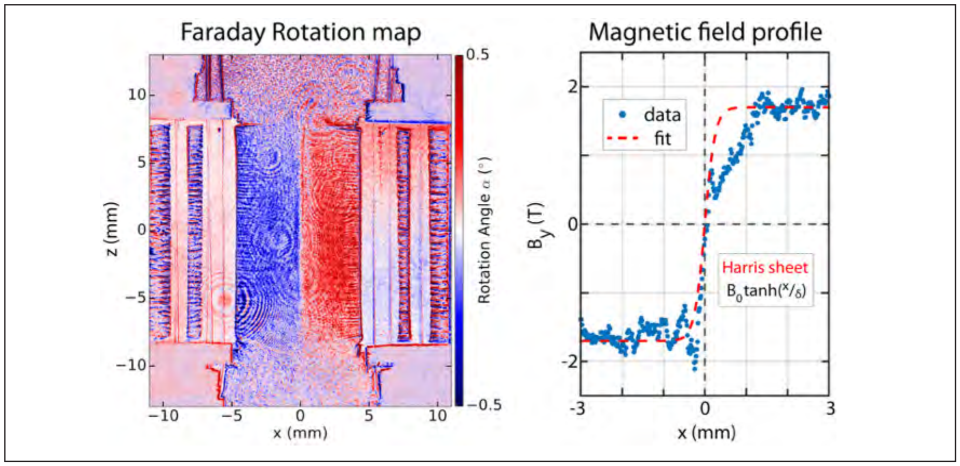

Figure 1. Faraday rotation data and B-field near reconnection.

Faraday rotation measurements of magnetic reconnection experiments are being carried out at Imperial College with a suite of spatially and temporally resolved, laser-based diagnostics.[1] As shown in Figure 1, two exploding wire arrays drive streams of magnetized plasma toward a central plane where a reconnection layer is formed. Magnetic field lines into and out of the page in the blue and red regions result in a small rotation to the linear polarization of the probing laser beam. Details of the field in the reconnection region are shown in the graph. Their recent work has shown that the structure of the reconnection layer, including the magnetic field profile, is significantly affected by changes in the rate and properties of the inflowing material and that these changes can have a fundamental impact on the stability of the reconnection process.

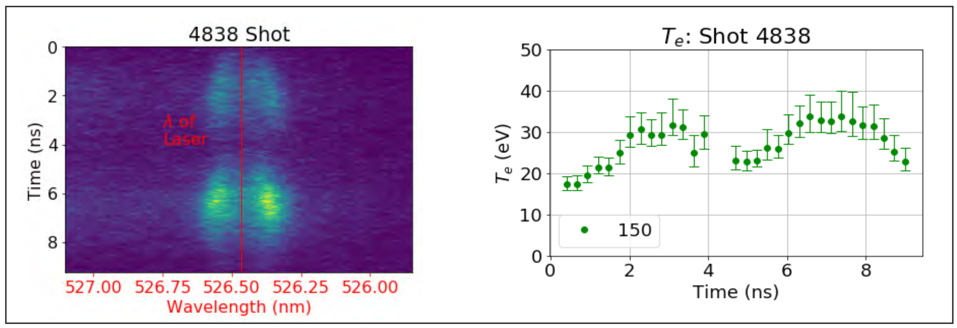

Figure 2. Double pulse and time streaked Thomson scattering in a plasma jet.

Zeeman spectroscopy is being developed at the Weizmann Institute of Science to measure magnetic fields and determine current density as a function of time in imploding gas puff z-pinches. The two-polarization method used is based on viewing visible light emission from the plasma along magnetic field lines and measuring the splitting between the right-hand and left-hand circularly-polarized components of the lines.[2] The magnetic field dependent splitting of the two polarizations can be determined even in the presence of substantial Stark and Doppler line broadening. In 300 kA peak current, 1.6 μs rise time Ar-puff z-pinch experiments, this diagnostic was used to demonstrate that a relatively small axial magnetic field compared to the azimuthal magnetic field in the imploding z-pinch (0.4 T vs. 4 T) causes 80% of the plasma current to be carried in a 28 mm outer-radius low density plasma instead of in the higher density, < 20 mm radius, stagnating plasma that carries close to 100% of the current in the absence of an axial field.

Multi-pulsed and time-streaked or time-gated Thomson scattering measurements at Cornell University have provided new information on gas puff z-pinch and laboratory plasma jet experiments.[3] These measurements observed scattering from both ion acoustic and electron plasma waves, and have provided time, and spatially resolved electron and ion temperatures, electron plasma densities, and plasma flow velocities. Figure 2 shows a time-resolved ion acoustic wave scattering result from the center of a laboratory plasma jet. The laser was split into two pulses ~5 ns apart and the scattered spectrum time-streaked. The spacing of the two peaks in the scattered spectrum gives the electron temperature that has been graphed as a function of time. Spatial resolution is accomplished using a linear bundle of 10 optical fibers observing scattering from along a 5-mm-long, focused laser path. These measurements with the plasma jet have provided information on its rotational velocity. In the gas puff experiments, spatially resolved scattering measurements near pinch time and near the stagnated plasma column from electron plasma and ion acoustic waves have been used to estimate the electron and ion temperatures as functions of position and time.

References

[1] L.G. Suttle, PRL (2016), PoP (2018), J.D. Hare PRL (2017), PoP (2017, 2018).

[2] G. Rosenzweig et al., JINST 12, P09004 (2017).

[3] J.T. Banasek et al., IEEE Trans. Plasma Sci, 46, (2018), Rev. Sci. Inst., 89, 10C109 (2018).

The Center of Excellence in Nuclear Training and University-Based Research

Texas A&M University ✦ PI: Dr. Sherry Yennello (yennello@comp.tamu.edu)

The Center of Excellence in Nuclear Training and University-Based Research (CENTAUR) is a new, multi-institutional effort supported by a Stewardship Science Academic Alliances program. The participating institutions are Texas A&M University (TAMU), Florida State University (FSU), Washington University in St. Louis (WUStL), the University of Washington, Louisiana State University, and the University of Notre Dame. Scientists from Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and Pacific Northwest National Laboratory are also involved, resulting in collaborations and new opportunities for students and postdoctoral researchers.

CENTAUR participants pursue basic research relevant to the NNSA mission through collaborative experimental, theoretical, and technical programs using accelerators at TAMU's Cyclotron Institute and FSU's John D. Fox Superconducting Linear Accelerator Laboratory as well as facilities at other participating institutions. Students receive broad training in theoretical and experimental low-energy nuclear science with an emphasis on stockpile stewardship-relevant topics.

Theoretical activities within CENTAUR focus mostly on nuclear reactions: supercomputer simulations of nuclear fission within microscopic, time-dependent density functional theory, quantum molecular dynamics simulations of medium-energy, heavy-ion collisions, photon emission as a probe of the medium formed in these reactions, developments in indirect nuclear reactions for astrophysical reactions rates, and the construction of microscopic optical potentials for exotic isotopes from high-precision, two- and three-body chiral nuclear forces. These efforts will help guide and interpret experiments performed within the scope of CENTAUR.

The development of fast neutron detectors with high resolution and efficiency is important both for basic nuclear science and for national security applications. To this end, the CENTAUR collaboration is undertaking

Figure 1. Dustin Scriven, graduate student at Texas A&M University, is working in Assistant Professor Greg Christian's group on developing next generation neutron detectors.

a neutron detector research and development project to investigate methods of constructing a highly granular, large-area neutron detector with fast timing capabilities. The focus of the project will be on evaluating novel detector construction schemes that use wavelength shifting bars to funnel scintillation light away from the neutron interaction point into a photodetector. Such readout schemes will allow large arrays of small (~1 cm^3) scintillator cubes to be realized with a modest number of electronics channels, keeping the overall cost and complexity to a reasonable size without sacrificing performance.

Interest and education in stewardship-related sciences begins before graduate school. Research shows under-representation of females and minorities starting at or before high school math and science classes. This past July, CENTAUR initiated a week-long summer Nuclear Medicine and Science Camp on FSU's campus in Panama City, Florida for rising ninth graders in the Bay County School District to attract young students to sciences of interest before this sorting occurs. Two physics teachers from the school district's lowest income high school ran the camp with support from the CENTAUR faculty at FSU, thereby improving student preparation for science, technology, engineering, and math (STEM) college majors. The

Figure 2. Mya Mitchell (left) and Amy Brightbill (right), rising freshmen in Bay County's public high schools, measure the reduction of radiation intensity with distance from a source on the first day of the Nuclear Medicine and Science Camp at the Panama City Campus of Florida State University.

28,000-student school district saw an increase in the number of students taking high school physics in the fall of 2018. Bay County high school students will have access to radiation monitors, sources, and gamma-ray spectroscopy equipment used during the camp through the "STEM Closet" program to enhance classroom learning during the school year.

To learn more about CENTAUR, from current research programs to currently available graduate student and postdoctoral positions, visit centaur.tamu.edu. You also may contact the Director of CENTAUR, Sherry Yennello (yennello@comp.tamu.edu), or the author of this article, Lauren Heilborn, Managing Director & Science Coordinator (centaur@comp.tamu.edu).

Harnessing Nanoscale Control to Dissolve Normally Insoluble Actinide Materials

University of Notre Dame ✦ PI: Dr. Peter Burns (pburns@nd.edu)

The mission of the Actinide Center of Excellence (ACE) is to conduct research in actinide chemistry and materials with integration of experimental and computational approaches and an emphasis on research questions and priorities that are important for security of the Nation via stockpile stewardship. Workforce development is also a motivating goal.

Figure 1. University of Notre Dame PhD candidate Sarah Hickam inspects a solution containing uranium.

Actinides comprise naturally occurring thorium and uranium as well as synthetic transuranium elements beginning with neptunium, plutonium, and americium. Actinide chemistry is unique and complex with a broad range of accessible oxidation states. Actinides, the fuels of nuclear weapons and power plants for electricity generation and naval propulsion, are needed to produce medical isotopes, are major components of nuclear waste, and are environmental contaminants at many sites worldwide. All actinides are radioactive, and radiological hazards associated with the transuranium actinides require special laboratory facilities and procedures to ensure the safety of researchers. A major focus of ACE is training students to plan and conduct experiments safely with actinides.

ACE researchers pioneered the study of nanoscale self-assembling uranium, neptunium, and plutonium oxide clusters that form in water under ambient conditions. Many of these are uranium-based cages that encapsulate various other cations. These chemically and structurally diverse clusters provide unique opportunities to control the chemistry of actinides during chemical processing. Indeed, nanoscale sizes often enhance or even change properties of materials. Actinide oxide clusters are excellent models for understanding structure-property-size relationships at the scale of hundreds of atoms. ACE researchers have synthesized and characterized dozens of such clusters and are exploring their potential applications in actinide materials processing.

Chemical processing of solid actinide materials (such as fuels and weapon components) requires dissolution in a solvent such as water. Most solid actinide materials are strongly resistant to dissolution in many solvents. Usually, hot nitric acid is needed to achieve dissolution which renders minor components of the system soluble as well. Solvent extraction methods, such as PUREX, then are needed to separate the various valuable components and wastes.

As an alternative to using hot nitric acid for dissolution of actinide solids, ACE researchers have emphasized the potential importance of nanoscale actinide clusters for enhancing the dissolution of materials under much milder chemical conditions. ACE researchers demonstrated that uranium oxide, the most common form of nuclear fuel, dissolves in mildly basic water that contains hydrogen peroxide; because nanoscale uranium peroxide cage clusters spontaneously form in solution. These clusters are a highly soluble form of uranium, and ACE PhD student Sarah Hickam, University of Notre Dame (see Figure 1) showed it is possible to reach uranium concentrations in water as high as 44 weight percent via the simple dissolution of uranium dioxide, a value comparable to that achieved in hot nitric acid.[1] Sarah's experiments also showed that the amount of uranium dioxide that dissolved and, consequently, the final concentration of uranium in solution is controlled by the concentration of alkali cation that she added to the water. These cations are needed to charge-balance the nanoscale clusters that form in solution. Peter C. Burns, Director of ACE, noted "in terms of fundamental science, it is fascinating to probe the role of nanoscale clusters in dissolution of solids. At a more applied level, dissolution of actinide materials is central to many processes, so Sarah's findings have many potential applications. These and other ACE studies are providing unique opportunities for our graduate students to develop skills working with actinides."

Reference

[1]S. Hickam, S.M. Aksenov, M. Dembowski, S.N. Perry, H. Traustason, M. Russell, and P.C. Burns, "Complexity of Uranyl Peroxide Cluster Speciation from Alkali-Directed Oxidative Dissolution of Uranium Dioxide," Inorganic Chemistry 57, 9296-9305 (2018).

The Center for Research Excellence on Dynamically Deformed Solids

Texas A&M University ✦ PI: Dr. Michael Demkowicz (demkowicz@tamu.edu)

The Center for Research Excellence on Dynamically Deformed Solids (CREDDS) aims to discover, understand, and predict the influence of microstructural heterogeneities—such as interfaces, inclusions, and porosity—on the high strain-rate (>10^4/s) mechanical response of additively manufactured, multiphase materials. High strain-rate deformation of single crystals and single-phase materials is of great fundamental interest and continues to be studied extensively. However, the dynamic mechanical response of multiphase engineering materials is often governed by microstructural heterogeneities. Such materials bear outstandingly different and complex microstructures, challenging conventional knowledge on how microstructure dictates dynamic mechanical response. CREDDS is working to close this knowledge gap by developing predictive capabilities for the effect of microstructural inhomogeneities on dynamic failure mechanisms.

CREDDS brings together Texas A&M University (lead institution), the University of Michigan–Ann Arbor, the University of California, Santa Barbara (UCSB), and the University of Connecticut. It focuses on student-centered research activities coordinated with NNSA laboratories, including Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and Sandia National Laboratories, with the aim of training the next generation of leaders in stockpile stewardship science. "I am thrilled by the superb team of students and mentors who who have come together to make CREDDS a reality," says Dr. Michael Demkowicz, Director of CREDDS. "We have only been up and running for three months but are already forging deep connections with National Nuclear Security Administration labs and making exciting discoveries."

Catastrophic failure at high strain rates frequently can be linked to fracture, void formation, and cracking at microstructural heterogeneities such as grain boundaries, interfaces, or brittle precipitates. However, depending on their structure and properties, such heterogeneities also may be efficient dislocation sinks or obstacles leading to enhanced damage tolerance. To discover the effect of specific heterogeneities on dynamic mechanical response, CREDDS supports 12 PhD students collaborating across the four partner universities. For example, Texas A&M CREDDS student Liya Semenchenko (pictured below) is using severe plastic deformation to systematically vary the microstructures of multiphase metallic materials. By testing these materials under high strain rate loading, her collaborator at UCSB, CREDDS student Avery Samuel (see page 32), will identify the microstructure elements most susceptible to damage. Through such integration of advanced synthesis, mechanical testing, characterization, and modeling, CREDDS students aim to accelerate prototyping of new materials, to improve mechanical failure predictions, and to advance efficient certification for service.

To promote stockpile science research and to engage early career researchers at other top-tier U.S. research universities, CREDDS will organize a week-long summer school on stewardship science in its fourth fiscal year (2021-2022). This summer school will be open to PhD students, postdoctoral researchers, as well as faculty at U.S. universities.

CREDDS student Liya Semenchenko uses severe plastic deformation to synthesize multiphase metallic materials with designer microstructures.

Center of Excellence for Matter Under Extreme Conditions

University of California, San Diego ✦ PI: Dr. Farhat Beg (fbeg@eng.ucsd.edu)

The University of California, San Diego (UCSD) operates a new Center of Excellence focused on high energy density science (HEDS) as part of the National Nuclear Security Administration's (NNSA's) Stewardship Science Academic Alliances (SSAA) program. The Center for Matter under Extreme Conditions (CMEC) is based at UCSD but operates in partnership with three other University of California campuses (Berkeley, Davis, and Los Angeles), the University of Chicago, Florida A&M University, and General Atomics.

With workforce development a top priority, CMEC prepares undergraduate and graduate students and postdoctoral researchers for careers at Department of Energy/NNSA laboratories. The Center is tasked with the following objectives: 1) train students in all aspects of HEDS, 2) create a sustained flow of high quality, young scientists and engineers into the Stockpile Stewardship Program (SSP) workforce, 3) engage world-class faculty in HEDS collaborations, and 4) become the world's premier academic center for HEDS research.

Figure 1. Graduate students and research scientists working with the 1 MA Linear Transformer Driver at the UCSD Center for Energy Research.

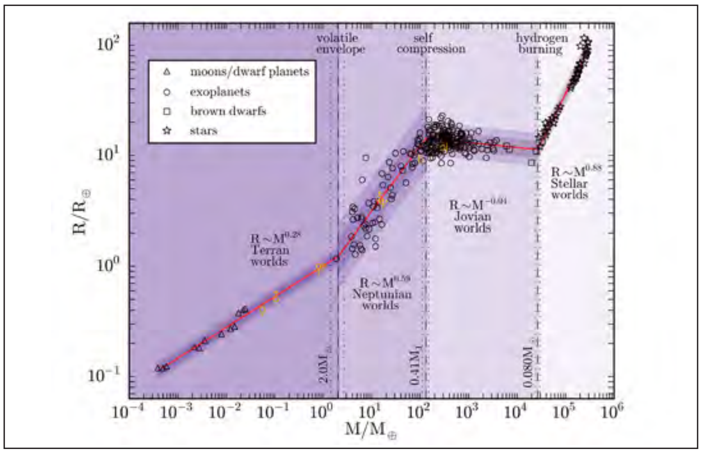

Figure 2. Exoplanet radius vs. mass diagram showing distinct classes of planets dominated by different compositions. A new and diverse class of Neptunian worlds falls between rocky planets like Earth and gas giant planets like Jupiter. Image credit: Jingjing Chen, Columbia University

CMEC addresses the complex, interdisciplinary scientific problems pertinent to the SSP in three areas of research: 1) energy transport in HED systems (conductivity, species separation, laser-plasma instabilities, and opacity), including the effect of external magnetic fields, 2) material properties across the HED regime (electrical and thermal conductivity, equation of state, structure, and phase separation), and 3) nature under extreme conditions (broad equation of state models for planetary and astrophysical applications and particle acceleration in collisionless shocks).

The research team consists of faculty and students from across the partnering universities, General Atomics, and scientists from three national laboratories—Lawrence Livermore National Laboratory, Sandia National Laboratories, and Los Alamos National Laboratory. They use cutting-edge facilities, such as the Jupiter Laser Facility, Linac Coherent Light Source, OMEGA laser, National Ignition Facility, and the Z Pulsed Power Facility to train future stockpile stewards. CMEC also uses in-house facilities such as the 1 MA Linear Transformer Driver (see Figure 1) at UCSD and the two-stage gas gun at UC Davis.

A previously mentioned focus of CMEC is nature under extreme conditions. The rapid discovery of exoplanets has revealed populations of planets that were not predicted by theories based on our solar system. CMEC strengthens HEDS in the broader community of planetary science and astrophysics by applying our developments in equations of state and material properties to major questions about the origin and evolution of planets (see Figure 2). Such relevant properties include the conductivity of silicates and miscibility of metal-silicates and silicate-volatiles in extreme conditions.

One of the key findings of exoplanetary sciences is the significant abundance of planets from 1-15 Earth-masses, including rocky super-Earths and hydrogen-rich mini-Neptunes. It is now clear that exoplanetary systems have a more diverse continuum between rocky planets and "ice giants" like Uranus and Neptune than ours. We must expand our imaginations, modeling tools, and corresponding physical inputs. Understanding the interior state and thermal evolution of these planets requires a new generation of experimental and computational work. CMEC addresses these problems by integrating the components (experiment, computation, applied modeling) to enable high profile advances in understanding and predicting the structure and evolution of massive planets.

Farhat Beg, a professor in the Mechanical and Aerospace Engineering Department at UCSD and Director of the Center for Energy Research, leads the Center's research. Beg said, "CMEC provides a unique environment to conduct research into high energy density science and inspires young scientists to pursue work at our national laboratories in stockpile stewardship. The partnership with other universities, national labs, and private industry allows for an unprecedented level of collaboration."

The Wootton Center for Astrophysical Plasma Properties

University of Texas at Austin ✦ PI: Dr. Donald Winget (dew@astro.as.utexas.edu); Author: Rebecca A. Johnson

Based at The University of Texas at Austin (UT Austin), the Wootton Center for Astrophysical Plasma Properties (WCAPP) was started with a cooperative agreement from the National Nuclear Security Administration. The Center exists to study “star stuff” on Earth under laboratory conditions. Its work gives astronomers a never-before-seen chance to look at their quarry up close rather than through a telescope.

Another purpose of the Center is to train young scientists for future positions in the national laboratories. For this reason, a major part of its five years of funding will go to support graduate students and postdoctoral researchers.

The collaboration includes scientists from UT Austin, the University of Nevada, Reno, University of Arizona, West Virginia University, NASA, and Sandia National Laboratories (Sandia).

Figure 1. This artist’s impression shows an accretion disk swirling around the central black hole of a galaxy, powering the bright jet emerging from its center.

How will WCAPP study stars in the laboratory? By using the world’s most powerful x-ray source. Located in Albuquerque, New Mexico at Sandia, the Z Pulsed Power Facility re-creates temperature, density, and radiation levels equal to that within the stars. Called the Z machine, it creates conditions of 2 to 3 million degrees Kelvin.

“Here, if we want to study a white dwarf whose surface is at 15,000 degrees, then we’re doing the experiment at 15,000 degrees,” said WCAPP Deputy Director Mike Montgomery. “It really is like taking a piece from the Sun and looking at it under a microscope.”

It’s a new way to do astronomy, according to WCAPP Director Don Winget, the Harlan J. Smith Centennial Professor in Astronomy at UT Austin.

“The really amazing thing about this research is that it changes the way astronomy research is conducted,” he said. “There are a lot of things we thought we understood or knew we didn’t understand in astrophysics. By re-creating those conditions and making real measurements in the laboratory, we’re changing how we think of not only specific astronomical objects but of astronomy as a field.”

Though the Z machine is extremely complex, the WCAPP team’s idea for using it to understand the cosmos is a simple three-step process. First, they start with an existing theory about some type of behavior observed from a star or other extreme cosmic environment. Next, they test the theory to either falsify it or benchmark it. They do so by using the Z machine to reproduce the stars’ conditions—zapping a sample of hydrogen to heat it to millions of degrees and carefully measuring the sample’s behavior under those conditions. Finally, they compare their lab results to what they see from telescope observations from UT Austin’s McDonald Observatory in West Texas.

Though WCAPP is a new organizational framework, Winget, Montgomery, and colleagues have been using the Z machine to unlock the secrets of the stars since 2009.

The Center has several experiments planned already. One experiment includes investigating how photons travel through the Sun to emerge as light. A second concerns understanding features seen in telescope observations of white dwarfs (ancient remnants of Sun-like stars). A third involves decoding the processes that go on in accretion disks (disks of material being pulled in by a star’s or galaxy’s gravity) around black holes.

These are just a few of the Center’s planned projects. The team may add others in the future. One thing is certain: when astronomers find a new way to study the universe, you never know what they might find.

We’re going back and asking very fundamental questions,” Winget said. “Instead of doing calculations, we’re doing experiments and checking. We’re going to learn a lot of things we plan on learning, and we’re going to learn a lot of things we didn’t plan on learning.”

Capital-DOE Alliance Center: A Center of Excellence for High Pressure Science and Technology

The George Washington University ✦ PIs: Dr. Russell J. Hemley (rhemley@email.gwu.edu) and Dr. Stephen A. Gramsch (sgramsch@email.gwu.edu)

Now in its 16th year, the Capital-DOE Alliance Center (CDAC), formerly the Carnegie-DOE Alliance Center, continues as a Center of Excellence for materials research at extreme conditions within the Stewardship Science Academic Alliances program. Now headquartered at The George Washington University (GWU) in Washington, DC, CDAC maintains its mission to facilitate the education and training of the next generation of scientists and engineers for work in the National Nuclear Security Administration (NNSA) laboratories. The scientific goals of the Center are to significantly enhance our understanding of a broad range of materials in extreme pressure-temperature (*P-T*) regimes and to integrate and coordinate static compression, dynamic compression, and theoretical studies of materials.

Since its founding in 2003, CDAC has focused on six areas of materials science: high *P-T* phase relations and structures; *P-V-T* equations of state; phonons, vibrational thermodynamics and elasticity; plasticity, yield strength, and deformation; electronic and magnetic structure and dynamics; and high *P-T* chemistry. CDAC is a multi-institutional effort that consists of groups of academic partners and NNSA laboratory collaborators. The academic partner group represents a broad range of research interests. External university partners include Brent Fultz (California Institute of Technology), Dana Dlott (University of Illinois at Urbana-Champaign), Steve Jacobsen (Northwestern University), Raymond Jeanloz (University of California-Berkeley), Lowell Miyagi (University of Utah), Eva Zurek (State University of New York at Buffalo), Maik Lang (University of Tennessee), Susannah Dorfman (Michigan State University), and Elif Ertekin (University of Illinois at Urbana-Champaign). GWU faculty Saniya LeBlanc and Santiago Solares (Mechanical and Aerospace Engineering) and Tianshu Li (Civil and Environmental Engineering), as well as CDAC research faculty also join the academic partner group. In addition, NNSA laboratory collaborators include extreme conditions researchers at all three laboratories. An extensive array of external collaborators remains a key part of the Center's research program.

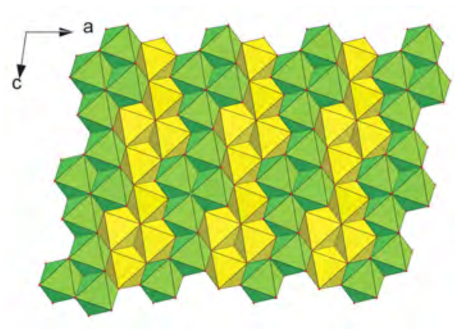

Figure 1. Crystal structure of the high density cristobalite X-IH polymorph of SiO_2 showing its octahedral chain geometry, as studied by the Zurek (Buffalo) and Dera (Hawai'i) groups, together with staff at HPCAT.[3]

CDAC largely is an experimental program, but the Center is also seeing an increased use of theoretical and computational methods in studies of materials, many jointly with experiments. New academic partner Elif Ertekin (University of Illinois at Urbana-Champaign) brings a new effort to the Center with her group's studies of materials and properties at larger length scales.[1] Lowell Miyagi's group is using machine learning techniques to predict new superhard materials.[2] The students of Eva Zurek (Buffalo) and Przemyslaw Dera (University of Hawaii at Manoa) are performing joint experimental and theoretical studies, including work done at the High Pressure Collaborative Access Team (HPCAT) (see Figure 1).[3]

A major component of the Center's efforts is coordinating research and training activities at NNSA-supported facilities at DOE laboratories (see Figure 2). These facilities include, in particular, the HPCAT at the Advanced Photon Source (APS) at Argonne National Laboratory for x-ray diffraction and spectroscopy and the synchrotron infrared program at the National Synchrotron Light Source II at Brookhaven National Laboratory, including the Frontier Infrared Spectroscopy (FIS) beamline. Highlights include the recent discovery of the 260 K lanthanum superhydride superconductor, an effort partially led by former CDAC student and postdoc Zachary Geballe.[4] In its new phase, CDAC is supporting research and training activities at other APS sectors as well as sample preparation and characterization labs at the facility. The Center also supports research and training at major NNSA facilities, including Z at Sandia National Laboratories and the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory. A recent highlight from NIF is the study of the insulator-metal transition in fluid deuterium that was published in *Science* and co-led by the University of California-Berkeley and GWU partners.[5]

Figure 2. Students and postdoctoral researchers from three departments (Earth Science, Chemistry, and Materials Science) collaborate within the academic partner group of Steven Jacobsen (Northwestern University). The team uses CDAC discretionary beam time to explore the high-pressure materials genome.[6] Pictured here at beamline 16-ID-B are, from left: Allison Altman, Alexandra Tamerius, Hannah Bausch, Vinay Hegde, James Walsh, and Ryan Klein.

Since CDAC's inception, 66 graduate students have received the PhD degree with CDAC support. In addition, as of this past quarter, 30 students or postdoctoral researchers supported by CDAC or in CDAC-supported laboratories have gone on to positions in the NNSA laboratories with 11 of these obtaining Staff Scientist positions.

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Center for Advanced Nuclear Diagnostics and Platforms for ICF and HED Physics at OMEGA, NIF, and Z

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The High Energy Density Physics (HEDP) Division of the Massachusetts Institute of Technology (MIT) Plasma Science and Fusion Center has participated in National Nuclear Security Administration (NNSA)-sponsored research since the late 1980s in collaboration with the national laboratories and the University of Rochester Laboratory for Laser Energetics (LLE). It was designated as a Center of Excellence as of 2019 together with partners at the University of Iowa; University of Rochester; University of Nevada, Reno; and Virginia Polytechnic Institute and State University. The formation of the Center will result in expansions in the development of new plasma diagnostics, in scientific investigations, and in the recruitment and training of exceptional experimental and theoretical PhDs in HEDP and inertial confinement fusion (ICF) science.

The HEDP Division (see Figure 1) has performed a wide range of research in ICF, nuclear science, and laboratory-scaled astrophysics at LLE's Omega Laser Facility, Lawrence Livermore National Laboratory's National Ignition Facility (NIF), and Sandia National Laboratories' Z machine, utilizing a wide range of MIT-developed diagnostic techniques. These include spectrometry of charged particles and neutrons, measurement of the time evolution of multiple nuclear reactions in ICF experiments, imaging of the spatial distribution of nuclear reactions that produce charged particles in ICF, and radiography of plasmas with monoenergetic charged particles.

Important new diagnostics growing out of MIT's previous work will include 1) a radiography platform with a tri-particle backlighter that will provide three or more different monoenergetic charged particles (including 14.7-MeV protons, 9.5-MeV deuterons, 3-MeV protons) used with a matched detector in the form of a charged-particle spectrometer or a charged-particle imaging detector and 2) a Particle-X-Ray Temporal Diagnostic (cryoPXTD) that will measure the time history of multiple nuclear burn products and multiple energy bands of x-ray emissions during cryogenic ICF experiments with 10-ps relative timing accuracy.

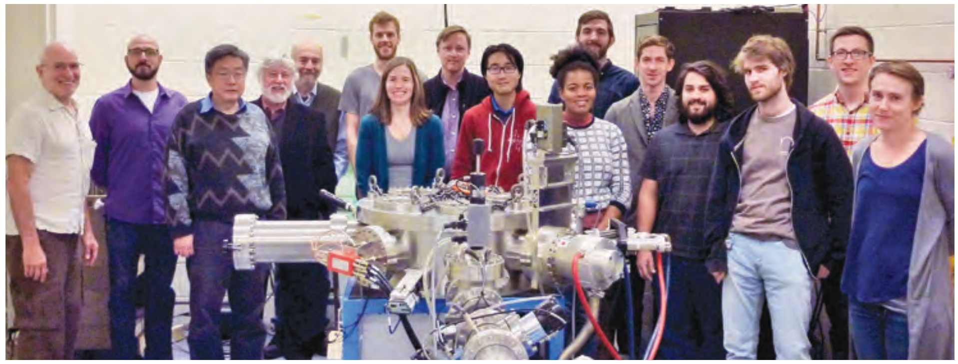


Figure 1. The MIT HEDP Division, shown behind the target chamber of MIT's Accelerator for HEDP research. The accelerator facility will be essential for the development of new diagnostics in the Center program.

These new diagnostic techniques will be used for new research. For example, the tri-particle backlighter will be used to study the energy loss of charged particles when passing through a plasma with more accuracy and constraints than before, because an important new monoenergetic particle (deuteron) and energy will be used. The backlighter will also be used to make radiographic images of plasmas and their electromagnetic fields. The addition of the deuteron will be beneficial for mapping electric and magnetic fields. The cryoPXTD will be used for new and unique studies of kinetic and multi-ion effects and shock dynamics in cryogenic ICF implosions. Intriguing connections between this work and Supernova 1987A are now being explored.

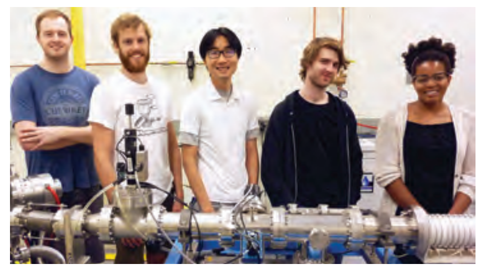


Figure 2. Five of the six MIT PhD students who won awards for their research. From left to right with their specialties: Patrick Adrian (stopping power and ion-electron equilibration in ICF), Graeme Sutcliffe (Tri-Particle backlighter program), Hong Sio (PXTD and multi-ion and kinetic effects in ICF), Brandon Lahmann (experimental and theoretical studies of ICF implosion convergence), and Raspberry Simpson, a new NNSA Laboratory Residency Graduate Fellowship (fuel areal-density asymmetries in cryogenic). Neel Kabadi (multi-ion and kinetic effects in ICF) is pictured in Figure 1 (fourth from right).

Nine graduate students and two postdoctoral researchers worked in the HEDP Division during 2018, and all have made important contributions to areas of interest to NNSA. Six of them received awards (see Figure 2). Hong Sio, who was an NNSA Stewardship Science Graduate Fellow, completed his PhD thesis on kinetic/multi-ion physics and shock dynamics on OMEGA and the NIF and is being nominated for the Rosenbluth Outstanding Doctoral Thesis Award. Hong is also a finalist for the prestigious Lawrence Fellowship.

HEPD Division scientists also received awards. The American Physical Society's (APS's) John Dawson Award for Excellence in Plasma Physics Research was presented to Drs. Chikang Li, Richard Petrasso, and Fredrick Seguin at the APS Division of Plasma Physics conference in FY 2018 for their development of the technique of radiography with monoenergetic charged particles and for using it in a wide range of plasma physics experiments in ICF and laboratory astrophysics. The award was shared with Prof. Marco Borghesi, Queen's University Belfast; Dr. Andrew Mackinnon, Lawrence Livermore National Laboratory; and Prof. Oswald Willi, University of Düsseldorf. Other Division scientists continued to make important contributions, including Dr. Johan Frenje's plasma stopping power and new neutron spectrometry techniques, and Dr. Maria Gatu-Johnson's nuclear physics relevant to both ICF and astrophysics.

Experiments and Simulations of Rayleigh-Taylor Instability Growth in High Energy Density Plasmas

University of Michigan ✦ PIs: Dr. Paul Drake and Dr. C.C. Kuranz (ckuranz@umich.edu) ✦ Author: L. Elgin (lelgin@umich.edu)

The University of Michigan (UM) was recently awarded a new Center of Excellence, the Center for Laboratory Astrophysics: Structure Formation and Energy Transport After the Dark Ages (CLA), with Professors Carolyn Kuranz and R. Paul Drake as Primary Investigators. CLA trains PhD students and works closely with Department of Energy/National Nuclear Security Administration national laboratories creating, diagnosing, and simulating astrophysically relevant, high-energy-density processes. To do so, high-energy lasers and pulsed power devices are used. This work at CLA builds upon work performed in UM's previous Center for Laser Experimental Astrophysical Research (CLEAR). One focus of CLEAR was hydrodynamic instabilities, for example, the Rayleigh-Taylor instability (RTI), which occurs in inertial confinement fusion (ICF) experiments and supernova explosions.

The RTI occurs when two fluids of different densities are in contact at an interface, and there exists a pressure gradient in opposition to the density gradient, i.e., a bottle filled with half oil (light fluid) and half water (heavy fluid). Under the force of gravity, this configuration is unstable: light-fluid bubbles and heavy-fluid spikes emerge and interpenetrate across the interface, forming a mixed-fluid region which continues to grow, thereby lowering the potential energy of the system. RTI also occurs in high-energy-density plasma systems, such as supernovae explosions, nuclear weapons explosions, and ICF capsule implosions. In ICF, RTI can thwart ignition at two stages of the implosion process. First, during the ablative acceleration phase, the outer surface of the shell is RT-unstable and seeded by target imperfections and non-uniform irradiation. Second, during the deceleration or stagnation phase, RTI occurs at the inner surface between the ablated shell and the fuel core. The ability to model and predict the evolution of RTI has profound consequences, concerning national security and nuclear safety and our fundamental understanding of the universe.

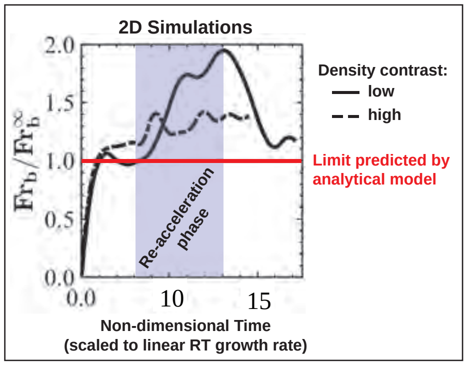
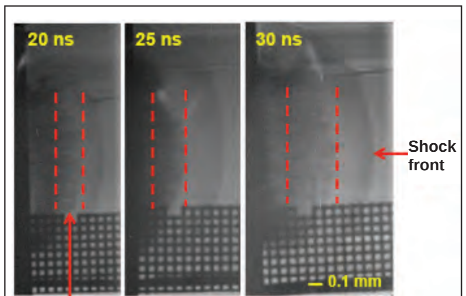


Figure 1. University of Michigan simulations (using CRASH, a radiation-hydrodynamics code) predict re-acceleration of bubble growth for low-density-contrast fluids. Plotted here, the Froude number characterizes the ratio of the instantaneous bubble velocity to the asymptotic value predicted by analytical models.



Mixed fluid region with RTI spikes (dark) and bubbles (light)

Figure 2. Radiography data showing evolution of mixed-fluid region for low-density contrast targets with 3D λ=40 μm seed perturbation pattern.

In late-time, nonlinear RTI, secondary instabilities may arise, causing spikes and bubbles to interact and break up and the onset of turbulent mixing.[1] When does this transition occur and how does it depend on the density contrast of the two fluids? At low-density contrast, simulations show an unexpected re-acceleration of spikes and bubbles in the nonlinear phase prior to turbulent mixing (see Figure 1). A possible explanation is that this re-acceleration is driven by accumulation of vorticity at the bubble and spike tips,[2] but the effect may be non-physical and created by numerical artifacts. Radiation-hydrodynamics simulations are notoriously complex, and their results are only as good as the numerical methods, physical models, and assumptions they incorporate. Therefore, experimental data are needed to validate simulation results and elucidate the underlying physics.

In addition, funded in part through CLEAR, PhD student Laura Elgin executed experiments at the Omega Laser Facility at the University of Rochester Laboratory for Laser Energetics to investigate the late-nonlinear growth stage of single-mode RTI and its dependence on density contrast. High-energy laser beams create a blast-wave, which drives RTI growth at a material interface inside a shock tube. The choice of materials determines the density contrast, and a micromachined, single-mode pattern seeds the instability growth. A time-series of x-ray radiographs captures the evolution of RTI growth and the structure of the mixed-fluid region (see Figure 2). From the radiography images, spike and bubble growth rates can be measured and compared with simulations and analytical models. This project trains new researchers to question their results and to understand the limitations and capabilities of simulations, target fabrication, and facility diagnostics. Computational scientists and experimentalists work together to refine the experimental design, analyze data, interpret results, and determine whether the simulations accurately represent the physical processes involved in the experiments. According to Center Director Kuranz, "This work seeks to fundamentally understand instabilities that have adverse consequences in inertial confinement fusion and astrophysical systems."

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Neutron Capture Cross Section Measurements on Short-Lived Isotopes

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The goal of the present project is to provide experimentally-constrained neutron capture cross sections on short-lived nuclei far from stability to understand how isotopes are produced in energetic events. During the past two years, two graduate students and one postdoctoral researcher have been supported by the Stewardship Science Academic Alliances (SSAA) grant. The availability of basic data on nuclear properties is critical to understand the astrophysical processes responsible for the synthesis of heavy elements. Most elements above iron are produced in two neutron-capture processes: the slow (s) process and the rapid (r) process. Both processes require data on neutron-capture reactions on short-lived nuclei that are not currently available. Directly measuring the neutron capture cross section on a short-lived nucleus is currently not feasible, and theoretical calculations vary by orders of magnitude just a few neutrons away from stable nuclei further emphasizing the need for experimental input. The present project focuses on experimentally constraining neutron-capture reactions that are of importance for both s- and r-process nucleosynthesis.

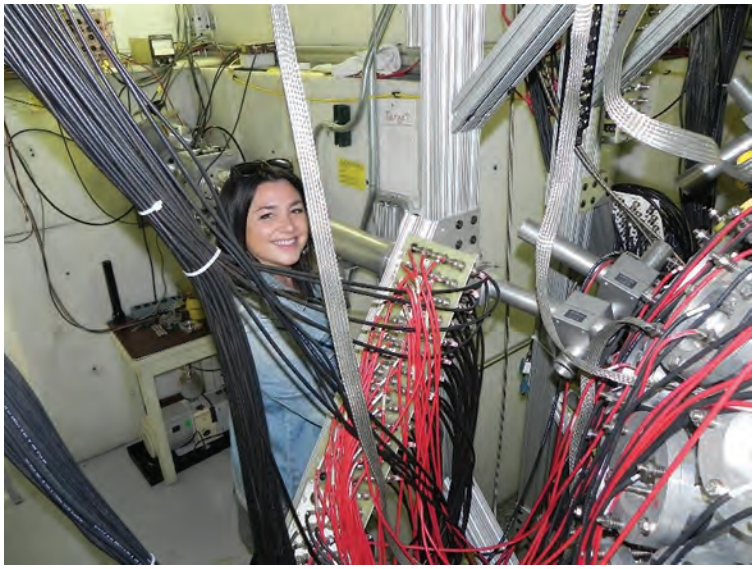

Figure 1. Debra Richman at Los Alamos National Laboratory standing next to the DANCE array.

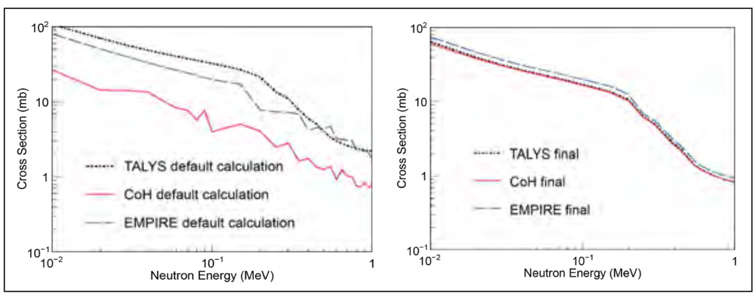

Figure 2. Neutron capture cross section calculations for $^{73}Zn(n,\gamma)^{74}Zn$. (Left) Cross section comparison between TALYS, CoH, and EMPIRE using default nuclear data input. (Right) Cross section comparison between the three reaction codes after accounting for differences in the treatment of input nuclear data.

A new technique was developed by researchers at Michigan State University and the University of Oslo, Norway to provide constraints on important neutron capture reactions. The technique already has been applied to neutron-rich isotopes in the mass 60-120 region in collaboration with multiple institutions, including Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL).

The SSAA grant enabled both supported graduate students, Rebecca Lewis and Debra Richman, to be placed at LANL for various periods of time to work closely with staff scientists investigating neutron capture reactions. Debra Richman, who now is permanently stationed at LANL, is working on constraining the neutron capture cross section of ^{59}Fe based on data taken at the National Superconducting Cyclotron Laboratory (NSCL). The reaction is of critical importance to producing ^{60}Fe, a signature of active galactic nucleosynthesis and one that can be measured directly with γ-ray telescopes. Debra also has participated in direct neutron capture measurements at LANL using the Detector for Advanced Neutron Capture Experiments (DANCE) array (see Figure 1). Rebecca Lewis is analyzing data from the mass 70-80 region to constrain neutron capture cross sections in Ni and Zn isotopes. She has experimentally constrained the ^{73}Zn neutron capture cross section and worked with LANL staff to quantify the systematic uncertainty associated with the choice of reaction code used to constrain the neutron capture cross section. The codes TALYS, CoH, and EMPIRE were chosen for the comparison and are shown in Figure 2. Only after accounting for differences in the treatment of the input nuclear data between the three models was it possible to obtain an error between the codes of a factor of two.

Malory Smith (a postdoctoral researcher funded on the SSAA award) was instrumental in implementing a new moving tape collector which allowed the use of the experimental system with short-lived thermal ion beams at NSCL. An experimental campaign was initiated in collaboration with Nick Scielzo and Darren Bleuel at LLNL to study the neutron capture cross sections critical to understanding the reaction network involved in the production of ^{95}Zr for stockpile stewardship. The data is part of a thesis project of Adriana Ureche (University of California, Berkeley). The studies will continue in the future, especially after the Facility for Rare Isotope Beams is completed, allowing access to even more exotic nuclear systems.

Planetary Materials Under Extreme Conditions

Washington State University ✦ PI: Dr. C.S. Yoo (csyoo@wsu.edu)

This Stewardship Science Academic Programs project's purpose is to investigate novel states and phase behaviors of simple low Z planetary mixtures over a large PT phase space (see Figure 1)[1] and to establish comprehensive understandings of extreme material behaviors that go beyond simple thermodynamic constraints to kinetics, chemistry, diffusion, miscibility, opacity, and dense interfaces. This project is important for the Principal Investigator to provide graduate students significant hands-on research opportunities with cutting-edge high-pressure science and technologies at Washington State University, synchrotron facilities, and National Nuclear Security Administration (NNSA) laboratories; to develop collaborations with outstanding scientists at NNSA laboratories; and to establish a robust workforce pipeline to Department of Energy (DOE)/NNSA national laboratories with the necessary skills, knowledge, and education. In the past year, this project has resulted in eight technical publications, a new PhD who now is working at the Sandia National Laboratories, and has supported the research of three graduate students and one postdoctoral fellow.

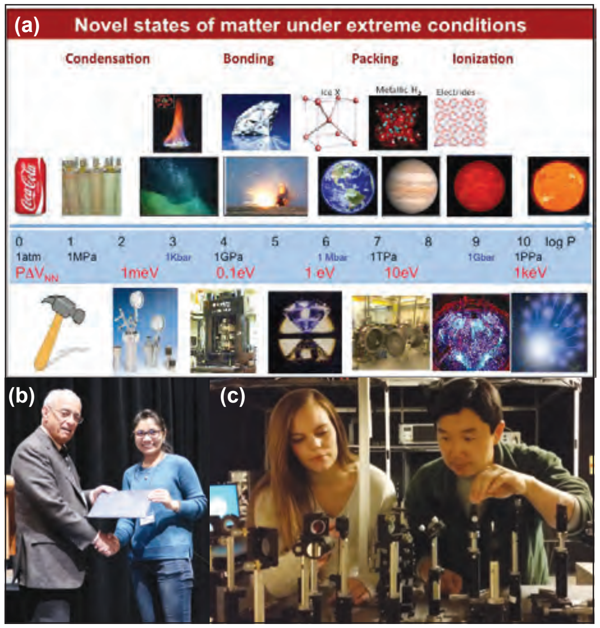

Figure 1. (a) Novel states of matter at extreme planetary conditions (b) Ms. Duwal (WSU) receiving a best poster award from Dr. Michael Kreisler at the 2018 SSAP Symposium in Bethesda, Maryland, (c) Dr. Lim (a postdoctoral researcher at WSU) and Ms. Thiessen (2nd-year graduate student at WSU) are setting up high-pressure Raman experiments.

Compression behaviors of dense H_2 and He are critical to understanding many body effects of these quantum solids, to develop new condensed matter theories, and to gain insights into the internal structures of Jovian planets. In support of this project, we now have completed the binary phase diagram of H_2-He mixture to 75 GPa (see Figure 2a).[2] The phase diagram consists of homogenous H_2-He mixture F (i.e., a fluid below 5 GPa), H_2-rich fluid (i.e., F_1), He-rich fluid (i.e., F_2), H_2-rich solid (i.e., S_1 and metastable S_1'), He-rich solid S_2 and S_3. The present phase diagram also emphasizes the formation of H_2-rich crystallite (S_1') in He-rich fluid mixtures and the structural phase transition in He lattice (from the S_2 to the helium rich solid S_3) and indicates the phase separation of homogeneous H_2+He mixture (F) into two immiscible fluids (F_1 and F_2) in the narrow pressure region between ~5.0-6.5 GPa. Clearly, the S_1' phase is metastable, formed by faster diffusion of solid H_2 crystallites in fluid He and, once it formed, exists at least to 75 GPa. The Raman vibrational data also indicates a significant level of mixing between H_2 and He even in solids, giving rise to new vibrational bands in He-rich solid at ~2,400 cm^{-1} for H-He stretching and 140 cm^{-1} for the lattice phonon of H_2 incorporated *hcp*-He. Therefore, the present result signifies unexpected, miscibility and strong chemical association between these quantum solids.

Whereas the presence of small miscibility between H_2 and He is not a surprise but driven by the entropy as defects always present in solids (even in He), their chemical reaction is rather unexpected considering the chemical inertness of He. This motivates us to investigate further the chemistry of He with other molecular systems such as N_2 abundant in Titan, a moon of Saturn. The main findings include the spectral evidences that He does react with a small amount of N_2 (~10% or less) to form novel helium nitride, as shown in Figure 2b. A series of microphotographs show the visual evidence for transformation to an optically dark phase upon the solidification of He, which occurs reversibly. The optical darkness likely is due to the scattering of lights by small nm-particles of nitrogen. The Raman spectra, on the other hand, show N_2 vibrational frequency at ~2,400 cm^{-1} characteristic to nitrogen-rich Van der Waals solid, $He(N_2)_{11}$, i.e., a solid held together by the weak Van der Waals force a solid He as well as an interesting peak at ~1,600 cm^{-1}, which is weak at 24 GPa but becomes strong at 56 GPa. The latter peak likely is from N-He and/or N=N, both of which indicate the occurrence of chemistry between He and N_2 impurities. Furthermore, the distinctive phonon features below 500 cm^{-1} signify the formation of novel helium-nitrogen compounds which become dominant in the Raman spectra at high pressures. Therefore, these results advocate many unexpected phase and chemical behaviors of He mixtures with molecular impurities to be uncovered.

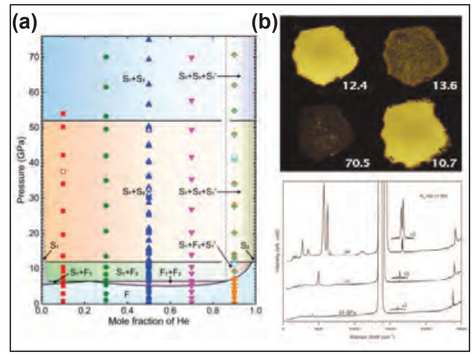

Figure 2. (a) The binary phase diagram of H_2 and He. (b) 1% N_2 in He mixture showing unusual chemistry of He with N_2 impurities (b) Microphotographs (top) and Raman spectra (bottom) of 1% N_2 in He at several pressures.

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Extreme Condition Mechanical Testing of Additively Manufactured Materials Using Complementary Methods

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This research is aimed at studying the extreme condition deformation of additively manufactured (AM) alloys in comparison with conventional cast-wrought (CW) alloys. High-speed machining is used as a mechanical test. Measurements of the forces, strain rate, and temperature are coupled with analytical models and finite element analysis (FEA) to infer constitutive models for AM and CW nickel-based superalloy IN 625 under extreme conditions of strain (> 100 %), strain rate (> 10^4 s^{-1}) and temperature (> 1,000 °C). Results at lower strain rates and temperatures are validated by comparison to those from Kolsky bar compression tests. This research project began two years ago and partially supports three PhD students.

This is one of the first studies that have begun reporting high strain rate constitutive models for AM alloys and has the potential to inform material selection for use under extreme conditions. Machining is a key finishing process for AM parts. By improving machining industrial productivity would be increased. Several students have received training on advanced mechanical characterization techniques, including high-speed photography, digital image correlation (DIC), infrared (IR) thermography, metallography, and FEA. The PIs and students are developing highly instrumented setups similar to the one depicted in Figure 1, and plan to use these at the Advanced Photon Source (APS) for *in-situ* observations of the microstructural response under extreme conditions.

Figure 1.High speed linear cutting set up with pulsed laser illuminated ultra high speed camera.

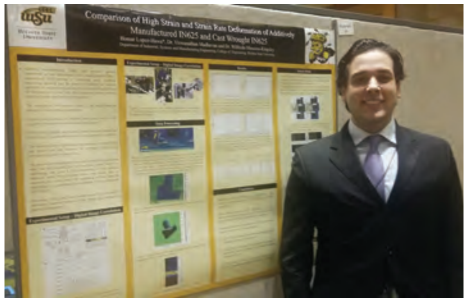

Figure 2. PhD Student Homar Lopez-Hawa presenting his poster at the NNSA SSAP Symposium held in February 2018.

AM is attractive particularly for manufacturing high-value products having intricate geometries from high-strength alloys such as IN 625.[1] However, their mechanical response to extreme loading conditions needs to be characterized in order to inform their use in high-performance nuclear and aerospace applications. The strain rate field in the primary shear zone (PSZ) is measured using DIC of high-speed image sequences, and the temperature field is measured by near-IR thermography. Measured cutting forces are used to estimate flow stress using analytical process models, under the measured strain rate and estimated temperature field in the PSZ. Constitutive model parameters are fine-tuned by comparing finite element simulations to experiments.

Under quasi-static conditions, the AM IN 625 is stronger and less ductile than the CW IN 625. In Kolsky bar tests under a wide range of temperatures up to 1,000 °C, strain up to 25%, and strain rate up to 2500 s^{-1}, AM IN 625 shows significantly higher yield strength, lower strain hardening, and lower ductility than CW IN 625.[2] In contrast, in machining tests at higher strain rates of the order of 10^4 s^{-1} and strains of the order of 100% under compressive hydrostatic stress, AM material shows a slightly smaller flow stress. It also shows a higher degree of shear banding, indicative of lower hardening and lower ductility. Metallography of chips produced shows that under the same cutting conditions, AM IN 625 shows large variations in shear band spacing, whereas CW IN 625 shows a more periodic pattern. This suggests that shear bands may be initiated by microvoids within the AM material[3] that are known to arise from pores in the powder feedstock and due to incomplete fusion of the powder.[4] The presence of a deleterious nickel-niobium phase that sometimes forms during the synthesis and post-deposition heat treatment of the alloy[5] also may be contributing to the shear localization. FEA with the best-in-class simulation software for machining does not show shear banding under some conditions where shear banding is observed in experiments. This indicates that the material model needs to be improved, perhaps by including ductile damage that leads to strain softening.

Some of these findings were reported at the SSAP Symposium in 2018 (see Figure 2). These findings are significant for designing AM materials for use under extreme conditions, i.e., strain in excess of 100 %, strain rate in excess of 10^4 s^{-1}, and temperature in excess of 1,000 °C. Under such conditions, an apparently stronger AM component may fail catastrophically by adiabatic shear banding.

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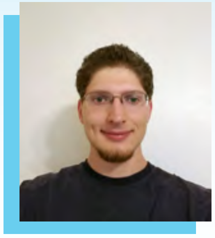
Tom Byvank, Los Alamos National Laboratory (tb395@cornell.edu)

LANL: 07/2018 to Present ✦ **Degree:** PhD, Applied and Engineering Physics, 2018 ✦ **SSAA Program:** 2013-2018, Cornell University



I am a postdoctoral research associate at Los Alamos National Laboratory (LANL) in the P-24 Plasma Physics Group. I am working on the development of a nuclear-fusion concept called plasma-jet-driven magneto-inertial-fusion, sponsored by the DOE Advanced Research Projects Agency–Energy (ARPA-E). In this concept, an imploding plasma liner (spherical shell) compresses a magnetized target to fusion conditions. Both the target and liner are produced by the merging of supersonic plasma jets (directed flows), and each jet is generated by a pulsed coaxial plasma gun. The merging of discrete jets forms shock structures that seed nonuniformities in the liner. I am developing diagnostics to experimentally characterize these nonuniformities which may degrade the eventual target compression. These diagnostics include schlieren imaging, spectroscopy along multiple radii, and pressure sensors. Additionally, I am conducting simulations using a multi-physics radiation magnetohydrodynamics code (FLASH) which includes adaptive mesh refinement that permits the study of these shock structures and their consequences in two- and three-dimensions. Furthermore, using both experiments and FLASH simulations, I am exploring how to create a magnetized target by merging pre-magnetized plasma jets. The merging jet experiments also are providing data for studies of fundamental shock physics, including understanding the structures (thicknesses, temperatures, and densities) of multi-ion-species shocks, sponsored by the DOE Office of Fusion Energy Sciences. Projects such as this attract people like me to LANL, where we will likely go on to contribute to important national security missions.

Figure 1 shows me placing a shorting stick on a discharged capacitor bank next to the three-meter-diameter chamber of the Plasma Liner Experiment (PLX). At present, seven pulsed coaxial plasma guns are mounted on the chamber. The seven guns allow for studying the merging jets and formation of a section of the liner. As planned, a total of 36 plasma guns will be installed around the full 4π steradian spherical chamber.

Figure 1. Postdoctoral research associate Byvank working with the Plasma Liner Experiment.

Prior to becoming a postdoc at LANL, I was a graduate student supported by Cornell University's Stewardship Science Academic Alliances Center of Excellence. Secondarily to the awesome coworkers, the aspect I most enjoyed about my graduate school experience was the chance to perform hands-on, pulsed power experiments and concurrently run an extended magnetohydrodynamics simulation (PERSEUS) to learn about fundamental physical processes. During one summer as a graduate student, I had a wonderful time interning at Sandia National Laboratories in the High Energy Density Experiments group. Along with analyzing results of instability growth rates from experiments conducted on the Z machine, I got exposure to running a magnetohydrodynamics simulation (ALEGRA) on the Sandia supercomputers which is now directly applicable to the simulation part of my present postdoctoral work. The summer internship was an excellent opportunity to better appreciate the large collaboration efforts needed to conduct “big science” experiments.

The Stewardship Science Academic Programs facilitates engaging learning experiences by providing the resources and expertise necessary to conduct challenging scientific research. These learning opportunities include attending conferences, interacting with national laboratories, and understanding the context of science in relation to national security and stockpile stewardship. National laboratories are productive environments to collaborate with creative and intelligent teams of researchers. These collaborations explore exciting scientific problems. As a researcher at a national lab, I am afforded a fruitful combination of the freedom to problem solve and a goal-oriented mission, both of which motivate me to engage in fundamental and applied scientific inquiry.

Patrick L. Poole, Lawrence Livermore National Laboratory (poole11@llnl.gov)

LLNL: 09/2016 to Present ✦ **Degree:** PhD, Physics, 2016 ✦ **SSAA Program:** 2009-2016, The Ohio State University

My initial involvement with Stewardship Science Academic Alliances Program-related experiments came in graduate school building the 400 TW upgrade to the short-pulse Scarlet laser at The Ohio State University. Systems like this can create relativistic plasmas relevant to the high energy density regimes produced on longer pulse, greater energy systems like OMEGA at the University of Rochester Laboratory for Laser Energetics, and the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). One benefit to the short pulses systems is a much higher shot rate, and my graduate work focused on developing a target apparatus that could produce automatically aligned targets at rates nearing 1 Hz. This enables new high-repetition-rate lasers to finally be used at those speeds, as well as providing variable target thicknesses to tailor the laser plasma interaction such that the resulting energetic particle beams can be optimized for the desired application.

As part of this work, I was fortunate enough to travel to many laser facilities in the United States and abroad to perform plasma physics experiments and, as a result, I gathered significant knowledge about the breadth of both laser system and experimental diagnostic designs. Learning common pitfalls and the individual intricacies of the systems of my colleagues led me to an interest in pushing laser and experimental capabilities to their limits. It's no surprise that my efforts at LLNL have centered around extending laser-plasma interactions to atypical regimes.

Along those lines, I now work on a NIF experiment that studies the limits of cross-beam energy transfer (CBET). This is a process by which energetic laser beams that intersect within a plasma (as the 192 NIF beams do just as they approach the target) will interchange energy between one another using ion waves within the plasma as a transfer medium. This effectively ruins the symmetry painstakingly prepared by initial laser conditioning, creating an asymmetrical fuel capsule implosion with lower resulting energy output. Significant effort went into the mitigation of this effect, including shifting the wavelength of sets of beams to tune them away from resonance with the plasma ion wave.

It was surmised that this effect also could be harnessed to intentionally transfer energy between beams and, thereby, create a "plasma optic" for beam combination that would result in a more powerful laser pulse than from conventional amplification. To this end, the beam combiner experiment consists of a gas plasma initially irradiated by 40 NIF beams to generate appropriate density and thermal uniformity. Figure 1a depicts this plasma ball target being subsequently irradiated by pump lasers such that they intersect with a single seed beam to be amplified. Here we use the wavelength tuning initially developed to mitigate CBET instead to enhance the resonant transfer of energy to the seed beam. The ultimate intensity is measured using x-ray emission from a Ta witness plate above the plasma, with separate beams impacting this directly without traveling through the combiner plasma to serve as a calibration.

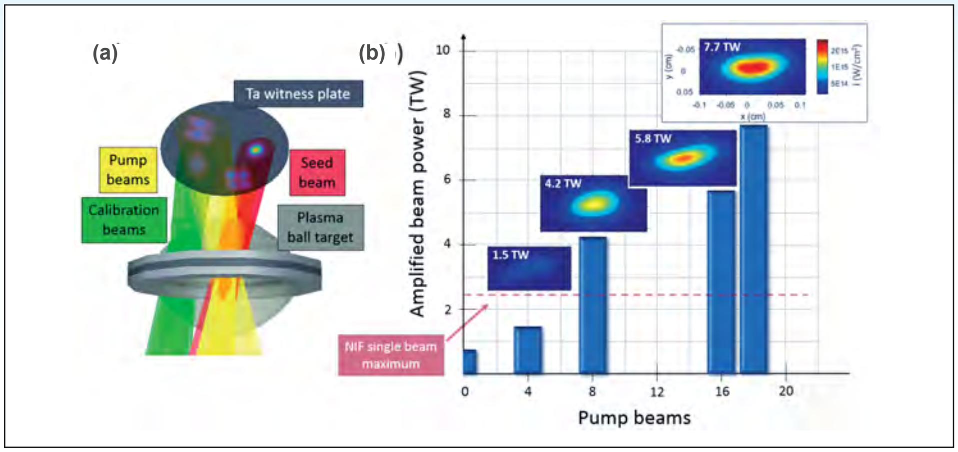


Figure 1: (a) Beam combiner experimental platform consisting of a plasma ball target and a Ta witness plate above which irradiates x-rays dependent on the intensity of the beams striking it. A variable number of pump beams intersect the trajectory of a single seed beam within the plasma ball to transfer energy. (b) Amplified seed beam power as a function of pump beam number, culminating in an enhancement of over 10x with 18 pump beams. The resulting ~8 TW seed beam is several times higher than the maximum possible from an individual NIF beam and constitutes the most powerful 1 ns beam ever created.

The history of beam combiner performance is shown in Figure 1b, where the number of pump beams (each with ~3 kJ of initial energy) has been increased over time to enhance the amplification of the single seed beam. The current record is nearly 8 TW of seed power with 18 pump beams, an amplification of more than 10x resulting in the most powerful 1 ns beam ever produced.

Whereas the geometry and beam capabilities on NIF necessitate this being a low efficiency energy transfer, it has the immense benefit of amplification using a plasma rather than a conventional optic where pump energy is limited by the damage threshold of that material. The plasma beam combiner, therefore, can accommodate much greater pump energies than demonstrated so far. Future work aims not only to increase pump energy on the 1 ns seed beam but also to amplify a much shorter seed pulse; this will generate a high intensity beam possibly beyond that currently achievable by conventional laser systems. This would also provide a crucial step toward unlocking long-sought applications of energetic particle beams for applications from novel fusion techniques to hadron cancer therapy.

Christopher Seagle, Sandia National Laboratories (ctseagl@sandia.gov)

SNL: 11/2011 to Present ✦ **Degree:** PhD, Geophysics, 2009 ✦ **SSAA Program:** 2005-2009, University of Chicago

I participated in the Stewardship Science Academic Programs through the Carnegie/DOE Alliance Center (CDAC), a DOE/NNSA Stewardship Science Academic Alliances (SSAA) Center of Excellence, during my graduate work at the University of Chicago from 2005-2009. In addition to financial support, CDAC provided routine access to partner time on a dedicated high-pressure beamline, the High Pressure Collaboration Access Team, at the Advanced Photon Source, an x-ray synchrotron user facility. This access was critical to my dissertation project on the behavior of iron and iron alloys at extreme conditions. Another unique benefit of the SSAA program was being able to participate in yearly reviews, showcasing my work and interacting with NNSA federal and laboratory staff. These meetings facilitated personal relationships that were instrumental in obtaining employment at Sandia National Laboratories (Sandia) beginning in 2011.

Figure 1. Left: Gas gun target with glass samples before impact at the SNL DICE Facility. Right: Target 100 microseconds after impact by a 350 m/s projectile.

I was attracted to Sandia because of their amazing facilities, the group of physicists I would be working with, and the admirable reputation of the Sandia dynamic materials program of delivering data at the highest levels of academic integrity. I worked as technical staff in the Dynamic Material Properties Department at Sandia from 2011 to mid 2018. In this role, I was fortunate to be able to conduct experiments on Sandia's Z Pulsed Power Facility, colloquially known as the Z machine. Z is the country's largest pulsed power machine utilized for a variety of stockpile stewardship applications, including materials research at extreme conditions. The machine can deliver energy to a target in a very controlled fashion, which enables unique dynamic loading paths, e.g., isentropic compression and the probing of material response on high temperature isentropes has been a major area of my research at Sandia. I have also led and been involved in many dynamic compression studies involving gas gun facilities at Sandia supporting a variety of national security missions. Unique drivers, advanced diagnostics, an excellent team of coworkers, and supportive management at Sandia have contributed to my successes and have resulted in a fulfilling career that includes accomplishments which have real impacts on national security.

Many current collaborators of mine were met through or participated in the SSAP. The SSAP has facilitated the technical growth of many individuals, including me, now employed at the NNSA national laboratories. The support of this program has enabled continued development of critical skills of the next-generation of scientists that are required within the NNSA complex.

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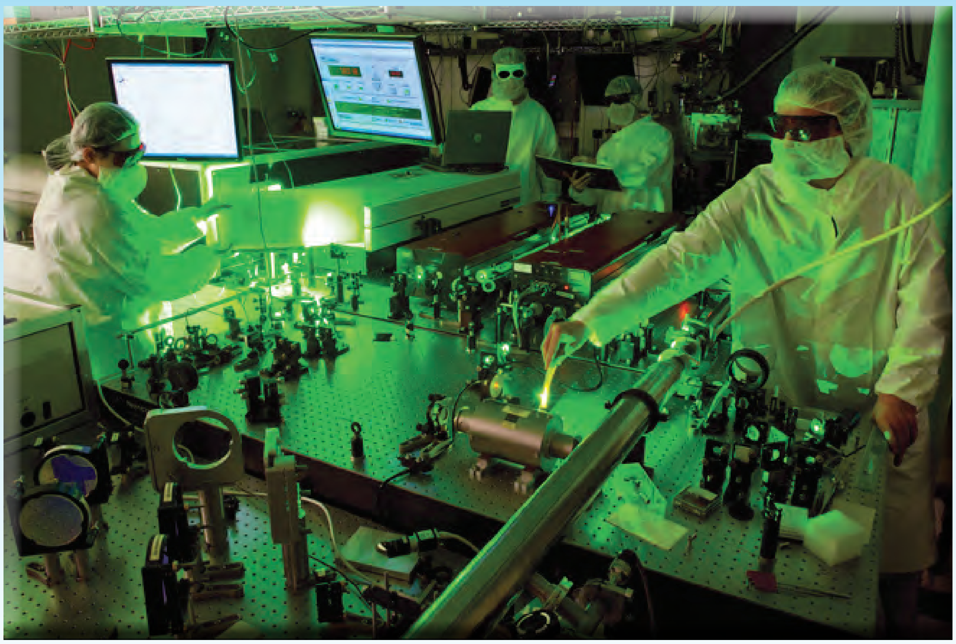
In mid-2018, I was promoted to Manager of the Dynamic Material Properties Department at Sandia. This position includes line management responsibilities for approximately 12 physicists and several supporting technicians, as well as programmatic management of the dynamic materials program at Sandia which includes defining the scope of work at Z and gas gun facilities in support of the science campaigns within the Stockpile Stewardship Program. Although still new to me, this leadership opportunity has been enormously rewarding both in terms of the deeper understanding of how our work relates to the national program, and being involved in a large variety of projects on which the Dynamic Materials Department staff at Sandia work. Current thrusts are the development of new diagnostics for Z (x-ray diffraction and infrared temperature measurements), more enabling containment systems and configurations for hazardous materials work, and providing high fidelity equation of state information on many materials of interest, which range from low Z gases to high Z metals.

Many current collaborators of mine were met through or participated in the SSAP. The SSAP has facilitated the technical growth of many individuals, including me, now employed at the NNSA national laboratories. The support of this program has enabled continued development of critical skills of the next-generation of scientists that are required within the NNSA complex. I highly recommend that anyone interested in the SSAP, or work within the national laboratory system, apply for one of the graduate fellowships or participate in an individual grant or DOE/NNSA Center of Excellence. The community that has emerged from this program has opened many doors for me and will surely provide opportunities for many others in the future.



High Energy Density Laboratory Plasmas

Laser Scattering from Strongly Magnetized Dense Plasmas

Princeton University ✦ PI: Dr. Nathaniel J. Fisch (fisch@princeton.edu) ✦ Co-authors: Yuan Shi and Hong Qin

A key question addressed in this Stewardship Science Academic Programs project was how strong magnetic fields affect collective laser scattering in plasmas. There is interest in this both for inertial confinement fusion and for novel techniques for amplifying laser pulses.[1] This effort was an important part of the PhD thesis of Dr. Yuan Shi, who received his PhD from Princeton University in 2018 and is now a Lawrence Postdoctoral Fellow at Lawrence Livermore National Laboratory.

Magnetic fields can affect laser scattering when the electron gyrofrequency is no longer negligible when compared to the laser frequency. For optical lasers, this happens for mega gauss fields which either can be generated spontaneously due to azimuthal asymmetries or imposed externally to enhance particle confinements. Unlike in unmagnetized plasmas for which Langmuir waves and acoustic waves mediate Raman and Brillouin scattering, what now mediates collective laser scattering are the magnetized plasma waves, including the hybrid waves, the Bernstein waves, and the magnetohydrodynamic waves. These magnetized plasma waves are highly anisotropic and substantially can change how lasers are scattered when plasmas become magnetized.

A simple formula for the scattering strength at an arbitrary angle is valuable for both understanding and designing implosion experiments. The analytic formula can provide coupling coefficients in reduced models, such as radiation hydrodynamics, which then can be used to model implosion experiments. However, no such simple formula was available for magnetized plasmas, at least not for general geometry, due to the analytical difficulty when background magnetic fields are present. Only special cases in which the incoming laser and scattered electromagnetic wave propagate either parallel or perpendicular to the magnetic field were treated. These special cases are but an incomplete subset for laser-driven implosion experiments for which multiple laser beams propagate at angles with respect to each other and the background magnetic field. However, by systematically solving the fluid-Maxwell's equations to the second order, a simple but general formula for laser scattering in magnetized cold-fluid plasma now has been obtained.[2]

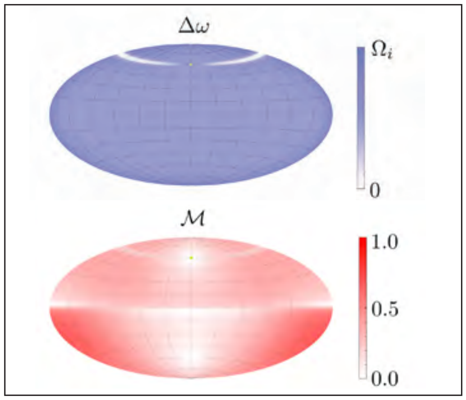


Figure 1. Frequency (upper) and intensity (lower) maps of the scattered electromagnetic waves. Incident laser (marked by the green dot) is scattered from the lower-hybrid wave in a magnetized hydrogen plasma target, placed at the center of the sphere.

Once the incident laser parameters are specified, the analytical formula can be evaluated to compute the frequency and intensity of the scattered electromagnetic wave. For example, in a magnetized hydrogen plasma, the incident laser can be scattered from the lower-hybrid wave. In Figure 1, the incident laser propagates in the direction marked by the green dot, and two maps of the scattered electromagnetic waves are plotted, assuming the plasma target is placed at the center of the sphere. The upper panel is the frequency map, indicating the frequency downshifts of the scattered wave from the incident wave. The lower panel is the intensity map measured in units of backwards Raman scattering, which shows the scattered light at each latitude (θ) and longitude (ϕ). Unlike in unmagnetized plasmas, where the scattering has simple angular dependence, scattering from the lower-hybrid wave, as well as other magnetized plasma waves, has a far more complicated angular dependency,[3] a previously unknown dependency that might now be exploited.

A key question addressed in this Stewardship Science Academic Programs project was how strong magnetic fields affect collective laser scattering in plasmas. There is interest in this both for inertial confinement fusion and for novel techniques for amplifying laser pulses. This effort was an important part of the PhD thesis of Dr. Yuan Shi, who received his PhD from Princeton University in 2018 and is now a Lawrence Postdoctoral Fellow at Lawrence Livermore National Laboratory.

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A Novel Study of Warm Dense Matter Using Hybrid PIC/MD Simulation Approaches Combined With Hybrid Ultrafast Diamond Anvil Cell-Based Experiments

The Ohio State University ✦ PI: Dr. Douglass Schumacher (schumacher.60@osu.edu) ✦ Co-Authors: Drs. Wendy Panero and Enam Chowdhury

Warm dense matter (WDM) is a material regime for which electrostatic and thermal energy scales are comparable and includes solid density matter at temperatures up to 10 eV. WDM lies in between the condensed matter and ideal plasma states, incorporating the complexities of both. This makes understanding WDM a key challenge in high energy density laboratory plasmas (HEDLP). Important examples where WDM occurs are during laser damage, in planetary interiors, and during inertial confinement fusion. We are developing new computational and experimental tools to use ultrashort laser pulses to drive extreme laser-matter interactions to create and characterize WDM.

This research program, which just got underway in late 2018, uses a novel, coupled experimental and computational approach. We have developed a particle-in-cell (PIC) simulation method that, motivated by molecular dynamics simulations, incorporates atomic pair-potentials to more realistically represent matter that is not in an ideal plasma state.[1] PIC codes excel at modeling plasmas by integrating Maxwell's equations and the Lorentz force law to obtain an *ab initio* model of plasma evolution. The inclusion of pair potentials permits representation of a system that can heat, melt, flow or ablate, and freeze while still preserving the ability of PIC to handle relatively large systems over time.

Figure 1 shows the crater found by a simulation of copper heated by an ultrashort pulse laser during which the WDM state was reached, followed by subsequent ablation and crater formation. The simulation followed the evolution over six orders of magnitude in timescale (from femtosecond to nanosecond) and with nanometer resolution on a several micrometer spatial scale. We obtain reasonable quantitative agreement with experiment as shown in the figure. One goal of this project is to heat larger systems and to employ time-resolved diagnostics to better benchmark and extend our model.

The experimental program begins with a study of microexplosions in free standing targets to develop single-shot, time-resolved diagnostics. One diagnostic will use frequency domain holography which employs a pair of delayed chirped, ultrashort pulses with the target excitation timed to occur between them. Measurement of the interference of the chirped pulses can be used to recover the evolution of the system. From free-standing targets, we will progress to targets with an embedded material such as Ni in MgO disks, and finally to laser heated targets in diamond anvil cells (as shown in Figure 2) for excitation of static compressed targets. Work is beginning with our >3 mJ, 40 fs short pulsed laser system to develop the experimental apparatus and will ultimately move to the use of the 10 J, 30 fs OSU Scarlet laser (see Figure 3).[2]

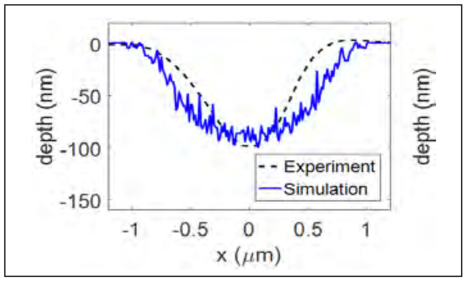

Figure 1. Results of a PIC simulation incorporating atomic pair potentials showing crater depth versus transverse position on a copper surface for an 800 nm, 40 fs, 5.5 J/cm² fluence pulse incident on the target. The laser-target interaction was modeled with sub-femtosecond resolution whereas the entire simulation occurs over two nanoseconds.

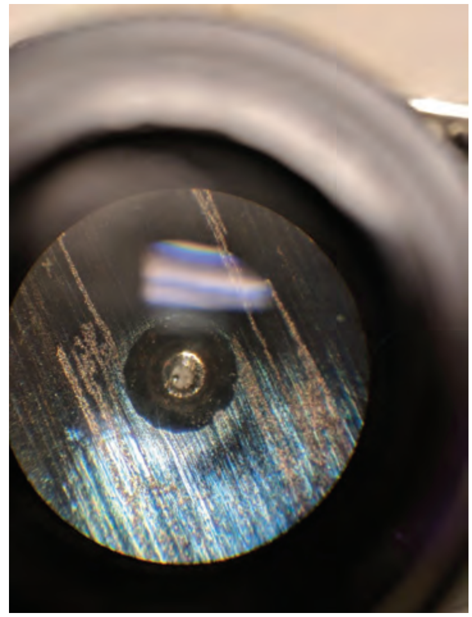

Figure 2. A sample loaded in a diamond anvil cell. The field of view is ~1 cm across and the center shows a 50 um sample at the tip of a 300 um diamond.

Figure 3. The Scarlet laser bay. Scarlet is now a part of LaserNetUS.

The Scarlet laser was constructed primarily with NNSA support, and our research program has been supported by Stewardship Science Academic Programs (HEDP) for five years. In that time, five NNSA-supported students have joined the national labs as postdoctoral fellows; two are now laboratory staff. These students wrote dissertations based on some combination of laser design and development, laser-based experiments, and PIC simulation studies. Two of these students have been featured in this annual review in past years, Dr. Sheng Jiang and Dr. Ginevra Cochran. There are only a few lasers operating near or at petawatt power levels at universities. The chance to work with Scarlet combined with continued interaction with leading scientists at the national labs has been a satisfying and productive experience for our students.

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Kimberly Schultz, Los Alamos National Laboratory (kimberlys@lanl.gov)
LANL: 01/2018 to Present ✦ **Degree:** PhD, Physics, 2017 ✦ **SSAA Program:** 2012-2017, The University of Nevada, Reno

My career as an experimental physicist began as a graduate student at the University of Nevada, Reno (UNR) where I had the pleasure of working under Professors Victor Kantsyrev and Alla Safronova. The group focused on High Energy Density Laboratory Plasma (HEDLP) research in Z-pinch and laser-produced plasmas, and I was fortunate to participate in both experimental areas throughout my graduate career. Performed under the HEDLP award to UNR, the Z-pinch research investigated line emission from high-Z, multiply-ionized ions influenced by dielectronic recombination and polarization. I was heavily involved in collecting data and organizing the experimental setup on the UNR Zebra Generator, a 1-MA, 100-ns Z-pinch machine. In the Z-pinch realm, I studied the x-ray temporal characteristics of molybdenum and silver X-pinches for their prospects in spectropolarimetry.

Another part of my graduate research involved irradiating pulsed noble gas puffs with high-intensity lasers to create debris-free sources of radiation ideal for backlighting applications. I characterized the density and time evolution of the gas puffs with several optical techniques prior to laser irradiation studies at larger facilities. Those experiments required coordination with scientists at both the UNR Leopard laser and at Lawrence Livermore National Laboratory's Jupiter Laser Facility. Throughout the several experimental campaigns at both of these institutions and as the lead graduate student on this project, I learned how to design experimental runs and communicate with people of different disciplines to ensure the success of the campaign. While working at these facilities, I came to appreciate the teamwork and cooperation needed to be successful in experimental physics. This inspired me to search for positions at National Nuclear Security Administration national laboratories.

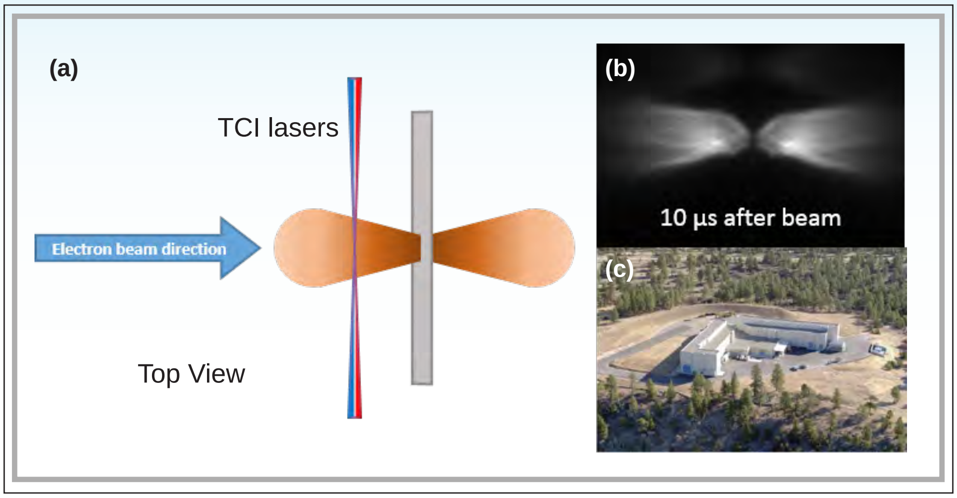

Figure 1. (a) Cartoon schematic of two-color interferometry (TCI) measurements of a plasma plume. The electron beam strikes the target from the left, creating expanding plasma plumes of both sides of the target. Then, two co-propagating laser beams pass through the plasma and measure its density. (b) Visible light emission from the plasma plumes on DARHT Axis II 10 µs after an electron beam pulse. (c) Aerial view of the DARHT Facility.

In January of 2018, I began work as a postdoctoral research associate at Los Alamos National Laboratory, where I work with the fantastic team at the Dual-Axis Radiographic Hydrodynamic Test (DARHT) Facility. The DARHT facility is the world's most powerful x-ray machine and is essential to national security efforts in the Stockpile Stewardship Program. It is comprised of two linear induction accelerators (Axis I and Axis II) that produce orthogonal electron beams: a single, 20-MeV, 85-ns electron beam and a 1.6-µs, 17-MeV beam, respectively. The longer pulse on Axis II provides the capability to kick out four, shortened pulses. After acceleration, the beams impinge on a converter target, creating bremsstrahlung x-rays energetic enough to penetrate extremely dense materials. This results in five high-quality radiographic images.

While creating the necessary x-rays, the electron beam-converter-target interactions also produce plasma plumes that propagate away from the surface. In multi-pulse radiographic machines like DARHT Axis II, the pre-existing plasma plumes interfere with subsequent pulses and cause degradation in beam quality and, therefore, radiograph quality.

Knowledge of the plume properties will allow us to mitigate their effects on the electron beam dynamics. My goal is to characterize these plasma plumes by designing a two-color interferometry (TCI) system (see Figure 1). Standard interferometry of HEDLP measures the free electron density of a plasma. However, they tend to have very high ionization states and the free electron density dominates the detected signals. In the plasmas created at the DARHT Axis II target, we observe fractional ionizations, meaning contributions from neutral atoms and ions cannot be neglected. The power of TCI is that it uses lasers of two wavelengths to simultaneously measure both neutral and free electron densities. This new diagnostic will allow the electron density, ionization, and shape of the plasma plumes to be measured as a function of time for various beam parameters. In addition, these measurements will explore high-brightness, electron-beam heating and propagation through plasmas.

National Laser Users' Facility

Dynamics of Magnetic Reconnection in High Energy Density Plasmas

Princeton University ✦ PI: Dr. A. Bhattacharjee (amitava@princeton.edu)

The recent generation of laboratory high energy density physics facilities has opened significant opportunities for experimentally modeling astrophysical plasmas. This project aims to study several processes important for converting energy and for energizing superthermal particle populations in astrophysical plasmas. This project has been active through the National Laser Users' Facility program since 2013, and the project supports an Associate Research Scholar at Princeton. Two graduate students in the Princeton University Program in Plasma Physics also participate in the projects.

The goal of this project is to study the fundamental dynamics and role of magnetic fields in these high energy density plasmas using newly developed facilities for applying strong (5-10 T) magnetic fields at the OMEGA EP laser facility plus newly-developed experimental techniques for generating and colliding magnetized plasmas. Simultaneously, the high energy available at OMEGA EP allows the generation of collisionless plasmas, for which ion mean-free-paths are larger than the system size. The experiments have studied the dynamics of supersonic plasma flowing through another magnetized, ambient plasma. Such systems are common in both space and astrophysical plasmas – including the interaction of the solar wind with the Earth's magnetosphere and the explosive expansion of supernova ejecta through the interstellar medium—and in terrestrial plasmas like those associated with the MagLIF fusion concept. These complex, strongly-driven phenomena can drive magnetic reconnection and collisionless shocks which are known to accelerate particles to high energies.

A typical experimental setup is shown in Figure 1. It consists of a set of coils to generate a magnetic field, a background target to generate an ambient plasma, and two piston targets to create the supersonic drive flows. First, an anti-parallel magnetic field is created which has opposite direction near each coil and goes to zero at the center. The background target is then irradiated by a laser beam, and the expanding plasma fills the region between the two piston targets and mixes with the magnetic field. Additional lasers then hit the piston targets ablating counter-streaming plasmas that expand through the magnetized, ambient plasma. The interaction is probed with angular filter refractometry (AFR) to measure two-dimensional (2D) images of density gradients and proton radiography to measure 2D images of the line-integrated magnetic field.

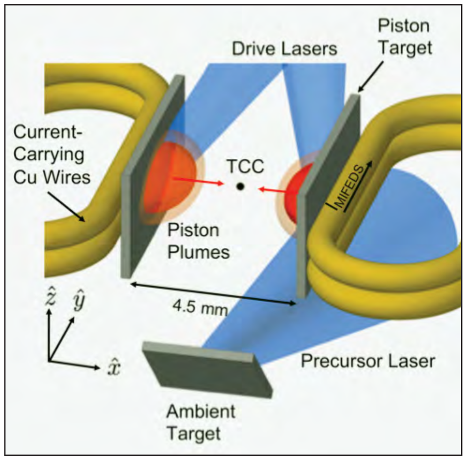

Figure 1. Setup at OMEGA EP for experiments with colliding magnetized plasmas showing expanding laser-produced plasmas. Copper wires wound near the targets carry electrical current driven by MIFEDS and generate 5-10 T magnetic fields during the experiments.

Depending on the time being probed, the experiments can study magnetized collisionless shocks or magnetic reconnection. At earlier times, before they meet, the two piston plasmas can drive shocks as they sweep up ambient plasma and magnetic fields like snow ploughs. A snapshot of this process is shown in the AFR image in Figure 2a. The two piston plasmas are expanding from the left and right edges of the image, and the wide colored arcs reflect the small density gradients associated with the bulk of the piston plasma. Ahead of these arcs are two very thin bands, representing steep density gradients that correspond to fast (high-Mach-number) moving shock waves. These were the first observations of fast magnetized collisionless shocks in the laboratory.[1,2]

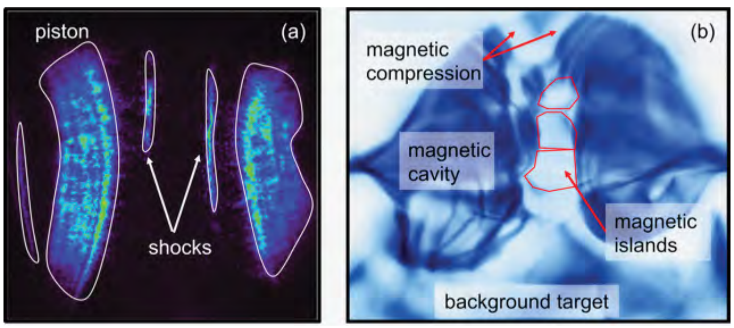

Figure 2. Experimental results showing (a) formation of magnetized shocks observed with angular refractometry of an optical probe beam; and (b) magnetic reconnection between colliding plasmas observed with proton radiography.

As the piston plasmas expand, they drag magnetic flux with them. Allowing them to collide results in magnetic reconnection, as the oppositely-directed fields violently annihilate. This can be seen in the proton radiograph in Figure 2b. Here, the dark blue regions represent high proton fluence and, thus, low magnetic flux consistent with the magnetic fields being dragged along by the piston plasmas. All that flux piles up at the edge of the plumes, resulting in the white ribbons surrounding the dark region. At the center, there is an extended area of mixed dark and light regions which indicates the onset of magnetic reconnection and the formation of magnetic islands (plasmoids). These were the first observations of plasmoids in laser-driven plasmas.[3]

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[1] D.B. Schaeffer, W. Fox, D. Haberberger et al., Physical Review Letters 119, 025001 (2017).

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[3] G. Fiksel, W. Fox, A. Bhattacharjee et al., Physical Review Letters 113, 105003 (2014).

[4] W. Fox, J. Matteucci, C. Moissard et al, Physics of Plasmas 25, 102106 (2018).

Development of a Photoionized Plasma Experiment at OMEGA EP

University of Nevada, Reno ✦ PI: Dr. Roberto C. Mancini (rcman@unr.edu)

We have been working on experiments at the Omega Laser Facility at the University of Rochester Laboratory for Laser Energetics (UR/LLE) with support from the National Laser Users' Facility (NLUF) program for over 15 years. Our first focus was on x-ray spectroscopy of inertial confinement fusion experiments at the OMEGA 60 laser, where we pioneered the extraction of the spatial distribution of temperature and density in the implosion core using many multi-color x-ray images. A key component of this project was the development of the multi-monochromatic x-ray imager (MMI) instrument, which is now a diagnostic used in many OMEGA campaigns by other users as well as UR/LLE scientists. Several students graduated with a PhD degree during this project: I. Golovkin (2000), Prism Computational Sciences; Leslie Welser-Sherrill (2006); XTD-IDA Group Leader at Los Alamos National Laboratory (LANL); Taisuke Nagayama (2010), Senior Staff Member at Sandia National Laboratories; Heather Johns (2013), Staff Scientist at LANL; and Tirtha Joshi (2015), postdoctoral researcher at LANL. Recently, our emphasis has been laboratory astrophysics and, in particular, photoionized plasmas. In this connection, we are developing a new experiment at OMEGA EP with the goal of achieving photoionization equilibrium in the laboratory for the first time. Two graduate students are involved in this effort: Daniel Mayes and Ryan Schoenfeld.

The NLUF program has allowed our group to design and execute high energy density science experiments at a world-class facility: the Omega Laser Facility. The opportunity of applying our theory and modeling capability on atomic and radiation physics to the interpretation and analysis of data is a transformational experience for my students since it shows them how theory connects with and can be tested by experiments. A spinoff of our research has been the development of a semester-long, graduate-level course on plasma spectroscopy that is broadcasted in real-time through internet, so students and postdocs at other institutions and NNSA labs can also benefit from it.

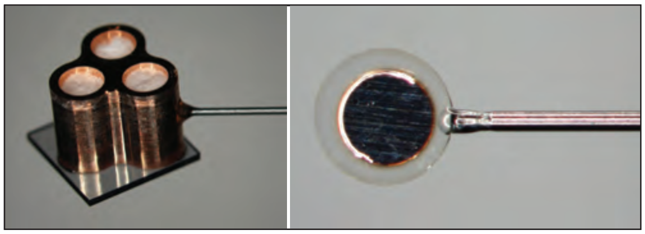

Figure 1. Photos of three-Cu hohlraum "Gatling-Gun" x-ray source (left) and plastic-tamped silicon microdot sample (right).

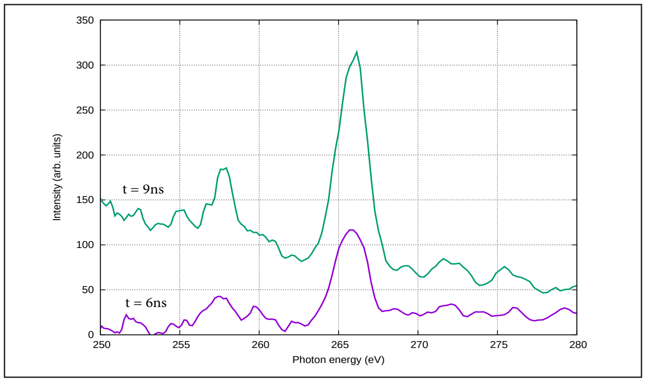

Figure 2. Photoionized silicon plasma self-emission recorded in OMEGA EP shot 26079. The spectral features at photon energies of 257 eV and 266 eV are due to L-shell line transitions in B-like and Be-like silicon ions.

Photoionized plasmas are widespread in space and found in many astrophysical systems, including active galactic nuclei, x-ray binaries, and the accretion disks surrounding black holes.[1] In these plasmas, the ionization is driven by photoexcitation and photoionization due to an x-ray flux characterized by a broadband distribution of photons. Yet, in spite of their astrophysical relevance, the increasing number of observations from orbiting telescopes, and the complexity of the astrophysics environment only a small number of laboratory experiments have been done under controlled conditions in order to test simulation codes and establish what physics models are needed to describe the plasma.

Previous work done by our group at the Z Pulsed Power Facility[2] with support from the joint HEDLP program has motivated the development of a new NLUF experiment at OMEGA EP. The setup uses a plastic-tamped silicon microdot driven by the 30-ns duration, broadband x-ray flux produced by the "Gatling-Gun" x-ray radiation source. This source is comprised of three copper hohlraums that are driven by three OMEGA EP beams, each delivering 4 kJ of UV energy in a 10 ns square pulse shape. The laser beams sequentially illuminate one hohlraum at a time, thus producing an x-ray drive characteristic of 90 eV radiation temperature for 30 ns. The silicon microdot has a diameter of 1 mm, and it is placed at a distance of 7 mm from the source. It has an initial thickness of 0.2 microns, and it is coated with two 1-micron-thick layers of plastic (see Figure 1). Heated by the x-ray flux, the silicon microdot expands and ionizes, thus producing a photoionized silicon plasma.

The plasma is probed with emission and absorption spectroscopy. The latter will be afforded by a 1-ns duration, titanium backlighter driven by the fourth laser beam of OMEGA EP. Figure 2 displays emission from line transitions in B- and Be-like silicon ions recorded at t=6 ns and t=9 ns. No measurable line emission in these ions is seen before t=6 ns. The x-ray flux starts at t=−15 ns and lasts until t=+15 ns. Hence, these observations were taken during the second half of the x-ray drive duration. This is reasonably consistent with pre-shot estimations based on radiation-hydrodynamics simulations. The spectra demonstrate the formation of a highly-ionized silicon plasma driven by the x-ray flux. The absorption spectroscopy will permit the extraction of the silicon charged state distribution and electron temperature, and it will test the photoionization equilibrium condition.

References

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[2] I.M. Hall et al., Phys. Plasmas 21, 031203 (2014).

Collaborators

Robert Heeter and David Martinez (Lawrence Livermore National Laboratory) and Sean Regan (UR/LLE).

Willow Wan, Los Alamos National Laboratory (willow@lanl.gov)

LANL: 08/2017 to Present ✦ **Degree:** PhD, Atmospheric, Oceanic, & Space Sciences, 2017 ✦ **SSAA Program:** 2010-2017, University of Michigan

I began my study of hydrodynamic instabilities in the high energy density regime while working on my PhD at the University of Michigan with Dr. R Paul Drake and Dr. Carolyn Kuranz supported by the Stewardship Science Academic Programs. These instabilities are mixing properties that allow a systems of fluids to rearrange themselves into a more stable state. A classic example of this is the Rayleigh-Taylor instability which occurs when a lighter fluid is pushing against a heavier fluid. This mechanism allows the heavier fluid to displace the lighter fluid beneath it until the two fluids swap positions (e.g., water settling beneath oil). Instabilities such as these remain poorly understood and are of interest to the stockpile stewardship and inertial confinement fusion (ICF) communities because they result in undesired mixing between hot fusion fuel and material from the surrounding capsule, which reduces the efficiency and subsequent energy yield of fusion reactions. The mitigation of these instabilities is essential to improving the performance of fusion experiments and achieving ignition.

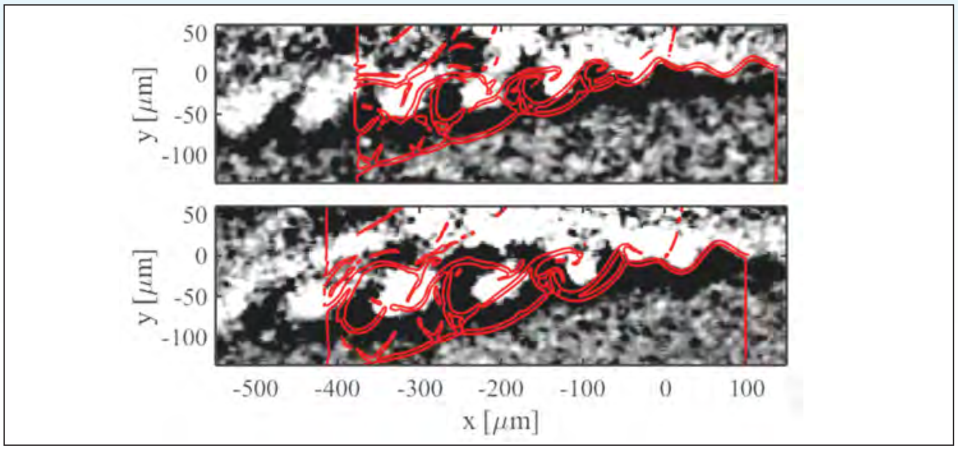

Figure 1. Vortex-merger and instability growth inhibition were observed in a compressible, dual-mode Kelvin-Helmholtz instability experiment. Contours from the simulations (red) are overlaid upon the contrast-enhanced data (black and white). Simulations performed by G. Malamud, Nuclear Research Center Negev (Israel).

My graduate research focused on the inhibition of the Kelvin-Helmholtz instability's growth rate in a compressible flow. The Kelvin-Helmholtz instability is a hydrodynamic instability that occurs when the fluid motion is parallel instead of perpendicular and enhances asymmetries and non-radial flow by creating intricate vortices. The SSAP provided me with the resources I needed to develop an experimental platform for the OMEGA EP laser facility that obtained the first measurements of the evolution of well-controlled and well-characterized, single-mode and dual-mode seed perturbations in a sustained supersonic flow. These experiments improved our understanding of the two core elements of the Kelvin-Helmholtz instability: single-vortex evolution and two-vortex merger. The experiments I performed through the SSAP's National Laser Users' Facility (NLUF) program were rare and unique opportunities to get a head-start on the world-class research performed at the national laboratories. These experiences allowed me to find mentors within the scientific community that I work with today and were crucial to training me for my responsibilities as a postdoctoral researcher.

Upon graduating, I took a postdoctoral research position at Los Alamos National Laboratory as a natural continuation of the research I performed as a graduate student. I continue to study the evolution and mitigation of hydrodynamic instabilities in fusion implosions by performing experiments primarily at the OMEGA 60 laser facility. These experiments are part of the Double-Shell campaign which focuses on the development of an alternative and complimentary capsule design for ICF experiments. This design sacrifices a higher potential energy yield in favor of producing a robust, reliable, and adaptable experimental platform for the study of plasma physics. I currently am working on a novel experiment studying whether hydrodynamic instability growth can be mitigated further through the use of material and density gradients. Although the theory suggests that these density gradients could be used to control the growth of problematic instabilities, these models do not account for more complicated effects of mixed materials such as mixed opacities and mixed equations of states. Now that a technique finally has been developed to produce these material-gradient shells, I am evaluating their efficacy in a series of simulations and planar experiments to study the relevant one-dimensional (1D) and 2D physics before incorporating them into a full capsule implosion. The skills I obtained through the NLUF program have been pivotal to my success as both a graduate student and as a postdoctoral researcher and have left me well-prepared to take on these roles as both the experimentalist and designer for this project.

"The experiments I performed through the SSAP's National Laser Users' Facility program were rare and unique opportunities to get a head-start on the world-class research performed at the national laboratories."

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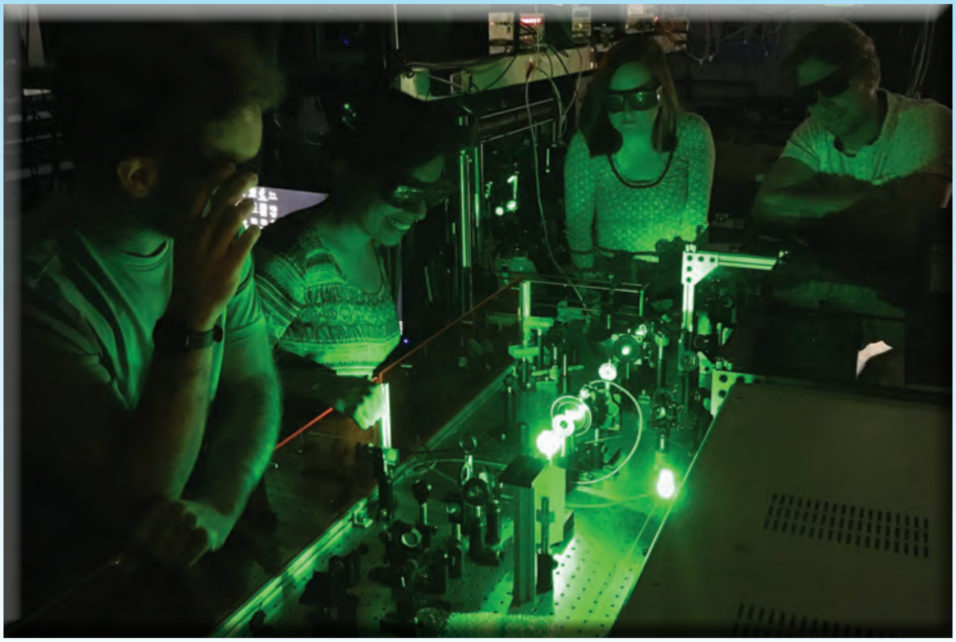


Students

Jason Hamilton (jmh566@cornell.edu)

SSAP: 2016 to Present ✦ **Degree in Progress:** PhD, Applied Physics, Cornell University, Advisor: Dr. Charles E. Seyler

Research Topic

Non-Equilibrium Transport with Moment Equations

Research Responsibilities

My graduate research involves further developing the PERSEUS code here at Cornell. Specifically, I am expanding the code to model non-equilibrium plasmas, which includes the presence of heat flow and anisotropic pressures. Traditionally, this code has been used to model plasmas where non-ideal effects such as electron inertia, resistivity, and the Hall effect are important. My work will extend this to include the physics of thermal conductivity, viscosity and thermoelectric forces such as the Nernst Effect, all of which are present in the High Energy Density plasma experiments being conducted at the national labs. The goal is to have a more sophisticated simulation of these experiments.

I am using the moment equations to model this departure from ideal plasma, which requires care when considering the pitfalls of this method, such as hyperbolicity, positivity, and entropy production. After having implemented the model into PERSEUS, I am now performing validation tests that predict the importance of including these additional physics.

Benefits of the SSAP

The most important impact the SSAP has had on my research is that it has introduced me to the larger community of high energy density plasma scientists, particularly at the SSAP annual symposium. Through connections made at the symposium, I have gained invaluable insight from leaders in my field from the national labs who continue to work with me on my research goals. My project now feels larger than a mere thesis and a piece of the larger field of computational plasma physics. The symposium also has exposed me to the research going on in the national labs, which not only gives my own research goals a stronger direction, but allows me to learn the techniques and strategies used when part of a large team of scientists which can differ greatly from working with a small group here at Cornell with fewer resources.

What Students Should Know

When many students first hear "stockpile stewardship" they may get the wrong impression of what that entails. From what I have seen, at the heart of the SSAP is basic science research that has applications to an incredible diversity of fields and specializations. Being part of this community gives you access to all the benefits that come along with that diversity.

Joseph Heideman (jheidema@vols.utk.edu)

SSAP: 2017 to Present ✦ **Degree in Progress:** PhD, Nuclear Physics, University of Tennessee, Knoxville, Advisor: Dr. Robert Grzywacz

Research Topic

Developing a Neutron Spectrometer for the Decay Station at the Facility for Rare Isotope Beams (FRIB)

Research Responsibilities

I am working on designing and building a neutron time-of-flight detector that utilizes state of the art scintillator and detector technologies. Beta-delayed neutron emitters are nuclei important for studying beta decay transitions, r-process calculations for rapid neutron capture, fission products for reactor control, and stockpile stewardship. When FRIB comes online, one of the major goals is to have developed a decay station that will improve past neutron emission measurements and explore the new regions of isotopes that currently are unavailable. NEXT (Neutron dEtector with Tracking) is designed around two new technologies: segmented detectors and plastic scintillator with neutron-gamma discrimination capability. I have been working on characterizing and improving the timing capabilities of this new plastic scintillators in conjunction with position sensitive detector readouts while also implementing pulse shape discrimination analysis. We currently are assembling the first prototype of segmented detector that will be coupled to a position sensitive PMT.

Benefits of the SSAP

This project has helped me develop a strong understanding of particle detection methods and how to measure nuclear decays. Having to design this detector from the ground up has shown me the steps needed to build a high precision detector, something I have never done before. Also, I have been able to work with detectors and equipment that will lay the foundation for future ground-breaking experiments. I will be able to apply what I have learned from this project towards future career endeavors. SSAP has given me numerous chances to display my research at the SSAP symposium and other conferences as well as to collaborate in developing a new, large scale detector array for ground breaking experiments at FRIB.

National Laboratory Experience

Currently, all NEXT research and development is conducted at Oak Ridge National Laboratory outside Knoxville, TN. Working at a national lab provides numerous resources and personnel with years of experience that have helped propel the development of NEXT. I received advice from many staff scientists concerning different pulse shape discrimination methods and performing fast timing with high-precision digital electronics. We now are building the first NEXT prototype and soon will use the neutron generator at the ORNL physics division to perform the first preliminary tests of neutron time-of-flight measurements with the detector.

Heath LeFevre (hjlefe@umich.edu)

SSAP: 2016 to Present ✦ **Degree in Progress:** PhD, Applied Physics, University of Michigan, Advisors: Dr. R. Paul Drake and Dr. Carolyn Kuranz

Research Topic

Producing Photoionization-Dominated Heat Fronts with Astrophysical Relevance in the Laboratory

Research Responsibilities

I conduct experiments on photoionization fronts at the OMEGA 60 laser and then analyze the data. This requires detailed design of the laser-irradiated target and selection of the appropriate diagnostic instruments. Each of the diagnostics require further consideration to ensure that the measurement geometry is correct and the signal is sufficiently above the background noise. I make initial-condition measurements of each target before they are destroyed in the experiment using an in-house optical camera system. For recent experiments, this meant designing a target that can produce a laser-produced plasma as a soft x-ray source incident on a gas cell. The goal is for the soft x-ray source to heat N gas such that photoionization dominates the heating at the interface of hot and cold gas. We infer the plasma parameters at the front from absorption spectra, produced when a small concentration of Ar atoms in the gas is irradiated by x-rays from an imploding plastic capsule. Following the analysis and interpretation of experimental data, I present posters at various conferences and write journal articles to communicate my results to the larger research community.

Benefits of the SSAP Program

Experiments for my work would not be possible, or at least much more difficult, without access to the OMEGA 60 laser facility at the University of Rochester Laboratory for Laser Energetics through the National Laser Users' Facility (NLUF) program. The NLUF program supplies funding for travel, targets, and personnel as well as time at the laser facility for my experiments. I had the opportunity to be a principal investigator on recent OMEGA 60 shot day through the NLUF program which provided data for my thesis and invaluable experience for a future career in high energy density physics.

National Laboratory Experience

I participated in two experiments at the Jupiter Laser Facility (JLF) at Lawrence Livermore National Laboratory (LLNL), through a collaboration with LLNL staff working on energy transport in underdense magnetized plasmas. I found working at JLF especially rewarding due to its dedication to training students. Being able to get hands-on experience with the operations of a kJ-class laser facility has been very helpful for understanding larger facilities such as OMEGA or the National Ignition Facility. The discussions and continued work with our LLNL collaborators have been useful not only as a physics resource, but also as an insight into the benefits of a career at the laboratories.

Erin Nissen (enissen2@illinois.edu)

SSAP: 2017 to Present ✦ **Degree in Progress:** PhD, Physical Chemistry, University of Illinois at Urbana-Champaign, Advisor: Dr. Dana Dlott

Research Topic

Liquids in Extreme Conditions

Research Responsibilities

I am interested in the fundamental properties of liquids in extreme conditions from explosive nitromethane to liquid water. We have developed a table-top shock compression apparatus that produces gigapascal pressures and thousands of Kelvin temperatures in nanoliters of material. Our experimental configuration allows us to employ a plethora of diagnostic techniques to probe questions such as the following:

- ✦ What is the mechanism of initiation for nitromethane to detonate? Can we manipulate this mechanically or chemically?
- ✦ How much does water dissociate upon single-shock compression? Can we use this super reactive water to do unique chemistry unachievable at standard conditions?

Benefits of the SSAP Program

I have benefitted from multiple aspects of the Stewardship Science Academic Programs (SSAP), through the Capital-DOE Alliance Center (CDAC) within the Stewardship Science Academic Alliances program and the Stewardship Science Graduate Fellowship (SSGF) program. Obviously, the financial support is incredible, and the ability to focus solely on research instead of teaching and grading responsibilities has allowed me to pursue multiple projects. CDAC and SSGF have provided travel funds for conferences, such as the annual SSAP symposium where I presented a poster in 2018. Another benefit was spending a summer at Sandia National Laboratories (Sandia) where I had the opportunity to interact and network with amazing scientists. I am unbelievably thankful for the chance to visit the impressive facilities at multiple DOE/NNSA laboratories and engage with other fantastic fellows and alumni.

What Students Should Know About SSGF

This program is amazing. You should 100% apply! Besides the financial support and networking opportunities, the depth and breadth of science I have been exposed to is certainly something I wouldn't have had the opportunity to experience otherwise. Also, all the fellows are really fun, and we always have a wonderful time together.

National Laboratory Experience

I spent three months working with Dan Dolan at Sandia performing experiments on THOR. This experience showed me how supportive and collaborative the national lab environment is, and I certainly enjoyed my time there. The scientific advancements taking place truly are inspiring.

Avery Samuel (asamuel@ucsb.edu)

SSAP: 2018 to Present ✦ **Degree in Progress:** PhD, Materials, University of California, Santa Barbara, Advisor: Dr. Frank Zok

Research Topic

Role of Heterogeneities in High Strain Rate Mechanical Response

Research Responsibilities

I am part of a collaboration investigating deformation of multiphase metallic materials due to loading at high strain rates. The materials of interest, produced by additive manufacturing and severe plastic deformation (e.g., ECAP), have exceptionally complex microstructures which leads to unconventional responses. Unlike single-crystal and single-phase materials, the dynamic deformation behavior of multiphase materials is related strongly to microstructural heterogeneities; interfaces and boundaries dominate the response. I will be planning and conducting experiments involving high strain rate testing with primary focus on the response at the macroscale as a complement to nanoscale measurements. Dynamic loading conditions, meaning strain rates of 10^2/s to >10^6/s, will be achieved with split-Hopkinson pressure bars, light gas guns, and lasers (for laser shocks). The information from these experiments will guide modeling efforts to identify and develop predictive capabilities for deformation mechanisms in these materials.

Benefits of the SSAP

Whereas I still am in the initial stages of my involvement, my participation in this program promises opportunities for communication with experts across academia as well as for collaborations at NNSA laboratories such as the testing capabilities at Los Alamos National Laboratory and the characterization faculties at the Advanced Photon Source. These interactions will help to expand and develop my research skillset. The collaborations also will expose me to a wider cross-section of the field and will broaden my basic knowledge of the associated science. Access to the specialists and advanced experimental facilities associated with this program would not be available to me without the SSAP.

Unexpected Collaboration Opportunities

The SSAP provides opportunities to collaborate that otherwise would not have been available. The program enabled the establishment of a center of excellence which brings together several leading universities and government laboratories from across the country. Although these institutions have complementary areas of expertise, the SSAP provided the requisite means and motivation to enable the undertaking of a project of this scale. This center establishes connections between these disparate groups and, as a part of the program, I will be in closer contact with members of these fields than if I had been performing similar work undertaken solely by UCSB. In addition to researchers well-established in the field, this program facilities interactions with graduate student researchers outside of my immediate group. Without the SSAP, we might have met only at conferences and not developed closer connections that this project will require.

Travis Volz (travis.volz@wsu.edu)

SSAP: 2014 to Present ✦ **Degree in Progress:** PhD, Physics, Washington State University, Advisor: Dr. Yogendra Gupta

Research Topic

Shock-Induced Graphite to Diamond Phase Transformation: Role of Initial Microstructure

Research Responsibilities

My PhD research is focused on understanding shock wave induced phase transitions. Specifically, I am working to understand the role of different initial graphite microstructures (crystallite size, crystallite alignment, and crystallinity) on the graphite to diamond phase transition under shock compression. In my research, I design, fabricate, conduct, and analyze planar shock experiments at two different locations. At the Institute for Shock Physics (ISP) at Washington State University, I use laser interferometry to determine the continuum response of each graphite type. Analysis of the experimentally-obtained wave profiles determines the transition stresses and sound speeds in the high pressure phase. At the Dynamic Compression Sector (DCS) at Argonne National Laboratory, the crystal structure of the shock-compressed graphite samples is probed in real time, using high-energy x-rays. By analyzing the x-ray diffraction (XRD) data, I have determined the lattice parameters just below the transition and have identified new crystal structures and lattice parameters above the transition. By combining the continuum and XRD results, I will address the following: how different initial microstructures affect the resulting high pressure phase and how microstructural properties govern the graphite to diamond transition mechanisms. Understanding how graphite microstructure affects the shock-induced phase transition could have significant implications for meteorite impact science and, more generally, for understanding shock-induced phase transformations.

Benefits of the SSAP

The SSAP has been invaluable to me as a graduate student. First, I have benefitted through its generous funding. It has helped to create the two world-class research capabilities (ISP and DCS) that I have been fortunate enough to use for my PhD research. Without these experimental capabilities, my research would not be possible. Hands-on involvement in experiments at these unique laboratories and access to the knowledgeable scientists and staff at each location has been an in-depth learning experience for each experiment type. The SSAP also funds my graduate research stipend and tuition. Lastly, the annual SSAP symposium and the funding allowing me to attend have been very beneficial. The symposiums and the interactions with researchers who attend them have opened my eyes to many other fields within stewardship science, a field I would like to remain in after earning my degree, likely within the year.

Predictive Science Academic Alliance Program II

STANFORD UNIVERSITY

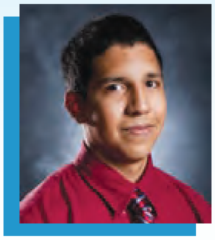
UNIVERSITY of FLORIDA

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

THE UNIVERSITY OF UTAH

Exascale Computing Engineering Center

Stanford University ✦ PI: Dr. Gianluca Iaccarino (jops@stanford.edu) ✦ Author: Hilario Torres (hctorres@stanford.edu)



Hilario Torres

PhD in Progress

Mechanical Engineering, Stanford University; Advisor: Gianluca Iaccarino

PSAAP

2014-Present

Research Topic

HPC Multi-Physics Solver Development for Particle-Laden Turbulence in a Radiation Environment

Research Objectives

The objective of the Stanford Predictive Science Academic Alliance Program (PSAAP) Center is to develop and demonstrate exascale computational tools to investigate the interplay of turbulence, radiation, and particle transport. The focus is on scenarios in which turbulence and particles interact strongly forming regions of preferential particle concentration, thus leading to non-uniform absorption of radiative energy and, therefore, to temperature gradients and buoyancy forces in the underlying air carrier. The Center seeks innovations in physical modeling, computer science and uncertainty quantification to enable predictive simulations of this process on next-generation supercomputers. It also includes a dedicated experimental campaign designed to validate the Center's predictions.

Research Responsibilities

The PSAAP Center at Stanford is focused on particle-laden turbulent duct flows subject to external thermal radiation for solar energy receiver applications. I am part of a team of researchers who are working to develop and deploy a high performance computing (HPC), multi-physics solver, Soleil-X, to investigate the physics associated with the Stanford PSAAP Center's target application. The novel aspect of Soleil-X is that it is being written entirely in a programming language that targets the Legion task-based parallel runtime. One advantage of Soleil-X is its portability because it does not explicitly require communication protocols (MPI) or special syntax for operating on graphics processing units and CUDA, a parallel computing platform. This means that we can move our solver from one HPC system to another without having to rewrite large portions of it to get performance. Another advantage is that it takes the burden of coordinating and balancing the computational load among processing units away from the application programmer. This is handled by the runtime using task analysis. My research is focused on the numerical methods that the solver uses, the solver structure, and task decomposition such that the code is both performant and maintainable and designing, running, and analyzing cases that are of interest to the PSAAP Center at Stanford.

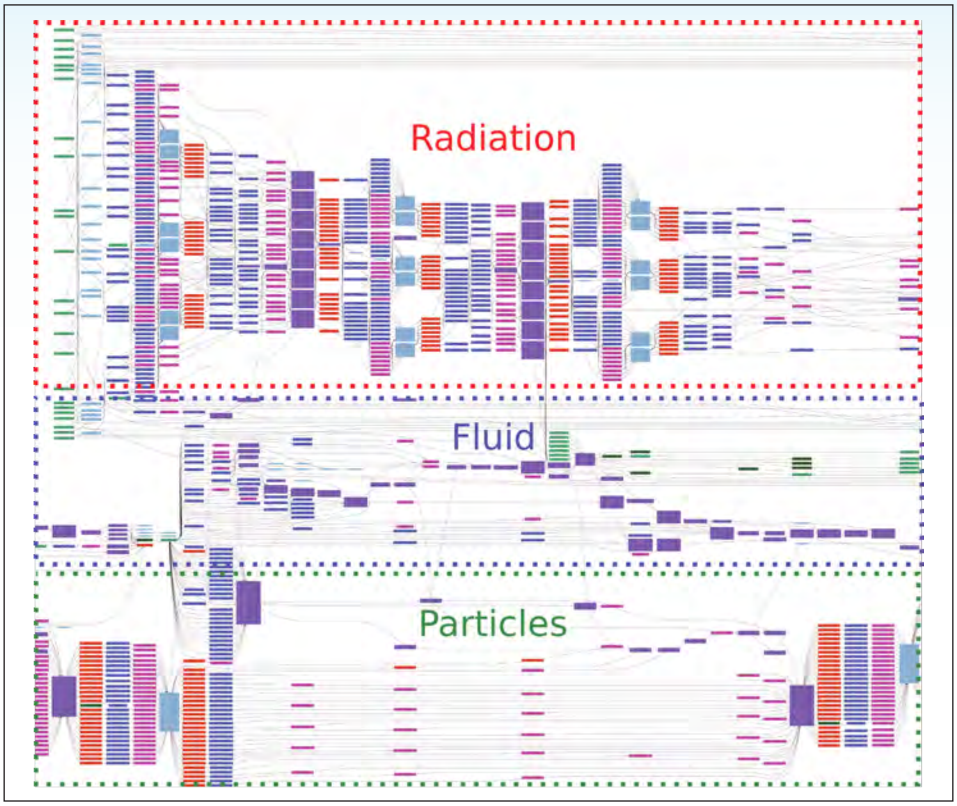


Figure 1. Legion task-graph for Soleil-X, an exascale solver for multiphysics simulations of particle-laden turbulent under radiation. The boxes correspond to different and concurrent software modules, while the lines correspond to data transfer and explicit task dependency.

Benefits of the SSAP

I have benefited from the Stewardship Science Academic Programs (SSAP) though its support of the PSAAP Center at Stanford which, in turn, supports my graduate studies. I also have benefited from the multidisciplinary research environment that the PSAAP Center at Stanford created due to SSAP support, particularly the close collaboration between the mechanical engineering and computer science groups on campus. My research also benefits from SSAP support though our access to various high performance computational resources, including the leadership computing facilities at Argonne (ALCF) and Oak Ridge (OLCF).

National Laboratory Experience

I participated in the 2017 Computational Physics Student Workshop at Los Alamos National Laboratory (LANL). While there, I worked with LANL researchers and computational tools to simulate Richtmyer-Meshkov instabilities, a problem that is quite different than my research at Stanford. The 10-week workshop also had an associated series of lectures, tours, and interactions with lab researchers. These activities gave me an understanding of the lab's mission, research focus, and people and highlighted the large overlap between the work that happens at LANL and my own current graduate research.

Performance Model for Parallel Particle-Transport Calculations

Texas A&M University ✦ PI: Dr. Jim Morel (morel@tamu.edu); Author: J. Dillon Herring

The Center for Exascale Radiation Transport (CERT) at Texas A&M works to improve the predictive capability of high-fidelity simulations of physical phenomena that include the transport of thermal radiation and/or other subatomic particles. CERT pursues many ingredients of improved capability, including solution algorithms that more efficiently use modern, massively parallel computers. The most time-consuming element of many widely used particle-transport methods is the transport sweep in which the particle intensity—a function of position, energy, and direction—is calculated given the most recent estimate for the collisional source. The intensity in a given spatial cell depends on the intensity entering from neighboring cells in the given direction which imposes restrictions on the order of calculations and implies that cells must communicate exiting intensities to their downstream neighbors. Such dependencies and communication requirements make parallel execution more difficult.

A parallel transport calculation in CERT's particle-transport code partitions the spatial domain across processors as directed by partitioning parameters. It aggregates spatial cells into cellsets, directions into anglesets, and energy groups into groupsets as directed by aggregation parameters. A single work unit during a sweep calculates particle intensities in a single cellset/angleset/groupset combination. At each stage of the sweep every processor with available work executes one work unit and communicates outflow intensities to processors responsible for adjacent downstream cellsets. The ingredients of the optimal sweep methodology developed by CERT in collaboration with the NNSA labs are: (i) a provably optimal scheduling algorithm which executes the sweep in the minimum possible number of stages for any given partitioning and aggregation factors; (ii) a performance model that predicts sweep time for that execution; and (iii) an algorithm that choses partitioning and aggregation factors that minimize sweep time. The

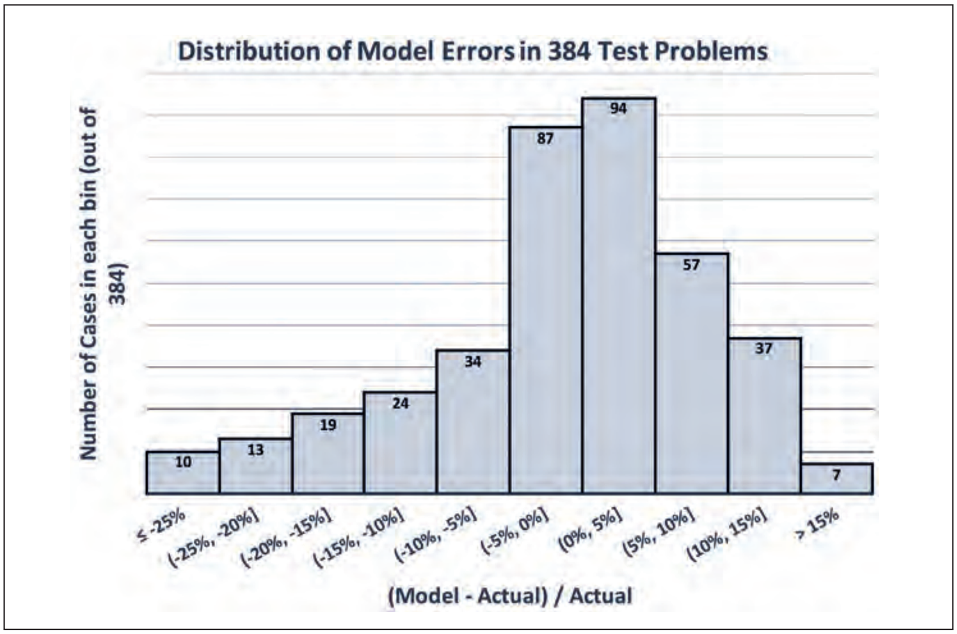


Figure 1. Distribution of relative errors in model estimates of sweep-execution times across 384 test problems.

performance model in this work has the form

$$T_{\text{sweep}} = N_{\text{stages}} \Big[T_{comm} + T_{wf} + A_{cell} \Big(T_{cell} + A_n \left(T_n + A_g \, T_g \right) \Big) \Big] \quad (1)$$

Here T_{wf}, T_{cell}, T_n, and T_g are machine- and code-dependent constants, each representing execution time for a sub-step of a sweep stage. T_{comm}, communication time per stage, depends on machine, code, and aggregation parameters. To determine T_{wf}, T_{cell}, T_n, and T_g—performance-model parameters required for our optimal sweep methodology—we execute 384 transport problems, each with a unique combination of A_{cell}, A_n, and A_g, and record sweep time divided by total unknowns (grind time) for each. We then perform a least-squares fit to obtain the values of T_{wf}, T_{cell}, T_n, and T_g and that minimize the sum of the squared relative differences between the measured and modeled grind times across the 384 problems. We assess the adequacy of our model by examining the relative difference between measured and modeled grind time. As seen in Figure 1, the model is reasonably accurate with less than 5% error on 181 of the 384 problems and less than 10% error on 272 of the 384 (3/4 of the cases). This is adequate for our purposes.

We now are using our model in the execution of optimal sweeps using its results to prioritize code improvements (such as new data structures that will reduce T_{wf} and T_{cell}), and extending it so that it predicts memory usage as well as execution time.

Center for Compressible Multiphase Turbulence

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

The overarching goals of the University of Florida's Single Discipline Center are threefold: (1) to radically advance the field of compressible multiphase turbulence (CMT) through rigorous first-principle, multi-scale modeling; (2) to advance very large-scale predictive simulation science on present and near-future platforms; and (3) to advance a co-design strategy that combines exascale emulation with a novel energy-constrained numerical approach. The Center for Compressible Multiphase Turbulence is performing petascale, and working towards exascale, simulations of instabilities, turbulence, and mixing in particle-laden flows under conditions of extreme pressure and temperature.

The PI, Professor S. Balachandar, states, "The PSAAP program 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."

The overarching demonstration problem consists of a cylindrical core of explosive surrounded by an annular region of polydisperse metal particles. Simulations of the demonstration problem were successfully carried out on the DOE supercomputer Quartz, and a number of prediction metrics were compared to experiments. See Figure 1 for a typical simulation output. A total of 2 million particles and 14.5 million degrees of freedom were simulated on 32k processors. The particle forces (quasi-steady and pressure gradient) are coupled back to the fluid and the particle-particle interactions are handled by a soft-sphere collision model giving rise to a 4-way coupled simulation. The state-of-the-art simulations of this problem at the micro (O(1000) particles), meso (O(10^9) particles), and macroscales, along with validation-

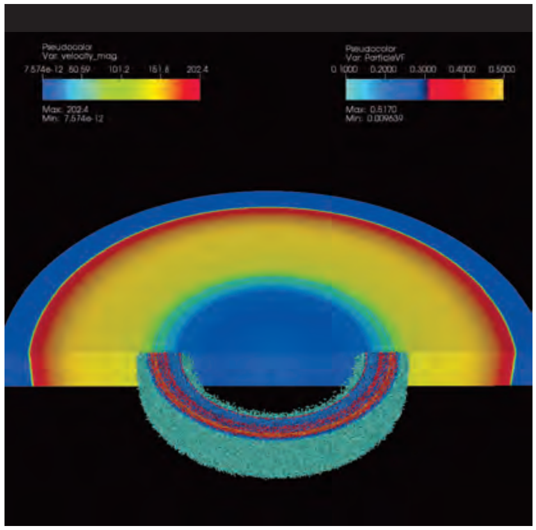


Figure 1. Multiphase three-dimensional simulation of cylindrical blast wave.

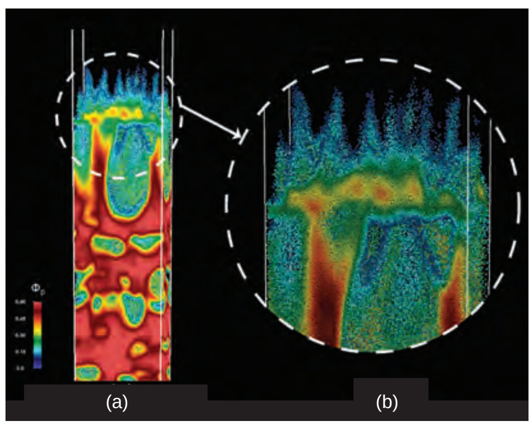


Figure 2. Multiphase three-dimensional simulation of an expansion fan moving through a bed of particles.

quality experiments, allow us to better understand the fundamental physics of compressible multiphase turbulence and to translate this understanding to modeling and simulation of a wide variety of problems of national importance. For example, at the microscale, recent three-dimensional simulations of shock propagation through a random bed of particles has led to the development of next-generation pairwise interaction extended point-particle (PIEP) force models that systematically incorporate effect of nearest neighbors. Uncertainty reduction is a key goal of the center, and it drives micro and mesoscale-informed model development apart from error reduction in both experimental and numerical approaches. Simulation and experimental uncertainty budgets determine the biggest contributors to the overall uncertainty and the drive to reduce these biggest uncertainties dictate the center's focus.

There have been numerous developments in CMT-nek over the past year. One of the key enabling technologies has been in the development of a highly parallel particle algorithm. This algorithm, called the binned ghost particle (BGP) algorithm, has allowed for simulation of larger problem sizes than previous approaches especially when a large number of particles occupy only a small portion of the overall computational domain. Whereas such cases may be extremely load-imbalanced in the spatial distribution of particles, this algorithm shows near-perfect scaling independent of the underlying non-uniform distribution. The BGP algorithm also has been shown to weakly scale up to 100,000 MPI ranks totaling over 300 million particles. Furthermore, the scaling trends suggest that this performance will continue past an even million MPI ranks. One of the simulations that the BGP algorithm has enabled is the mesoscale simulation of an expansion fan propagating into a bed of particles. A single instance in time is shown in Figure 2, with particles colored by their local volume fraction. In frame (a), a small portion of an expanding particle bed is shown at 20 ms after the diaphragm of the shock tube has burst. Void regions as well as jetting at the particle front are apparent. In frame (b), the individual spherical particles at the uppermost portion of the expanding bed are shown. Using state-of-the-art algorithms and implementations, we have been able to gain invaluable insight at unprecedented scales using CMT-nek.

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

We briefly introduce 3 of the Center's 20 PhD student researchers, representing a range of the activities at the Center for Exascale Simulation of Plasma-Coupled Combustion (XPACC).

Andrew Reisner is co-advised by Profs. Olson and Gropp. He works on achieving parallel performance at scale for the elliptic solves required in electric-field computations for Center predictions. In close collaboration with Dr. David Moulton at Los Alamos National Laboratory (LANL), he has developed a parallel robust structured multigrid library using legacy BoxMG kernels. The package, called Cedar (https://github.com/cedar-framework/cedar), addresses limitations to parallel scaling and performance using predictive performance modeling to guide dynamic data redistribution. It is designed to target the heterogeneous architectures of anticipated exascale platforms. During his time with XPACC, he did three summer internships at LANL, and he anticipates defending his dissertation in Spring 2019.

Kyle Mackay was co-advised by Profs. Johnson and Freund. His focus has been on surface physics and boundary conditions for plasma species. In XPACC, he has used techniques, based in part on the molecular dynamics techniques and tools (LAMMPS and ddcMD) from his Lawrence Livermore National Laboratory (LLNL) internship with Dr. Heather Whitley, to developed multi-scale models for ion- and radical-surface interactions. These now are coupled with Center codes. This also involved discretizing boundary condition expressions in a way compatible with the core numerical methods of the plasma-flow solver. They were used both for Center predictions and applied to assess a novel application of plasma actuation in microcombustion where chemical and thermal effects at wall boundaries are critically important. In addition to his LLNL internship, he has visited both Sandia National Laboratories (Sandia) and LANL to discuss his multi-scale plasma-simulation efforts. He recently defended his dissertation (August 2018) and has continued as a short-term XPACC postdoctoral researcher.

Jon Retter is co-advised by Profs. Elliott and Glumac, and has worked closely with additional center PIs in developing and diagnosing the physics of a novel plasma actuator for combustion. This actuator was designed to modulate a hydrogen diffusion flame with an applied electric field and accelerate chemical reactions by generation of radicals. It was a target for annual predictions for the first three years of the Center. He developed extensive diagnostics for both the flow and thermal fields, using a novel self-seeding particle image velocimetry method and Raman/Rayleigh scattering techniques. He also worked closely with Dr. Sean Kearney at Sandia during an internship, performing femtosecond-CARS imaging measurements on the XPACC actuator to provide validation. Illinois has since acquired a similar laser system and, with the help from our collaborators at Ohio State, developed electric-field measurements for detailed comparison with physics predictions. He recently defended his dissertation in Fall 2018, and he has returned again to Sandia as a postdoctoral researcher.

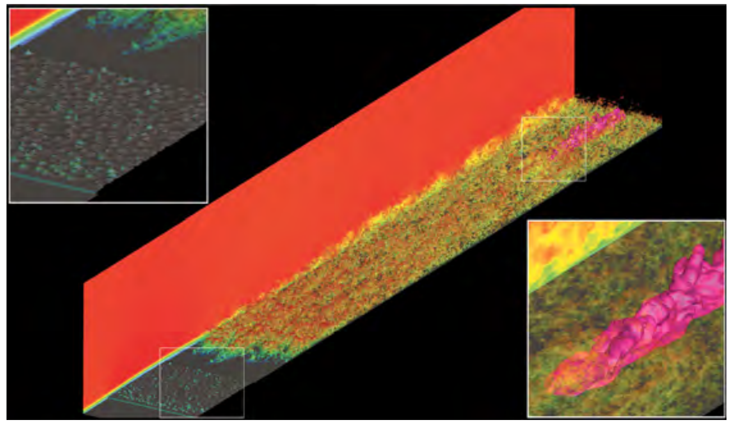
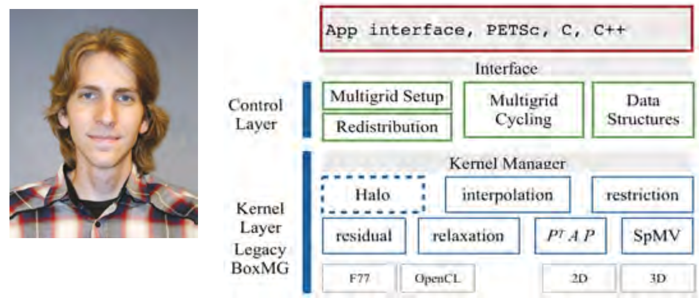
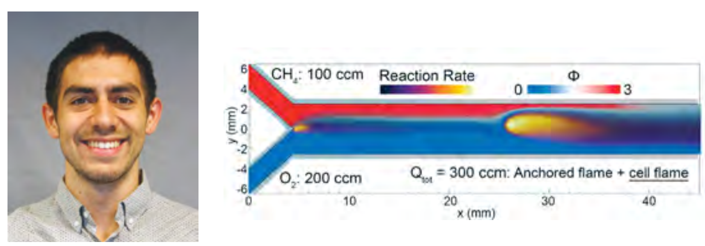


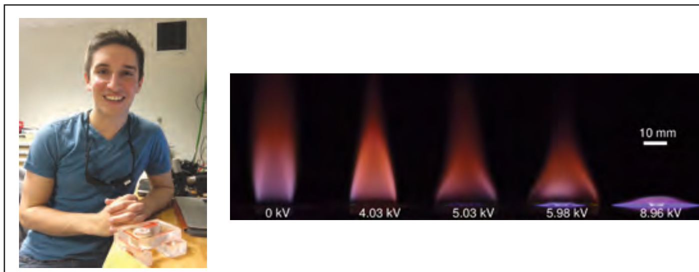
Figure 1. Simulation visualization showing scale-resolved sandpaper turbulence trip and sustained flame in turbulent cross flow.



Andrew Reiser and the Cedar framework for exposing legacy kernels for performance at scale.



Dr. Kyle Mackay and simulation of a plasma-actuated microburner with multi-scale-modeled wall boundary conditions.



Jon Retter is pictured with the plasma actuator and its effect on a hydrogen diffusion flame.

Center for Shock Wave-Processing of Advanced Reactive Materials

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

The Center for Shock Wave-processing of Advanced Reactive Materials (C-SWARM) is focused on advancing predictive computational tools for multiphysics and multiscale modeling of heterogeneous mixtures under extreme conditions. Using adaptive simulations that execute effectively on high-performance computing platforms, C-SWARM's goals are to predict conditions for the synthesis of novel materials. In particular, researchers at C-SWARM develop verified and validated (V&V) models and perform uncertainty quantification (UQ) of high-performance simulations to synthesize cubic boron nitride (c-BN). The hardness of c-BN is similar to that of diamond, but its thermal and chemical stability are superior making it ideal for cutting tools. Shock synthesis of c-BN achieved in this year, enabled by Exascale predictive computations, is a significant scientific achievement.

C-SWARM scientists advance adaptive computational schemes for problems with vast spatial and temporal scales to study reactive nanomaterials that form during shock synthesis. Moreover, the C-SWARM team is developing novel computational tools such as the multiscale and multiphysics finite element solver (PGFem3D), Multi-Resolution Wavelet Toolkit (MRWT), and the Image-based Multiscale Multigrid Solver (I-M2). "Complex multiscale and multidisciplinary problems cannot be solved with the required accuracy for decision making without the development of novel numerical schemes that execute effectively on future Exascale platforms," says Karel Matouš, College of Engineering Collegiate Associate Professor of Computational Mechanics and the project's director. "Our students and staff are tackling a difficult problem that requires an interdisciplinary approach and the use of parallel computers which cannot be done without sustained support for predictive science and high-performance computing from NNSA."

In the last calendar year, researchers of the Computational Physics team have focused on developing a data-driven multigrid solver, enhancing the wavelet toolkit and performing Design and Analysis of Computer Experiments (DACE). In particular, the Computational Physics team performs predictive simulations and optimizes design parameters to increase the pressure, density, and temperature conditions during shock synthesis experiments. As an example, Figure 1 shows the large parallel thermo-mechanical simulation of nickel and aluminum nanocomposite during impact loading. Based on the computational design, the experiments are performed to confirm the validity of the predictions.

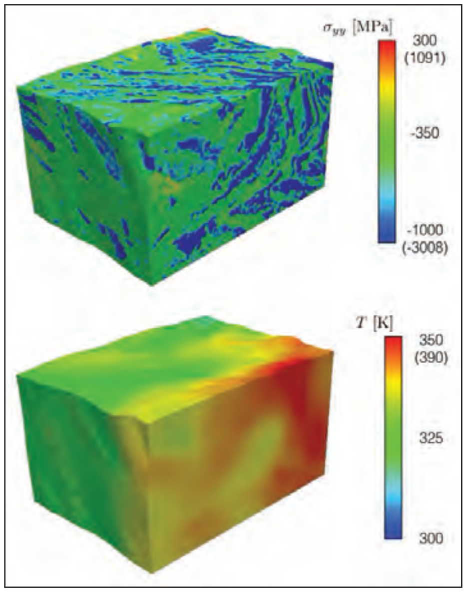


Figure 1. The thermo-mechanical impact simulation of nickel and aluminum nanocomposite. (Top) Stress field. (Bottom) Temperature. The simulation contains 1.6M computational cells, 153.6M nonlinear Ordinary Differential Equations (ODEs) from crystal plasticity constitutive model, and 26k integration time steps. The simulation was performed on 7,200 computing cores on QUARTZ at the Lawrence Livermore National Laboratory.

To support these computational predictions, the Computer Science team develops an advanced asynchronous multi-tasking runtime system and advanced software libraries. Moreover, to separate scientific applications from details of the runtime system, C-SWARM researchers are developing a Domain Specific Embedded Language (DSEL) and Active System Libraries (ASLib) that are based on the concepts of generic and meta-programming techniques to effectively eliminate the abstraction penalty. In particular, C-SWARM's researchers are focusing on the development of Matrix and Tensor Template Libraries (MTL/TTL), Photon networking, multiscale graph scheduling, adaptive wavelet multi-processing, and Exascale architectures. In the last calendar year, significant effort has been devoted to graphics processing units using CUDA (a parallel computing platform) for the programming.

The integrated V&V/UQ program provides a platform for 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.

On the educational side, research performed in C-SWARM provides a unique setting for the multidisciplinary education of students and research staff to join the work force in critically important areas of national importance. Intensive interactions with NNSA laboratories are common in terms of student, staff, and faculty visits. C-SWARM continues a vibrant seminar series attended primarily by research staff from NNSA laboratories. Recurring effort continues to deliver outstanding U.S. nationals to the PhD program.

Thermal Treatment for Pulverized Coal Boiler Boundary Conditions

The University of Utah ✦ PI: Dr. Philip J. Smith (philip.smith@utah.edu) ✦ Author: MinMin Zhou

Min-min Zhou, currently a PhD candidate working in the Carbon Capture Multidisciplinary Simulation Center on multi-phase reacting flows.

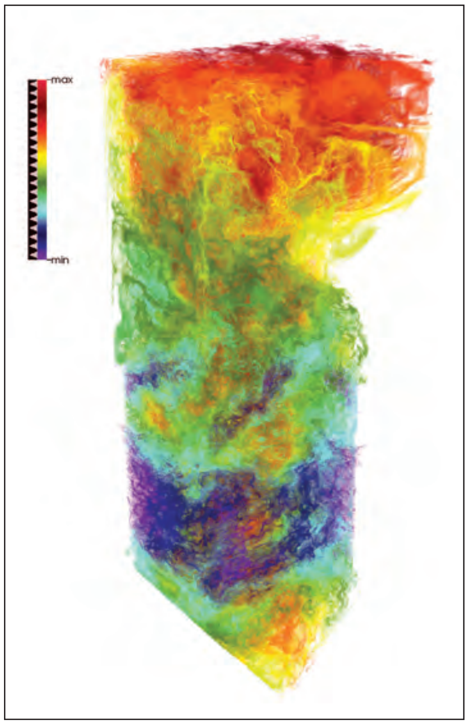


Figure 1. Gas phase residence time within a pulverized coal power boiler. Boiler design relies on understanding residence time of particles and gases to incorporate appropriate steam flow rates and boiler dimensions.

In order to demonstrate a positive societal impact in extreme computing, the Utah Center has focused efforts on accurately modeling industrial-scale, pulverized coal power boilers, which currently produce ~30% of the electricity in the United States.[1] Boiler manufacturers and utility companies are in need of simulation tools that adequately can accelerate deployment of new technology (e.g., AUSC, oxy-coal), design and test retrofit strategies for existing units, and predict day-to-day performance for system control and operational questions. As these units are used to generate steam which, in turn, powers turbines for electricity, the primary quantity of interest (QOI) in these systems is accurately representing the local net flux of energy through the walls. The Center has employed large-eddy simulations to resolve the large-scale mixing and reacting events in the system. A discrete ordinance model is used to solve for the radiation transport in the system. A quadrature method of moments, DQMOM,[2] is used to model the transport of the coal particles within the system. A detailed summary of the modeling strategy used in these computations can be found in recent literature.[3]

Impact factor analysis for these simulations has shown that a reduced set of physical phenomena produce significant sensitivity and uncertainty when trying to predict the QOI for these systems. In particular, the thermal resistance and surface emission properties of the ash layer on the walls require attention due to significant impact on predictivity. The ash deposits come from non-combustible mineral matter contained in the coal particles. After reaction of the organic matter, the remaining ash particles are transported through the boiler. When heated, the particles become viscous and coat the internal surface of the boiler, inhibiting the heat transfer through water wall tubes. I have concentrated my PhD efforts on adding physics-based models to this deposition process at the wall in order to reduce uncertainty. In order to estimate the flux of ash particles to the wall, I have incorporated a novel methodology which integrates three particle deposition mechanisms. These mechanisms include particle melting fraction, adhesion due to the viscous property of the particle and surface, and energy conservation for the particle impaction process. These mechanisms are interdependent and integrated using a novel regime map.[4] I model the emissivity of the ash surface using our novel methodology which estimates the effective surface particle size by incorporating viscous sintering effects and using Mie theory to predict spectral emissive properties of the surface.[5] Given appropriate time-scales for these deposits, which are evolving at a much slower time-scale than the LES simulation, I can estimate deposit properties such as thermal conductivity, thickness, porosity, and emissivity.

Validation and uncertainty quantification has been fundamental in driving the Center towards higher fidelity model form and predictivity. The Center's hierarchical approach incorporates data from multiple design scales, including a pilot scale unit an order of magnitude smaller than the industrial scale boilers. The Center's Bayesian and B2B consistency hybrid V/UQ approach has provided reduced uncertainty in input parameter space while achieving consistency with experimental data-sets. In general, the Center has observed the addition of physics-based models. In contrast to empirical models, they have allowed one to move from small lab-scale experiments to pilot-scale experiments without needing to adjust model form. Forward error propagation analysis of reduced uncertainty parameters in a full-scale 750 MW boiler (shown in Figure 1) has resulted in an average local heat flux error of ±10%, which is well within design standard error. This allows boiler manufacturers to make dramatic changes to these systems while maintaining significant confidence in the changes due to the accuracy of the simulations.

References

[1]U.S. Energy Information Administration, Monthly Energy Review, Table 7.2a, March 2018.

[2]Marchisio et al., "Computational Models for Polydisperse Particulate and Multiphase Systems," Cambridge U. Press, 2013.

[3]Wojciech P. Adamczyk et al., "Application of LES-CFD for Predicting Pulverized-Coal Working Conditions After Installation of NOx Control System," Energy 160 (2018): 693-709.

[4]Min-min Zhou et al., "Large-Eddy Simulation of Ash Deposition in a Large-scale Laboratory Furnace," Proceedings of The Combustion Institute, 2018. (Accepted)

[5]J. Parra-Alvarez, B. Isaac, S. Smith, T. Ring, S. Harding, and P. Smith. "Radiative Properties of Ash Deposits," 27th International Conference on the Impact of Fuel Quality on Power Production and the Environment, Alberta, Canada, Sept. 24-28, 2018

Sean R. Copeland, Lawrence Livermore National Laboratory (copeland23@llnl.gov)
LLNL: 03/2015 to Present ✦ **Degree:** PhD, Aeronautics and Astronautics, 2015 ✦ **PSAAP II:** 2014, Stanford University

I've had a passion for aviation and space exploration for most of my life. In fact, if you had asked a younger version of me what career he envisioned for himself, he would have immediately and confidently replied pilot, aerospace engineer, or astronaut. As a young adult, I worked hard to build strong academic and professional credentials supporting my career goals. In a strange twist of fate, when graduation was imminent, and I was forced to choose an initial trajectory for my professional future, I chose none of the options that had been bedrock elements of my identity. Instead, I chose a career as a computational physicist at Lawrence Livermore National Laboratory (LLNL).

So Why the Change in Course?

As a Stanford University graduate student, supported in part by the Predictive Science Academic Alliance Program (PSAAP) II, I became interested in scientific computing for simulation-based analysis and design of complex engineering systems. I enjoyed building software tools to address interesting scientific questions that were consequential to the future of our world. In retrospect, I think one of the most appealing aspects of my thesis project was in the interdisciplinary nature of the work since it required a comprehensive knowledge of linear algebra, partial differential equations, numerical methods, compressible fluid mechanics, computer science, and more. I loved the challenge. I loved working for a greater purpose, and it seemed that any direction I turned there was something fascinating to learn.

As a student, the PSAAP II provided a unique window into the practice of big science, or work characterized by large, interdisciplinary scientific teams working with unique experimental and computational facilities on problems of global significance. My experience in the PSAAP II was formative because it took the elements of what I loved about my research and scaled everything up. PSAAP II sought answers to fundamental questions about the future of renewable energy, computer science, and predictive simulation and created a rich environment for interdisciplinary, collaborative research.

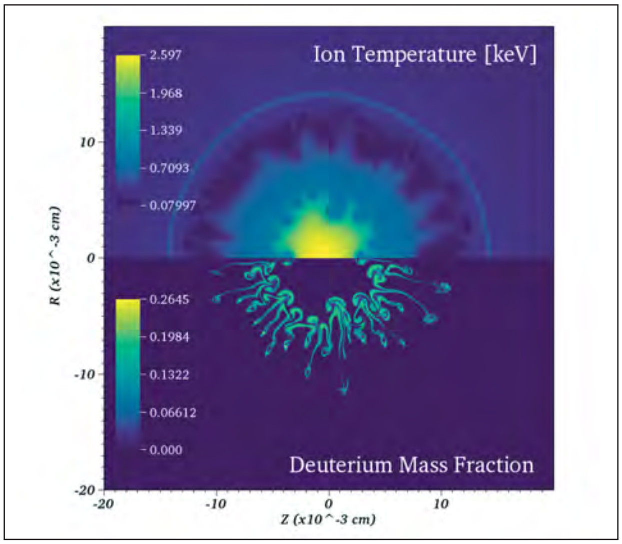


Figure 1. Simulation of an inertial confinement fusion (ICF) experiment performed at the National Ignition Facility to study the effects of turbulent mix on hot-spot formation and ICF target performance. Large-scale Rayleigh-Taylor instabilities are seeded by capsule surface roughness, sending cold ablator material into the burning thermonuclear fuel, quenching the reaction.

I can't stress enough how different that experience is from a typical PhD candidacy, working alone, or in a small group, on a very targeted, focused, and narrow research question. Without my experience in PSAAP II, I might never have known about the career opportunities that existed within the Department of Energy/National Nuclear Security Administration (NNSA) national laboratory system or that I enjoyed doing big science, and that the best place in the world to do that was at LLNL.

In my three years as a computational physicist, I have come to appreciate how well the PSAAP II prepared me for my responsibilities as a staff scientist at LLNL. My work portfolio has included formulating, implementing, verifying, and validating physics models in large, multi-physics code projects (see Figure 1); using techniques from machine learning, statistics, multi-disciplinary optimization, and uncertainty quantification to assess experimental platform designs; and deploying software solutions to enable scientific computing on the largest, most sophisticated computing resources in the world. These activities were all major research components of the PSAAP II, and I was able to leverage my academic experience to support those activities and make meaningful programmatic contributions at an early stage in my career.

My friends and family have asked why I work at an NNSA laboratory, and I tell them many of the things that I've articulated above: the research environment is unique, the problems are challenging, and I'm surrounded by intelligent, hard-working, peers, evidenced by the Gordon Bell prize winners, *Science* article authors, Nobel laureates, and former astronauts. Whereas all those statements are true, they don't really address the charter of the laboratory, to provide technical expertise on matters of nuclear safety, security, and reliability. As I advance in my career at LLNL, I am continually reminded of the consequence and importance of the work conducted at the NNSA laboratories, and I strongly believe that the questions we answer inform policies and decisions that help keep the world a safer place. We need the best and brightest in the world to maintain the intellectual vitality that exists within the NNSA complex, and the Stockpile Stewardship Academic Programs is a critical avenue to introduce the next generation to the unique and challenging environment that exists at the NNSA laboratories.

Stewardship Science Graduate Fellowship

Christopher Young, Lawrence Livermore National Laboratory (young110@llnl.gov)

LLNL: 2016 to Present ✦ **Degree:** PhD, Mechanical Engineering, 2016 ✦ **SSGF:** 2011 to 2016, Stanford University

As a designer in the Inertial Confinement Fusion (ICF) and High Energy Density Science (HEDS) programs at Lawrence Livermore National Laboratory (LLNL), I run complex radiation-hydrodynamic simulations in support of experiments carried out at the National Ignition Facility (NIF). A key component of science-based stockpile stewardship, our multiphysics codes model all phases of laser-driven fusion experiments and run on some of the nation's largest supercomputers. These simulations are used to help design NIF experiments, interpret results collected from a slew of diagnostic instruments and, ultimately, refine the experimental platforms and improve fusion performance.

The indirect drive approach to ICF uses a hohlraum, or radiation cavity, to convert 3ω NIF laser light at 351 nm into x-rays that bathe a 2-mm-diameter capsule containing deuterium-tritium fuel. The outer layers of the capsule absorb the x-rays and ablate away, producing a rocket-like force that spherically compresses the inner fuel to high densities and pressures. Energy is released through the ensuing fusion reactions.

As a hohlraum designer, I examine the precise aiming of the 192 NIF beams, in addition to the laser pulse shape and hohlraum geometry, to try to produce a symmetric radiation field for as long as possible throughout the experiment. In near vacuum hohlraums, things remain relatively straightforward early in time. As the cavity begins to fill with low density material ablated from the walls and target capsule, however, laser power is redistributed around the hohlraum, reducing our ability to control symmetry in the critical latter stages of the implosion (see Figure 1). Mitigating these effects, by using novel hohlraum shapes, for example, is an active area of research.

I have also focused on the capsule side of the problem as a part of the pushered single shell (PSS) campaign on NIF.

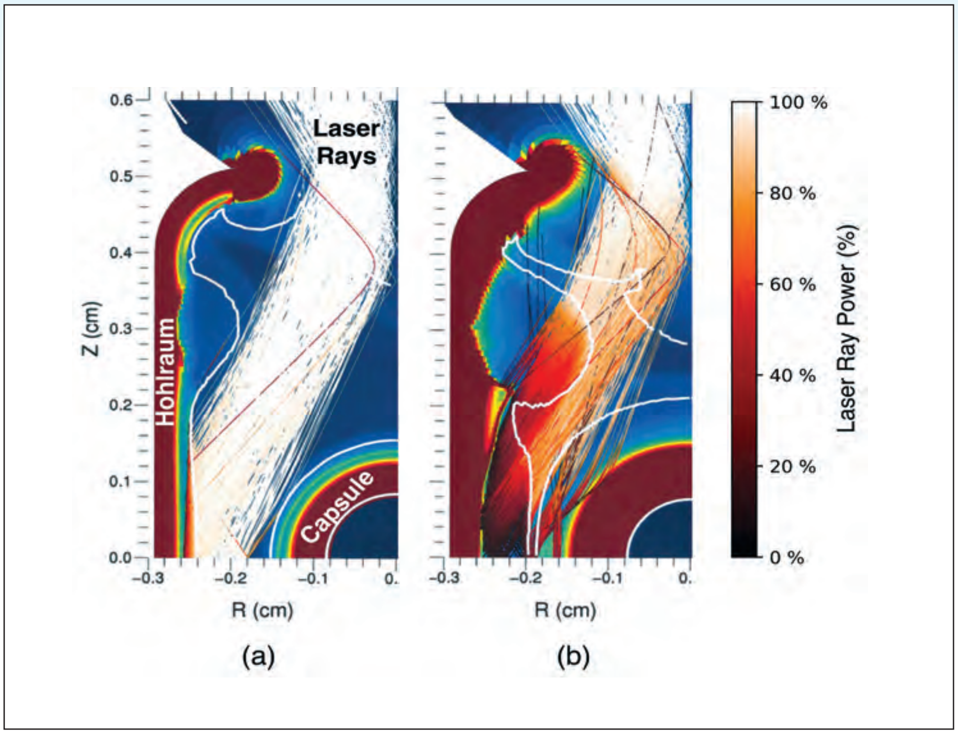


Figure 1. Radiation-hydrodynamic simulation of a NIF hohlraum demonstrating loss of symmetry control. (a) At early time, laser rays are absorbed near the hohlraum waist (z = 0 − 0.15 cm) as intended. (b) At late time, laser rays are absorbed too early by ablated hohlraum wall material.

This unique design uses a continuous density grading between an outer low atomic number ablator (e.g., beryllium) and an inner high atomic number layer (e.g., chromium) to better control hydrodynamic instabilities that reduce capsule performance.

My first experience at LLNL came as a graduate student in the 2011 High Energy Density Physics (HEDP) summer program. There, I was introduced to the world of NIF and ICF design by my mentor, Nathan Meezan, who became one of my project managers when I started as a staff scientist in 2016. As a Stewardship Science Graduate Fellow, I returned for a second summer doing kinetic simulations with David Larson, expanding my plasma modeling toolkit. Both summers spent in what is now the Design Physics Division brought me in close contact with the incredible people and facilities conducting world-class science at LLNL and made a strong impression on me. Maintaining contact with laboratory staff and my mentors at annual SSGF and American Physical Society (APS) conferences only reinforced my desire to one day join the ranks at LLNL. When it came time to graduate, it was an easy decision to apply, and my experience with the SSGF program ensured the hiring process was a smooth one. I am very grateful to be a part of the SSGF community and look forward to remaining involved as a lab employee.

Erin Good (eringood@gmail.com)

SSGF: 2016 to Present ✦ **Degree in Progress:** PhD, Experimental Nuclear Astrophysics, Louisiana State University, Advisor: Dr. Catherine Deibel

Research Topic

Development and Implementation of a New Split-Pole Spectrograph Experimental Setup at Florida State University

Research Responsibilities

My research responsibilities vary from day to day. One day I might be in my office analyzing data from an experiment on which our group has worked or designing a new part for an experimental apparatus using CAD design software. The next I could be out of the state at a lab sitting shifts on an experiment or helping with its setup. Or I could be down in our lab, testing detectors we've designed and built to be used at one of those experiments, or teaching our younger group members how to set up an electronics processing scheme for the detectors. There's never a dull moment with this large range of projects, all of which are essential to making measurements of nuclear properties.

Benefits of the SSGF Program

My fellowship practicum at Lawrence Livermore National Laboratory (LLNL)this past summer gave me the opportunity to widen the scope of my studies and learn more about my career options after graduation. I was able to learn more about beta decay experiments that are especially important for studying the neutron-rich isotopes important to my field as well as work with data using some of the programs and techniques that are essential to beta spectroscopy simulation and analysis. Spending the summer at LLNL also taught me about what it's like to work at a national lab and what kind of nuclear physics research they conduct. It was an extremely valuable experience for my career, as it helped me to explore my post-graduation job options and make connections with scientists in my field.

What Students Should Know

The Stewardship Science Graduate Fellowship (SSGF) has been a wonderful experience for me, especially attending the program review every summer. I've really enjoyed getting to meet students from scientific disciplines new to me as well as other nuclear physicists, and the NNSA facility tours have been fascinating. Students applying for the SSGF should know that it's more than just a fellowship—it's a networking opportunity and a chance to expand your knowledge of everything from your field to the inner workings of our country's stewardship science programs and policies.

Figure 1. Overjoyed that the Enge Split-Pole Spectrograph for my thesis project was finally installed at Florida State University in the summer of 2017.

A. Miguel Holgado (holgado2@illinois.edu)

SSGF: 2016 to Present ✦ **Degree in Progress:** PhD, Astronomy, University of Illinois at Urbana-Champaign, Advisor: Dr. Paul M. Ricker

Research Topic

Gravitational-Wave Astrophysics

Research Responsibilities

I mainly work on using gravitational waves to uncover how compact objects like black holes and neutron stars form in close binaries. For example, in order for two neutron stars to merge within the age of the Universe, they need to somehow be brought close enough together such that gravitational radiation is strong enough to cause them to inspiral and merge. How this occurs still is an open question since the size of compact objects are many orders of magnitude smaller than the massive stars that produced them before exploding as supernovae. Two massive stars orbiting each other may interact before turning into compact objects. One particular evolutionary phase that is still uncertain is the common-envelope phase, where a massive star expands so large that its compact-object companion enters its envelope and begins to inspiral due to gravitational drag. If common-envelope evolution is successful, then what would be left is the helium core of the massive star and the compact object at a closer orbit such that the resulting compact-object binary would merge due to gravitational waves. This phase has never been observed directly since the inspiral is taking place under an optically thick envelope. Gravitational waves, however, may be emitted during this phase and reveal new insights into how common-envelope evolution forms compact-object binaries.

Benefits of the SSGF Program

Graduate school can be viewed as "finding one's voice" in the scientific community. The Stewardship Science Graduate Fellowship (SSGF) Program has given me the opportunity to focus more heavily on my research as well as provided me some freedom for exploring additional subfields within astrophysics and cosmology. Being able to come up with one's own research ideas and leading these investigations is an essential part of finding one's scientific voice during graduate school, and the SSGF is one of the best programs for supporting this development.

What Students Should Know

Engaging with fellows, alumni, and lab scientists from various fields and disciplines not only builds a supportive network but also may lead to new research ideas that one may not have thought of otherwise. The SSGF annual meetings are something for all fellows to look forward to.

Christopher Miller (christopher.miller@gatech.edu)

SSGF: 2015 to Present ✦ **Degree in Progress:** PhD, Mechanical Engineering, Georgia Institute of Technology, Advisor: Dr. Min Zhou

Research Topic

Effects of Microstructure on the Ignition of High Explosives

Research Responsibilities

My role involves designing and carrying out simulations to better understand the physical processes at play when an energetic composite material is subjected to a sudden shock loading. I work with available experimental data to model heat generation in the microstructure due to friction, pore collapse, and plastic deformation, and study the subsequent effects it has on the chemical initiation of the sample. Many length scales of physics are important to studying the likelihood of ignition of a high explosive (HE), and my goal is to determine the relative importance of each of these factors. To facilitate this, I use clusters of high performance supercomputers to model two-dimensional (2D) and 3D simulations of granular materials ranging from micron lengths to millimeter lengths.

Benefits of the SSGF Program

The SSGF program has given me the freedom to pursue the research topics I feel most invested in. With allocated travel funding, I have been able to attend and speak about my work at multiple shock physics conferences around the nation. Having worked at both Sandia National Laboratories and Lawrence Livermore National Laboratory on behalf of this fellowship, I have had the opportunity to work with some of the leading experts in my research field, as well as have access to national lab computational resources which allow me to push the limits of what I am capable of studying. These collaborations have continued, even after my return to campus, and have made my graduate experience better than I ever thought possible.

What Students Should Know

To anyone considering applying for the SSGF, absolutely do it! This fellowship has provided countless opportunities, ranging from hands-on experiences at national labs to a network of like-minded fellows to personal tours of some of the most advanced scientific labs in the nation. To me, the most important aspect of this fellowship always has been the breadth of research not directly related to my field to which I have been exposed. It is sometimes easy to get caught up in the specifics of one's own studies that we lose track of the larger picture. With the SSGF, getting a chance to talk to other graduate researchers dealing with plasma physics, asteroid impacts, geological modeling, or nanoscale lubrication has been a fascinating experience.

Gabriel Shipley (gabrielalanshipley@gmail.com)

SSGF: 2017 to Present ✦ **Degree in Progress:** PhD, Electrical Engineering, University of New Mexico, Advisor: Dr. Mark Gilmore

Research Topic

Magneto-Inertial Fusion Target Design

Research Responsibilities

Magnetized Liner Inertial Fusion (MagLIF) uses pulsed, intense current (18 million Amperes in 100 nanoseconds) to implode a solid metallic cylindrical tube (or "liner") filled with premagnetized, laser-preheated fusion fuel to thermonuclear conditions.

Traditionally, premagnetization has been supplied by an external field coil system which limits x-ray diagnostic access to the liner, necessitates use of a high inductance transmission line that reduces current delivery to the liner, and can produce premagnetization fields below approximately 30 T. I am investigating the auto-magnetizing (AutoMag) liner concept which eliminates the need for external field coils. I have designed and tested AutoMag liners that are composed of discrete helical conductors separated by electrically insulating material. These liners are designed to produce 30-50 T premagnetization during a prepulse on the Z machine before the driver current rises rapidly and the AutoMag liner implodes.

Additionally, helical conduction geometries can be used to surround a normal MagLIF liner to produce a dynamically rotating helical drive magnetic field that reduces growth of instability structures during implosion for improved liner stability. I am developing this method of liner implosion stabilization, known as a Solid Liner Dynamic Screw Pinch (SLDSP), via simulation and design of planned Z Pulsed Power Facility experiments.

Benefits of the SSGF Program

Touring the national labs and DOE/NNSA facilities during the Program Review has been eye-opening for me. Above and beyond that, my lab practicum appointment was utterly amazing. Not only did I get to jump into a field of interest (a field in which I was not entirely proficient), but I got to spend time learning from and working with the world experts in that field—a singularly profound experience.

What Students Should Know

The scientific development of the fellow—supporting the journey of the fellow towards becoming an effective research scientist—is the goal of the program. Achievement of this goal is facilitated by several aspects of the fellowship and, as I've continued progress towards completing my PhD, I've come to realize just how important each of these aspects is. The talks and posters at the Program Review, the lab tours, the practicum, the financial support, the comradery with the other fellows… all of these have greatly enhanced my time in graduate school—and I'm still making my way towards the finish line!

List of Grants and Cooperative Agreements

Stewardship Science Academic Alliances

High Energy Density Physics

Cornell University
David Hammer
Multi-University Center of Excellence for Pulsed-Power-Driven High Energy Density Science

Massachusetts Institute of Technology
Richard Petrasso
Center for Advanced Nuclear Diagnostics and Platforms for ICF and HED Physics at OMEGA, NIF, and Z

University of California, San Diego
Farhat Beg
Center for Matter Under Extreme Conditions

University of Michigan
R. Paul Drake
Center for Laboratory Astrophysics: Structure Formation and Energy Transport After the Dark Ages

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

University of Texas at Austin
Donald Winget
Center for Astrophysical Plasma Properties

Low Energy Nuclear Science

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

Duke University
Calvin Howell
Measurements of Induced Fission Product Yields from Photon-Induces Fission of Special Nuclear Materials

Duke University
Werner Tornow
Measurements of Neutron-Induced Fission Product Yields and Fission Neutron Energy Distributions

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

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

Michigan State University
Sean Liddick
Neutron Capture Cross Section Measurements on Short-Lived Isotopes

Michigan State University
William Lynch
Asymmetric Nuclear Matter Under Extreme Conditions

Michigan State University
Witold Nazarewicz
Microscopic Description of the Fission Process

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

Ohio University
Carl Brune
Scattering and Reactions of Light Nuclei

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

Rensselaer Polytechnic Institute*
Yaron Danon
Experiments with Neutron Induced Reactions

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

Texas A&M University
Sherry Yennello
Center for Excellence in Nuclear Training and University-based Research (CENTAUR)

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

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

University of Notre Dame*
Anna Simon
Low Energy Nuclear Science

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

Properties of Materials Under Extreme Conditions

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

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

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

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

Georgia Technology Research Corporation
Devesh Ranjan
Detailed Measurements of Turbulent Rayleigh-Taylor Mixing at Large Atwood Numbers

Harvard University*
Isaac Silvera
High Pressure Metallic Hydrogen

Lehigh University
Arindam Banerjee
The Effects of Materials Strength and Demixing on Rayleigh Taylor Turbulence

Research Foundation for the State University of New York
Baosheng Li
Thermodynamic and Mechanical Properties of SSP Materials from Simultaneous Ultrasonic and X-ray Studies at High Pressure and Temperature

Texas A&M University
Michael Demkowicz
Center for Research Excellence on Dynamically Deformed Solids (CREDDS)

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

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

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

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

University of California, San Diego
Marc Meyers
Viscous Plastic Flow, Dislocation Velocities, and Amorphization at Extreme Pressures and Strain-Rates

University of Nevada, Las Vegas*
Michael Pravica
Development of Useful Hard X-ray Induced Chemistry

University of New Mexico*
Peter Vorobieff
Quantification of Normal and Oblique Shock-Driven Phase Interaction and Transition to Turbulence in Media with Multiscale Density Interfaces

University of Wisconsin, Madison*
Zhenqiang Ma
Development of Useful Hard X-ray Induced Chemistry

Washington State University*
Yogendra Gupta
Institute for Shock Physics

Washington State University*
C.S. Yoo
Planetary Materials Under Extreme Conditions

*Currently under a no cost extension

University of Wisconsin, Madison
Riccardo Bonazza
Investigation of the Turbulent Mixing in a Twice-Shocked Interface

Wichita State University
Viswanathan Madhavan
Extreme Condition Mechanical Testing of AM Materials Using Complementary Methods

Radiochemistry

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

University of Notre Dame
Peter Burns
Actinide Center of Excellence

University of Notre Dame
Ani Aprahamian
A Novel Technique for the Production of Robust Actinide Targets

Other

Washington State University
Yogendra Gupta
Dynamic Compression Sector

High Energy Density Laboratory Plasmas

Cornell University
Gennady Shvets
Theory and Modeling of the Physics of Relativistic Shocks and Fermi Acceleration, and of Their Implementation Under Laboratory Conditions Using Petawatt Laser Systems

Idaho State University
Rick Spielman
Pulsed Power Driver to Generate and Measure HED States

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

Polymath Research Inc.
Bedros Afeyan
Resonant Excitation and Multi-Stage Re-Amplification of Nonlinear Plasma Waves with Ultrafast High Energy Density Applications

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

The Ohio State University
Douglass Schumacher
A Novel Study of Warm Dense Matter Using Hybrid PIC/MD Simulation Approaches Combined With Hybrid Ultrafast DAC-Based Experiments

University of California, Los Angeles
Chan Joshi
Development of a Self-Modulated Laser Wakefield Accelerator Platform for a Hyper-Spectral Photo Source from 10 KV to 1 MV for HEDS

University of California, San Diego
Christopher McGuffey
Characterization of Ion-Heated Warm Dense Matter and Its Ion Transport Properties

University of Nevada, Reno
Roberto Mancini
Atomic Kinetics of Laboratory Photoionized Plasmas Relevant to Astrophysics

University of Nevada, Reno
Alla Safronova
Hard and Soft X-ray Line Emission from High-Z Multiply Ionized Ions Influenced by Dielectronic Recombination and Polarization from HEDLP

University of Nevada, Reno
Bruno Bauer
Seeding and Evolution of Magnetohydrodynamic Instabilities of a Metal Surface Driven by Intense Current

University of Rochester
Jessica Shang
Probing HED Turbulence with Lasers and Coherent Light Sources

University of New Mexico, Albuquerque
Mark Gilmore
Seeding and Evolution of Magnetohydrodynamic Instabilities of a Metal Surface Driven by Intense Current

Virginia Polytechnic Institute and State University
Bhuvana Srinivasan
Seeding and Evolution of Magnetohydrodynamic Instabilities of a Metal Surface Driven by Intense Current

West Virginia University
Mark Koepke
Spectroscopic Methods for Obtaining Plasma Parameters Applied to Soft X-ray Absorption Spectra from Radiatively Heated Z-pinch Plasmas

National Laser Users' Facility

General Atomics
Christine Krauland
Hot Electrons from Nonlinear Plasma Interaction in Shock Ignition Regime

Johns Hopkins University
Dan Stutman
Demonstration of Talbot-Lau X-ray Deflectometry (TXD) Electron Density Diagnostic in Laser Target Interactions

Massachusetts Institute of Technology
Richard Petrasso
HEDP Explorations of Kinetic Physics, Plasma Stopping Power, Hohlraum Fields and Nuclear Astrophysics

Princeton University
Thomas Duffy
Laser-Based Dynamic Compression of High-Pressure and Planetary Materials

Princeton University
Hantao Ji
Particle Acceleration Due to Magnetically Driven Reconnection Using Laser-powered Capacitor Coils

Princeton University
Amitava Bhattacharjee
Dynamics of Magnetic Reconnection in High-Energy-Density Plasmas

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

University of California, Berkeley
Raymond Jeanloz
High Energy Density Chemical Physics and Planetary Evolution

University of California, San Diego
Farhat Beg
Transport of Relativistic Electrons in Cylindrically Imploded Magnetized Plasmas

University of Chicago
Don Q. Lamb
Properties of Magnetohydrodynamic Turbulence in Laser-Produced Plasmas

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

University of Michigan
Karl Krushelnick
Investigations of Relativistic Reconnection Using OMEGA EP

University of Nevada, Reno
Roberto Mancini
Development of a Photoionized Plasma Experiment at OMEGA EP

Predictive Science Academic Alliance Program II

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

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

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

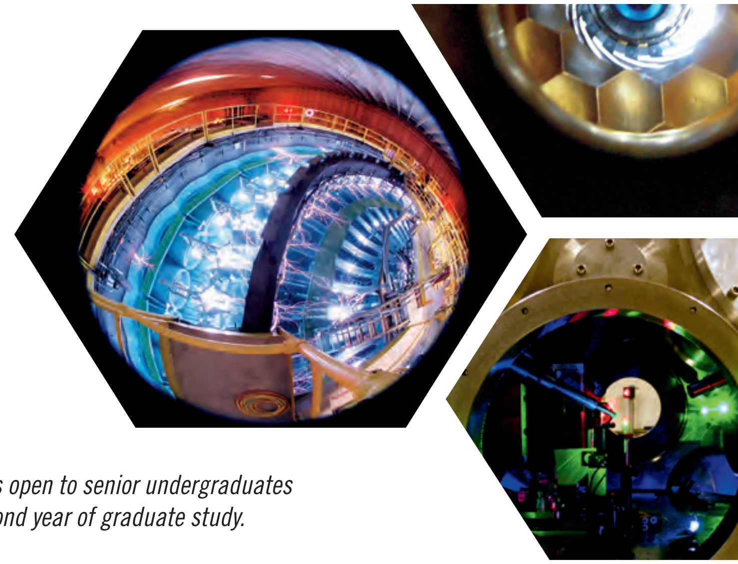
University of Florida, Gainesville
S. Balachandar
Center for Compressible Multiphase Turbulence

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

University of Notre Dame
Karel Matouš
Center for Shock Wave-Processing of Advanced Reactive Materials

DEPARTMENT OF ENERGY NATIONAL NUCLEAR SECURITY ADMINISTRATION

STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP



SSGF

The DOE NNSA SSGF program is open to senior undergraduates or students in their first or second year of graduate study.

The Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship (DOE NNSA SSGF) program provides outstanding benefits and opportunities to students pursuing a Ph.D. in areas of interest to stewardship science, such as **properties of materials under extreme conditions and hydrodynamics, nuclear science,** or **high energy density physics.** The fellowship includes a 12-week research experience at Lawrence Livermore National Laboratory, Los Alamos National Laboratory or Sandia National Laboratories.

BENEFITS

+ $36,000 yearly stipend
+ Payment of full tuition and required fees
+ $1,000 yearly academic allowance
+ Yearly program review
+ 12-week research practicum
+ Renewable up to four years

www.krellinst.org/ssgf

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

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

KRELL institute

DOE CSGF

DEPARTMENT OF ENERGY

COMPUTATIONAL SCIENCE GRADUATE FELLOWSHIP

The DOE CSGF is open to senior undergraduates and students in their first year of doctoral study.

BENEFITS

+ $37,000 yearly stipend
+ Payment of full tuition and required fees
+ Yearly program review participation
+ Annual professional development allowance
+ 12-week research practicum experience
+ Renewable up to four years

www.krellinst.org/csgf

The Department of Energy Computational Science Graduate Fellowship (DOE CSGF) provides up to four years of financial support for students pursuing doctoral degrees in fields that use high-performance computing to solve complex problems in science and engineering.

The program also funds doctoral candidates in applied mathematics, statistics or computer science who are pursuing research that will contribute to more effective use of emerging high-performance systems. Complete details and a listing of applicable research areas can be found on the DOE CSGF website.

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

U.S. DEPARTMENT OF ENERGY | Office of Science

NNSA National Nuclear Security Administration

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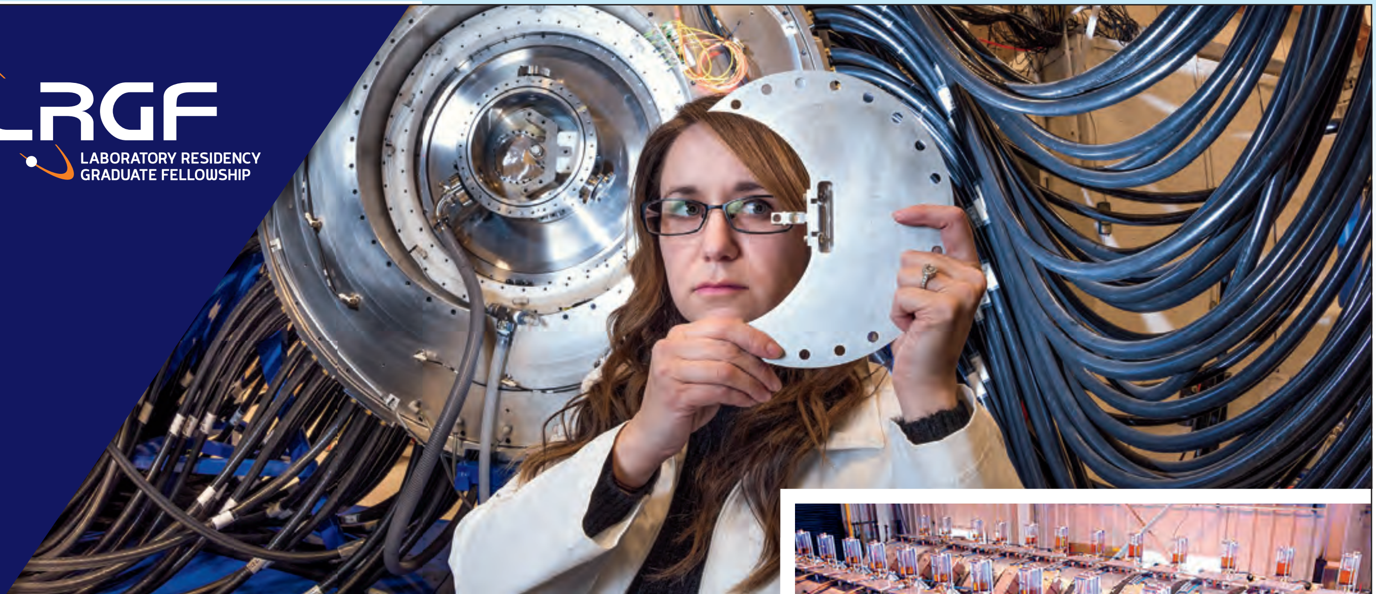
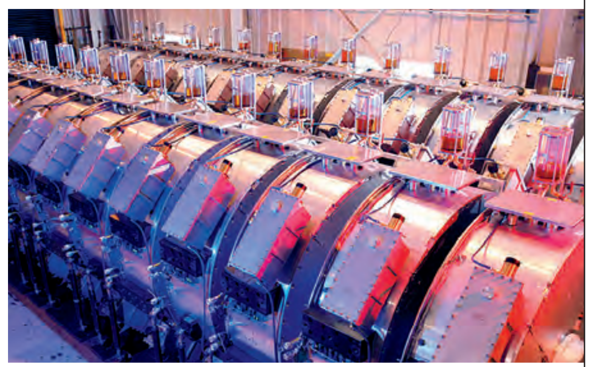
LRGF
LABORATORY RESIDENCY GRADUATE FELLOWSHIP





Top: *Thor pulsed-power accelerator at Sandia National Laboratories.*
Bottom: *Dual-Axis Radiographic Hydrodynamic Test (DARHT) facility at Los Alamos National Laboratory.*

DEPARTMENT OF ENERGY
NATIONAL NUCLEAR SECURITY ADMINISTRATION

LABORATORY RESIDENCY GRADUATE FELLOWSHIP

The Department of Energy National Nuclear Security Administration Laboratory Residency Graduate Fellowship (DOE NNSA LRGF) provides outstanding benefits and opportunities to U.S. citizens who are entering their second (or later) year of doctoral study to work at premier national laboratories while pursuing degrees in fields relevant to the stewardship of the nation's nuclear stockpile.

LAB RESIDENCY Fellowships include at least two 12-week research residencies at Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Sandia National Laboratories, or the Nevada National Security Site. Fellows are encouraged to extend these residencies to carry out thesis research and other studies at the four DOE NNSA facilities.

BENEFITS

– $36,000 annual stipend
– Payment of full tuition and required fees
– Yearly program review participation
– Annual professional development allowance
– Two or more 12-week-minimum national laboratory residencies
– Renewable yearly

FIELDS OF STUDY

APPLIED SCIENCE AND ENGINEERING

Pulsed Power Technology › Particle Accelerators

ATOMIC PHYSICS

Theory and Modeling › Experimental Visible/UV/X-Ray Spectroscopy

MULTI-SCALE, MULTI-PHYSICS THEORY, SIMULATIONS AND EXPERIMENTS

Nuclear Astrophysics › Fluid Physics (including PIC-Fluid Hybrid Methods, Hydrodynamics, Instabilities and Shock Physics) › Laser-Plasma Interactions › Radiation Hydrodynamics and Radiation Magneto-Hydrodynamics › Dynamic Materials

READ FULL DESCRIPTIONS ONLINE.

www.krellinst.org/lrgf

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

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