DOE/NA-0109

# 2020 Stewardship Science Academic Programs Annual

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

National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY

## *On the Cover*

University of California, San Diego graduate student Gaia Righi adjusts a target in the Janus laser at Lawrence Livermore National Laboratory's Jupiter Laser Facility.
— Image courtesy of the University of California, San Diego

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## 2020 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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*"Throughout the pages of this Stewardship Science Academic Programs Annual, the value of the people contributing to this technical work and the value of the work itself are evident. The work presented herein, however, represents only a small sampling of the outstanding work done in the Stewardship Science Academic Programs that provides a critical pipeline of talent and new ideas to the stockpile stewardship community."*

*— Dr. Mark C. Anderson*
Acting Assistant Deputy Administrator
for Research, Development, Test, and Evaluation

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

The primary mission of the National Nuclear Security Administration (NNSA) is to ensure a safe, secure, and effective nuclear deterrent without nuclear explosive testing. The NNSA and its national laboratories have developed a science-based Stockpile Stewardship Program (SSP) to maintain and enhance its scientific, engineering, and computational capabilities to sustain the ability to assess and certify the nuclear stockpile in the absence of testing.

Every day we have evidence that our efforts are keeping the United States, its allies, and the world at-large safe. World-class, state-of-the-art theoretical, computational, and experimental science and technology is key to maintaining the effectiveness of our country's nuclear deterrent. Whereas key aspects of nuclear weapons' work is, and needs to be, appropriately classified, it is based upon solid science and engineering. Throughout the pages of this *Stewardship Science Academic Programs Annual*, the value of the people contributing to this technical work and the value of the work itself are evident. The work presented herein, however, represents only a small sampling of the outstanding work done in the Stewardship Science Academic Programs (SSAP) that provides a critical pipeline of talent and new ideas to the stockpile stewardship community.

In addition to the high quality research and work presented, we feature select students pursuing doctoral degrees and the alumni of the SSAP who write in their own words about their research and about their perspective on the SSAP and the opportunities provided. We remain diligently committed and grateful to the many former participants of the Stewardship Science Academic Programs who have chosen a career with the NNSA national laboratories. They continue to be an important part of our current and projected future success.

As we look to the future, the science-based SSP will continue to be core to NNSA's nuclear mission with SSAP playing a pivotal role in ensuring that future. To all of you participating in the SSAP, I extend my best wishes for your continued success and congratulations on your successes to date.

Dr. Mark C. Anderson

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

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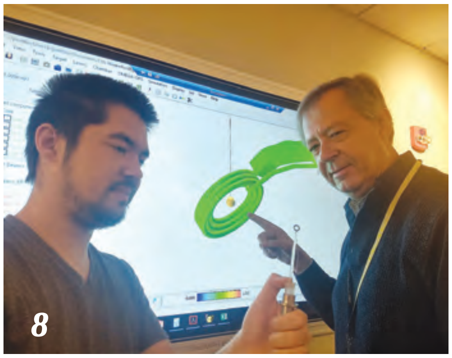



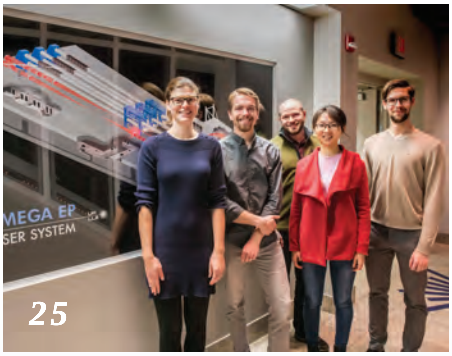


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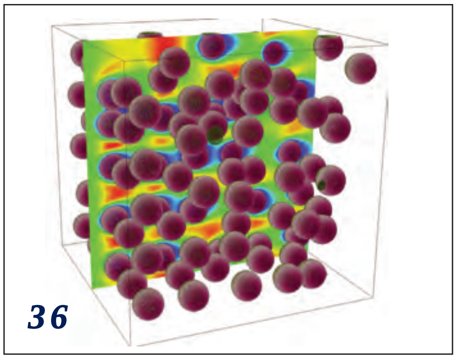
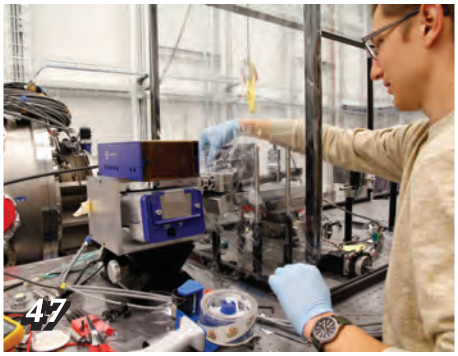


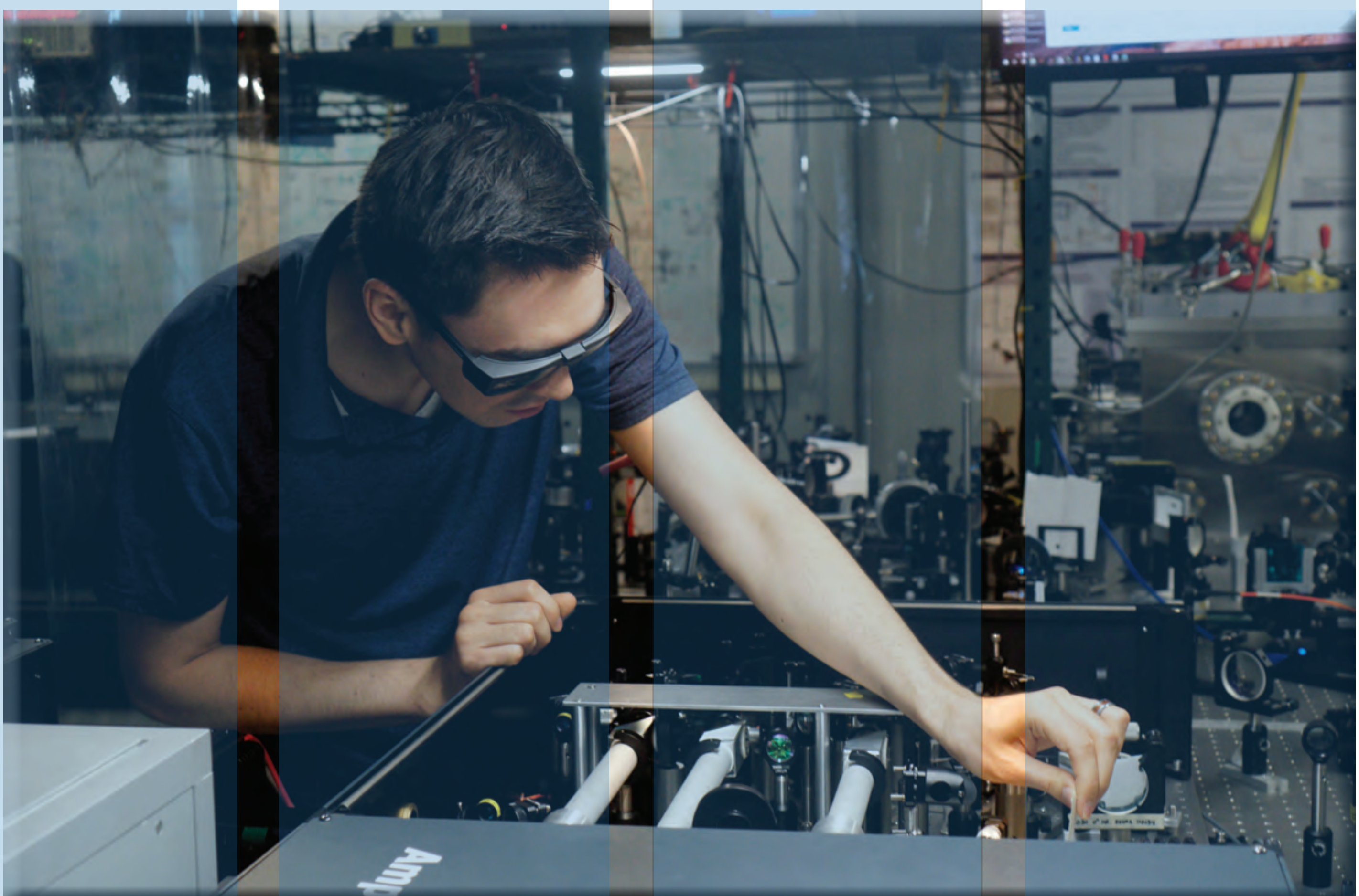

## Outstanding Poster Award Winners 2019

The 2019 Stewardship Science Academic Programs (SSAP) Annual Review Symposium was held in Albuquerque, New Mexico February 19-20, 2019. The Symposium, which hosted nearly 300 attendees, featured overviews of work to date from ongoing grants and cooperative agreements from the SSAA, HEDLP, and NLUF programs. Pictured below are the recipients of the Outstanding Poster Awards of the 2019 SSAP Symposium.

## Friends and Former LANL Postdocs Reunite

Nenad Velisavljevic (left), Devesh Ranjan (middle), and Michael Demkowicz met as postdoctoral researchers at Los Alamos National Laboratory (LANL) in 2006 and were the original members of the group that established the Los Alamos Postdoc Association. At the 2019 Stewardship Science Academic Programs (SSAP) Symposium, the trio had time to catch up but also used the opportunity to discuss future collaborations that are vital in helping strengthen the effort between the national laboratories, NNSA university partners, and NNSA-funded external experimental facilities such as the High Pressure Collaborative Access Team (HPCAT).

# Overview



# Stewardship Science Academic Programs

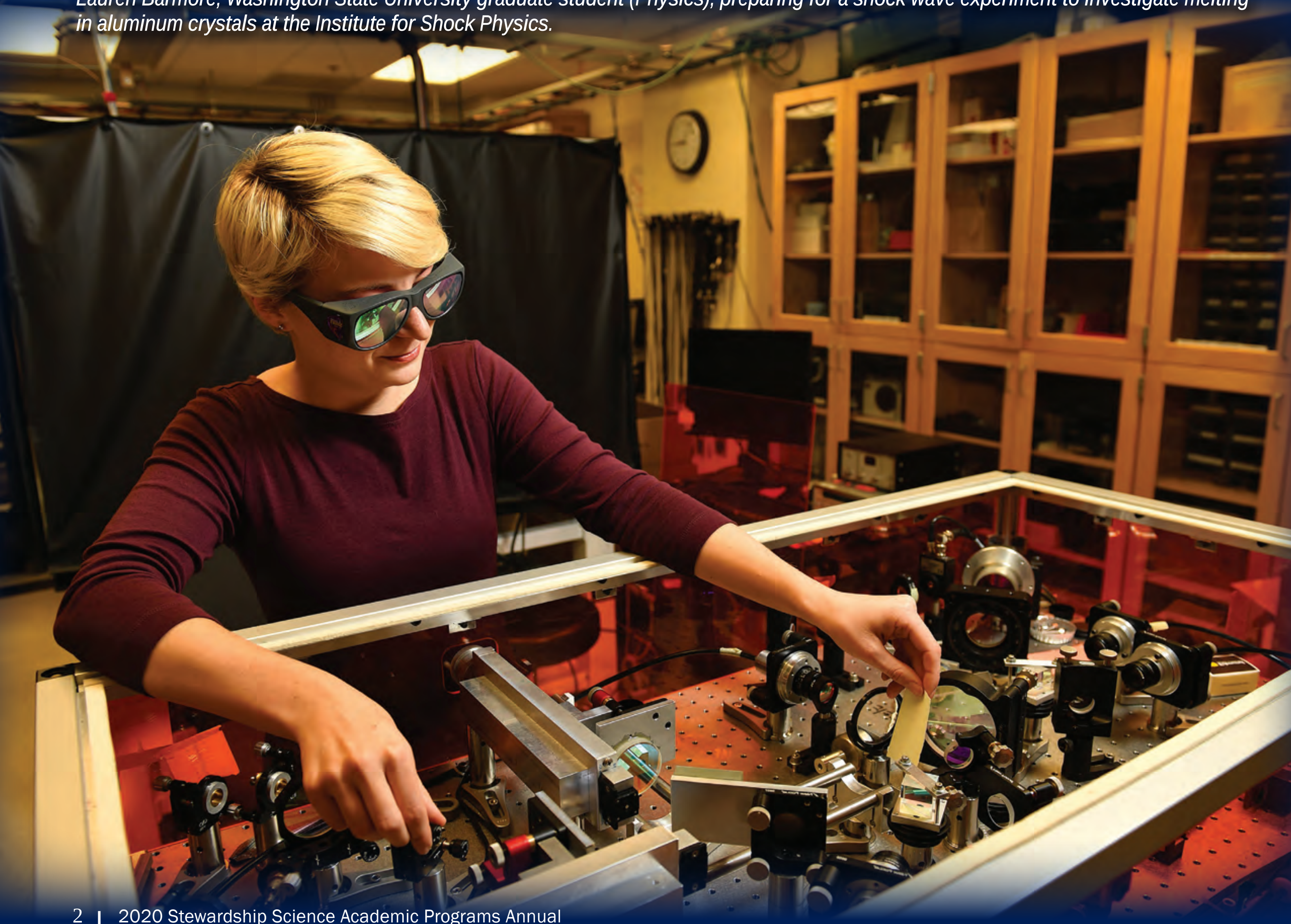
## — Future Stockpile Stewards

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 2020 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).

*Lauren Barmore, Washington State University graduate student (Physics), preparing for a shock wave experiment to investigate melting in aluminum crystals at the Institute for Shock Physics.*




Left: Dr. William Bookless, Principal Deputy Administrator of NNSA, welcomed attendees to the 2019 SSGF LRGF Annual Meeting. Right: Dr. Njema Frazier, Director, NNSA Office of Experimental Sciences, gave the keynote address entitled *Science, Stewards, and the Nuclear Deterrent*.

Dr. Sarah Nelson, Deputy Director, NNSA Office of Experimental Sciences, kicked off the Fellows Poster Session of the 2019 LRGF/SSGF Annual Meeting.

These programs support U.S. research at universities in scientific areas important to ensuring a safe, secure, and effective nuclear deterrent. A fundamental objective is the support and training of doctoral and masters degree students studying science and engineering with a view towards these students becoming future stewards of the stockpile. A second objective is to connect highly-skilled academic and NNSA scientists so that new ideas and techniques can be introduced into the NNSA's areas of expertise. A third 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 the NNSA.

## DOE/NNSA Fellowship Programs

The SSAP includes the Stewardship Science Graduate Fellowship (SSGF), Laboratory Residency Graduate Fellowship (LRGF), and Computational Science Graduate Fellowship (CSGF) 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). Also included is a highlight from one of the first LRGF students. For more information about these programs, please visit http://www.krellinst.org/fellowships.

## Stewardship Science Academic Alliances 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, hydrodynamics, low energy nuclear science, radiochemistry, and high energy density physics.

## High Energy Density Laboratory Plasmas Program

The NNSA's Office of Experimental Sciences 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 for 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 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

The primary focus of this program is the emerging field of predictive science, i.e., the application of verified and validated computational simulations to predict the behavior of complex, multiscale, multiphysics systems with quantified uncertainty. This is relevant to a variety of applications from nuclear weapons' effects to efficient manufacturing, global economics, and 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.

### User Facilities

The SSAA Program partially supports two advanced materials research activities at the Advanced Photon Source at the DOE's Argonne National Laboratory (ANL): the High-Pressure Collaborative Access Team (HPCAT) and the Dynamic Compression Sector (DCS). DCS, sponsored by the DOE/NNSA, is a first-of-its-kind capability dedicated to dynamic compression science. Operated by Washington State University, DCS is a novel and visionary capability in support of NNSA's scientific mission and offers an opportunity to pursue fundamental science that has not been possible to date at other synchrotron facilities. DCS, with an emphasis on condensed matter and materials research activities using a variety of dynamic compression platforms, is an excellent complement to other national user facilities.

HPCAT is a research consortium to advance compression science in multidisciplinary fields using synchrotron radiation. The consortium operates Sector 16 at ANL 's Advanced Photon Source where four simultaneously-operational beamlines have been established with an array of X-ray probes optimized for high-pressure research using X-ray diffraction, X-ray spectroscopy, and X-ray imaging techniques. HPCAT has been a phenomenal resource to NNSA scientists from its very inception.

# Stewardship Science Academic Programs Making a Difference

## — *By the Numbers*

### *Scientific Impact*

**6,500+** peer-reviewed articles published since 2002

### *Student Training*

**Hundreds** of graduate students supported through grants, centers of excellence at universities, and fellowships

— **80** academic institutions training students in science and technology disciplines relevant to stockpile stewardship

### *Workforce Development*

More than **150** graduate students and approximately **65** postdoctoral scholars/researchers are supported each year by the Stewardship Science Academic Alliances, High Energy Density Laboratory Plasmas, and National Laser Users' Facility programs

**77** students have been supported by the Stewardship Science Graduate Fellowship and Laboratory Residency Graduate Fellowship programs since 2006

— **48** alumni: **25** work for the NNSA national laboratories and **7** work for other government agencies

**379** alumni of the Computational Science Graduate Fellowship program

— **76** alumni work for the U.S. government

— **52** work for DOE/NNSA national laboratories (**29** NNSA national labs) and **24** at other government agencies

**92** students (MS and PhD) have graduated from the Predictive Science Academic Alliance Program

— **29** are employed by the DOE/NNSA national laboratories

— **79** graduate students and **13** postdoctoral scholars/researchers supported on average annually

***Supporting hundreds of faculty, research scientists, postdocs, graduate students, and undergraduate students at universities across the United States will aid in developing the next generation of highly-trained technical workers able to support NNSA's core mission.***

# Stewardship Science Academic Alliances

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

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

The Multi-University Center of Excellence for Pulsed-Power-Driven High-Energy-Density Science at Cornell University combines the skills, capabilities, and interests of six of the world's leading research universities on pulsed-power-produced, high-energy-density (HED) plasmas. The Center partners carry out experiments separately and in collaboration to understand the dynamics of current-driven HED plasmas, often supporting them with extended magnetohydrodynamic (XMHD) computer simulations using PERSEUS (Cornell) and the XMHD-capable GORGON (Imperial College). Below, recent results are discussed from gas-puff z-pinch and dynamic screw-pinch experiments and from an upgraded Thomson scattering diagnostic. Also described are the latest developments in the PERSEUS XMHD code.

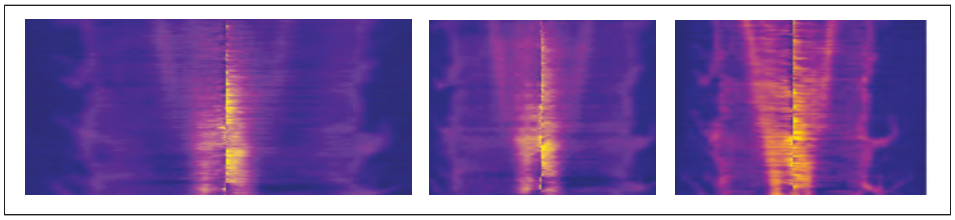


Figure 1. Abel-inverted interferometry images showing the electron density profile in an Ar gas puff z-pinch at 158, 168, and 178 ns into a 215 ns implosion illustrate the formation of a precursor plasma by photoionization of the center gas-puff before the arrival of the shock front and piston.

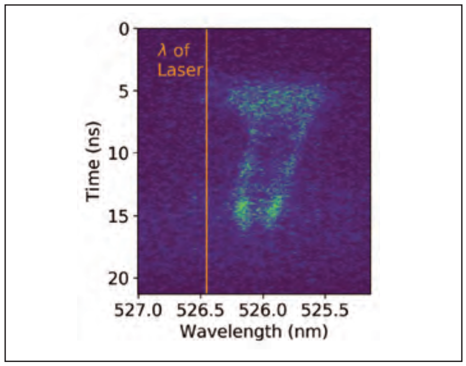



Figure 2. Streaked Thomson scattering spectrum from an Ar gas puff implosion shows the piston (5-7 ns) followed by decreasing velocity trailing plasma (7-16 ns).

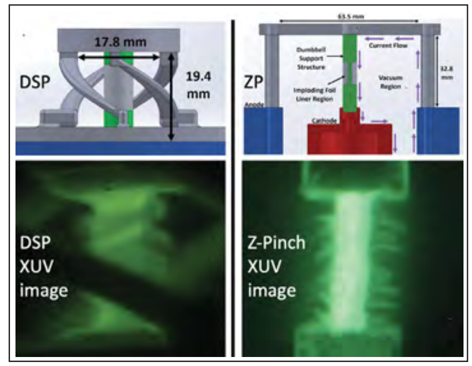



Figure 3. Comparison of a DSP (left) and a standard z-pinch (right) implosion.

Gas-puff z-pinch research on the COBRA pulsed-power machine at Cornell utilizes a triple coaxial nozzle in order to tailor the density profile to improve stability during implosion. Cornell Research Associate E. Sander Lavine has focused on the implosion dynamics and stability of Ar, Ne, and Kr implosions at a peak current of 950 kA and a current rise time of 240 ns. Enabled by a multitude of diagnostics, including multi-frame shearing interferometry, extreme ultraviolet cameras, and a high-speed, 12-frame camera, the structure and trajectory of a stable shock front and magneto-Rayleigh-Taylor unstable piston can be measured and compared to experimentally informed analytical models. The instability growth rate is observed to depend on shock structure and gas species and is, generally, much smaller than linear theory predictions. Application of a weak axial magnetic field reduces the growth rate further and introduces helical unstable modes. At high center-puff densities, the formation of a precursor plasma by photoionization often is observed in Ar gas-puff z-pinch implosions. Example interferometry images showing the evolution of this plasma are presented in Figure 1.

The gas-puff z-pinch has been used by Cornell PhD student Sophia Rocco and postdoctoral associate Jacob Banasek to test an upgraded Thomson scattering diagnostic system. They implemented a prism-based, beam-splitting scheme that allows production of four consecutive 2.5 J laser pulses from the 10 J, 526.5 nm, 2.2 ns (FWHM) Thomson scattering laser by using one prism to bisect the beam vertically and a second to bisect it horizontally. The beam quadrants are then delayed relative to each other by 3 ns and delivered colinearly to the experiment champer in order to produce a train of four 2.2 ns pulses that, when coupled to a spectrometer and streak camera, can monitor the time-evolution of HED plasmas produced on COBRA for 12 ns. An example is shown in Figure 2.

University of Michigan PhD student Paul C. Campbell used COBRA to test the theory of Schmit et al. [PRL 117, 205001 (2016)] that a magnetic field configuration called the dynamic screw pinch (DSP) could stabilize magnetically-driven implosions of initially solid-metal tubes (liners). The DSP is generated using a helical return-current structure (see Figure 3) which produces a helical magnetic field with a time-dependent pitch. By contrast, the standard z-pinch uses a straight return-current structure which produces an azimuthal magnetic field and azimuthally correlated instability structures. The instability amplitudes in the DSP cases were smaller than in the standard z-pinch cases by up to a factor of 3 by the time the liner had imploded halfway to the cylindrical axis, as shown in Figure 3. This work is relevant to Sandia National Laboratories' magnetized liner inertial fusion (MagLIF) approach to magneto-inertial fusion, and similar DSP tests are planned for the 25 MA Z facility at Sandia.

The PERSEUS XMHD code has been upgraded to include modelling of anisotropic thermal conductivity, thermoelectric forces, and stress tensors by solving up to 13-moments of the Fokker-Planck equation instead of the usual 5. This approach enables a more accurate calculation of transport since no perturbation methods are used. It is being tested against validation problems with analytical solutions. Including diffusive corrections, called regularization, gives good agreement with these tests in the collisionless limit, thereby showing the benefit of using this method. The model has been tested on non-local heat flow, showing qualitative agreement with kinetic theory without the use of artificial heat flux limiting, allowing PERSEUS to retain predictive power when studying non-equilibrium plasma states.

## Small Samples, Big Instruments: CDAC Students Tackle Extreme Conditions Research at National User Facilities

George Washington University ✦ PI: Dr. Stephen A. Gramsch (sgramsch@gwu.edu)

As the finer details of structure-property relationships in materials become increasingly important, ever more sophisticated and powerful tools are required for analysis of the response of material structures and properties to increasing pressure. Significant investments in national facilities throughout the Department of Energy (DOE) laboratories in recent years have provided new and unique opportunities for groundbreaking work in the study of matter at extreme conditions.

In the Capital/DOE Alliance Center (CDAC), students have taken advantage of DOE facilities for working on a diversity of high pressure materials problems. More recent examples include exploring the unusual reactivity patterns of the elements enabled by high pressure, understanding the evolution of structural effects resulting from heavy ion irradiation, and evaluating texture development in multiphase assemblages.

Research in mineral physics aimed at understanding processes in Earth's deep interior has been a key scientific driver of advancements in high pressure research since its earliest days. Most Earth materials are inherently complex, and the need to attain the pressures and temperature conditions they experience in the mantle has resulted in some of the key developments in high pressure research. High pressure geoscience research programs have allowed students to develop the skills necessary to understand complex materials more broadly and the detailed interplay of structure, properties, and composition in materials. Combined with experience at DOE/NNSA national user facilities, these research directions have provided students with the background necessary for advanced work in stockpile stewardship.

One of the key goals in the CDAC scientific program is to perform experiments that bridge the gap between static and dynamic compression. To that end, a number of CDAC students have been moving toward studies of materials using shock compression techniques at specialized facilities within the DOE/NNSA laboratories.

Ben Brugman, a graduate student at Michigan State University in the group of CDAC Academic Partner Susannah

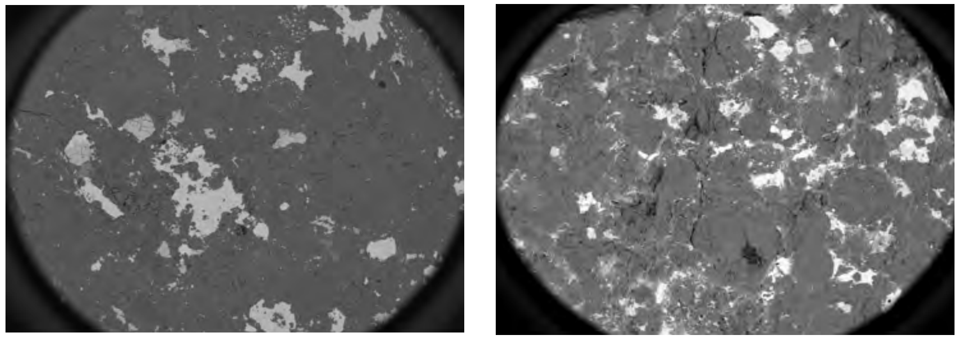


Figure 1. SEM images of chondrite samples following laser shock. Left, unweathered Tamdakht chondrite. Right, weathered Allen Hills chondrite. The crack density at the center of the sample resulting from laser shock is much higher for the weathered chondrite, indicating a lower dynamic strength. Images are about 5 mm across.

Dorfman, has recently carried out a study on the dynamic strength of chondrites under laser shock compression using the Trident laser at Los Alamos National Laboratory. Chondrites are multi-phase, non-metallic meteorites and represent material from the primitive solar system. Apart from a purely fundamental interest in the properties of these objects, Ben's goal is to provide input to the development of models for asteroid hazard mitigation.

In these preliminary experiments, samples of 1-2 mm thickness are compressed by 50-60 J laser irradiation of a foil until it ablates. The ablation drives a shock wave through the sample. Recovered samples are analyzed for crack density, which appears to increase with weathering and indicates a decrease in dynamic strength (Figure 1). Further work will include experiments at the Jupiter Laser Facility at Lawrence Livermore National Laboratory to investigate regions of samples in which the grain size is small compared to the drive beam. This will allow a systematic evaluation of the impact of weathering class and iron content on dynamic strength.

Hannah Bausch (see Figure 2), a graduate student in the group of CDAC Academic Partner Steve Jacobsen at Northwestern University, is interested in the behavior of the solid solution system (Mg,Fe)O at pressures corresponding to those found at Earth's core-mantle boundary and in the interiors of exoplanets. Although (Mg,Fe)O has been studied extensively from both the material science and geophysical perspectives, a detailed understanding of how Fe substitution into MgO changes the physical properties of the solid solution system is lacking. The differences are striking: MgO is a wide-gap insulator that undergoes a phase

Figure 2. Hannah Bausch (Northwestern University) prepares thin wafers containing MgO and FeO for high temperature synthesis of target compositions in the (Mg,Fe)O solid solution system.

transition only at pressures above 1 TPa, but FeO displays several low-pressure phase transitions and becomes metallic at moderate pressures.

Collaborating with former CDAC students Josh Townsend and Chris Seagle at Sandia National Laboratories, Hannah plans to carry out dynamic compression experiments at Sandia's Z machine on samples with different compositions in the (Mg,Fe)O system to gain an understanding of how its thermodynamic properties change with increasing Fe content. Measurements under dynamic compression will provide information on thermodynamic states that are not accessible with other high pressure methods and will result in key data for models of planetary formation and differentiation as well as for applications in high energy density physics and stockpile stewardship.

## Overview of the Initial Work of the Center of Excellence for Advanced Nuclear Diagnostics and Platforms for ICF and HED Physics at Omega, NIF, and Z

Massachusetts Institute of Technology ✦ PI: Dr. Richard D. Petrasso (petrasso@psfc.mit.edu)

The newly created Center for Advanced Nuclear Diagnostics and Platforms for Inertial Confinement Fusion (ICF) and High Energy Density (HED) Physics at Omega, NIF, and Z, comprised of the Massachusetts Institute of Technology (MIT), Virginia Polytechnic Institute and State University (Virginia Tech), University of Iowa, University of Nevada, Reno (UNR), and University of Rochester (UR) has just begun combining together the complimentary and unique capabilities of the Center partners to significantly advance HED physics, from implosion physics to lab astrophysics.

In September, UR and MIT had an Omega shot day in which the effects of large magnetic fields upon directly-driven implosions were explored. Through the use of magnetic coils, fields as large as 45 tesla were generated (see Figure 1), and implosions were studied that either were shock or compressively driven. The effects of such large magnetic fields are expected, among other effects, to significantly impact the implosion electron thermal conductivity, as the electrons will be magnetized strongly and, therefore, cannot freely stream across the magnetic field lines. Among other interesting features of this comparative study is that the temporal, temperature, and density scales for these two types of implosions are quite different, with the shock-driven implosions occurring on a much faster time scale, at a much higher temperature, and at a much lower density. Because of these special shock-generated conditions, the mean-free-path of the implosion fuel ions is much longer than the ion gyro radius, making the ions and the electrons both "strongly magnetized". This is the first time such unique conditions have been achieved in directly-driven implosions. The detailed analysis of these innovative shots is just beginning and should prove an exciting area of research for the Center of Excellence (COE) and HED colleagues in the larger community.

One important feature of the shock-driven implosions is that the fuel is comprised of three different ions: tritium, $^{3}$He, and deuterium. There is experimental evidence, just published by recent MIT PhD Hong Sio (in *Physics of Plasmas*; the article was selected as the Editor's Pick), that the implosion dynamics cannot

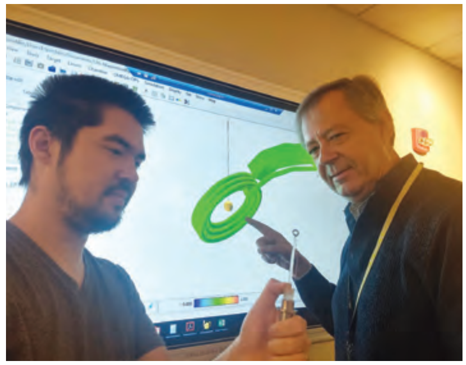


Figure 1. UR Postdoc Jonathan Peebles (left) and Chief Scientist Professor Riccardo Betti discuss the field coils (schematic on the screen with capsule in the center of the coil; and the actual coil hardware held by Jonathan) used to generate strongly magnetized directly-driven implosions.

be accurately simulated as a single-average ion which is the standard way that implosions usually are treated. (This is the case for LASNEX, HYDRA, LILAC, FLASH, and many other simulation codes.) To that issue, Virginia Tech is undertaking new hydro simulations that would treat individual fuel ions as distinct fluid components and not average them together. This extension would be insightful since during either the shock and/or compressive phase of any implosion the fuel usually is comprised of different ion species. This work is also being supported by University of Iowa, where they are working on transport coefficients that could be utilized in the Virginia Tech simulations. (For his work on this topic at last year's Stewardship Science Academic Programs symposium, University of Iowa's David Bernstein was awarded an Outstanding Poster Award.) In support of this overall effort, MIT is upgrading, through the work of PhD students Neel Kabadi and Patrick Adrian, a temporally-resolved diagnostic that can measure different nuclear burn histories of these implosions to 10 psec accuracy. These multiple nuclear burn histories add another important constraint to the simulations of Virginia Tech.

To fully constrain the dynamics of these shock-driven implosions, it will be important to have an accurate measurement of the electron temperature and density. To that objective, UNR is working on a new crystal spectrometer that would be sensitive to trace krypton

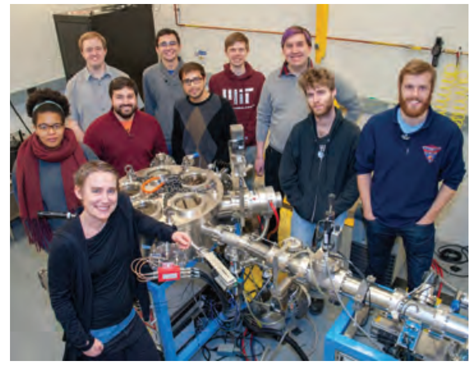


Figure 2. Dr. Maria Gatu Johnson, American Physical Society 2019 Weimer Award for Women in Plasma Science recipient, shown with MIT graduate students at the MIT accelerator lab which is used, under Maria's direction, for developing and testing diagnostics fielded at Omega, NIF, and Z. This HED facility is where students obtain hands-on experience, critical to the success of their experiments at the major facilities.

impurities and from which the implosion electron temperature and density could be inferred. For his poster on this topic at the 2019 Omega Users Workshop, Dylan Cliche, the UNR grad student leading the project, was awarded first prize.

As electric and magnetic fields are pervasive in all HED plasmas, MIT and collaborators obtained in August the first preliminary data with the new tri-particle backlighter which utilizes monoenergetic 3.0 and 15 MeV protons and 9.5 MeV deuterons. Through the radiographs of the three different particles, one has, approximately speaking, 3 equations with 3 unknowns from which to deduce the effects of electric, magnetic, and plasma density. This effort, including detector calibration (see Figure 2), its utilization for characterizing a range of lab astro experiments, and the conditions inside hohlraums, is just starting. On the basis of using only the "dual version" of this backlighter, i.e., the 3 and 15 MeV protons, Chikang Li et al. recently published on collisionless shocks in PRL and gave an invited talk at the 2019 DPP meeting at Fort Lauderdale. Utilizing this backlighter platform, the COE supports 25 shot days each year of other university and national lab researchers' experiments on NIF and Omega.

## Center for Research Excellence on Dynamically Deformed Solids

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

The Center for Research Excellence on Dynamically Deformed Solids (CREDDS) combines expertise at four leading U.S. universities to investigate advanced metallic materials undergoing extremely rapid deformation. Advanced processing methods, such as additive manufacturing, provide exciting opportunities for making new materials with radically-improved performance. However, they pose challenges to the current understanding of how these materials behave, especially under high-strain-rate, mechanical loading. CREDDS researchers at Texas A&M University (TAMU), the lead institution, University of California Santa Barbara (UCSB), University of Michigan Ann Arbor, and University of Connecticut are working to fill this knowledge gap. They are collaborating on all aspects of processing, characterizing, testing, and modeling materials with complex, multiphase structures. The ability to predict and improve the performance of such materials is critical to the continued success of stockpile stewardship.

To create advanced metallic materials, CREDDS uses a wide range of processing methods, including additive manufacturing by direct metal deposition, physical vapor deposition, and severe plastic deformation. For example, during a semester-long internship at Los Alamos National Laboratory (LANL), University of Michigan student Ben Derby, shown in Figure 1, synthesized novel composites of copper and molybdenum. These materials exhibit a previously unseen range of microstructures, including ones with finely interpenetrating, folded sheets of the constituent elements. Ben used transmission electron microscopy to demonstrate that the microstructure of these materials may be controlled readily down to the nanometer-level by adjusting processing parameters such as temperature or deposition rate.

Once materials are processed and characterized, they undergo testing under high-strain-rate deformation. CREDDS researchers work on improving well-established techniques for performing such tests as well as on developing novel approaches for high-strain-rate testing. UCSB student Avery Samuel (see Figure 2) spent a semester gaining expertise in the testing methods used by staff at LANL. With this knowledge, he

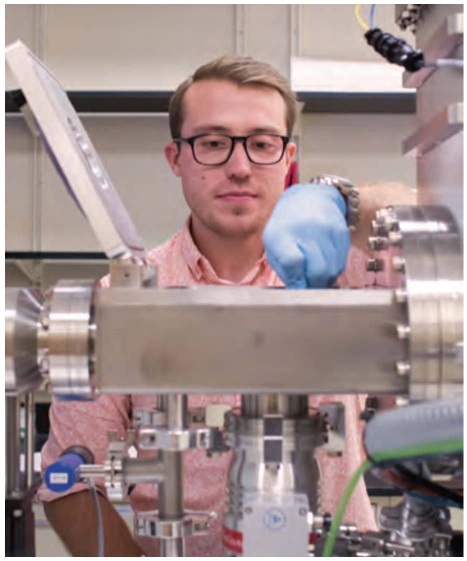


Figure 1. Ben Derby synthesizes advanced nanocomposite metallic materials using physical vapor deposition.

Figure 2. Avery Samuel prepares a high-strain-rate mechanical test using a split-Hopkinson pressure bar.

Figure 3. CREDDS supported eight undergraduate researchers in the summer of 2019. Left to right: Peter Evans, Carrie Jones, Rowan Baird, Andres Ramirez, Elizabeth Schiesser, Sasha George, Hunter Harris, and Anthony Chavez.

now is performing experiments using a split-Hopkinson pressure bar newly-installed at his home institution. This new instrument allows for *in situ* monitoring of material deformation during loading using high speed cameras, a capability that will shed unprecedented insight into the limits of survivability of advanced metallic materials under rapid loading.

Making reliable performance predictions for materials with complex microstructures requires high fidelity computer modeling. Marco Echeverria from the University of Connecticut spent a summer at Lawrence Livermore National Laboratory perfecting simulations used to model processing and deformation of multi-phase metals. To this end, he used the molecular dynamics technique, which tracks the locations of all individual atoms in a material model and yields detailed insight into microstructure evolution. The outcomes of Marco's simulations may be incorporated into hydrocodes, macro-scale simulations to predict material behavior under shock loading.

Training the next generation of leaders in stockpile stewardship is a core goal for CREDDS. The Center supports sixteen PhD students, five of whom went on extended internships to NNSA laboratories last year. In the same year, CREDDS supported ten undergraduate researchers. In addition to interacting with CREDDS faculty and engaging in CREDDS research, these students participated in activities intended to increase their awareness of the NNSA's mission and career opportunities in the stockpile stewardship enterprise. For example, eight summer researchers at TAMU (see Figure 3) attended seminars organized by both CREDDS and another SSAA center of excellence headquartered at TAMU, the Center for Excellence in Nuclear Training and University-Based Research (CENTAUR). This effort builds the foundation of future success for CREDDS and all Stewardship Science Academic Programs-sponsored projects by mentoring and encouraging students as they prepare to transition to graduate school.

## Center for Excellence in Nuclear Training and University-based Research

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Now finishing its second year, the Center for Excellence in Nuclear Training and University-based Research (CENTAUR) is a collaboration of low-energy nuclear science faculty at six universities, i.e., Florida State University, Louisiana State University, Texas A&M University, University of Washington, Washington University in St Louis, and the recently added University of Notre Dame (UND) that makes use of university accelerators to do basic research relevant to stockpile stewardship while developing the workforce to support DOE/NNSA laboratories.

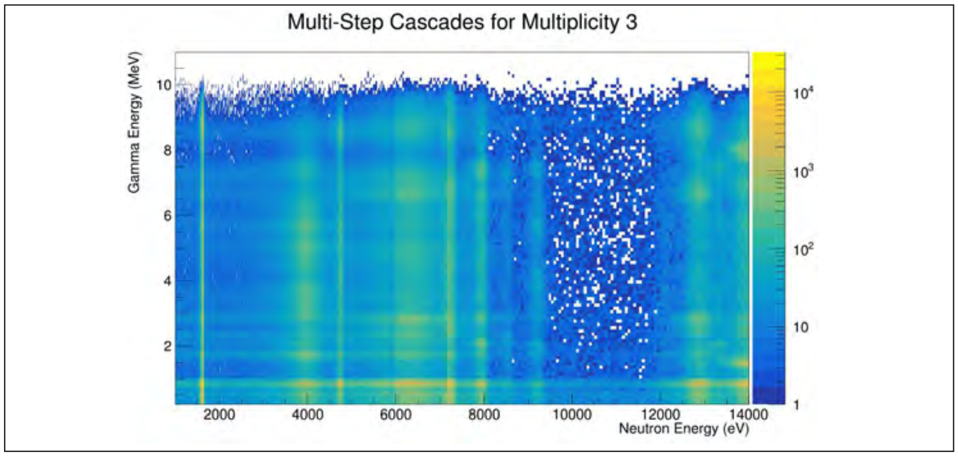


Figure 1. Plot of neutron energy versus gamma energy gated on multiplicity 3 (only 3 gamma rays were observed during the deexcitation). It shows the different cascades for different neutron resonances in the capture data.

Figure 2. Eames Bennett (Texas A&M) presents work done during his summer at LANL at the CENTAUR SAC meeting in August.

*"Spending a summer at LANL opened my eyes to the world-class research taking place there and sparked an interest in pursuing a career at the labs."*

One of the scientific foci of the CENTAUR is understanding how conditions in stars affect the production of heavy elements. Astrophysical environments can be quite neutron-rich (contain a higher neutron fraction than a stable nucleus), so understanding them can be useful to stockpile stewardship. Combining experiment and theory to describe, in precise detail, the process of nucleosynthesis in stars always has been a goal of astrophysics. There are many different isotopes whose creation is important in slow neutron capture nucleosynthesis, many of which are what is known as "branch-point" in the chain of nucleosynthetic pathways in stars.

Iron-60 is the product of one such branch-point. It has a half-life less than the age of the solar system but has been found on the moon, nearby in the galaxy using spectral lines, on the ocean floor, in Antarctic snow, and raining down on earth from space via spectrometers in space such as the Cosmic Ray Isotope Spectrometer (CRIS). A collaboration within CENTAUR, made up of scientists from Los Alamos National Laboratory (LANL), UND, and Texas A&M, is constructing an experiment at the Texas A&M Cyclotron Institute to measure the photon strength function, which governs the probability that photons of any particular energy are released from an excited nucleaus, of $^{60}$Fe via the surrogate $^{59}$Fe(d,p)$^{60}$Fe reaction in order to better understand $^{60}$Fe production in astrophysical environments. The set up will use the recently refurbished Oak Ridge National Laboratory-Texas A&M $BaF_2$ array to measure the gamma rays of the photon strength function. To test the viability of the set up with the expected beam rate, a stable beam reaction, $^{57}$Fe(d,p)$^{58}$Fe, will be run to test similar nuclear physics. This experiment, using the surrogate reaction technique, will be compared to the direct (n,γ) experiment run with the Detector for Advanced Neutron Capture Experiments (DANCE) at LANL in Fall 2017.

Senior CENTAUR (Texas A&M) graduate student Eames Bennett spent his summer as a guest of Aaron Couture and the rest of the P-27 group at LANL focused on understanding the photon strength function of iron-58 utilizing data from DANCE. He extracted multi-step gamma cascades for multiple neutron capture resonances in iron. Better understanding of this nucleus allows us to push the frontiers of nuclear physics and provide insight into how common materials are affected by high neutron-fluence environments. Preliminary results from his experimental cascades are shown in Figure 1. Once he completes the theoretical work to interpret the data, we will have an improved understanding of the electromagnetic de-excitation of this key nucleus, which builds our broader understanding of neutron-induced nuclear reactions.

Bennett learned he would have the opportunity to work on half of his thesis at LANL shortly before visiting New Mexico for the 2019 Stewardship Science Academic Programs Symposium. "Spending a summer at LANL opened my eyes to the world-class research taking place there and sparked an interest in pursuing a career at the labs," said Bennett about his experience. He then was able to show some fellow graduate students around Los Alamos when CENTAUR convened their annual Scientific Advisory Committee (SAC) meeting at LANL this August. Bennett, second from left, is pictured presenting his summer research to interested members of the CENTAUR SAC (see Figure 2). To learn more about other CENTAUR projects, please visit centaur.tamu.edu.

## Center for Matter Under Extreme Conditions

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

The Center for Matter Under Extreme Conditions (CMEC) leads research and technological breakthroughs in high energy density (HED) science emphasizing the creation and diagnosis of extreme states of matter, both unmagnetized and magnetized, exploiting novel combinations of HED drivers utilizing both modeling and experiments to develop a physics understanding of HED systems, and training future scientists.

The Center's major coordinated effort between its partners (UC Berkeley, UC Davis, University of Chicago, Florida A&M, and General Atomics) has focused on three areas: (1) energy transport in HED systems, (2) material properties across HED regimes, and (3) nature under extreme conditions.

Area 1 strives to examine the effects of an external magnetic field on energy transport, in particular, the role of an external magnetic field on laser-plasma instabilities (LPIs). Understanding how to control LPIs becomes essential for efficient coupling of high-power laser energy to the target for a number of applications, including inertial confinement fusion. One promising strategy for reducing instabilities is to apply an external magnetic-field. These predictions are being tested in experiments at the Jupiter Laser Facility at the Lawrence Livermore National Laboratory (LLNL) (see Figure 1).

Fiigure 1. Graduate student Joe Strehlow sets up a Thomson scattering diagnostics at the Jupiter Laser Facility to validate a modeling prediction.

Another tool to study energy transport is with gas-puff Z-pinches in which one or more annular liners implode onto a central column. As the load implodes, the outer surface is highly susceptible to the magneto-Rayleigh-Taylor instability, the mitigation of which is critical to ensuring stable and uniform compression and heating. Among the numerous approaches to mitigation, we've explored density profile tailoring and axial pre-magnetization simultaneously. By altering the initial mass distribution of the load, the implosion trajectory is altered such that acceleration is zero or negative. If there is an axial field pre-embedded in the load, field line tension can act as a restoring force. These approaches can decrease the growth rate of perturbations. CMEC has been in the process of testing this approach both experimentally and numerically.

In area 2, the focus of activities is on high-precision, equation-of-state measurements of warm, dense matter at the National Ignition Facility. A new experimental platform has been developed which uses simultaneous X-ray Thomson scattering (XRTS) and streaked X-ray radiography to measure the density, electron temperature, and ionization state of warm, dense matter. The platform uses colliding planar shocks to minimize the distribution of states in the scattering volume to significantly improve the precision of the XRTS measurements. In addition, shock-and-release experiments have been performed to measure densities and temperatures along vapor curves of silicates (forsterite and bronzite) and to determine the amount of vapor produced during planetary collisions.

Lastly, in thrust area 3, CMEC partners with the Astrophysical Collisionless Shock Experiments in the Laboratory (ACSEL) team, an international collaboration including LLNL, SLAC, Oxford, Princeton, Osaka University, and MIT, to better understand shock formation in exotic astrophysical systems such as supernova remnants, where shocks form due to electromagnetic fields created by fast-streaming, collisionless particles. High-power lasers have been used to study the instabilities responsible for generating spontaneous electromagnetic fields in collisionless systems and to answer questions about how our universe evolves.

A central mission of CMEC is to engage graduate students in research at the national laboratories. This year, four graduate students spent their summers at LLNL and Los Alamos National Laboratory researching a variety of topics including neutron production from collisionless shocks, X-ray phase contrast imaging, and material properties under extreme conditions.

To expand the Center's educational reach to the greater United States, CMEC recently organized the High Energy Density Science Summer School (HEDSSS) at UC San Diego. Representing a key deliverable for the Center, HEDSSS covered broad topical areas such as material science in extreme conditions, HED astrophysics, and ultra-intense laser-matter interactions. The event was attended by more than one hundred students and postdoctoral scholars (see Figure 2).

Additionally, CMEC offers research opportunities to undergraduate students. This year, seven undergraduate students participated, completing research in computational and experimental plasma physics, nuclear physics, planetary science, and astrophysics from various colleges and universities across the United States.

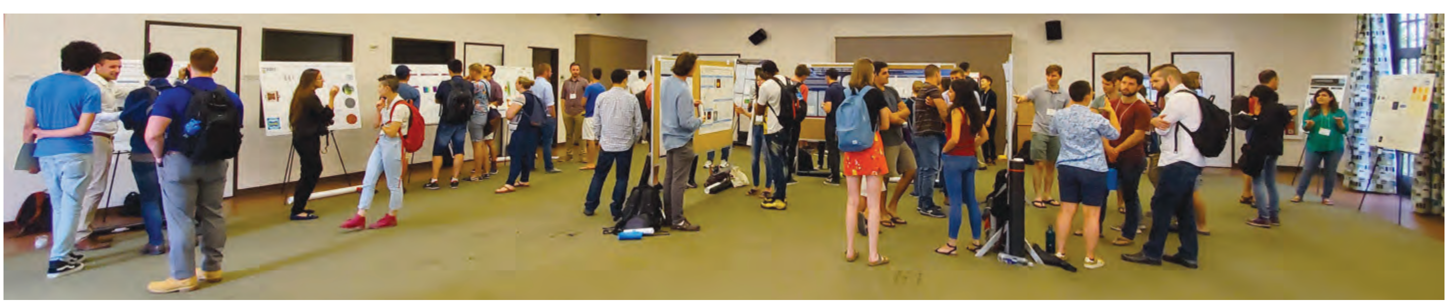

Figure 2. Poster session at the High Energy Density Science Summer School. Sixty-two students and postdoctoral researchers presented posters.

## Center for Laboratory Astrophysics: Experiments Studying Magnetic Bow Shocks Using the OMEGA Laser Facility

University of Michigan, Ann Arbor ✦ PI: Dr. Carolyn Kuranz (ckuranz@umich.edu)

The Center for Laboratory Astrophysics (CLA) at the University of Michigan explores high-energy-density phenomena that are relevant to astrophysics. Laboratory astrophysics can provide a bridge between astrophysical observations and simulations. Well-scaled experiments can visualize specific astrophysical processes in a controlled environment that are not well understood. High-energy-density facilities are uniquely suited to create astrophysical conditions relevant to accretion phenomena, star formation, supernova explosions, and other astrophysical systems. At CLA, we focus on three scientific areas: magnetized flowing plasmas, complex hydrodynamics, and radiation hydrodynamics. These areas have broad applicability in space science and astrophysics. For example, the hydrodynamics of supernova explosions affects astrophysical observations, and radiation can trigger or suppress star formation. According to Center Director Kuranz, “At CLA, students use NNSA facilities to explore fundamental high-energy-density physics relevant to astrophysical systems.” Figure 1 shows the current CLA team and scientific collaborators.

Figure 1. CLA team and scientific collaborators at the Omega Laser Facility Users Group meeting.

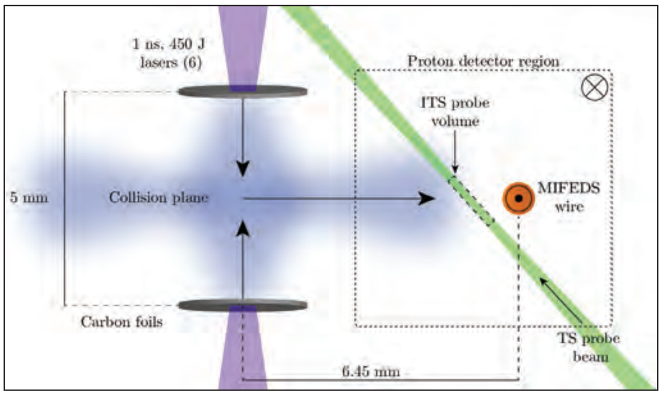


Figure 2. Cross-section of the experimental setup at the Omega Laser Facility.

Magnetic fields in high-energy-density plasmas are a main scientific thrust at CLA, with deep connections to many astrophysical systems. Magnetic fields permeate the universe, and because of the very large length scales and long-time scales of most astrophysical processes, even relatively weak (from a human perspective) magnetic fields of planetary bodies can be dynamically significant to the evolution of plasma flows. For instance, the sun constantly emits a wind of charged particles which is prevented from reaching the surface of the Earth because of the planet's magnetic field. The magnetic pressure balances the solar wind ram pressure at the magnetopause, approximately 10 Earth radii from the surface. A bow shock exists upstream of the magnetopause and redirects the incoming solar wind around the planet.

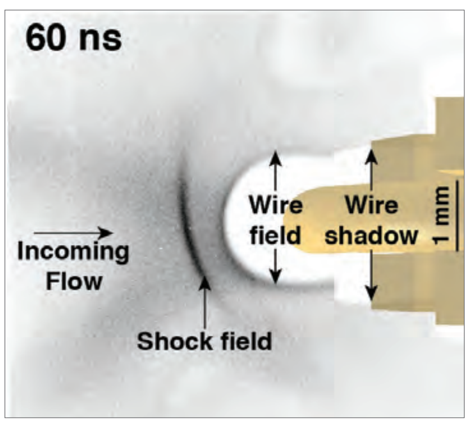


Figure 3. 14.7 MeV proton image of the experiment 60 ns after main laser drive for a 17 kA MIFEDS wire current (9 T maximum field at the wire surface). Darker regions indicate greater proton flux. The identifiable features are labeled, with a model of the wire holder overlaid.

Current understanding of this system relies on spacecraft measurements and computer models tailored to those data. As such, prediction of the magnetosphere response to new solar wind conditions from these models is limited. Laboratory-scale experiments could help to extend models by studying the effects of variable solar wind conditions on magnetospheric dynamics. However, reaching a similar regime in experiments is challenging, because laboratory length and time scales require very strong magnetic fields. Fortunately, the magnetic field generation capabilities of the magneto-inertial fusion energy discharge system (MIFEDS) at OMEGA is capable of producing dynamically significant magnetic fields over a range of laser-produced plasma conditions.

PhD student Joseph Levesque led two shot days at OMEGA, in which an unmagnetized, low-density, plasma flow impinged on the magnetic field of a current-carrying wire, as shown in Figure 2. The proton imaging diagnostic, developed by MIT, probes electromagnetic fields with high-energy, fusion-generated protons, forming an image of the path-integrated fields based on deflections of the probe protons. The probe protons travel into the plane of Figure 2, and the wire current flows out of the plane. This orientation results in the protons being deflected radially outwards from the wire. Proton images from this campaign display signs of significant magnetic field compression more than 1 mm from the center of the magnetized wire obstacle, as shown in Figure 3. Imaging Thomson scattering measurements show a large increase in electron number density roughly 1.5 mm from the wire, indicative of a shock. These results demonstrate that studying systems of dynamically significant magnetic fields is experimentally feasible and, with further tuning, may produce good analogues for magnetized astrophysical plasmas.

These experiments were performed at the Laboratory for Laser Energetics' OMEGA laser as part of a collaboration between Professor Carolyn Kuranz at the University of Michigan and Professor Patrick Hartigan at William Marsh Rice University through the National Laser Users' Facility program.

## Radiation and Uranyl Clusters

University of Notre Dame ✦ PI: Dr. Peter C. Burns (pburns@nd.edu), Author: Dr. Jay A. LaVerne (jla@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 the security of the Nation via stockpile stewardship, with workforce development as a motivating goal.

Actinides are important to many aspects of the Stockpile Stewardship Program, and actinide chemistry is an exciting and resurging area of science; however, it has some challenges. Its chemistry is complex, and the nature of 5f electrons is poorly understood. Actinides are used in fairly complex systems; they are the fuel for commercial power plants and naval propulsion systems and the heat sources in thermoelectric generators for space exploration. Another challenge is that all actinides are radioactive. Their self-radiolysis and the harsh radiation environments they encounter can lead to evolution into species that often have very different properties. Therefore, the examination of the radiation-induced effects on actinide materials is one of the important research areas of ACE.

Radiation traditionally has been used to accomplish two different chemical effects: the breakdown of compounds and the formation of new species. Both avenues are being explored within ACE. Actinide materials vary widely in properties and scale. They range from the relatively stable studtite, $[(UO_2)(O_2)(H_2O)_2](H_2O)_2$, to the salt of the $U_{60}$ uranyl peroxide cage cluster, $Li_{44}K_{16}[(UO_2)(O_2)(OH)]_{60}\cdot 255H_2O$. Many of these actinide compounds have been found in harsh radiation environments or they have been proposed for use in the nuclear industry. Studtite, a secondary uranium mineral, is found deposited on stored fuel rods, and a variety of actinide materials have been proposed for use in separations systems or permanent storage. Radiation studies on the stability of pristine compounds have concentrated on gamma radiolysis and accelerated He ions, the latter to mimic the natural alpha particle decay.

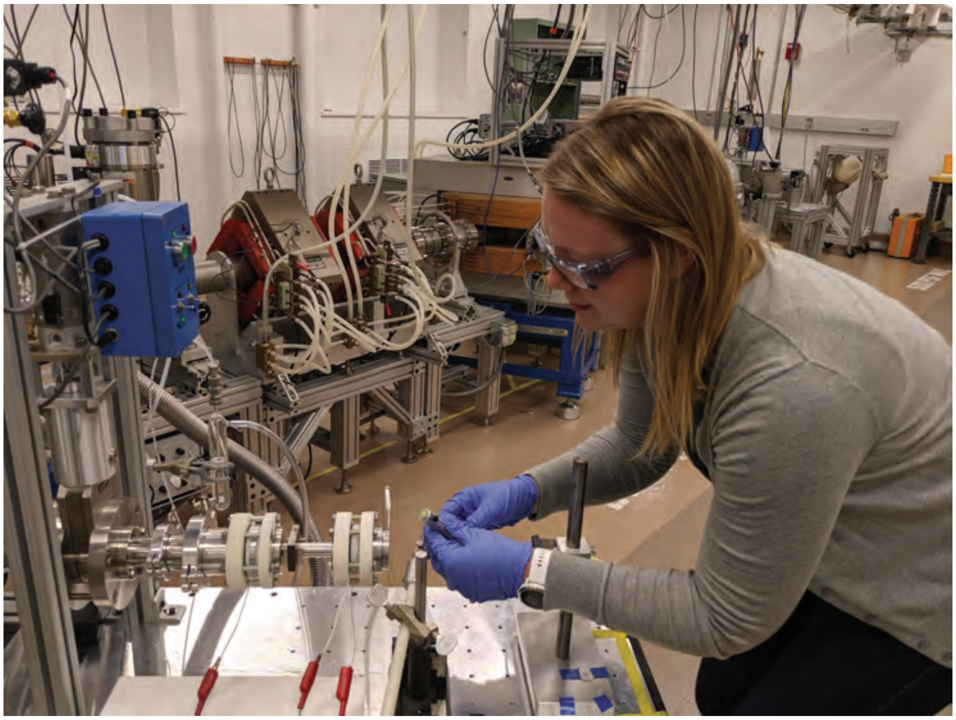

Figure 1. Postdoctoral Assistant Melissa Fairley (University of Notre Dame) preparing a sample for He ion radiolysis.

All the compounds examined show remarkable stability to radiation, despite their perceived delicate configuration.[1] Pristine samples or those exposed to small amounts of pure water have been probed, but the more challenging systems will be with slurries of added solutes. For instance, reactor water has added $H_2$, ground water has carbonates and organic material, and accidents like Fukushima combine nuclear materials with seawater having concentrations of halides. All of these solutes will modify the water radiation chemistry and, thereby, change the stability of the actinide materials.

Transformations like the formation of studtite from $UO_2$ fuel rods show that radiation can convert actinide materials into different configurations. Aqueous solutions of lithium uranyl triperoxide monomer ultimately will form uranyl clusters, specifically the uranyl peroxide cage cluster Li-$U_{24}$,$[(UO_2)(O_2)(OH)]_{24}{}^{24-}$. This process is accelerated by radiolysis. Newer studies have discovered that a similar reaction also may occur in the solid phase. Radiation induced formation of solid compounds is not new, but to find a compound this complicated is extremely new and exciting. These studies open a completely new avenue of materials syntheses that is waiting to be exploited.

These new findings are coming out of the efforts of Dr. Melissa Fairley, a Postdoctoral Associate at the University of Notre Dame (see Figure 1) who stated that “these solid-state pathways open opportunities for mechanistic studies and assembly of novel materials. Dose studies can be utilized to better understand the assembly and breakdown of uranyl peroxide materials. At a more applied level, it is important to understand how these materials are affected by intense irradiation fields.”

### Reference

[1]M. Fairley, N.M. Myers, J.E.S. Szymanowski, G.E. Sigmon, P.C. Burns, and J.A. LaVerne, "Stability of Solid Uranyl Peroxides Under Irradiation," Inorganic Chemistry, (2019). DOI: 10.1021/acs.inorgchem.9b02132

## The Wootton Center for Astrophysical Plasma Properties

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

The purpose of the Wootton Center for Astrophysical Plasma Properties (WCAPP) is to explore matter under a wide variety of cosmic conditions in the laboratory, transforming astrophysics into an experimental science. WCAPP enables graduate students and postdoctoral researchers to work in a national laboratory scientific culture and gain expertise in theoretical and experimental atomic physics, spectroscopy, and platform development. It prepares them to lead in these areas. Fundamental science experiments are conducted on the Z Pulsed Power Facility at Sandia National Laboratories (SNL) with others proposed for the National Ignition Facility (NIF). At present, WCAPP carries out four independent, astrophysically-motivated experiments simultaneously on each shot (see Figure 1).

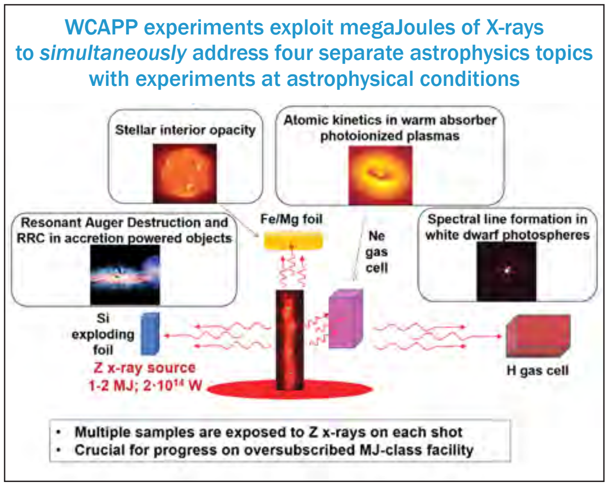


Figure 1. Illustrating the Four Simultaneous Experiments on Z.

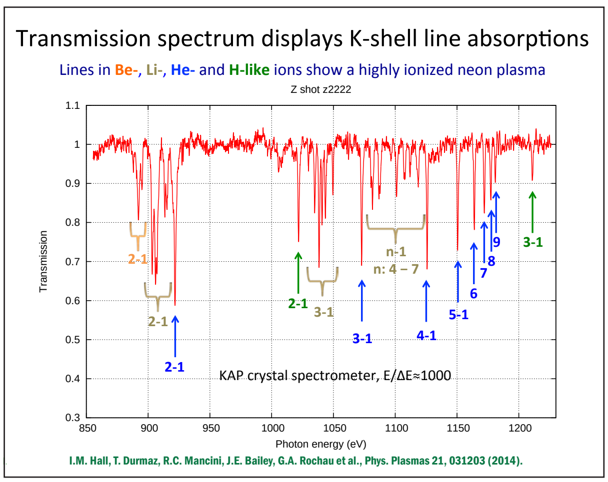


Figure 2. Transmission spectrum from a 30 Torr experiment: Z shot z2222. K-shell line transitions in Be-, Li-, He- and H-like neon ions show a highly ionized plasma. The labels are the principal quantum numbers of the transition.

### Atomic Kinetics, X-ray Heating, and Temperature of Photoionized Plasmas

The focus of this project is to study the ionization, X-ray heating, and electron temperature of plasmas driven by an intense flux of X-rays, i.e., photoionized plasmas. These are important for understanding a myriad of astrophysical systems including X-ray binaries, warm absorbers in active galactic nuclei, and the accreting disks formed around black holes. We have established a gas cell platform at Z to perform systematic experiments of single- or multi-element photoionized plasmas. Analysis of a transmission spectrum (see Figure 2) produces the charge state distribution of the ions and electron temperature of the plasma independent of detailed atomic kinetic and heating modeling calculations. Systematic measurements performed in several series of Z experiments have produced ground-breaking results about the heating and temperature of laboratory photoionized plasmas that impact physics models in astrophysical modeling codes.

### Accretion-Powered Matter and Radiation

When matter accretes in a disk around a compact object such as a black hole or a neutron star, copious amounts of X-ray light are generated. These accretion-powered objects emit spectra that contain information about the accretion process and the nature of the accretor. For instance, the mass and spin of a black hole could be extracted, thus enabling a test of general relativity. The Z facility recreates the relevant state of X-ray photoionization of the radiation-dominated disk environment and its spectral emission.[1] One feature of the emission is the radiative recombination continuum (RRC), which is used as an important astrophysical diagnostic of disk temperature. In the last year, the first-ever laboratory measurement of RRC was made on the Z machine, in an experiment on a photoionized silicon plasma, further testing a key feature of X-ray astronomy.

### Stellar Interior Opacity

Solar models presently disagree with helioseismology. This could be resolved if the true mean opacity (a measure of the absorption of light by matter) is higher than the calculated opacity used in the solar models by 10-30%. In past work, Jim Bailey and collaborators successfully measured iron opacity at conditions similar to the solar-convection-zone base. The measurements, published in the journal *Nature*,[2] were higher than predictions. If correct, the data accounts for approximately one half the opacity increase needed to resolve the solar problem. Research must continue until the opacity theory and measurements are reconciled. Last year, the opacity of chromium and nickel at similar conditions as iron was measured. By studying how the model-data opacity disagreement changes as a function of atomic number, this restricts the hypotheses for the discrepancy.[3] Staff at SNL also have developed a time-resolved measurement capability. This makes it possible to measure the time history of the opacity of our sample.

### White Dwarf Stars

Over the past year, we have made experimental and theoretical advances in our understanding of the fundamental properties of white dwarf stars. Our team reported results of hydrogen experiments, highlighting a measured difference in the width of a line when measured in absorption versus emission.[4] We also are incorporating a new generation of hydrogen line calculations into model white dwarf atmospheres using models developed by Thomas Gomez (former graduate student, now a SNL postdoc). In exploring other compositions, they recently achieved carbon plasma conditions relevant to white dwarfs with carbon-dominated atmospheres. These stars likely are the result of mergers of two white dwarfs and are potentially useful in understanding type Ia supernovae.

### References

[1]G.P. Loisel et al., PRL 119 (2017).
[2]Bailey et al., Nature 517, 56 (2015).
[3]Nagayama et al., PRL 122, 235001 (2019).
[4]Schaeuble et al., ApJ, 885, 86 (2019).

## The Total Kinetic Energy Release in Fission

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Most of the energy release in fission is in the form of the kinetic energy of the fission fragments. An understanding of this total kinetic energy (TKE) release in fission and its variation with the excitation energy of the fissioning system is vital for weapons and nuclear energy where the magnitude of the energy release in fission has practical consequences.

For the past three years, Oregon State University has participated in an SSAA project to explore these issues. Four graduate students (3 PhD and 1 MS) have graduated during this time, and two postdoctoral researchers, one graduate student, and one undergraduate student also have participated in the research. In the past three years, 19 papers detailing this research have been published in the open, refereed literature. See, for example, “The total kinetic energy release in the fast neutron induced fission of $^{235}$U,” R. Yanez, J. King, J.S. Barrett. W. Loveland, N. Fotiades and H.Y. Lee, Nucl. Phys. A 970, 65 (2018).

Two issues need to be addressed to make accurate and precise measurements of the TKE release in fast-neutron-induced fission of the actinides ($^{232}$Th, $^{233}$U, $^{235}$U, $^{238}$U, $^{239}$Pu). The first of these is that the actinide targets need to be thin (~100 μg/cm$^2$), uniform (< 2% variation in thickness over the target area), and free from extraneous contaminants such as cracked solvent molecules frequently found in targets prepared by molecular plating. The fluoride compounds of the actinide elements are synthesized using World War II technologies (see Figure 1). These fluoride compounds are then used to prepare samples of the actinides using vapor deposition.

The measurements of the TKE are performed at the Los Alamos Neutron Science Center (LANSCE) using the Weapons Neutron Research white neutron source. The neutron energies are determined by time of flight with an uncertainty of 4.7%. Because of the relatively low beam intensity at LANSCE, high geometry detection setup is used involving 4 pairs of 1 cm$^2$ Si PIN diodes positioned 2.1 cm from the target to detect the fission fragments. To benchmark this technique, the same apparatus is used to measure the TKE release in the thermal neutron induced fission of the actinides at the Oregon State TRIGA reactor. Excellent agreement is found between the measured TKE values for thermal-neutron-induced fission and the known values of these quantities. Thus, these TKE measurements are absolute measurements.


Figure 1. Graduate student Ashley Pica is shown while synthesizing fluorides of neptunium.

*"Four graduate students (3 PhD and 1 MS) have graduated during this time, and two postdoctoral researchers, one graduate student, and one undergraduate student also have participated in the research. In the past three years, 19 papers detailing this research have been published in the open, refereed literature."*

It is found that as the neutron energy increases from 2 to 90 MeV, the measured TKE values decrease by ~ 7 MeV. Where has all the energy gone? The answer is that the energy of the projectiles has gone into the excitation energy of the heavy fragment (as measured by the fragment neutron multiplicities). The variances of distributions are remarkably constant for neutron energies from 2 to 90 MeV. Comparison of these data (and related measurements of the fragment mass distributions) with modern models of fission shows the theories are woefully bad at the 5% level.

## Thin Actinide Targets

University of Notre Dame ✦ PI: Dr. Ani Aprahamian (aapraham@nd.edu)

Stewardship Science Academic Programs (SSAP) is supporting a research project to investigate novel approaches for the preparation of actinide targets that are isotopically pure, cost-efficient, reliable, robust, and highly uniform with controlled thicknesses. The project started on October 1, 2018 and presently involves three graduate students (Stefania Dede, Cyclotron Laboratory of Texas A&M; Ashabari Majumdar and Jordan Roach, University of Notre Dame (Notre Dame)) and one undergraduate student (Jacob Galden, Notre Dame).

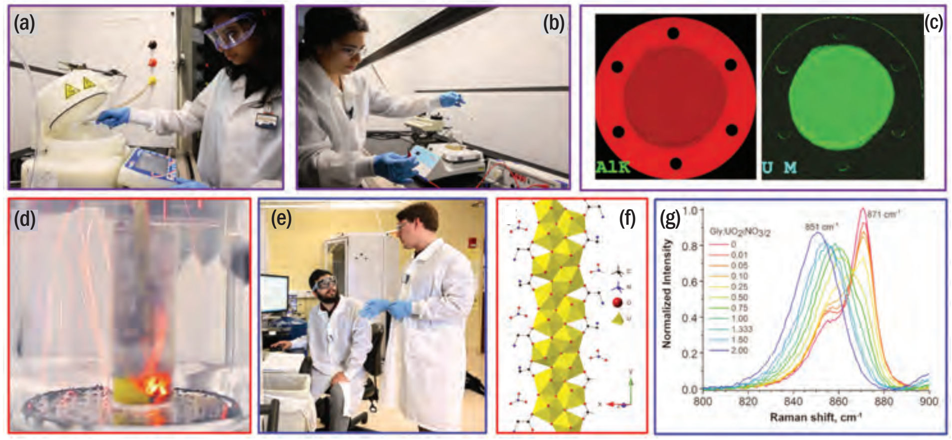


Figure 1. Shows preparation of thin actinide films by CS in combination with the spin coating (a) and spraying (b). X-ray fluorescence imaging of a target prepared by CS and spin coating (c). Investigation of the CS process in bulk solutions (d). X-ray crystallographic analysis of intermediates (e). The structure of the glycine-uranyl coordinate compound (f). Raman spectra of reactive solutions with different glycine-uranyl nitrate molar ratios (g).

The principal investigator of the project, is Ani Aprahamian, Professor of Physics at Notre Dame. This project brings together expertise from material science, radiochemistry, and nuclear science. The aim of the project is to develop new ways to prepare thin actinide targets for research in nuclear science and stockpile stewardship. This grant provides exciting opportunities for carrying out cutting-edge research while educating the next generation of STEM scientists capable of exploiting the techniques that are developed. This project expands the scope with novel techniques and the training of new personnel that can satisfy national needs at both Los Alamos and Lawrence Livermore National Laboratories.

The nuclear science and stockpile stewardship components rely on experiments to extract key nuclear cross-section and structure information. Typically, thin, uniform films of radionuclides with thicknesses in the range of from few to several hundreds of nanometers are deposited on a backing. Current target preparation techniques are based on decades-old approaches that do not take advantage of recent developments in materials science. This project develops revolutionary new approaches for the preparation of actinide targets.

The novelty relies on the use of combustion synthesis (CS) reactions between actinide metal nitrates (or metal-oxide clusters) with different organic compounds. CS of thin-film targets involves deposition of reactant solutions on backings using spin coatings (Figure 1a) and spraying processes (Figure 1b) followed by short periods of heating, resulting in rapid exothermic chemical reactions in thin solution layers. The result is the formation of crystalline actinide oxide films with desired tunable thicknesses. For example, Figure 1c shows an X-ray fluorescence image of a thin uranium oxide film formed on an aluminum backing. The distribution of Aluminum K and Uranium M X-ray lines indicate that the uranium layer is distributed uniformly on the substrate. The project also is utilizing an array of spectroscopic, electron microscopic, and ion beam analysis methods to investigate the effectiveness of the process parameters on the composition, uniformity, adhesion, and other characteristics of the thin films.

Figure 2. Team members of the project, from left to right: Jacob Galden, Dr. Ginger Sigmon, Jordan Roach, Prof. Ani Aprahamian, Jennifer Szymanowski, Stefania Dede, Dr. Khachatur Manukyan, Prof. Peter Burns (Director, NNSA Actinide Center of Excellence), and Ashabari Majumdar.

The research program also investigates CS (Figure 1d) in a bulk solution to establish relations between processing conditions and characteristics of the resulting products. Students utilize X-ray crystallographic methods (Figure 1e) to investigate intermediate products of the reactions to reveal the chemical mechanisms of these processes. For example, recently a glycine-uranyl coordinate compound (Figure 1f) was isolated from reactive solutions. The exothermic thermal decomposition of this compound can be the driving force of the CS process. Currently, this research is being complemented by in-depth investigations of reactive solutions using Raman spectroscopy (Figure 1g) and other methods to reveal the mechanism of chemical reactions that govern thin film deposition for nuclear target preparation.

The training of a diverse student body with interdisciplinary skills is an essential part of the project (see Figure 2). The students are being exposed to a wide range of experimental techniques related to actinide chemistry, preparation of targets, characterization of actinide materials by ion beam analysis and X-ray based techniques, vibration spectroscopy, electron microscopy, and other methods. Such a cross-disciplinary program prepares the next-generation of leaders in nuclear science that can be integrated into the workforce of the national laboratories.

## Tuning of Competing Quantum States Under Extreme Conditions

University of Rochester ✦ PI: Dr. Ranga Dias (rdias@rochester.edu)

The University of Rochester was awarded the Stewardship Science Academic Alliances grant in March 2019 to find superconducting material with a critical temperature comparable or higher than room temperature and to develop novel experimental techniques that are essential to discovering such transitions at extreme pressures. Under this research program, two graduate students and one undergraduate student are supported and will provide a recruiting pipeline supporting the DOE/NNSA laboratories in fundamental research. Thus far, the students have learned how to use the high-pressure apparatus and to perform conductivity measurements at multi-megabar conditions, a very advanced skill. They built a micron-Raman spectroscopy system from scratch to perform experiments at extreme conditions. At this point in the research, the students have developed a new probing technique using a two-dimensional material, such as graphene, to measure the conductivity at extreme conditions. They have found a near-room temperature superconductivity in yttrium superhydride at 262 K (the highest $T_c$ ever recorded), which will impact the understanding of superconducting mechanisms. It may allow us to obtain insight into designing new, room temperature superconducting materials at ambient pressure.

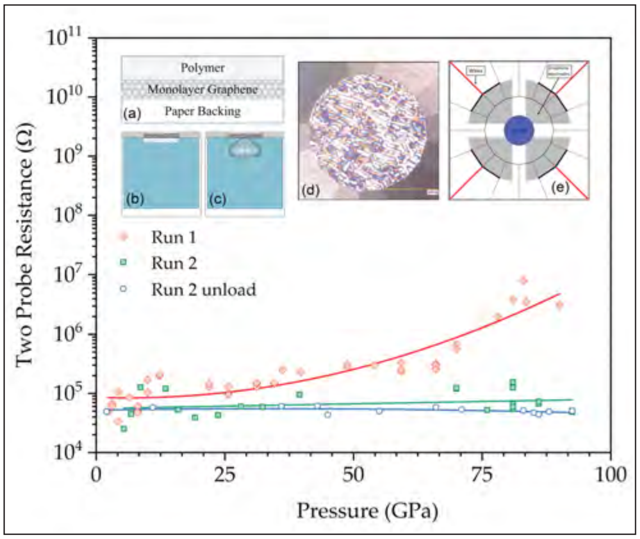


Figure 1. The pressure dependence of the two-probe, electrical resistance of monolayer graphene at room temperature. The inset (a) shows the composition of the transfer film. It consists of monolayer graphene coated in polymer sitting on a paper backing. (b) The transfer film is placed into a container of distilled water causing the graphene and polymer to release from the paper backing. (c) The diamond is brought up from under the water, catching the floating graphene and polymer layer. (d) Following graphene adhesion and polymer removal processes, a monolayer graphene film is left on the diamond culet. (e) Shows possible shapes the graphene could be made into on the diamond culet.

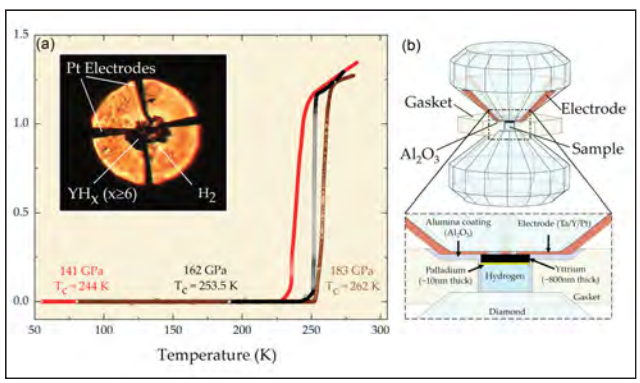


Figure 2. (a) The temperature dependent electrical resistance behavior of $YH_9$ showing superconductivity as high as 262K. (b) Schematic of the new experimental setup.

Electrical resistivity experiments have dominated the study of pressure-induced superconductivity. Performing resistivity measurements in diamond anvil cells (DACs) is, however, technically challenging, as it is difficult to make electrical contact with a tiny sample and keep it insulated from the metallic gasket up to extreme pressures. To overcome this barrier, the PI used graphene as a replacement for standard electrodes in the DAC experiments. The ratio between the thickness of the insulation layer and the graphene electrode is about 1,500:1 (standard methods are about 4:1). The value of this work is twofold. First, the behavior of graphene under pressure is of interest. Second, incorporating graphene into the DAC apparatus as electrical contacts is beneficial. A procedure was developed to place monolayer graphene directly onto the diamonds for use within DACs. The "Graphene Easy Transfer" process is shown in Figure 1. The graphene resistance was measured up to pressures approaching 1Mbar (see Figure 1). Direct measurement of the electrical resistance of liquid metallic hydrogen is the key input in magnetic dynamo action models for solar Jovian planets, which enable a new robust platform to explore the physics of metallization and ionization in pure elemental hydrogen. Therefore, the present results signify the use of 2D materials for new experimental capabilities to multi-Mbar pressures.

Superconductivity has been one of the most profound quantum phases in condensed matter physics. Efforts to identify and develop room temperature superconducting materials are an intensive area of research, motivated by fundamental science and the prospect of applications for their materials. The metallic alkaline or rare earths (RE) such as Sc, Y, and La hydrides which form sodalite-like, clathrate-based, hydrogenic lattices (superhydrides) predicted to display close to, or even higher than, room temperature superconductivity.[1] Yttrium is extremely reactive. To overcome these difficulties, the Yttrium thick film (800 nm) was evaporated under ultra-high vacuum and coated with a thin layer of palladium (10 nm) through which hydrogen can diffuse to the yttrium film (see Figure 2b) and that protects the yttrium from oxidation. The hydrogen is loaded into the yttrium sample at 3,000 bar. The hydrogen diffuses into the Y to form YHx. Then, it was pressurized to over 1 Mbar at which the sample was heated to ~2,000 K. Raman spectrosopy was performed as were electrical conductivity studies up to ~180 GPa. Strikingly, at higher pressures (above 130 GPa), the sample became a superconductor with $T_c$ as high as 262 K at ~183 GPa (see Figure 2a). This is the highest $T_c$ ever observed for this pressure range.[2] Therefore, the present results suggest the discovery of high $T_c$ superconductor at close to room temperature.

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**Katheryn Jinae Ham, Lawrence Livermore National Laboratories (ham6@llnl.gov)**
**Years at LLNL:** August 2019-Present, **Degree:** PhD, Physics
**SSAA Program:** 2015-2019, University of Alabama at Birmingham

During my PhD research at the University of Alabama at Birmingham I worked in Dr. Yogesh Vohra's high-pressure physics group. I conducted the bulk of my thesis and dissertation experiments at Argonne National Laboratory at the Advanced Photon Source, Beamline 16-BM-B, working on X-ray radiography and diffraction on borosilicate and Zr-based, bulk, metallic, glass samples in high-pressure and high-temperature conditions.

For me, the Stewardship Science Academic Programs (SSAP) has been monumental in providing opportunities along my path from a graduate student to a postdoctoral researcher at Lawrence Livermore National Laboratory (LLNL). Through the SSAP, I learned about and was accepted as one of the eight graduate students to attend the NNSA-CEA/DAM (Commissariat à l'Énergie Atomique et aux Énergies Alternatives/Direction des Applications Militaires) Postdoctoral Workshop held in Paris, France, May 2018. This experience opened my eyes to the diversity of impactful research being conducted at the NNSA labs, as well as the dynamic and stimulating work environment each one seemed to foster. From this workshop forward, I had a clear idea of the type of environment I wanted for my future career. At the following SSAP symposium in February 2019, I had the chance to meet with one of the representatives from LLNL who was sharing information about the postdoc opportunities at the lab. Through this interaction, I was put in touch with the director of the Nondestructive Characterization Institute, Harry Martz, and the group leader of the Nondestructive Evaluation Group, Joe Tringe. I interviewed and was hired as a postdoctoral researcher in the Nondestructive Evaluation Group in August 2019. I am extremely grateful to be able to work with this outstanding group of scientists, engineers, technicians, and staff.

In general, I have found that working at an NNSA laboratory has opportunities not found in academia or industry. The range and scale of the work being conducted at these national laboratories is unparalleled, from housing the world's largest and most energetic laser, to contributing to research that keeps millions of Americans safe every day, to working with so many highly-skilled and brilliant individuals on a daily basis. After working here for a month and talking to people in all different positions at the lab, from the onsite taxi drivers to the technicians to the staff scientists and engineers, everyone has had a very positive view of their time at the lab.

My first month in my postdoctoral researcher appointment at LLNL in the Nondestructive Evaluation Group has been a whirlwind of exciting opportunities combined with cutting edge research and development. The Nondestructive Evaluation Group is a rapidly expanding, highly innovative group at LLNL whose members have a wide breadth of expertise applied to tackle a wide array of problems from developing technology to detect explosives in luggage to using X-ray-based computed tomography (CT) capabilities to create 3D models of fossils. I currently am the Principal Investigator of an NNSA Office of Major Modernization Program-funded Flash X-ray CT project for which we are building a 3-ring, 15 X-ray source/detector system to image dynamic events occurring at short time scales. In addition to this main project, I am working on David Stobbe's Laboratory Directed Research and Development (LDRD) project looking at sub-surface defect detection via laser-based ultrasound in additively-manufactured parts. I also am contributing to Joe Tringe's LDRD shock ignition project for which three non-destructive testing methods, X-rays, neutrons, and acoustics, will be combined to measure surface geometry and composition within a complex 3D system.

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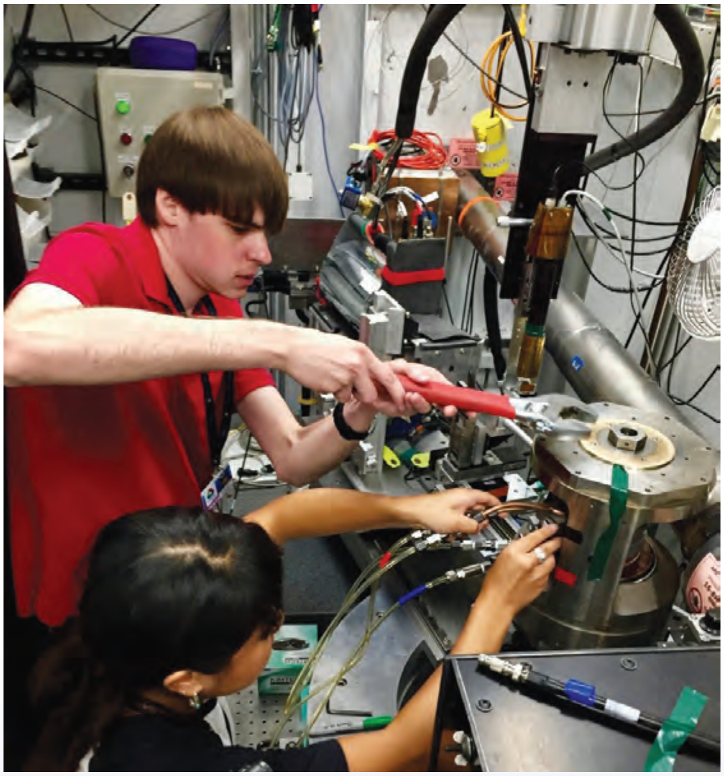


Figure 1. Kathryn Ham and Chris Perreault setting up for a high-pressure, high-temperature experiment at Argonne National Laboratory, Advanced Photon Source, Beamline 16-BM-B.

**Robert V. Morgan, Los Alamos National Laboratories (rvmorgan@lanl.gov)**
**Years at LANL:** November 2014-Present, **Degree:** PhD, Mechanical Engineering
**SSAA Program:** 2010-2014, The University of Arizona

I began working with shock waves, compressible fluid dynamics, and fluid dynamic instabilities as a graduate student working under Professor Jeffrey Jacobs at the University of Arizona. Dr. Jacobs's research group focuses on understanding turbulent mixing produced by the Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instabilities, which result from the continuous and impulsive acceleration of density interfaces in fluid systems. Experiments conducted by the group study miscible and immiscible liquids as well as gases. I was fortunate to have the opportunity to work on both the RM instability in gas shock tube experiments and the RT instability in a novel rarefaction tube experiment developed while I was a graduate student. These rarefaction tube RT studies were supported by the Stewardship Science Academic Alliances program.

The rarefaction tube functions in a similar way to standard shock tubes but uses a vacuum chamber as a low-pressure region that is separated by a membrane from a high-pressure test region. When the membrane separating these sections is ruptured, a rarefaction wave, rather than a shock wave, impacts the density interface. This experiment was capable of producing peak accelerations much higher than previous RT experiments, approximately 1,000 times the acceleration of gravity. Additionally, the experiment was capable of using gas combinations having much larger density ratios than the miscible liquid combinations used in standard RT experiments. This experiment was used to study single-mode two-dimensional, single-mode three-dimensional (3D), and multi-mode 3D perturbations. During the process of completing this work, I spent two summers at Lawrence Livermore National Laboratory (LLNL) carrying out large eddy simulations of my experiments using LLNL's high performance computing facilities. The observations of mixing produced by this study helps to inform turbulence models that can be used to predict the behavior of National Ignition Facility fuel capsules during implosion.

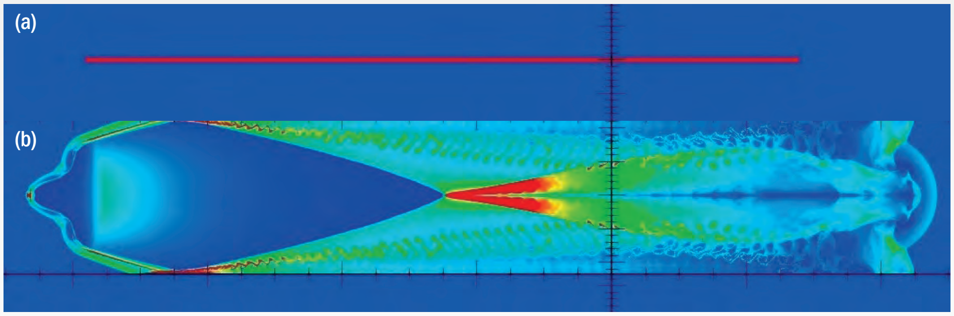



Figure 1. Density profiles developed during the detonation of high explosives in the LANL blast tube facility. (a) Initially a long charge is suspended in the center of the domain (blast tube) and detonated from the left end. (b) Shock waves quickly develop and reverberate throughout the tube. Two main shocks develop and form a complex pressure profile.

*"Opportunities for employment at Los Alamos National Laboratory (LANL) presented themselves through Stewardship Science Academic Programs' contacts. I then began my career at LANL during November of 2014 as a postdoctoral research associate working with a team in the Mechanical and Thermal Engineering group."*

Opportunities for employment at Los Alamos National Laboratory (LANL) presented themselves through Stewardship Science Academic Programs' contacts. I then began my career at LANL during November of 2014 as a postdoctoral research associate working with a team in the Mechanical and Thermal Engineering group (E-1). This team specializes in mechanical design engineering, thermal-fluid research, and advanced manufacturing concepts. The group supports a wide range of programs around the laboratory including the weapons programs, the Los Alamos Neutron Science Center particle accelerator, and various experimental facilities. This support includes developing novel, high-speed, experimental test stands, manufacturing advanced concept parts, high pressure experimental testing, and computational analysis. While working in E-1, I have contributed to each of these areas, and I have further developed my skills with computational fluid dynamics (CFD) tools. Currently, I have been able to continue my career at LANL by advancing to a technical staff position. A key benefit of working at LANL is access to world class and large-scale experimental facilities capable of performing cutting edge research.

Recently, I have been working on CFD models of the LANL blast tube facility. The blast tube is a 45.7-meter-long, 2.40-meter-inner diameter, explosively-driven, gas shock tube. This shock tube was designed with one closed end, which means that it has a more complex compressible flow behavior than previous blast tubes with two open ends. To perform these simulations, I used the Sandia National Laboratories code CTH which is well suited to multi-phase simulations of explosive shock production. This simulation tool was used to produce air blast pressure profiles (see density in Figure 1) which then could be imported into Fluent, which is an industry standard CFD tool. Fluent then was used to perform an unsteady Reynold's averaged Navier-Stokes simulation of the flow exiting the blast tube and around experiments positioned in the exit of the tube. These simulations begin to form a predictive capability for costly blast tube tests and provide supplemental data for these tests. The SSAP gave me exposure to the science conducted at the national laboratories early in my career, which enhanced my research through access to computer facilities and research personnel. I plan to continue my career by further developing CFD and flow visualization capabilities in E-1.

**Andrew Ratkiewicz, Lawrence Livermore National Laboratories (ratkiewicz1@llnl.gov)**
**Years at LLNL:** September 2015-Present, **Degree:** PhD, Nuclear Physics
**SSAA Program:** 2011-2015, Rutgers University

When I graduated from Michigan State University (MSU) in 2011, my idea of the SSAP and its mission was hazy at best. I'd earned my PhD in Nuclear Physics for Nuclear Structure work done at the National Superconducting Cyclotron Laboratory at MSU, so I knew I liked working on Big Science at national labs. I also knew I liked working with smart, passionate people on hard problems, and finding that overlap was my top priority in my search for a postdoctoral position. I wanted to try new things and to work with people who would help me refine the scientific, technical, and project management skills I'd learned in graduate school.

This is what attracted me to Rutgers University and to the SSAA program. At the time, Rutgers (through Professor Jolie Cizewski) was the leader of a Center of Excellence in Nuclear Physics, and much of the science was being done at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL). The postdoc was based at ORNL, and I had a great technical project and a fascinating science project, both of which I thought would put me in an excellent position to continue my career in science. The technical project was to merge the NNSA-funded, Oak Ridge Rutgers University Barrel Array (ORRUBA) of silicon strip detectors with the large-scale gamma-ray spectrometer GAMMASPHERE. The combined detector, GAMMASPHERE-ORRUBA: Dual Detectors for Experimental Structure Studies (GODDESS) provides an unmatched capability for detecting particles and gamma rays in coincidence, enabling high-resolution, high-efficiency studies of nuclear reactions and nuclear structure for basic science and programmatic applications. The project was successful, and the GODDESS collaboration has, to date, conducted six experiments, all of which will provide (or have provided) dissertations for students or the first post-PhD project for a postdoctoral researcher.

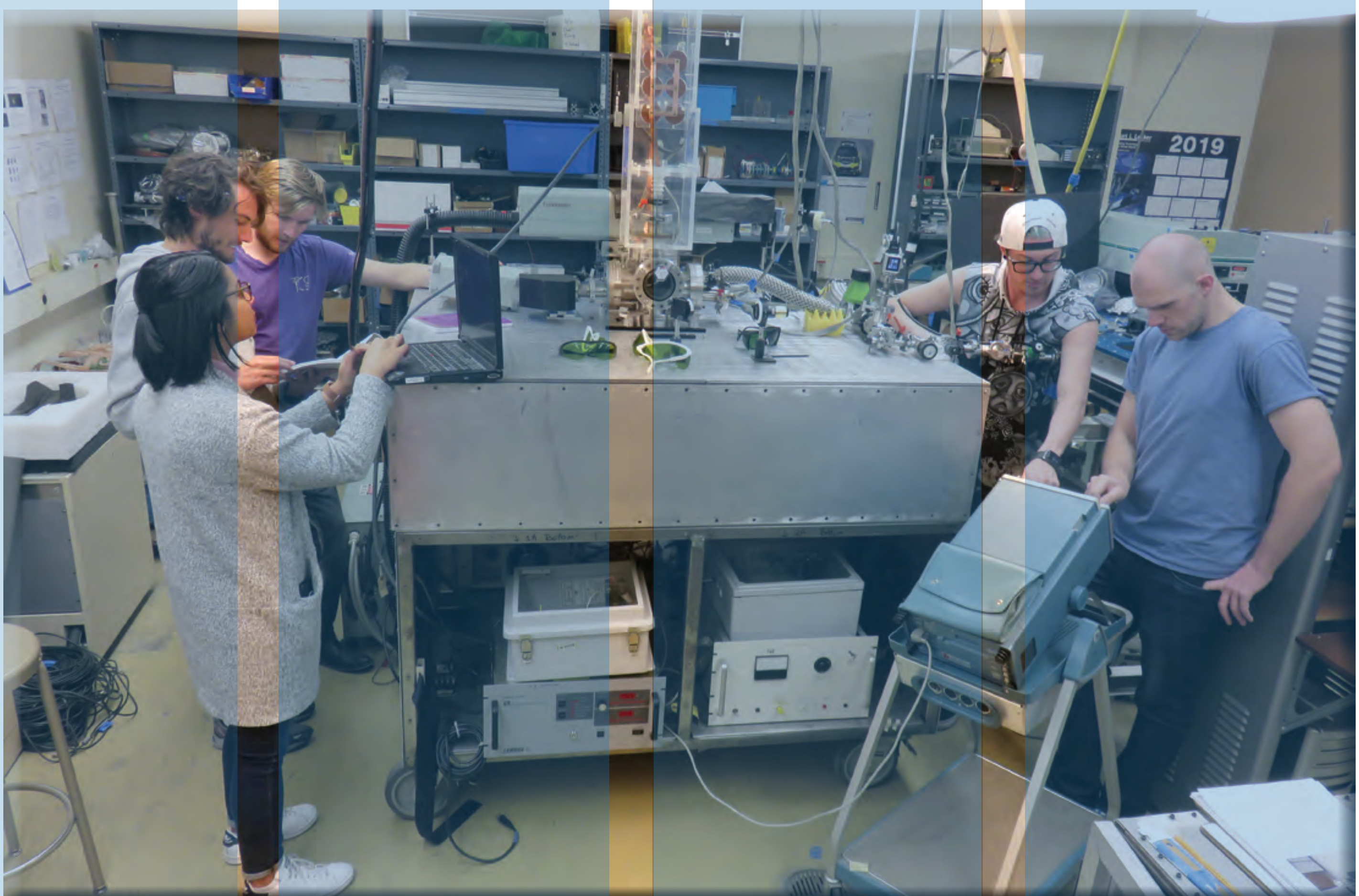
The science project presented a different challenge. Neutron-capture reactions are responsible for the nucleosynthesis of about half of the elements heavier than iron, which are produced in the rapid neutron-capture or r process. In r-process nucleosynthesis, nuclei rapidly capture neutrons, eventually converting those neutrons to protons via beta decay. The heavier element then can capture more neutrons and, in this way, very heavy elements can be produced. However, owing to the unstable nature of neutrons and the nuclei of interest, neutron capture rates on radioactive nuclei are difficult or impossible to measure directly. These rates are important for applied purposes, such as stockpile stewardship and nuclear reactor safety. My goal was to provide a benchmark for an indirect technique to constrain these important cross sections.

Figure 1. The GODDESS system configured with GRETINA at Argonne National Laboratory.

This technique uses an easily measurable surrogate reaction, which forms the same nucleus as would be formed in neutron capture, to provide experimental data which then can be used to constrain calculations of neutron-capture rates. This project also was a success, and we are planning to conduct many Surrogate Reaction Method experiments to constrain these important cross sections for stewardship and for basic science.

Now, of course, I have a much better idea of what the SSAP is. During my years as a member of the Center of Excellence at Rutgers, I went to several SSAP meetings and met many people involved in SSAP projects. This gave me a new appreciation for the breadth of science that is done under the Stockpile Stewardship umbrella. I conducted experiments with many people from NNSA labs, and it was through these connections and the biannual meetings at Los Alamos and Livermore labs, that I came to work at Lawrence Livermore National Laboratory (LLNL) where I am a member of staff. I am continuing my work with Surrogate Reactions, but I also work with nuclear technology in pure and applied ways. I currently am working on projects to understand the impact of uncertainties in nuclear data on the calculation of standard criticality benchmarks (an important tool for reactor safety), to use neutrons to image dense objects (which would, for example, help us ensure the reliability of spent nuclear fuel casks), and to understand the strength of the interaction between plasmas and nuclei. This last project is extremely exciting. While we know that nucleosynthesis occurs in stars, which are enormous plasmas, our models of nucleosynthesis currently do not include any interactions between nuclei and the plasmas in which they are formed. I love working at NNSA labs, in general, and LLNL in particular. I get to work on extremely hard problems with very smart people which is the only thing I have ever wanted to do.

# High Energy Density Laboratory Plasmas



## Characterization of Ion-Heated, Warm, Dense Matter and Its Ion Transport Properties

University of California, San Diego ✦ PIs: Dr. Christopher McGuffey (cmguffey@ucsd.edu) and Dr. Farhat Beg (fbeg@ucsd.edu)

The High Energy Density Physics research group at the University of California, San Diego conducts research on Warm Dense Matter (WDM) through the NNSA's HEDLP grant program. High-intensity ion beams generated by short-pulse lasers provide a unique means to heat a target to create WDM samples. Rapid, isochoric and volumetric heating is possible while the sample remains solid. State properties and equation of state measurements in difficult-to-construct WDM states are highly sought-after for modeling of inertial fusion and astrophysical plasmas and to calculate the composition of stars and planetary cores which consist of WDM states. Thus, a high-intensity proton beam capable of producing a wide range of states is valuable for its potential ability to map large state variable spaces.

This project is broadening the range of WDM states that have been created with laser-driven proton sources and is seeking better ways to characterize them. The tasks include (1) fundamental studies of proton beam transport and stopping dynamics using cutting edge computational tools, (2) demonstration of isochoric heating of a solid sample with today's kilojoule short-pulse lasers, (3) experiments to isochorically heat a pre-compressed sample to demonstrate versatility, and (4) development of advanced X-ray diagnostics to measure WDM samples.

A recent publication by the group details an experimental and computational investigation showing interesting beam behavior in multiple materials.[1] Another manuscript is under review,[2] showing how target design leads to proton beam focusing and sample heating enhancement. The experimental data were obtained on the OMEGA EP laser using curved target foils with cone-shaped focusing structures on the rear. The simulations conclusively show that electric fields that grow along the inner walls of the structure are responsible for the observed focusing. By post processing particle data with tabulated cross-sections and correcting for opacity, the X-ray emission profiles of the experiment were reproduced. To conclude the article, it is shown that with modification to the structure, a solid Cu foil could be heated to over 200 eV.

An ongoing effort is devoted to modeling an OMEGA EP experiment in which

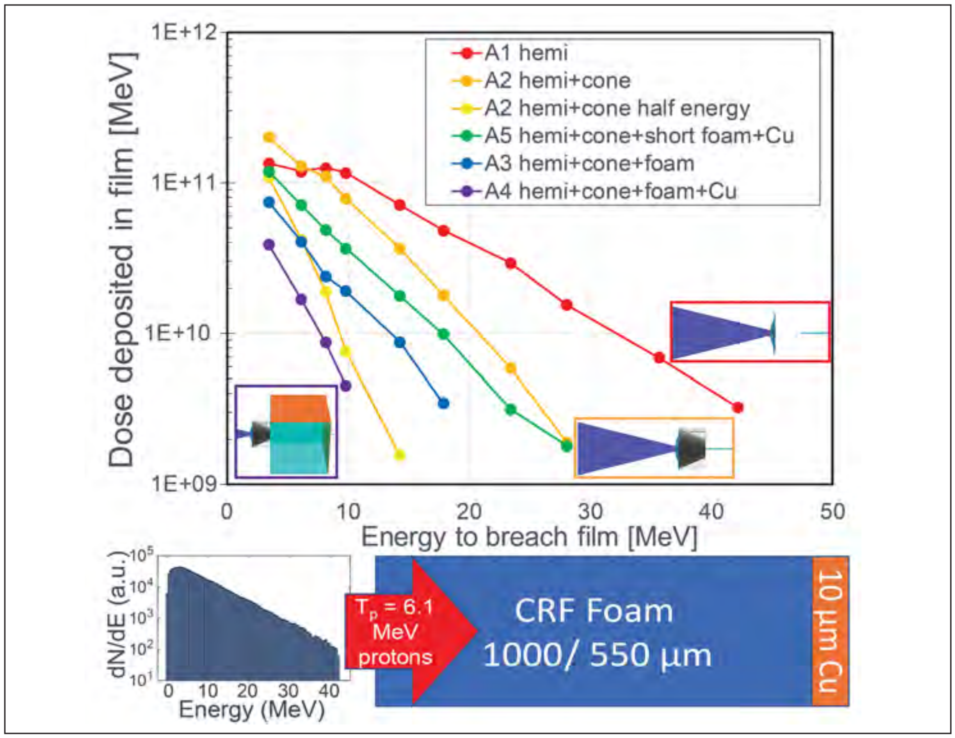



Figure 1. Top: Dose information for various targets. The extracted proton spectra from this data will be compared to spectra extracted from acceleration+transport simulations portrayed on the bottom.

a structured target like that mentioned above was focused into millimeter-scale plastic foam samples to investigate how an intense beam propagates through matter. As shown in Figure 1 (top), the proton spectrum from a freestanding curved foil exceeded 40 MeV, while addition of a bulky cone for focusing has a significant cost in the maximum energy. The spectrum escaping from three different WDM sample packages was collected and analyzed. Graduate student Krish Bhutwala has modeled the transport of the beam through the foam and Cu foil using particle-in-cell with a dynamic Cu stopping power[3] and continues to refine the modeling procedure. The transport simulations (shown conceptually in the image at the bottom of Figure 1) are investigating the heating that can be achieved.

The group has collaborated with Lawrence Livermore National Laboratory and others in a revival of laser-driven proton beam studies including experiments at the OMEGA EP laser and NIF ARC.[4] The team systematically mapped out the temperature that could be induced in a Cu micropuck with the OMEGA EP kilojoule class laser versus laser energy and pulse duration. With a 6 ps laser pulse, full energy, and a 25-µm-thick sample, the hottest temperature of >100 eV was measured. Atomic modeling with the PRISM code was carried out to produce synthetic X-ray emission spectra to find the parameters that fit the measured spectra including Cu Kα and Kβ yield with the ZVH HOPG and fine structure with the new HiResSpec diagnostic.

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## Assessing Line-Area Ratio of Like-Charge-State Spectral Lines for Plasma Temperature Determination

West Virginia University ✦ PI: Dr. Mark E. Koepke (mkoepke@wvu.edu)

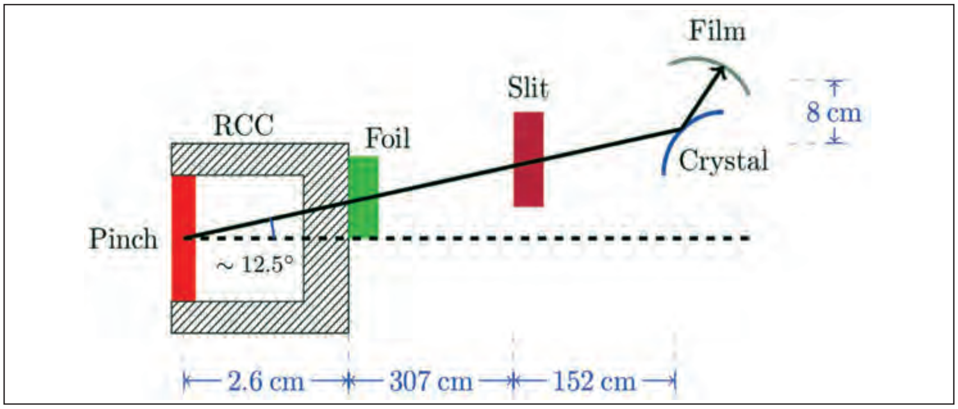


Figure 1. The X-rays from the pinch both heat and backlight a return-current canister (RCC) mounted target foil, whereupon a cylindrically bent crystal spectrometer records spectra onto a piece of X-ray film.

X-ray spectroscopy offers a line-ratio diagnostic for measuring temperature, electron temperature, and plasma density in hot, dense plasmas having multiple elements and ionization states. This project on cross-cutting X-ray spectroscopy on Z at Sandia National Laboratories (SNL) was carried out under the auspices of the Joint Program on HEDLP with four years supported by the DOE Office of Science and one year supported by NNSA. The project's first focus was on documenting resonant Auger destruction using Z to irradiate a silicon foil for comparison with models.[1] Silicon Kα emission and absorption spectra $Si^{4+}$ through $Si^{11+}$ (0.006-0.007 nm) from L-shell ions were measured by the SNL-West Virginia University (WVU) team to test the astrophysical assumptions and to provide a new class of spectral diagnostics for X-ray-photoionized-plasma spectroscopy. WVU helped develop a new Return-Current-Can foil-mounting platform for achieving and studying hotter and denser plasmas, WVU-SNL tested the limits of tamper thickness on absorption spectra, and WVU performed a radiation-hydrodynamics (HELIOS) validity test in plasma parameters based on varying tamper thickness. A key component of this project was demonstrating an unprecedented wide spectral range of measurements for use in future line shape studies.

The project's second focus was on establishing optimal single-element, different-charge-state (isoelement) line pairs, and multi-element, identical-charge-state (isoelectronic) line pairs, in absorption for diagnostic accuracy and precision. Multilayered MgNaF foil was heated and photo-ionized and WVU applied spectral-line formation models (SPECT3D, XSTAR, ATOMIC, mentioned in Reference 1). Z's X-rays drive and backlight the foil plasma, yielding absorption spectra. WVU collected time-integrated absorption spectra of plastic-tamped MgNaF layered foil. Having a broadband backlighter and the KAP crystal's extra-wide spectrometer range benefitted the acquisition of absorption features of these three elements. The TAP crystal allowed for higher resolution. Exposed Kodak 2924 X-ray film was digitized, corrected for film fog, and inspected for saturation. PrismSPECT simulations were vital to analyzing the spectra. WVU tested the consistency of determining electron temperature across a range of isoelectronic line pairs using line ratio in the absorption spectrum. Besides demonstrating the successful implementation of the technique for the first time, WVU found that as foil-target's tamper thickness is increased the Helios-CR discrepancy with experiment increased and that increasing tamper thickness increases electron density in the foil plasma. Ted Lane, lead student on the project, graduated with a PhD degree in Summer 2019. He now is a tenure-track Assistant Professor at South Utah University, and his dissertation represents the first WVU PhD in the subfield of HEDLP.

As a contribution to the Z Fundamental Science Program, WVU-University of Nevada, Reno (UNR) studied the feasibility of implementing an optical Thomson scattering (OTS) system on Z.[2] The parameter range of the CHACO laser (an Nd:YAG laser, part of the Z-Backlighter Laser) suits the application. WVU found that co-injection onto an existing beamline is more economical than building a new, dedicated beamline. VISAR currently is being constructed to enter the target chamber through Line-Of-Sight 110 at a zero-degree inclination port. This beamline would be a good candidate for co-injection, as the beginning of the beamline sits only a meter or so away from the CHACO laser. Based on WVU-UNR simulations, it is possible to tune the CHACO laser down to the appropriate energy level for mitigating heating by the probe and maximizing signal, such that it can be measured by the streaked visible spectroscopy (SVS) instruments.

Two 2019 publications[3,4] resulted from ongoing collaborations at the Omega Laser Facility at the University of Rochester (UR) Laboratory for Laser Energetics and the University of Strathclyde, United Kingdom.

A spinoff of these research activities is the opportunity for WVU students (5 total) to participate in the series of Omega Laser User Workshops and for the PI to serve on the Omega Laser Users Group executive committee since 2012 (currently serving as Chairperson from April 2018 through April 2020). Also, WVU's research activities led to collaborations with Stanford University's SLAC National Accelerator Laboratory, Imperial College's MAGPIE, and UR's OMEGA.

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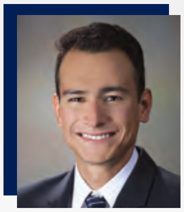
### Collaborators

ZAPP collaboration on Z, led by SNL scientists J.E. Bailey, G.P. Loisel, and G.A. Rochau.

**Daniel E. Ruiz, Sandia National Laboratories (deruiz@sandia.gov)**
**Years at SNL:** October 2017–Present, **Degree:** PhD, Plasma Physics
**SSAA Program:** 2015–2017, Princeton University



The Stewardship Science Academic Programs (SSAP) has played a vital role in the development of my scientific career. As a graduate student at Princeton University, the SSAP provided me financial support so that I could pursue research in the fundamental physics of waves in plasmas. Through the SSAP, the Princeton Program in Plasma Physics has developed strong ties with NNSA. This sponsorship allowed me to disseminate my results to a broader scientific community and helped me become aware of difficult and intellectually-stimulating problems that are of interest to our nation. The SSAP also played a role in my pursuit of a career at one of the NNSA national laboratories.

During my doctoral research, I worked under the supervision of Dr. Ilya Dodin on a HEDLP grant with Dr. Nat Fisch as the PI to develop a new systematic approach based on variational principles to describe waves in plasmas. In my thesis, I claimed that treating waves as dynamical objects of a Lagrangian theory rather than formal solutions of Maxwell's equations enables one to discover the underlying basic wave physics and to improve the modeling of waves. The results in my thesis were organized into three main parts. First, I extended and reformulated geometrical optics (GO) as a first-principle Lagrangian theory that captures polarization effects, such as polarization precession and the polarization-driven bending of ray trajectories. Perhaps surprisingly, I showed that two seemingly unrelated effects, the divergence of left- and right-polarized electromagnetic (EM) waves in isotropic dielectrics and the Stern-Gerlach force on spin-1/2 electrons both are manifestations of polarization effects.[1] Second, I theoretically demonstrated that waves propagating in modulated media, both classical and quantum, can experience time-averaged refraction caused by effective ponderomotive forces on wave rays.[2] This phenomenon is analogous to the well-known ponderomotive effect encountered by charged particles in high-frequency EM fields. Third, I used phase-space techniques to study drift-wave turbulence and the spontaneous formation of zonal flows in magnetized plasmas.[3]

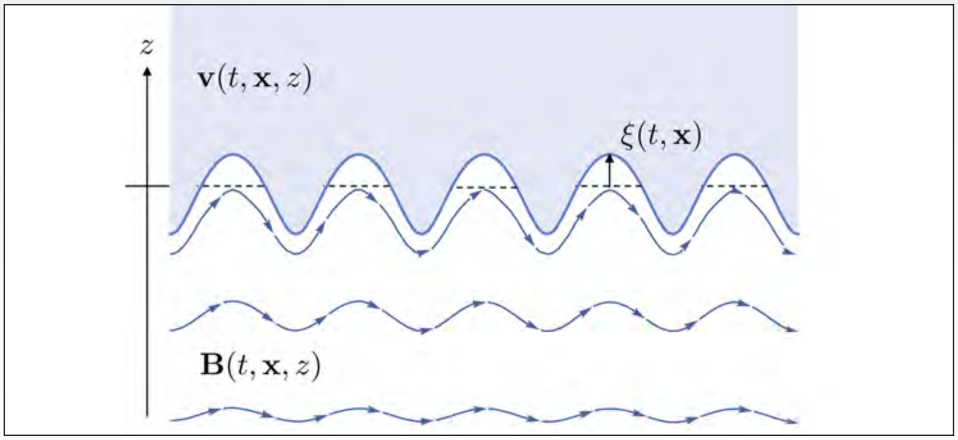



Figure 1. Schematic diagram of the MRTI. Here the bending of the magnetic-field lines introduces a stabilization mechanism for the classical Rayleigh-Taylor growth. In the diagram, the fluid is represented by the shaded region. The magnetic field is represented by the stream lines. The function ξ(t,x) describes the fluid-vacuum interface.

Before graduating, I received the Harry S. Truman Fellowship in National Security Science and Engineering. Since September 2017, I have been working at Sandia National Laboratories (Sandia) in the Radiation and Inertial Confinement Fusion Target Design group. My experience at Sandia has been fantastic! During the last two years as a Truman Fellow, I have been the lead investigator of my own research project. The intellectual freedom of the fellowship has permitted me to tackle problems that are aligned to my own research interests and to the stockpile stewardship mission of the laboratory. This marvelous opportunity has allowed me to expand my research in new directions and would not have been possible without the early sponsorship of the SSAP.

Currently, my research is focused on two main topics. First, I am developing new analytical models to describe the magneto-Rayleigh-Taylor instability (MRTI) (see Figure 1). This instability occurs in z-pinch experiments done at the Z facility. It is important to better characterize MRTI, since it can degrade the performance of z-pinch implosions. In this regard, I have made progress in building new models based on variational principles to describe MRTI.[4] In close collaboration with my experimental colleagues, I am comparing the theory to experiments conducted at the Z facility. For this work, I have reutilized some of the techniques in wave theory that I developed during graduate school and have applied them to a problem that is of high relevance to the mission of our program. Second, I am developing analytical models that can capture the basic physics governing the complex dynamics of z-pinch implosions. This work could help explain basic trends observed in our experiments as well as in simulations. In this regard, my colleague and I have submitted an article where we lay the foundations on how to scale z-pinch implosions so that the physics regimes of present-day experiments at the Z facility are maintained when scaling to higher currents.[5]

In summary, the SSAP has played an instrumental role in initiating and promoting my scientific research career. Working at Sandia has been a wonderful experience, where I am tackling problems that are both intellectually stimulating and important to the nation's interests.

### References

[1] D.E. Ruiz and I.Y. Dodin, Phys. Plasmas 24, 055704 (2017).

[2] D.E. Ruiz and I.Y. Dodin, Phys. Rev. A 95, 032114 (2017).

[3] D.E. Ruiz, J.B. Parker, E.L. Shi, and I.Y. Dodin, Phys. Plasmas 23, 122304 (2016).

[4] D.E. Ruiz, arXiv:1910.12167 (2019), submitted to Phys. Plasmas.

[5] P.F. Schmit and D.E. Ruiz, "A Conservative Approach to Scaling Magneto-inertial Fusion Concepts to Larger Pulsed-Power Drivers," submitted to Phys. Plasmas.


# National Laser Users' Facility

## Characterization of the Nonlinear Laser-Plasma Interactions in Electron-Assisted Shock Ignition

General Atomics ✦ PI: Dr. Christine Krauland (kraulandc@fusion.gat.com)

In support of the stockpile stewardship mission for fusion ignition, this work focuses on characterizing the potential benefits of an alternative inertial confinement fusion (ICF) concept known as Shock Ignition (SI). SI is designed to achieve ICF ignition by launching a strong convergent shockwave after fuel is assembled or compressed at lower velocities than traditional approaches mitigating hydrodynamic instabilities. In order to generate this strong shock, however, the experimental platform relies on the use of a roughly $10^{16}$ W/cm$^2$ laser pulse penetrating a long scalelength hot plasma. The feasibility of the SI concept depends heavily the laser-plasma instabilities (LPI) that take place during this interaction and their subsequent production of hot electrons. This work supported by SSAP over the past five years has allowed a collaborative group between General Atomics, University of California San Diego (UCSD), and University of Rochester to systematically study various laser and plasma parameters in the SI regime to better understand these fundamental LPI processes and their sensitivity in these experimental systems. The SSAP directly supported the graduate PhD thesis on this topic by Shu Zhang in addition to multiple postdoctoral researchers at UCSD, some of whom have gone on to work at the NNSA national laboratories.

This experimental work has been completed at the Laboratory for Laser Energetics in Rochester, NY on each of the OMEGA 60 and the OMEGA EP laser facilities. Both laser systems allow a surrogate SI-relevant laser-plasma interaction to be generated in a planar geometry. On OMEGA EP, ns-scale laser beams provide $2 - 4 \times 10^{14}$ W/cm$^2$ total irradiance to generate a $\geq 1$ keV CH plasma with length scale $L_n \sim 300$ µm. Between 1 to 1.5 ns after the beginning of this pulse, a single, tightly-focused, separate UV beam is injected into the plasma with $10^{16}$ W/cm$^2$ vacuum intensity. Figure 1a shows this experimental setup and the target design. On OMEGA 60, twenty UV beams are incident on the target with a shaped pulse that has a 2 ns plateau for plasma creation followed by a 300 ps higher power spike, as shown in Figure 2a. The beams are pointed in such a way that only a portion of the individual spots overlap. During the spike portion of the laser pulse overlapped beam intensity of $1.5 \times 10^{16}$ W/cm$^2$ is incident on the target center. A laser intensity map on target is shown in Figure 2b.

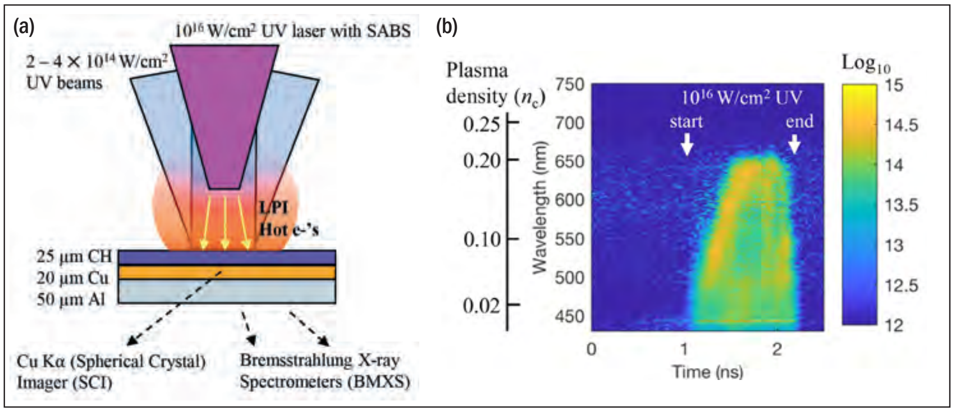



Figure 1. (a) Experimental platform for OMEGA EP shots. Two lower intensity UV lasers are used to create the plasma, after which we inject one high intensity UV beam. The sub-aperture backscattering spectrometer (SABS) observes light from the high intensity interaction beam. (b) Spectrum of the backscattered light in the single UV beam experiment. T-0 designates the start of the plasma creation beams. The high intensity UV pulse is injected at 1.0 ns.

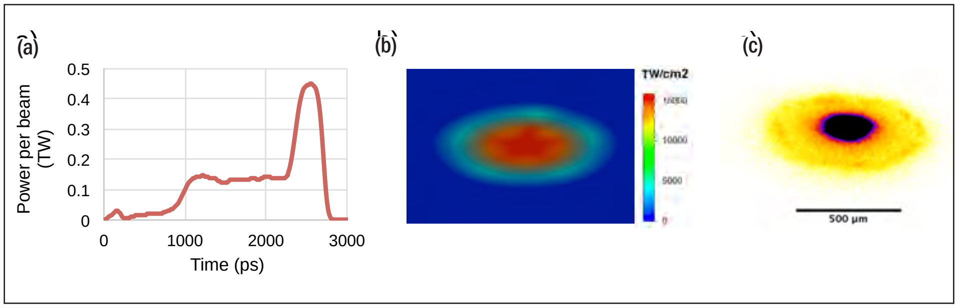



Figure 2. (a) Laser pulse shape for OMEGA 60 planar target shots. (b) Vacuum laser intensity map on planar targets as designed by distributing the pointing 20 beams uniquely off-center. (c) Self-emission X-ray data using a spherical crystal to image only characteristic lines from the Cu tracer, showing a map of hot electron interaction.

Data suggest that the overlapped UV lasers produce more hot electrons than a single UV beam of comparable intensity. Self-emission imaging data, as seen in Figure 2c, maps fluoresced X-rays from hot electrons, while X-ray spectrometers allow us to infer laser-to-hot electron conversion efficiency (CE) and hot electron temperatures. In the overlapped beam case, the CE is $4 \pm 2\%$ with $T_{hot} = 24 \pm 2$ keV. In the single beam experiment, we observed only $2 \pm 1\%$ energy conversion with $T_{hot} = 45 \pm 5$ keV. While both results are promising, the lower hot electron temperature and higher energy CE is likely is more beneficial to the SI goal as the pressure of an electron-driven shockwave may be increased with more readily deposited energy. Additionally, the better supplemental effects from moderate temperature hot electrons could reduce the required laser energy for the platform.

To understand LPI mechanisms creating these electrons, experiments often record the spectrum of scattered light. In both experiments, the data suggest that hot electrons mainly are generated from LPI known as stimulated Raman scattering (SRS). Figure 1b shows data from the single beam experiment, where the SRS signal indicates strong pump deletion in the lower density plasma during the first 0.5 ns of the high-intensity interaction. This is evidenced by scattering observed only in the sub-$0.1n_c$ region when the beam is initially injected. The SRS spectrum also indicates that the pump-depletion progresses from the 0.05 $n_c$ region to the 0.2 $n_c$ region over about half of the pulse duration. In combination with other observed data, this work found that the dynamics of the pump-depletion can be explained by the breaking of ion-acoustic waves in stimulated Brillouin scattering.

## Interactions of Laser-Driven Magnetic Field Structures Using OMEGA EP

University of Michigan ✦ PI: Dr. Karl M. Krushelnick (kmkr@umich.edu)

Recent experiments were conducted on the OMEGA EP laser system at the Laboratory for Laser Energetics at the University of Rochester to study a magnetic reconnection geometry produced by focusing a short-pulse laser adjacent to a long-pulse, ultraviolet beam onto solid targets (see Figure 1). In this case a 1 ns, 1,250 J UV beam was focused to an intensity of 2 x $10^{14}$ W/cm$^2$ onto a 25 µm-thick target. Non-parallel temperature and density gradients in the ablated plasma plume can generate azimuthal "Biermann battery" magnetic fields (of about a MegaGauss). As this long-pulse produced plasma developed, a 10 ps pulse containing 500 J was focused to relativistic intensity ($I > 10^{18}$ W/cm$^2$) in close proximity. In contrast to the slowly expanding Biermann battery fields ($v \approx c_s$), relativistic currents driven by the short pulse laser generate a strong azimuthal magnetic field (of between 10-100 MegaGauss) that spreads radially with a velocity near the speed of light. This dramatic difference in scales yields a highly asymmetric field geometry, with the rapidly expanding short-pulse generated field driving into a quasi-static Biermann battery field.

Proton radiography was implemented to diagnose the magnetic field dynamics of the interaction. A second short-pulse laser (300 J in 1 ps) accelerated protons via the target normal sheath acceleration (TNSA) mechanism from 20 µm-thick gold targets to energies exceeding 60 MeV. A stack of radiochromic film (RCF) detected the deflection of the proton beam by the electromagnetic fields of the target. The time-of-flight for a proton depends on the kinetic energy, and therefore, each layer in the RCF stack detects a different time in the interaction.

Figure 1 shows a schematic representation of the asymmetric reconnection geometry as well as a single-shot proton radiography time series for plastic targets. At $t_o$, the Biermann field has evolved for 750 ps when the high-intensity pulse arrives on a 25 µm thick plastic target. In the subsequent time steps, the proton radiography captures the high intensity magnetic field generation and the dynamic interaction between the two plasmas. As the magnetic field from the high intensity pulse drives into the long pulse produced plasma, there is evidence of a compression of the initially round magnetic field into a pointed structure at the interface of the two plasmas. In addition, there is an enhancement of proton signal surrounding the Biermann field structures in the region opposite the interface (near the top of the images).

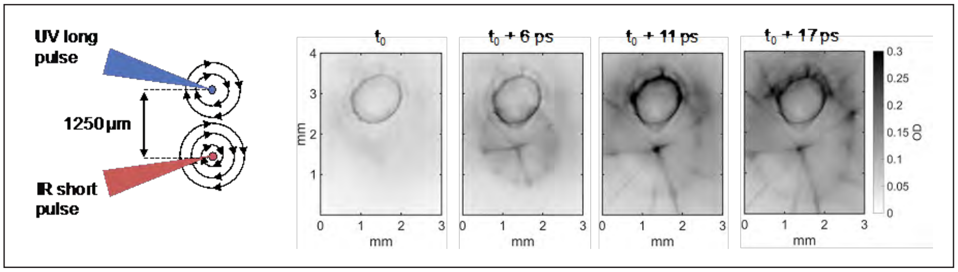



Figure 1. The schematic representation of the experiment demonstrates the asymmetric magnetic field configuration produced during the experiment using CH targets (insulators). Proton radiography captures the interaction of the rapidly expanding, high-intensity laser generated magnetic field with the quasi-static Biermann battery field. Regions of higher optical density (OD) correspond to a greater proton flux.

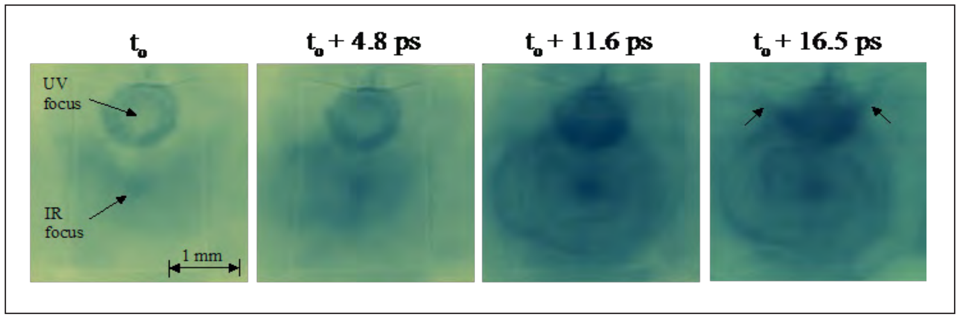



Figure 2. Proton radiography of asymmetric interactions using copper (conducting) targets noting the formations of a "shock-like structure" during the collision of the two fields.

As shown in Figure 2, the results from interactions with copper targets (conductors) are quite different. The resolution of the image is reduced due to scattering of the diagnostic proton beam in the target. However, the interaction physics also is quite different. After 11.6 ps, there is a local enhancement in proton flux along the edge of the Biermann field structure as the fields meet and interact, indicating a strengthening of the field gradient. At later time, there is evidence of outflow or shock structures emanating from the magnetic field interaction. The critical differences between insulating and conducting targets is thought to be due to the changes in hot electron dynamics within these targets.

Interactions of qualitatively similar magnetic field structures are thought to occur in highly magnetized astrophysical plasmas such as those in neutron star atmospheres, and investigations are ongoing to determine if some of the physics in these situations can be explored using this platform.

### Investigators

Paul Campbell, Gennady Fiksel, Karl Krushelnick, and Louise Willingale (University of Michigan)

Phillip Nilson and Chad Mileham (Laboratory for Laser Energetics, University of Rochester)

**Hong Sio, Lawrence Livermore National Laboratory (sio1@llnl.gov)**
**Years at LLNL:** August 2019–Present, **Degree:** PhD, Physics
**SSAA Program:** 2011–2018, Massachusetts Institute of Technology

I am currently a postdoctoral experimental physicist at Lawrence Livermore National Laboratory (LLNL), and I work on both inertial confinement fusion (ICF) and high energy density (HED) experiments at the National Ignition Facility (NIF). I am leading experiments on understanding how externally applied magnetic fields can improve ICF implosion performance and experiments to measure temperature in warm dense matter using Extended X-ray Absorption Fine Structure (EXAFS).

During my PhD in the high-energy-density physics group in the Plasma Science and Fusion Center at MIT, I worked on both the 60-beams OMEGA laser facility at the University of Rochester and the 192-beam National Ignition Facility at LLNL. My PhD work focused on understanding ICF implosions using high-precision, time-resolved nuclear diagnostics.

On OMEGA, I developed the Particle X-ray Temporal Diagnostic (PXTD) to study the impact of kinetic and multi-ion effects on ICF implosion performance. PXTD is a versatile, streaked instrument for measurements of multiple X-ray-emission and nuclear-reaction histories with high relative timing precision, and it was developed to probe the time evolution of plasma conditions during the shock phase of ICF implosions. We want to better understand this initial stage of ICF implosions, what effect it has later in the implosion when the shell finally reaches peak compression, and whether current simulation tools are sufficient. Assessing the roles kinetic and multi-ion effects play in ICF implosions is especially important, because ICF implosion simulations heavily rely on radiation-hydrodynamic codes that do not model these effects. Using PXTD, time-resolved observations of fuel-ion species dynamics in ICF implosions have been made using multiple nuclear reaction histories (see Figure 1).

On the NIF, I was the responsible scientist for the magnetic particle time-of-flight (magPTOF) diagnostic. MagPTOF is a timing diagnostic for simultaneously measuring shock- and compression-bang times—the moments of peak thermonuclear burn during ICF implosions. These measurements help researchers understand the implosion dynamics and provide necessary feedback for the next experiments.

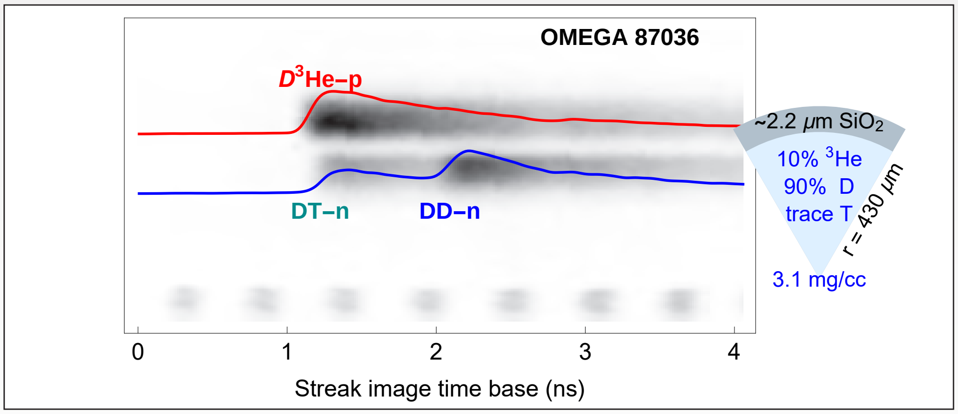



Figure 1. DD-n, DT-n, and $D^3He$-p streak signals simultaneously measured using the Particle X-ray Temporal Diagnostic (PXTD) in a $DT^3He$-gas-filled, shock-driven implosion on OMEGA (H. Sio et al., Phys. Rev. Lett. 122, 035001 (2019)). The DD, DT, and $D^3He$ reaction histories are obtained by fitting to the rising edge of the streak signals.

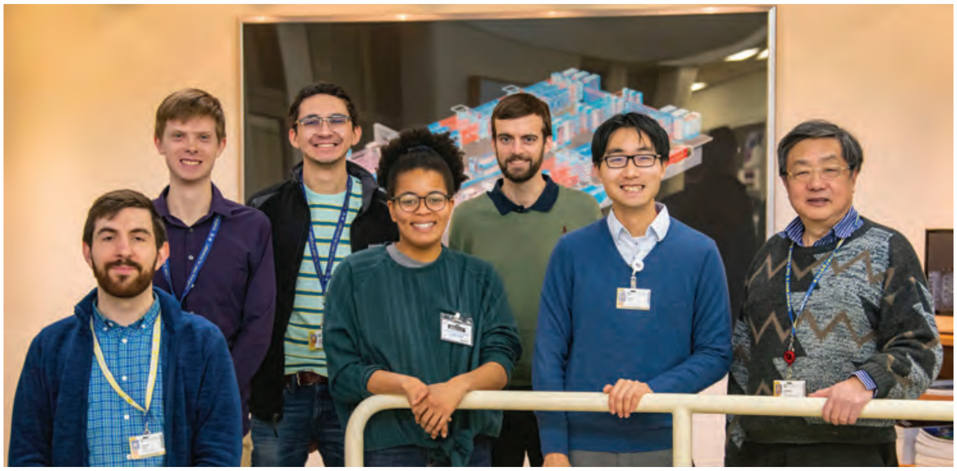


Figure 2. MIT experiment team at the Omega Laser Facility conducting high-energy-density B-field experiments. Photo: Eugene Kowaluk.

As a Stewardship Science Graduate Fellow, I also participated in experiments at both the Jupiter Laser Facility and the SLAC National Accelerator Laboratory. On Jupiter, I joined an experiment to measure thermal conductivity in warm dense matter. These measurements were used to test models for heat conduction in the strongly coupled plasma phase space and provided an experimental test of the Wiedemann-Franz law, where electrical conductivity is used to infer thermal conductivity. I appreciated the opportunity to put aside my own projects for a few months to learn about a new research area and to work in a national lab environment.

At MIT, I was able to work with many scientists at national labs and other universities through experiment collaborations, and some of these scientists became informal mentors in their own ways. These experiences combined gave me a good sense of the careers at these diverse scientific institutions. As I began to consider my next position after MIT, I felt comfortable and confident in my decision to pursue a career at a national lab.

Students

## Kaleb Burrage, University of Alabama at Birmington (kcburr@uab.edu)

**Degree in Progress:** PhD, Physics (Materials Science), University of Alabama at Birmingham, **Advisor:** Dr. Yogesh Vohra
**SSAP:** 2017–Present; **Research Topic:** Diamond Anvil Cell Designs for Ultra-High Equation of State Formation

### Research Responsibilities

My research includes using a variety of techniques for fabricating diamond anvil cell devices to achieve pressures nearing 1 terapascal to form accurate equations of state for materials. Namely, I grow micro-diamond anvils atop existing single crystal diamond using micro-lithography and chemical vapor deposition. This is done by introducing methane and hydrogen gas into a vacuum chamber and igniting them into a plasma using a DC microwave emitter. The heavier carbon in the methane dissociates from the hydrogen and descends onto the single crystal diamond substrate, growing graphite and diamond. The hydrogen gas then acts as an etchant to remove the weaker graphitic phase of carbon, leaving only grown diamond. These micro-anvils decrease the surface area of the material being compressed to increase the achievable pressure to several hundred gigapascals. New micro-anvils also can be created from the single crystal diamond utilizing Focused Ion Beam milling atop the single crystal anvils. These have been shown to reach over a half terapascal in static compression. X-ray diffraction at large synchrotrons can be used to probe the crystal lattice of sample materials under this extreme pressure to extract volume information and derive equations of state for materials in conditions replicating the core of planetary bodies.

### Benefits of the SSAP

Being a part of the Stewardship Science Academic Programs (SSAP) accelerated my learning experience in graduate school by allowing me to collaborate with facilities hosting NNSA stewardships, namely Sandia National Laboratories.

### National Laboratory Experience

In my second year of graduate school I came into contact with scientists from Sandia National Laboratories (SNL) at the SSAP Symposium hosted in Albuquerque, New Mexico. Thrilled that I was a part of the SSAP with research experience, SNL invited me to stay in Albuquerque in an internship position for the summer which later was extended to a year-long status. While there in the SSAP, I gained invaluable research experience working alongside talented physicists, engineers, and technicians at SNL's Z Pulsed Power Facility and THOR lab. The collaborations formed and the knowledge gained during my stay at SNL are beyond beneficial, as they facilitate the very nature of science and progress that returned with me to my home institution.

## Erik Davies, University of California, Davis (ejdavies@ucdavis.edu)

**Degree in Progress:** PhD, Earth and Planetary Science, University of California, Davis; **Advisor:** Dr. Sarah T. Stewart
**SSAP:** 2015–Present; **Research Topic:** Thermodynamics of Giant Impacts

### Research Responsibilities

I help design and conduct shock and release experiments at Sandia National Laboratories' Z Pulsed Power Facility and the University of California, Davis Shock Laboratory, to measure equation of state properties of minerals important to the formation of terrestrial planets. During planet formation, collisions onto planets and between planetary building blocks, such as asteroids, are common and can be energetic enough to melt or vaporize rock. Melting and vaporization alters the chemical and thermal evolution of the final planets. However, until recently, the extreme pressures and temperatures reached during planetary collisions could not be reproduced in laboratory experiments. We were missing key measurements on major materials that make up Earth's mantle, such as the mineral forsterite ($Mg_2SiO_4$). I conducted experiments with Sandia's Z machine, which can launch projectiles up to 40 $k/s^{-1}$, and the University of California, Davis shock laboratory, which can launch up to 8 $k/s^{-1}$, to measure the properties of forsterite and other important minerals at extreme conditions. I use these measurements to calculate impact criteria in which melting and vaporization is likely to occur during planet formation. I analyze the thermodynamic path of these collisions, including post impact decompression, the evolution of vapor plumes, and their effect on planet formation.

### Benefits of the SSAP

This project has given me the opportunity to work on one of the most sophisticated pieces of engineering in the world in order to tackle problems that are fundamental to the formation of planets. Furthermore, the Stewardship Science Academic Programs (SSAP) have connected me to experts in dynamic compression and high energy density physics at the national laboratories as well as at universities. These experts have helped me learn the nuances of experimental design and interpretations of the thermodynamic data that we measure. My research would not have been possible without the opportunities that I have been given by the SSAP. The SSAP has presented an exciting possible career path at the national laboratories.

### National Laboratory Experience

I have traveled repeatedly to Sandia National Laboratories to work primarily with Dr. Seth Root to perform Earth Science flyer plate experiments that are part of the Z Fundamental Science Program. These experiments have formed the bulk of my dissertation, and I am grateful for the opportunity to contribute to this collaborative work.

## Sara Gilson, University of Notre Dame (sgilson@nd.edu)

**Degree in Progress:** PhD, Chemistry, University of Notre Dame; **Advisor:** Dr. Peter C. Burns
**SSAP:** 2017–Present; **Research Topic:** Synthesis and Characterization of Actinide Metal-Organic Frameworks


### Research Responsibilities

As a third-year graduate student, the Stewardship Science Academic Program (SSAP) has profoundly impacted my graduate school research experience and future professional goals. A significant portion of my research focuses on synthesizing and characterizing actinide metal-organic frameworks (MOFs). MOFs are three-dimensional, crystalline, porous structures that can be tuned for a multitude of applications, such as fission product capture and gas storage. Few actinide MOFs have been studied compared to transition metal MOFs, for which thousands of structures have been described. Even fewer transuranic MOFs have been reported. Yet the singular chemistry of transuranic elements, specifically neptunium, may be a fruitful direction for synthesizing MOFs with novel metal-oxo nodes and advancing the fundamental chemistry of these poorly understood elements.

Neptunium is a synthetic element with atomic number 93. It is a byproduct of nuclear reactors and is of strategic importance due to its limited availability. As a potent α-emitter with a half-life of 2.14 million years, Np-237 is predicted to be a significant dose contributor in used nuclear fuel stored in a geologic repository. Prominent fundamental chemistry questions about neptunium are unanswered, although synthesizing and characterizing $Np^{5+}$ MOFs may help address these knowledge gaps.

### Benefits of the SSAP

In addition to my research responsibilities, the SSAP enabled me to explore a future career in nuclear energy. During the spring of 2019, I attended the first Investigations Supporting MOX Fuel Licensing in ESNII Prototype Reactors (INSPYRE) school on Generation IV nuclear reactors fuel cycles in Delft, The Netherlands. At this five-day school, I attended lectures given by experts in nuclear reactor designs, reprocessing cycles, and fuel fabrication specific to this new generation of nuclear technology. Most importantly, I networked with scientists and graduate students from all over the world. Hearing diverse perspectives on nuclear fuel reprocessing and closed fuel cycles greatly expanded my worldview. These experiences helped me generate ideas that propelled my research and led me to conduct irradiation studies of MOFs.

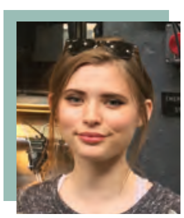
### What Students Should Know About SSAP

In my graduate school experience thus far, curiosity and desire for knowledge have driven my research. For students considering the SSAP: seek knowledge. Being self-motivated, inquisitive, and proactive are crucial skills for working at the cutting edge of science.


## Liya V. Semenchenko, Texas A&M University (liyasem@tamu.edu)

**Degree in Progress:** PhD, Materials Science and Engineering, Texas A&M University, **Advisor:** Dr. Michael Demkowicz
**SSAP:** 2018–Present; **Research Topic:** Processing Multilayered Metals via Severe Plastic Deformation for High Strain Rate Mechanical Testing


### Research Responsibilities



As a part of the Center for Research Excellence on Dynamically Deformed Solids (CREDDS), one of my research responsibilities includes processing multilayered metals via severe plastic deformation. Accumulative roll bonding is one such deformation method I have utilized at Los Alamos National Laboratory (LANL) to form bulk, multilayered metals of ultra-fine grain quality. Several processing parameters are varied in order to identify how materials processing affects microstructural features (e.g., interfaces, grain boundaries, etc.), and ultimately, the mechanical response under ballistic impact. A few processing parameters that I have investigated thus far include varying multilayer stacking patterns and annealing conditions in-between passes. Additionally, I am analyzing the materials pre- and post-impact testing to understand how these microstructural features play a role in the evolution from damage to failure under high strain rates. The information from these experiments is necessary to improve the predictive capabilities of current models in materials deformation.

### Benefits of the SSAP

The research opportunity within LANL was an invaluable experience. I was able to work with talented researchers and hands-on with unique instruments. The research scientists and technical staff were welcoming and inclusive. I sincerely appreciate them for setting aside time on a near daily basis for my research project as well as offering their advice and expertise. Without Stewardship Science Academic Programs (SSAP), I would not have been able to explore other labs and meet the many inspirational people who have guided me throughout the 5-month journey. The SSAP has reinforced my career choice of working as a materials research scientist at a U.S. national lab.

### What Students Should Know About SSAP

Future students, it is important to take time for yourself and explore extracurricular activities in order to avoid burnout. LANL does an excellent job by offering social events, including history lessons or research talks (on topics you may never have considered) and promoting extracurricular clubs. Even if it may seem difficult to make friends with similar interests outside of the lab, it is worth the effort to push yourself—you never know who you may end up meeting or what you may end up learning!

Harrison Sims, Rutgers University (harrysims94@gmail.com)

**Degree in Progress:** PhD, Nuclear Physics, Rutgers University, **Advisor:** Dr. Jolie Cizewski
**SSAP:** 2016–Present; **Research Topic:** Measuring Neutron Transfer Reactions to Reduce Uncertainties in Spectroscopic Factors for Low-Lying States in Neutron-Rich Nuclei

### Research Responsibilities

I am a core member of the GODDESS (Gamma-array—ORRUBA: Dual Detectors for Experimental Structure Studies) collaboration, measuring both charged particles and gamma rays in coincidence from structurally and astrophysically important reactions—particularly neutron transfer. Development of the Oak Ridge Rutgers University Barrel Array (ORRUBA) of charged particle detectors and the realization of GODDESS would not have been possible without the support of Stewardship Science Academic Programs (SSAP). Populating states of neutron-rich fission fragments through (d,p) and (d,pγ) reactions yield spectroscopic information on the purity of single particle states and can inform neutron capture rates. These are important measurements aligned with the goals of stewardship science as well as understanding r-process nucleosynthesis. Currently, I am finalizing analysis on $^{84}$Se(d,p) at 45 MeV/u to extract spectroscopic factors of low-lying states in $^{85}$Se. I am the primary investigator for the priority-one-approved experiment $^{80}$Ge(d,pγ), scheduled to be measured at the National Superconducting Cyclotron Laboratory (NSCL) in the summer of 2020.

### Benefits of the SSAP

My involvement with GODDESS has given me a strong understanding of charged particle and gamma-ray spectroscopy. I have been a core part of experimental campaigns, from designing essential equipment, to setting up and characterizing entire arrays of position-sensitive silicon detectors. The opportunity to present my work at SSAP symposia and at workshops at Lawrence Livermore (LLNL) and Los Alamos (LANL) National Laboratories has led to insightful collaborations at experimental facilities across the country. Without support from the SSAP, I would not have developed these critical technical and communication skills that I will now carry with me for the rest of my career.

### National Laboratory Practicum/Experience

As well as spending significant amounts of time at Argonne National Laboratory and the NSCL for experimental campaigns, much of my time as a graduate student has been spent at Oak Ridge National Laboratory working closely with world-leading experts to analyze data and further develop GODDESS for fast beam measurements. Through SSAP support, I was able to work with the Fission Time Projection Chamber group at LLNL during the summer of 2017. This allowed me to expand my experience to neutron-induced fission reactions. My primary responsibility was centered on the preparation of the fission TPC for (n,f) experiments at LANL.

Shu Zhang, University of California, San Diego (zhangshu@ucsd.edu)

**Degree in Progress:** PhD, Applied Physics, University of California, San Diego, **Advisors:** Dr. Farhat Beg and Dr. Mingsheng Wei (UR/LLE)
**SSAP:** 2015–Present; **Research Topic:** Hot Electron and Laser-Plasma Instabilities in Shock Ignition

### Research Responsibilities

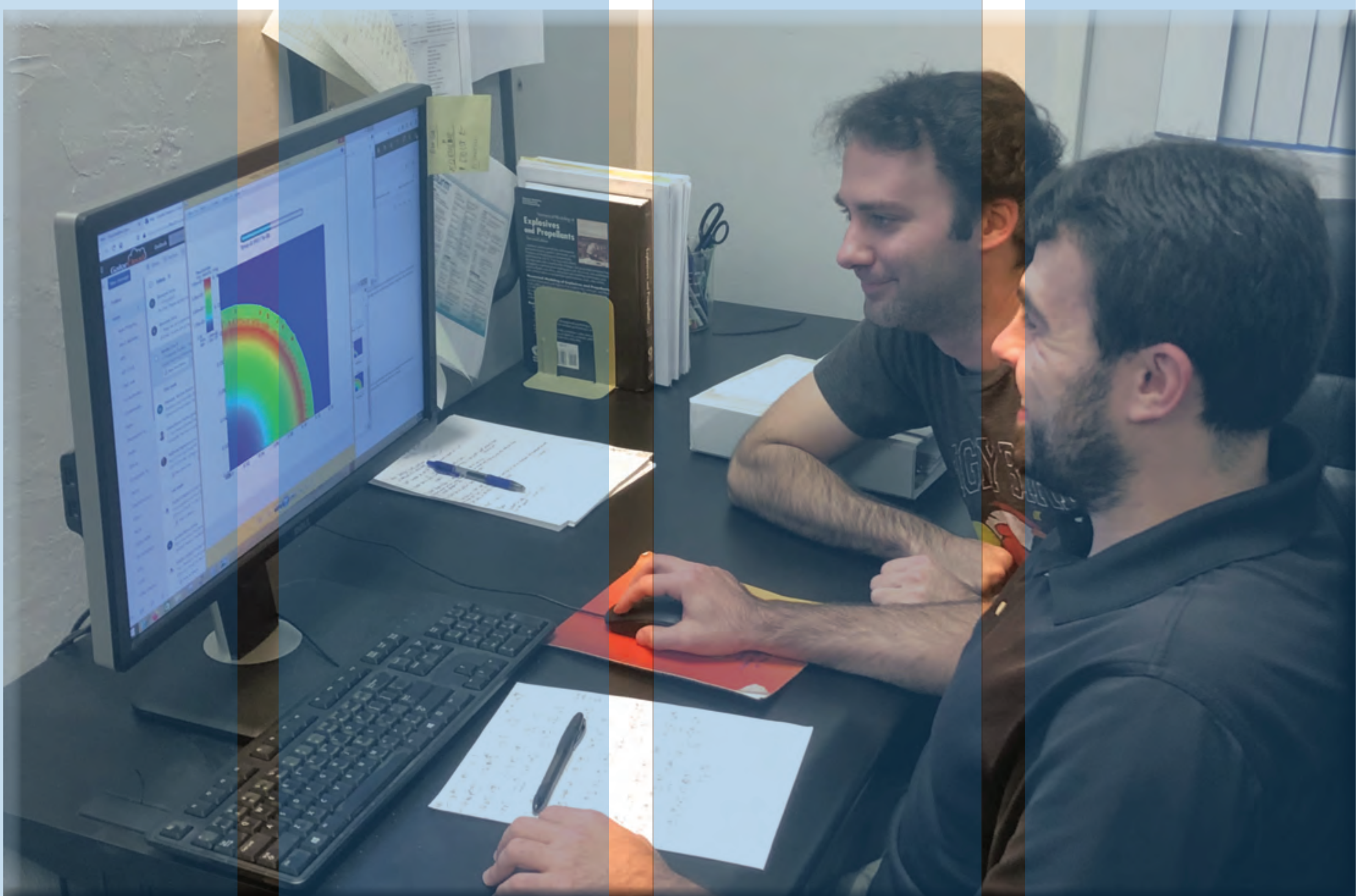
I am conducting experiments and simulations to measure and understand the hot electrons and laser-plasma instabilities in shock ignition conditions. Shock ignition is an alternative inertial confinement fusion scheme which requires a high-intensity, nanosecond laser to generate a high-pressure shock to ignite pre-compressed fusion fuel. In this scheme, laser-plasma instabilities can be highly non-linear and generate hot electrons as well as deplete laser energy. We have five experiment days on the OMEGA EP and OMEGA 60 lasers, and I have designed and led three of them. At Omega, we can have a high-intensity laser interact with a pre-formed, large-scale plasma to mimic the laser-plasma interaction in shock ignitions. In these experiments, we diagnosed X-rays, hot electrons, plasma profiles, scattering light, and shock speed. Besides the experimental measurement, I used multiple simulation tools to create synthetic data, which helps analyze the data and adjust the shot plan, especially when an unexpected feature is detected. By comparing the simulations with the experiments, I have, for the first time, discovered a dynamic pump-depletion of the high-intensity laser.

### Benefits of the SSAP

This research project is funded by both the HEDLP and NLUF programs. First of all, the Stewardship Science Academic Programs (SSAP) financially supported my years of PhD study. More importantly, the SSAP gave me the chance to conduct these experiments with the best resources. The Omega Laser Facility is necessary for this project with its versatile multi-beam configurations and diverse diagnostics. They have a short shot-cycle, which is essential when exploring wide ranges of the parameters. The NLUF program provides us opportunities to develop complicated targets with General Atomics. They developed a low-density Cu foam to improve our measurements and also made precise production and accurate metrology to create ideal experimental conditions. Since it is a DOE program, we were granted computational resources on the NERSC supercomputer, so we can run extensive particle-in-cell simulations to understand the physics in the experiments.

### What Students Should Know About SSAP

After four years supported by SSAP, I am astonished by how much this program can provide for this research project, basically everything I need! They will make you more focused on science, without the need to worry much about technical or resource problems. Being part of the community will expose you to many other impactive projects which can give you a wider choice for your future career.



# Predictive Science Academic Alliance Program II

## Predictive Simulations of Particle-Laden Turbulence in a Radiation Environment

Stanford University ✦ PI: Dr. Gianluca Iaccarino (jops@stanford.edu)

The number of uncertainties involved in the study of multiphysics turbulent flows is typically large due to (1) the modeling assumptions required to describe the coupled physical phenomena and (2) the incertitude resulting from the limited knowledge of the system properties and the initial and boundary conditions. As a consequence, analyses based on single simulations cannot be truly predictive. A possible strategy is to explicitly treat the inputs to the computations as a source of stochasticity and analyze the relation between inputs and outputs by means of efficient uncertainty quantification (UQ) methods. Within this framework, the objective of the PSAAP II project at Stanford University has been to perform large-scale, predictive simulations of irradiated, particle-laden turbulence in configurations inspired by particle solar receivers.

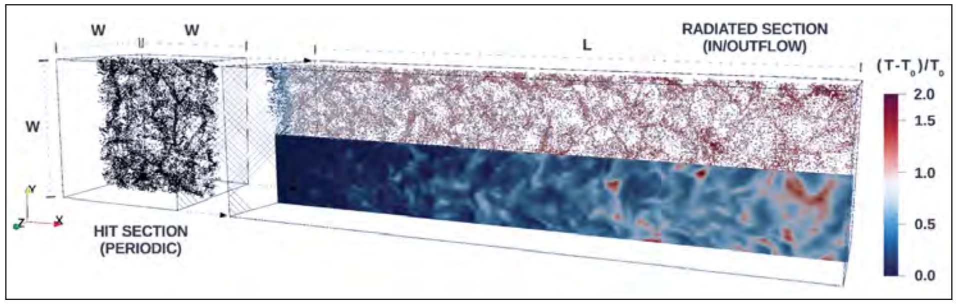



Figure 1. Setup of the irradiated particle-laden turbulent flow. The forced HIT (left) domain is utilized to provide fluid-particle inflow conditions to the radiated (right) section. The color scheme indicates normalized instantaneous temperature increment of the dispersed (top) and carrier (bottom) phases on the streamwise xy-plane.

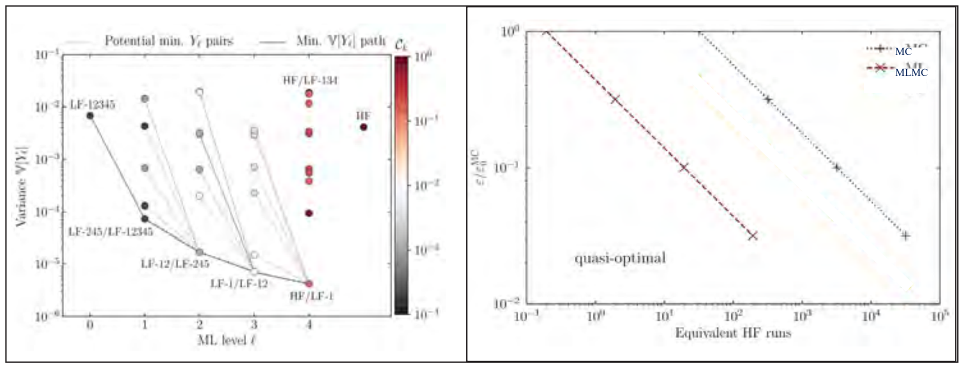



Figure 2. Variance of Yl (left) across levels for a set of potential pairs (dashed lines) and selected combination (solid line) with color indicating fidelity cost Ck. Normalized standard deviation (right) for MLMC and naive MC as function of the overall computational cost in terms of equivalent number of HF runs.

High-fidelity (HF) models that represent all the spatial and temporal scales of importance in the problem are the main target to describe accurately the system but, obviously, require considerable computational resources. On the other hand, it is possible to formulate low-fidelity (LF) models that can provide cheaper but less accurate representations. UQ studies require large numbers of simulations, resulting in unaffordable computational requirements if only HF models are used. The objective of multifidelity (MF) methods, therefore, is to reduce the cost of the overall UQ assessment by combining the accuracy of a few HF simulations with the efficiency achieved by a large number of LF computations. Different MF UQ strategies exist in the literature and have been compared in the PSAAP II at Stanford. Here, for simplicity, only the application of the Multilevel Monte Carlo (MLMC) is described briefly.

The MLMC analysis is performed on the computational model depicted in Figure 1 and considers 16 uncertain inputs (stochastic variables), which are assumed to be uniform and independently distributed, with a 10% variation with respect to the nominal values. The overall thermal response of the system is the principal objective function to characterize. Consequently, the time-averaged fluid temperature increase measured at the outlet of the radiated domain is chosen as a quantity of interest.

The performance of a selected set of different resolution levels within the MLMC framework is assessed by considering 5 configuration parameters and their combinations. These parameters correspond to the turbulent flow resolution in the (1) streamwise and (2) transverse directions, the (3) size of the clusters used to represent a set of physical particles and their (4) coupling with the flow, and (5) the total time integration interval used to complete the calculations. The Arabic numerals (1, 2, 3, 4, 5) indicate which low-fidelity parameters are activated for each level with respect to the full HF configuration. Following this notation, 31 different LF levels/models have been constructed corresponding to LF-1, LF-2, LF-3, LF-4, LF-5, LF-12, LF-13 … LF-12345.

The MLMC approach is designed using 5 levels, and it is constructed by considering all the possible combination of HF and LF models. It is highlighted in Figure 2 (left) with the solid gray line. These correspond to HF, LF-1, LF-12, LF-245 and LF-12345. A small set of pilot simulations is used to analyze the variance of the difference (Y) in the output of interest between two successive levels, for example HF vs LF-1, LF-1 vs LF-12. The guiding principle in MLMC is to maximize the variance and the cost reduction between each model fidelity couple.

The performance of the MLMC approach is reported in Figure 2 (right). The results show that the MLMC achieves a similar accuracy of a naïve MC approach applied to the HF simulations but with a 1,000x speedup. This corresponds to performing about 20 HF simulations compared to about 3,200.

## A New Algorithm for Residential Monte Carlo

Texas A&M University ✦ PI: Dr. Jim E. Morel (morel@tamu.edu), Author: Mr. Jan Vermaak (janv@tamu.edu)

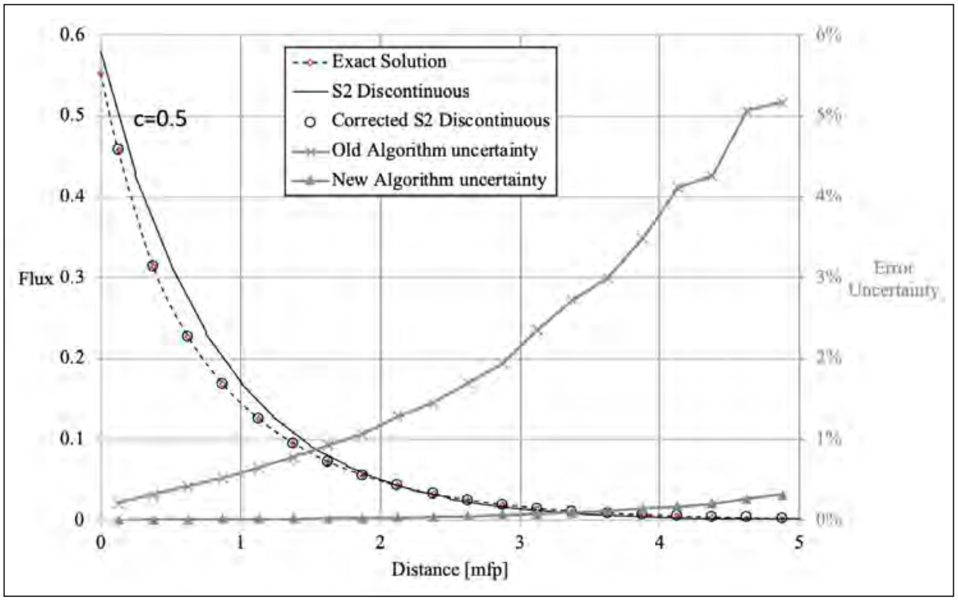



Figure 1. Shown are an exact scalar flux solution, an S2 solution, the S2 solution corrected by the error estimate, and statistical uncertainty in the error estimates using the old and new algorithms.

The primary goal of the Center for Exascale Radiation Transport (CERT) at Texas A&M is to improve the predictive capability of high-fidelity simulations of physical phenomena that include the transport of thermal radiation and/or other subatomic particles. Many ingredients of improved capability including Uncertainty Quantification (UQ) together with associated experiments and simulations are pursued at CERT. Error estimation for radiation transport simulations is an essential component of the UQ process. Standard error estimation methods often are problematic for transport because of the non-smooth nature of transport solutions. The workhorse method used for radiation transport calculations at CERT is the deterministic Sn method. The Monte Carlo method is essentially exact (neglecting statistical errors) for the problems of interest at CERT, but usually much more costly than the Sn method. The cost of estimating the error in deterministic Sn solutions via Monte Carlo can be reduced significantly by means of the residual Monte Carlo (RMC) method. This is a method by which the error is directly estimated as opposed to obtaining the error by performing a standard Monte Carlo calculation for the solution and then subtracting the Sn solution from the Monte Carlo solution. The RMC method can be explained as follows. Let us denote the transport equation by $L\psi - Q$, where $L$ is the transport operator, $\psi$ is the transport solution, and $Q$ is the source. Given an approximate solution, $\tilde{\psi}$, it is easily shown that the additive error, $\varepsilon = \psi - \tilde{\psi}$, satisfies the residual equation, $L\varepsilon = R$, where $R = Q - L\tilde{\psi}$, is the residual source associated with $\tilde{\psi}$. Using Monte Carlo to directly solve the residual equation for the error generally is expected to be far more efficient than using Monte Carlo to obtain the full solution. For instance, if one has an Sn error of 1%, one must obtain a Monte Carlo solution with a standard deviation of 0.1% to estimate the Sn error with a standard deviation of 10%. In contrast, if one uses a residual Monte Carlo calculation to directly estimate the error, the statistical error in the residual Monte Carlo solution need only be 10% to estimate the Sn error with a standard deviation of 10%. Assuming that the computational effort to achieve a given statistical error is roughly the same in both the standard and residual Monte Carlo calculations, the residual calculation should be a factor of 10,000 less costly than the standard calculation. However, this assumption is not necessarily true, primarily because the residual can be both positive and negative, unlike the strictly positive source in a standard calculation. In our previous algorithm, a simplification was made to the approximate solution that involved representing it as a constant within each cell with up-winding on the surfaces. This avoided the difficult 3D integrations of |R| required for sampling residual source particles but yielded a residual source term with large and nearly equal positive and negative components. These components led to a large amount of error cancellation with the result that the RMC calculation cost more than a standard MC calculation to estimate the error. A new algorithm subsequently was devised whereby the error is decomposed into uncollided and collided components. The uncollided component is computed deterministically along a space-filling set of random rays, whereas the collided component is computed via Monte Carlo. Using this approach, only 1D integrations of the absolute value of the collided-component source (which can vary in sign) are required rather than 3D integrations of |R|. This new algorithm results in much smaller positive and negative residual sources and is up to 100 times less costly than the standard Monte Carlo method for estimating the Sn error.

## Center for Compressible Multiphase Turbulence

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

The overarching goals of the University of Florida's PSAAP II 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 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 Predictive Science Academic Alliance 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 carried out successfully on the Department of Energy supercomputer Quartz, and a number of prediction metrics were compared to experiments performed recently at the blast pad facility at Eglin Air Force Base. 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 simulation was performed using 500,000 elements with 2 million computational particles and ran on 65,536 ranks for 84 hours (or roughly 5.5 million core-hours). The team was able to extract physical phenomena from the early times of this run which had not been seen in previous iterations of the simulation efforts. Figure 1 shows contours of density and particle volume fraction at the final time of 34 μs. Of note is the layering, or flaking, of the inner edge of the particle bed which occurs as the bed begins expanding outward. This feature previously was unobserved and may be due to the addition of the model for particle collisions into these simulations.

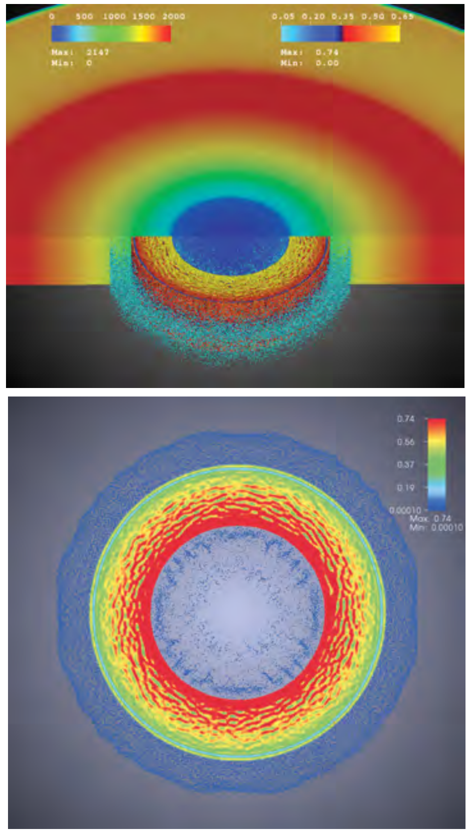


Figure 1. Top: Contour of density and particle volume fraction. Bottom: 2-D slice showing particle volume fraction. Results for the final time of 34 μs for the simulation of the explosive dispersal problem.

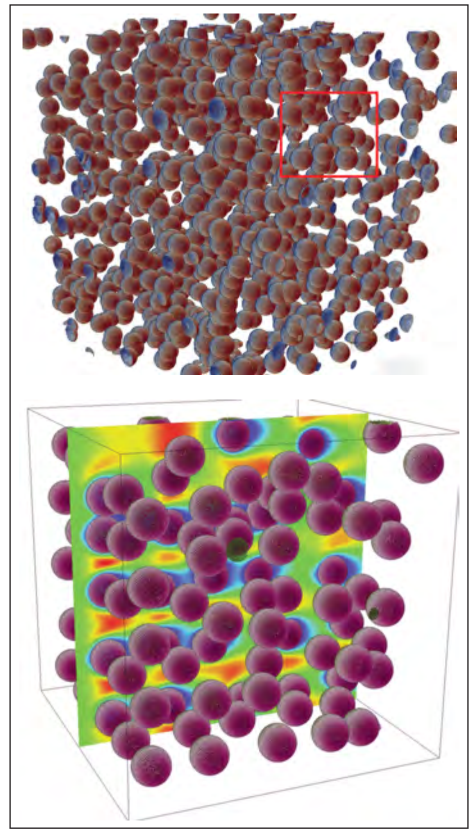


Figure 2. Example of fluid flow through a random pack of particles using the scalable DBGP algorithm for the immersed boundary method. Top: IBM showing particles. Bottom: Cut-away from top (red square) showing fluid flow in a two-dimensional plane.

One of the key enabling technologies developed in CMT-nek 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. A second key enabling technology is the scalable, immersed, boundary method (IBM) algorithm developed for multiphase flow simulations on the spectral element code Nek5000. Parallelism is accomplished naturally via domain decomposition methods and a suitable gather-scatter message passing interface (MPI) wrapper library. To pursue a fully-scalable parallel algorithm for the particle solver, a Double Bin Ghost Particle (DBGP) algorithm is developed. A queen/worker data structure for the IBM particles has been designed to represent particle-level and marker-level computation and communication, respectively. The binning of the physical domain creates the bin-to-rank map, which connects the ranks with specific bins. By searching the neighboring bins of the particle, the algorithm finds the list of MPI ranks that the particle interacts with. The ghost worker markers is used for parallel force projection. The DBGP algorithm has the features of scalable data transfer and fully distributed data structures. An example of fluid flow through a random pack of particles using the DBGP algorithm is shown in Figure 2.

Using state-of-the-art algorithms and implementations, the Center has been able to gain invaluable insight at unprecedented scales using CMT-nek.

## Center for Exascale Simulation of Plasma-Coupled Combustion

University of Illinois at Urbana-Champaign ✦ Directors: Drs. William Gropp (wgropp@illinois.edu) and Jonathan Freund (jbfreund@illinois.edu)

The Center for Exascale Simulation of Plasma-Coupled Combustion (XPACC), led by the University of Illinois, seeks to advance the use of plasmas to initiate and control turbulent combustion. This mission drives research efforts in both multi-physics predictive simulation and computer science techniques to harness the massive-scale, computational platforms necessary for high-fidelity simulations. PSAAP II funds have been the primary support for 25 PhD-level student projects. All of these students have completed at least one, 10-week internship at an NNSA lab, and seven of the nine who have graduated have taken positions at NNSA labs.

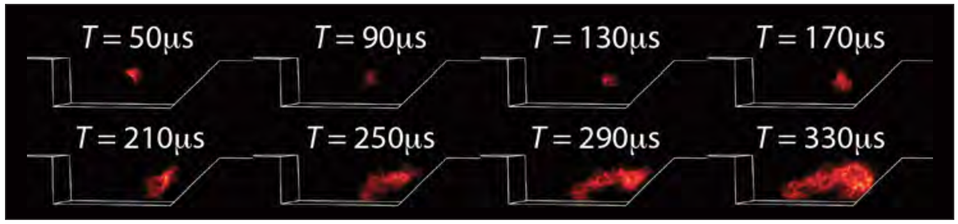



Figure 1. Transient Ignition Kernel (TIK) with OH chemiluminescence in the ACT-II arc-driven facility at Illinois. Moments of similar images provided QoI prediction target.

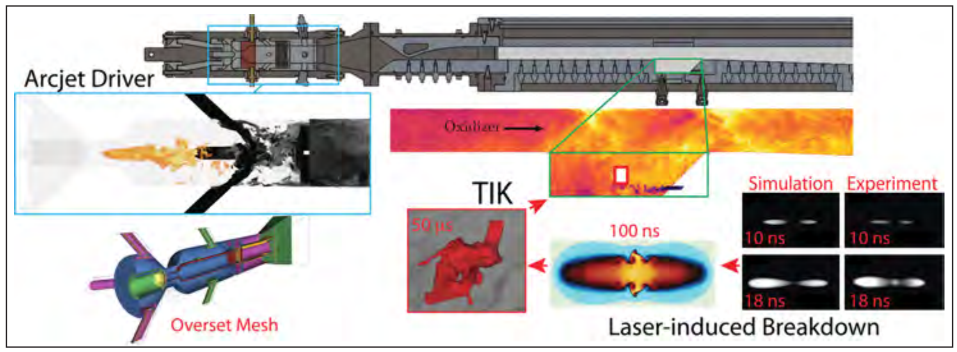



Figure 2. Integrated predictive simulations.

Figure 1 shows a prediction target: the behavior of a transient ignition kernel (TIK) as seeded by the optical breakdown of a focused laser (LIB) in a mixing supersonic flow. It is motivated by the challenge of combustion for high-speed propulsion. The primary quantity of interest (QoI) is the TIK evolution as quantified by its intensity, size, location, aspect ratio, and orientation based on its chemiluminescence. This TIK was designed specifically to expose the physics of ignition for assessing predictions while avoiding the limitations of a simple yes-or-no outcome. Scenarios for which the TIK grows to sustained flame or fails (due to poor mixing or strain) are both considered. Predictions, which were made before data was available, were based on provided laser energy, its focus location, combustor geometry, the fuel port location, and the combustor operating conditions.

The primary simulation tool used was *PlasCom2*. It is an XPACC-developed, overset-mesh solver that supports both high-order, finite difference and shock capturing discretizations of the chemically reacting Navier-Stokes equations. It interfaces with a widely used open-source chemistry and transport engine Cantera, though for production runs, especially for graphics processing unit off-loading, the XPACC tool *Prometheus* that generates light-weight stand-alone code based on Cantera output, provides significant speed-ups. The Center also developed *Overkit*, a scalable parallel tool to generate inter-mesh communication stencils. The early time (< 50 ns) LIB is simulated in a stand-alone finite-volume, optically-coupled, two-temperature, non-local, thermal equilibrium (NLTE) hydrodynamics solver called *Hegel*. It was found that *Hegel* required models for both multi-photon ionization and coupling of combustion and plasma kinetics to reliably match corresponding quasi-2D physics-targeted experiments.

Components of the main center prediction are visualized in Figure 2. The combustor and fuel injector are discretized with 7 overset meshes and run with WENO. The inflow conditions are informed by a 39-mesh simulation of the upstream arc driver. QoI uncertainty was assessed through a hierarchical sensitivity analysis and propagation of pacing uncertainties, including 0D homogeneous combustion kinetics, 0D and 1D reduced LIB models, 2D axisymmetric LIB simulations, and, finally, a limited number of full, 3D turbulence simulations for the fundamentally 3D QoI. Markov-chain Monte Carlo methods were used in the low-cost, physics-targeted configurations, and ANOVA surrogates were used for estimating global sensitivity and propagating uncertainty in more expensive configurations.

These simulations were supported by a suite of computer science tools. The operations of *PlasCom2* are expressed in a *GoldenCopy* form using common current coding standards (C++ control, Fortran computational kernels, with MPI and OpenMP parallelism). These then are exposed to additional tools—XPACC and others—to optimize and enhance functionality. These include an annotation and transformation framework *ICE*, which facilitates the replacement of code and autotuning with community tools (primarily LLNL-ROSE), a kernel language *Tangram* to generate highly optimized code for GPUs, an abstracted time integrator *Leap* that provides multi-rate capabilities, an annotation framework *PickPocket* that facilitates memory placement either for hierarchical memory architectures or for offloading, an OpenMP-based offloading framework *Hydra*, a scalable elliptic solver *Cedar* built around the legacy LANL-BoxMG kernels, and a just-in-time recompilation tool *Moya* that provides run-specific optimization and illuminates optimization opportunities. These have been released as open source (or soon will be) and have run with the full predictive science application. Overall, the Center achieves a close interaction between staff and students working with CS methods, simulation modeling, and experiments. Particular simulation goals led by particular staff were designated to exercise particular tools as steps toward full integration.

## Center for Shock Wave-Processing of Advanced Reactive Materials

University of Notre Dame ✦ PI: 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 it has superior thermal and chemical stability, making it ideal for several applications such as cutting tools. Shock synthesis of c-BN and other nanocomposites, enabled by predictive scientific 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 Image-based Multiscale Multigrid Solver (I-M$^2$).

"Working on such a complex problem would not have happened without the sustained support from NNSA," says Karel Matouš, Professor of Aerospace and Mechanical Engineering and the project's director. "Our students and research staff benefit greatly from working on a difficult problem that requires high-performance computing and an interdisciplinary approach."

Since the last calendar year, researchers of the Computational Physics Team have focused on many enhancements of the Eulerian wavelet toolkit and the Lagrangian finite elements solver as well as on advancing the data-driven multigrid solver. Furthermore, the Computational Physics Team performed several chemo-thermo-mechanical simulations to understand complex interactions during shock synthesis. As an example, Figure 1 shows the large, parallel, thermo-mechanical simulation of nickel and aluminum nanocomposite during impact loading. Experiments are performed to confirm the validity of these predictions.

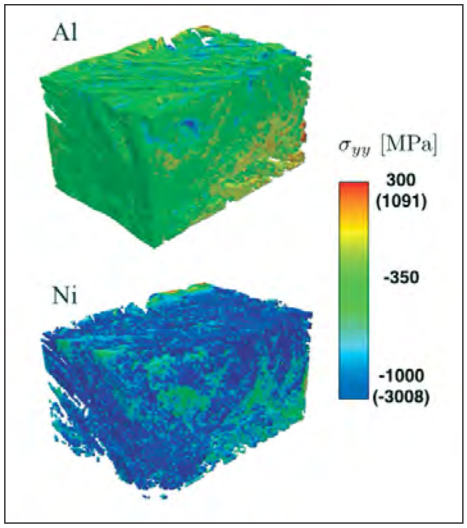



Figure 1. The thermo-mechanical impact simulation of Nickel and Aluminum nanocomposite. (Top) Stress field in Aluminum phase. (Bottom) Stress field in Nickel phase. The simulation contains 1.6M computational cells, 153.6M nonlinear Ordinary Differential Equations (ODEs) from crystal plasticity constitutive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

The computational predictions are supported by computer science development in Active System Libraries (ASLib) and asynchronous multi-tasking runtime components. The Computer Science Team advances the scaling profiles of C-SWARM production software as well as the productivity of C-SWARM code development by focusing on a Domain Specific Embedded Language (DSEL). DSEL is based on generic and meta-programming techniques to effectively eliminate the abstraction penalty. In particular, C-SWARM's researchers are focusing on the development of Photon networking and Photon-Objects to support multiscale modeling as well as on Matrix and Tensor Template Libraries (MTL/TTL). In the last calendar year, the scaling of PGFem3D was extended to 256k computing cores and a new multiscale modeling engine was constructed using Photon-Objects. Further advancements were made in GPUs Compute Unified Device Architecture 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 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 comparison of simulations with experimental results. Since the last calendar year, novel systems for shock synthesis of c-BN with large yield have been investigated.

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 critical areas of national importance. C-SWARM students have received recognition on a variety of fronts. Mrs. Dewen Yushu won the prestigious Robert J. Melosh Medal in the computational mechanics area. The Robert J. Melosh Medal was inaugurated by the Department of Civil and Environmental Engineering at Duke University in 1989. Moreover, Mrs. Katherine Ramos attended the Rising Stars in Computational and Data Sciences workshop. The event was held at the University of Texas, Austin and was sponsored by the Oden Institute for Computational Engineering and Sciences, Sandia National Laboratories, and the United States Association for Computational Mechanics.

Intensive interactions with NNSA laboratories are common in terms of student, staff, and faculty visits. C-SWARM continues to host a vibrant seminar series attended primarily by research staff from NNSA laboratories.

## Carbon Capture Multidisciplinary Simulation Center

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

*"CCMSC exists to demonstrate positive societal impact of extreme computing by accelerating deployment of a low-cost, low-carbon energy solution for power generation. Three teams contribute to the overarching predictive design: the validation/uncertainty quantification team, the physics team, and the computer science team."*

The Carbon Capture Multidisciplinary Simulation Center (CCMSC) exists to demonstrate the positive societal impact of extreme computing by accelerating deployment of a low-cost, low-carbon energy solution for power generation. Three teams contribute to the overarching predictive design: the validation/ uncertainty quantification (UQ) team, the physics team, and the computer science team.

The Center has been driven by the mission of predicting the heat flux profile for the design of a new technology for a full-scale, pulverized, solid-fuel, thermal power generation boiler to a proven level of uncertainty using large-eddy simulations on the largest computational resources available to us. To date, the Center has achieved predictivity to a level of 8% uncertainty on average and is on track to achieve the original goal of 5% by the end of the project this year. This predictivity comes through use of a validation/uncertainty quantification (V/UQ) process developed at the Center over the past 5 years. The experimental data, which provides the body of evidence for the predictive problem, includes a hierarchy of experiments from different laboratories at different scales to make predictions at full-scale. The v/uq process employed at the Center has evolved as a hybrid of Bayesian and Bounds to Bounds methodologies for reducing the model bias in both the simulation models and the instrument models used to produce the experimental measurements. To reach our objectives, the Center has developed the Arches multiphase combustion application code built on the Uintah computational framework. Uintah's adoption of MPI+Kokkos and Hypre adds run-time parameters that allow users to optimize performance. Strong and weak scaling has been shown for Uintah to 256k cores with 16k Graphics Processing Unit (GPU) on a range of production machines from Titan through Mira. This year, the PIDX data I/O library (a parallel API for writing data in an IDX formate) has matured from a proof of concept prototype to a fully integrated and supported file format within Uintah.

Coal-fired power systems remain the largest single source of power in the U.S. Over its history, the Center has explored four different boiler design options to match evolving societal targets. As each design targeted a different rank of coal, the Center has developed models to predict the performance of different fuel ranks in pulverized fuel boilers. With the continued global search for carbon neutral electric power generation, many countries, including the United States, now are turning to biomass as a retrofit option for coal-fired power plants. The biomass feedstock of choice is wood pellets because wood is so similar to coal in it geological rank. This year, the technology developed at the Center for coal firing has been deployed to predict the heat-flux profile in a power generation station that has been converted from coal to wood-pellet firing. The hierarchical data for coal has been augmented with a few simple targeted experiments growing out of a continued instrument modeling effort. Data from the Atikokan Power Station, the first power plant in North America that has accomplished this switch from coal to wood, is used for validation. In this way, the technology developed in the first five years of the Center to predict and validate both the heat flux distribution and its uncertainty in this carbon-neutral energy solution is applied.

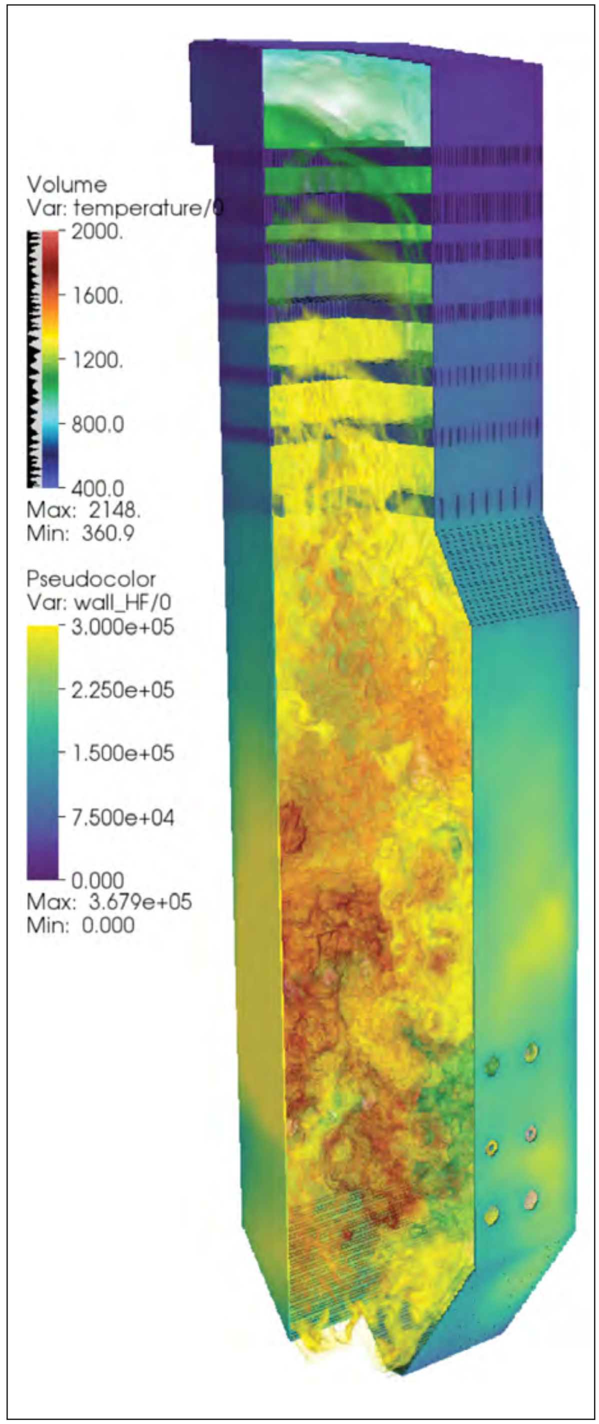



Figure 1. Cutaway view of the Atikokan boiler from a simulation at one instance in time. Internal to the boiler the coloring represents the local temperature (K) while the surface of the object is color by wall heat flux ($W/m^2$).

**M. Giselle Fernandez-Godino, Los Alamos National Laboratory (gisellefernandez@lanl.gov)**
**Years at LANL:** February 2019–Present, **Degree:** PhD, Aerospace Engineering
**SSAA Program:** 2014–2018, University of Florida

During my PhD, I was a member of the Center for Compressible Multiphase Turbulence, funded by the PSAAP II Program, at the University of Florida from 2014 until 2018. I focused my studies on the simulation of multiphase explosions, which are explosions that carry multiple materials and/or material phases. My research showed that small perturbations in the initial configuration of these detonations are amplified (see Figure 1). Because of the high computational burden of these simulations, the use of multi-fidelity models was imperative. For this reason, I became an expert in multi-fidelity models. These models combine information from multiple fidelity sources allowing cost reduction while maintaining accuracy. In my present position at Los Alamos National Laboratory (LANL), I am taking one step further, using my modeling knowledge to build neural networks.

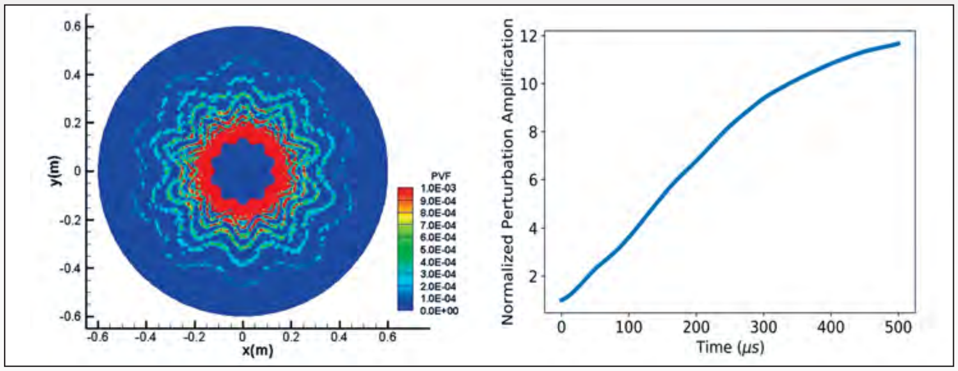



Figure 1. Left: Particle volume fraction (PVF) contours at t= 500 μs. Initial sinusoidal perturbations in PVF translate later in sinusoidal perturbations in particle locations. Right: Initial sinusoidal perturbations in PVF amplify with time.

As a PSAAP II student, I was part of a multi-disciplinary group where experimentalists, code developers, and data scientist worked together to study highly-complex, multiphase detonations. Being part of the PSAAP II program gave my research visibility among the most influential people in the field at LANL, Lawrence Livermore National Laboratory, and Sandia National Laboratories (SNL). This led to an internship at SNL and the opportunity to pursue postdoctoral researcher opportunities at the labs. The PSAAP provides uninterrupted research funding for four years, which allows stability and the possibility of focusing only on research relevant to the NNSA mission.

During my four years as a PSAAP II student, the NNSA national laboratories followed my progress. I met with them once every six months for progress updates. This communication helped me learn that at NNSA national laboratories I had the possibility of continuing to do cutting-edge research after graduation. Moreover, as part of LANL, I have the opportunity to be part of a team engaged in strategic science on behalf of national security.

One of the main missions of LANL is to protect the nation by ensuring the safety and reliability of weapons. Understanding material properties and behavior is a key component of this mission. For example, it is critical to characterize brittle metal behavior and to understand how failure occurs. Being able to predict crack propagation and interaction allows for potential accidents to be prevented.

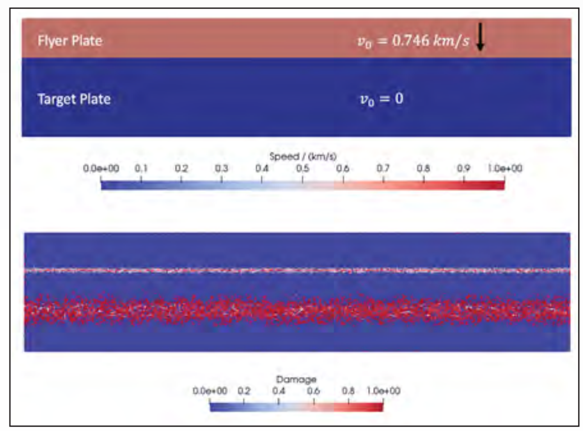



Figure 2. Flyer plate impact simulation using HOSS. Top: Initially the flyer plate impacts the target plate at a speed of 0.746 km/s. Bottom: At a time of 0.8 μs the target plate fails due to crack propagation.

As a LANL postdoctoral researcher, my main goal is predicting the behavior of brittle materials under various loading conditions leading to failure. For this goal, experiments usually are the most desired option, but the cost, instruments, and human resources needed are prohibitive even for performing no more than a few experiments. There are also available expensive computational models that, besides their limitations and approximations, predict material behavior accurately. However, producing the millions of simulations required for optimization, inference, or uncertainty quantification is not feasible due to the intensive computational cost. For this reason, I am developing applications of machine learning methods, mainly neural networks, to predict the evolution of stress and damage in high impact experiments. The training data is obtained from HOSS, a high-fidelity model-based on the Combined Finite-Discrete Element Methodology whose damage model predicts the evolution of individual cracks (see Figure 2). The goal is to train neural networks using HOSS predictions to rapidly provide upscale crack statistics for more accurate strength and damage modeling in the lower fidelity continuum hydrocode FLAG.

As a member of the X-Computational Physics, Verification, and Analysis group, I am part of a multi-disciplinary team that utilizes experimental data for validation and prediction of simulation uncertainty in large-scale physics simulations. I collaborate with experimentalist and physics subject matter experts to understand the sources and types of uncertainties in models and experiments.

# Fellowships

*"This year, I was fortunate to take on a new role at LANL, that of a mentor for three students. Mentoring has provided me with the opportunity to help contribute to the next generation in the same way so many of my mentors did for me. This experience also has highlighted one of the strengths of the SSGF program—a strong and encouraging community that cultivates mentorship at all levels. I look forward to maintaining an active role in both the future of LANL and in the growing SSGF community."*

*— Dr. Samantha Lawrence*
Los Alamos National Laboratory

Pictured on the previous page: The 2019-2020 LRGF and SSGF) Classes. Left to right are: Eldred Lee, LRGF; Dane Sterbentz, LRGF; Ryan Childers, LRGF; Lauren Smith, SSGF; Patrick Adrian, SSGF; David Chin, SSGF; Sylvia Hanna, SSGF; and Justin Cheng, SSGF. Not pictured: William Brooks, LRGF.

**Stephanie Miller, University of Michigan (smmil@umich.edu)**

**Degree in Progress:** PhD, Nuclear Engineering and Radiological Sciences, Pulsed Power High Energy Density Physics
University of Michigan, **Advisor:** Dr. Ryan McBride

**LRGF Program**
2018–Present

**Research Topic**
Laser Gate Experiment for Increasing Preheat Energy Coupling in Magnetized Liner Inertial Fusion

**Area of Study**

The goal of achieving nuclear fusion ignition is driven by clean energy and stockpile stewardship applications. My excitement toward this goal is fueled by my passion for improving the Earth's climate and, ultimately, developing a sustainable source of energy. One experimental platform for studying nuclear fusion is magnetized liner inertial fusion (MagLIF). MagLIF is studied on the Z Machine at Sandia National Laboratories (Sandia) in Albuquerque, NM. In MagLIF, a metal tube (or liner) full of preheated fuel is imploded to create fusion-relevant temperatures and densities. When I first learned about MagLIF, I was blown away by the successes of the platform and inspired by the scientists behind these advancements.

### LRGF Program Support and Influence

The LRGF program has given me the opportunity to work with and learn from these incredible scientists. Before I became an LRGF recipient, I was conducting my research only at the University of Michigan. Through the program, I have been able to spend a summer at Sandia. While I was there, I was able to experience what it is like to work at an NNSA lab. Even now, back at Michigan, I am in touch with my mentors from my residency, and they are still helpful in aiding my research outside of the lab. Spending time at Sandia exposed me to a lot of potential career paths at the national labs. There are more groups and projects than I could have imagined.

### Current Research Responsibilities

Right now, I am working on increasing the diagnostic capabilities on our test facility at the University of Michigan. In support of the MagLIF platform, I am studying a way to increase energy coupling from a preheating laser into the fusion fuel. Currently, the preheating laser ablates through a few-micron-thick plastic window that holds the fuel in place until it is compressed. This ablation process reduces the amount of energy that can preheat the fuel. I have been investigating a method called "Laser Gate" to remove the window before the laser passes through the laser entrance hole. I run a current pulse through a thin wire wrapped around the perimeter of this window. When the wire heats up, the window material weakens, and the fuel pressure inside of the target pushes the window up and out of the laser path. I have completed proof-of-principle work at Michigan and was able to work more on this concept at Sandia during my first residency.

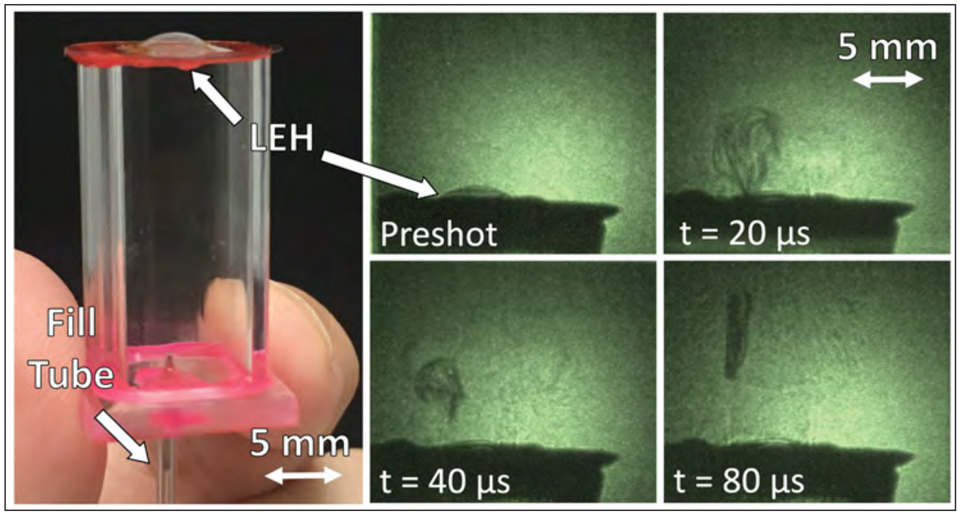



Figure 1. Target built at University of Michigan for testing Laser Gate. When pressurized, the window material stretches out into the domed shape (left). Images of the laser entrance hole (LEH) show the window opening up and out of what would be the preheating laser path in a MagLIF experiment (right). The largely intact window appears to ride along the edge of the escaping pressurized gas column.

### Recent Residency Experience at Sandia

I spent this past summer working at Sandia National Labs in Albuquerque, NM. I was able to shadow a target fabrication specialist who builds MagLIF targets. He helped me improve my own target fabrication abilities. With the lessons he taught me, I was able to scale the Michigan target design down to the size of MagLIF targets (about 2.5 times smaller). Now I can build more reliable targets and perform scaling studies with different sized targets. After I built new targets, I fielded them in a Sandia vacuum chamber facility with an interferometry system which allowed me to study the fuel propagating out of the targets. I now am working on designing a similar system back at Michigan to continue my studies.

### Benefits of the LRGF Program

One of my favorite benefits of the LRGF program is becoming part of the SSGF/LRGF cohort of Fellows. There is a program review every summer where all of the SSGF and LRGF students present their research. Being surrounded by a network of spectacular Fellows is motivating, and the friendships are invaluable.

**Samantha Lawrence, Los Alamos National Laboratory (slawrence@lanl.gov)**
**Degree:** PhD, Materials Engineering, 2015
**SSGF Program:** 2012–2015, Washington State University and Purdue University

The operating environment into which metals are placed affects their structural integrity and function. Extreme environmental conditions frequently push structures to the limits of their designed performance. My passion is learning how metals perform at their limits and designing new alloys or processes to better create resilient materials and fabricating structures to withstand environmental attack.

My fellowship through the Stewardship Science Graduate Fellowship (SSGF) program was the avenue where I first realized the impact of the NNSA national laboratories on solving complex science and engineering problems such as material degradation in extreme operating environments. Both of my practicum experiences at Sandia National Laboratories allowed me to work closely with experts in the field of hydrogen degradation of structural metals. In particular, my first practicum in 2013 allowed me the opportunity to explore the nature of hydrogen degradation on the mechanical integrity of nickel alloys. These experiences led directly to my postdoctoral research work at Sandia. As a postdoctoral researcher, I focused on applying a variety of novel characterization techniques, such as nanoindentation and sonic velocity measurements, to examine small volumes of bulk materials in order to connect small-scale degradation mechanisms with bulk-scale mechanical responses.

In 2016, I transitioned to a staff scientist position at Los Alamos National Laboratory (LANL) working in the Sigma Division. At LANL, my work spans the periodic table, from hydrogen to uranium, with particular emphasis on collaborating with the wealth of talent only available at a national laboratory to reveal new understanding in fundamental environmental degradation problems. The diverse programs at LANL allow me to work on a wide variety of topics ranging from projects directly related to revealing the future of our nuclear deterrent, to designing advanced processing strategies for high gradient radio frequency accelerators and research nuclear reactors, to contributing to the further understanding of hydrogen degradation of metals produced via advanced manufacturing tools for energy-critical applications.

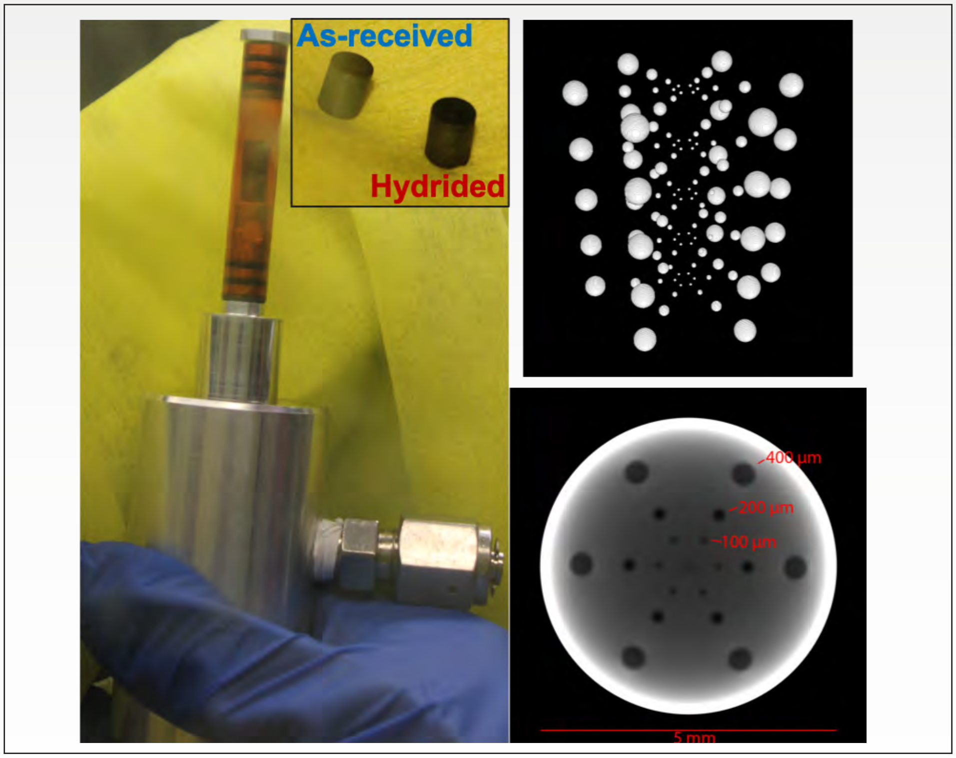



Figure 1. Depleted uranium samples loaded into an experiment vessel in an inert atmosphere glove box (left). Prepared samples shown in inset. Model of uranium hydride inclusions within a 5 mm diameter DU tomographic test object (top right). A slice through the synthetic radiograph obtained with a x7 magnifier produced by forward model simulations labeled with hydride inclusion sizes is shown on the bottom right.

The facility where I work, the Sigma Building, is unique within the NNSA complex. The constant drive of the people in the building is to advance the metallurgical understanding of the processing of materials from the first production steps through in-service performance. Our particular specialty is uranium metallurgy. Just as environmental degradation in extreme operating conditions is problematic for structural metals like steels and superalloys, extended lifecycles in extreme environments for uranium components necessitate the enhanced understanding of material corrosion and aging phenomena. Recently, I have been working with a cross-disciplinary team to develop a new capability to study a long-standing problem: hydride corrosion of uranium. We are attempting to utilize the 800 MeV proton radiography facility at the Los Alamos Neutron Science Center to visualize uranium hydride growth in a small, bulk-like depleted uranium sample in 3D with computed tomography (see Figure 1). Forward model simulations are promising, but only beam time will tell. If successful, this capability will allow us to enter into previously-uncharted regime of 3D-dynamic imaging within dense materials at high resolution.

This year, I was fortunate to take on a new role at LANL, that of a mentor for three students. Mentoring has provided me with the opportunity to help contribute to the next generation in the same way so many of my mentors did for me. This experience also has highlighted one of the strengths of the SSGF program—a strong and encouraging community that cultivates mentorship at all levels. I look forward to maintaining an active role in both the future of LANL and in the growing SSGF community.

## E. Paige Abel, Michigan State University (abelp@nscl.msu.edu)

**Degree in Progress:** PhD, Nuclear Chemistry, Michigan State University, **Advisor:** Dr. Greg Severin
**SSGF Program:** 2017–Present; **Research Topic:** Isotope Harvesting from a Heavy Ion Fragmentation Facility

### Research Responsibilities

Isotope harvesting from accelerator facilities is a promising new method of producing exotic radionuclides for applications from nuclear medicine to stewardship science. Only a fraction of the accelerated beams at these facilities is used for the primary physics experiment, and the remainder is collected in a metal block called a beam stop. At the National Superconducting Cyclotron Laboratory (NSCL), an isotope harvesting system has been built to replace the existing beam stop. This system includes a flowing-water target for the production of rare radionuclides and ion exchange resins for the collection of these radionuclides.

My research has involved experiments that test the durability of this system to withstand the harsh effects of an irradiation. I have been able to harvest and purify $^{47}$Ca for the generation of $^{47}$Sc, a medically interesting radionuclide. I look forward to future experiments in which I hope to generate $^{47}$Sc and use this scandium isotope to radiolabel relevant biological molecules for the treatment of cancer.

### Benefits of the SSGF Program

Being in the SSGF program allowed me to experience work at Lawrence Livermore National Laboratory. At the lab, I was able to apply the skills I've learned in graduate school to stewardship science. This was a new application of radiochemistry for me and, through the practicum, I was able to learn from experts in the field. Even though I've finished the laboratory experience, the collaboration with my mentors continues, as we work on the experimental data we collected while I was at the lab.

Another benefit of the program is the annual review at which fellows get to talk about the research they've done that year, learn about work being done outside of their field, and tour ground-breaking facilities at the national labs. In particular, the friendly environment at these meetings has helped me be more comfortable asking questions and learning about other fields of science.

### What Students Should Know About SSGF

Even if you're not familiar with applications of your field to stewardship science, consider applying for this fellowship. It's been an amazing experience and an opportunity to learn more about this application and the work performed at the national labs. I've learned that working at a national laboratory in the future would be an opportunity to do important work with a great community of scientists.

## Viktor Rozsa, University of Chicago (rozsa@uchicago.edu)

**Degree in Progress:** PhD, Molecular Engineering, University of Chicago, **Advisor:** Dr. Giulia Galli
**SSGF Program:** 2016–Present; **Research Topic:** Aqueous Systems at Extreme Conditions

### Research Responsibilities

I utilize first-principles simulation methods to study molecular properties of aqueous systems at extreme conditions. My research includes both thermodynamic extremes (elevated pressure/temperature) as well as mechanical extremes (nanoconfined liquids). Understanding the physics of water and water/ion mixtures at extreme thermodynamic conditions informs our understanding of the deep water and deep carbon cycles, with application to climate and planetary science. On the other hand, understanding the unique physics of nanoconfined aqueous systems is relevant to technologies ranging from water filtration to supercapacitors. I am broadly interested in understanding how these extreme conditions change the hydrogen bonding of a liquid, and also what is the consequence of those changes.

The simulations that I conduct are based on "first principles" theories, meaning that in principle we are using the most fundamental laws of quantum mechanics to drive the simulations. This gives access to a wide range of crucial quantities that are unavailable or unreliable with simulations based on more assumptions and also often difficult to measure experimentally. These include vibrational spectroscopy such as Raman and IR spectra, dielectric properties, and ionic conductivities.

### Benefits of the SSGF Program

I am indebted to the SSGF for many of the best experiences of my time in graduate school. The community of fellows and alumni are remarkable, both scientifically and personally. SSGF's summer program reviews allow us to tour labs and national security sites of incredible scientific and historical significance. The practicum was a wonderful experience to get a taste for both the type of scientific research happening at national labs and also the style/pace of life there. Finally, the organizational and institutional support in SSGF is top-notch.

### What Students Should Know About SSGF

Given the SSGF's name and funding agency, I had an initial misconception that the fellowship probably exclusively funds people working on the type of nuclear physics closely tied to maintenance of the stockpile. I soon learned that the fellowship supports a much broader scope of both basic and applied research. Stewardship science really isn't a narrow field. Science coming from the broadest definitions of fields including nuclear science, hydrodynamics, high energy density physics, and extreme conditions regularly becomes relevant to NNSA and is thus rightly supported by SSGF. I would encourage anyone whose research fits broadly into those fields of study to apply.

## Heather Nicole Sandefur, University of Illinois at Urbana-Champaign (heather.sandefur@gmail.com)

**Degree in Progress:** PhD, Nuclear Engineering, University of Illinois at Urbana-Champaign, **Advisor:** Dr. Jean Paul Allain
**SSGF Program:** 2016–Present; **Research Topic:** Plasma-Material Interactions

### Research Responsibilities

I perform research in the area of plasma-material interactions for nuclear fusion applications. My research focuses primarily on the surface chemistry of first wall materials in tokamak reactors.

### Benefits of the SSGF Program

I have benefitted tremendously from the SSGF program. It has provided me with a deeper understanding of the stockpile stewardship program and has given me the opportunity to make important professional contacts at leading national laboratories.

### National Laboratory Experience

As part of the SSGF, I was given the opportunity to participate in two separate research practicums at Sandia National Laboratories in Livermore, California in 2017 and 2018. These opportunities have proven to be invaluable to my graduate research and professional development. During my time at Sandia, I worked with the Plasma-Surface Interactions Science Center under the guidance of Dr. Robert Kolasinski. Using a novel, angle-resolved, ion energy spectrometer system, the Center routinely characterizes the structure and surface chemistry of materials for potential applications in hydrogen fuel cell and magnetic fusion technology. Because of the unique research capabilities at Sandia, I was able to perform unique material characterization experiments that would not have been possible at my home institution.

In addition to developing new research skills, my time at Sandia was extremely useful from a networking perspective. I was able to meet new scientists and engineers from NNSA and industry on a daily basis. The staff members were extremely helpful and welcoming, and I have been able to maintain the many contacts that I made during my practicum. This is extremely valuable as I consider my future career. The direct experience at a national laboratory has helped me gain a better understanding of the different career opportunities within the Department of Energy (DOE), and the staff members with whom I have interacted can provide important references if I choose to pursue a career with DOE. The research experience at a national laboratory is attractive to potential employers in industry. After presenting the results of my practicum research at national conferences this year, I was approached directly by several corporate recruiters in both the nuclear and chemical engineering fields. Many private companies that collaborate with national laboratories like Sandia often are excited to see a potential applicant that is familiar with the DOE and the national laboratory system. While I am not yet certain which career route I will take, it is comforting to know that my time at Sandia and in the SSGF has opened up so many potential career opportunities after graduation.

## Daniel Woodbury, University of Maryland, College Park (dwoodbu@umd.edu)

**Degree in Progress:** PhD, Physics, University of Maryland, College Park, **Advisor:** Dr. Howard Milchberg
**SSGF Program:** 2016–Present; **Research Topic:** Intense Laser Matter Interactions

### Research Responsibilities

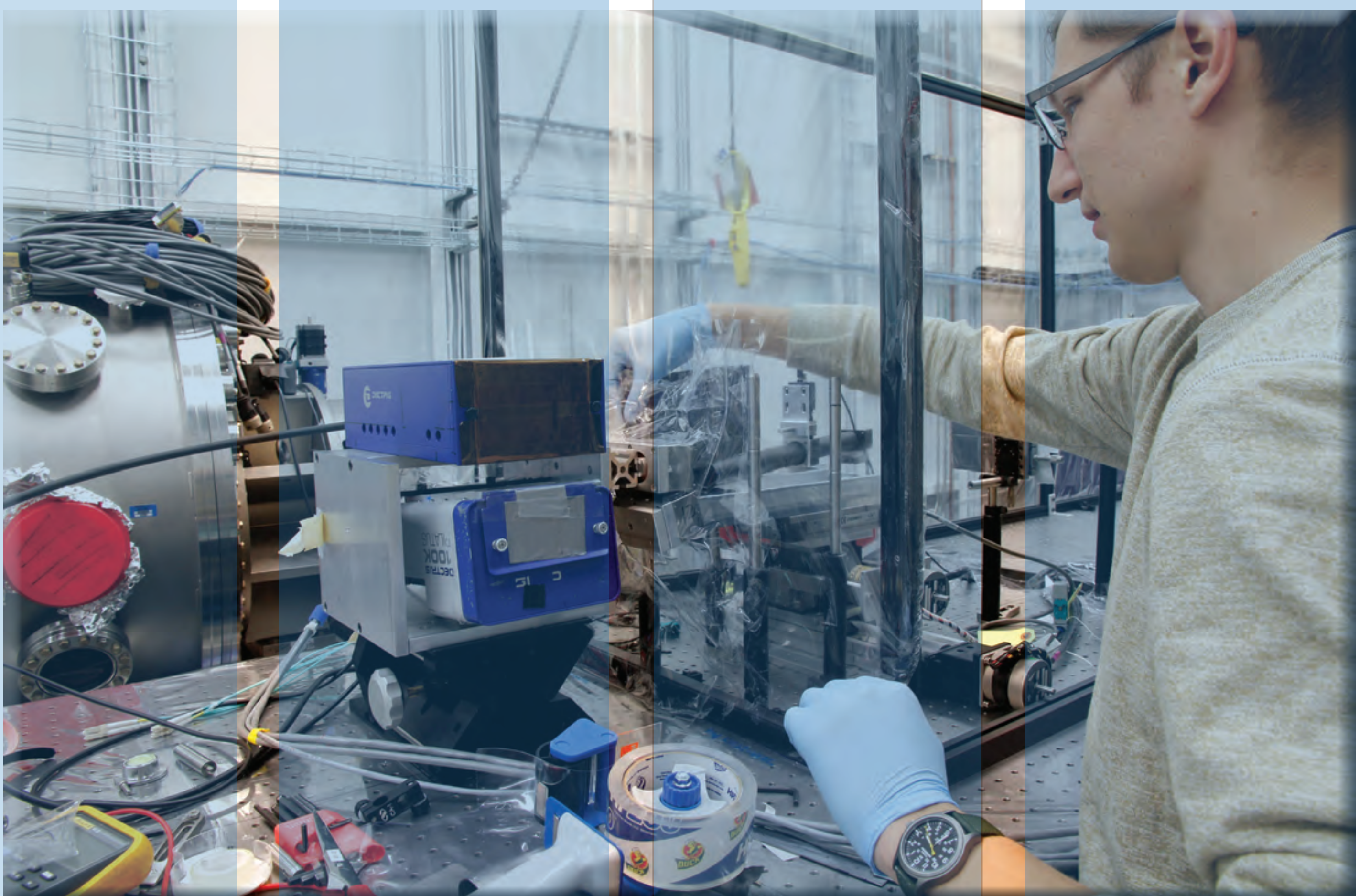
My research focuses on the interaction of short pulses of light with matter. By squeezing moderate amounts of energy into extremely short pulses and focusing them to miniscule spots, the strength of the electric field in the focused laser pulse is comparable to or exceeds the strength of an atomic field. This incredibly strong field leads to non-perturbative or even relativistic effects in its interaction with matter. In my lab, I operate a new, mid-infrared, short-pulse laser, which allows us to test how previously studied effects like strong field ionization, laser plasma electron acceleration, and plasma based THz generation change with the longer laser wavelength. Understanding these fundamental processes could lead to new laser-based radiation monitors and table-top electron accelerators and light sources. I get to work on all aspects of the research, developing new project ideas, building experimental setups, operating and maintaining the laser, and comparing results with relevant theory and simulations.

### Benefits of the SSGF Program

The SSGF program has given me unparalleled opportunities to interact with other scientists outside my subfield and to explore opportunities after graduate school, particularly through the yearly program review and practicum experiences. The network of program participants and alumni has allowed me to connect with researchers working on a variety of topics in academia, NNSA labs, and other government research and policy institutes. Of course the program has many other benefits, such as research allowances and financial support, which have allowed me to pursue different research directions more freely.

### National Laboratory Practicum Experience

Both during the fellowship and before it, I had the opportunity to intern at Sandia National Laboratories, working on different aspects of the Magnetized Liner Inertial Fusion program. Whereas these research opportunities were unrelated to my thesis work, they allowed me to gain valuable new skills, learn about different research topics, and experience research in a large team, collaborative environment. This has helped me to determine what job characteristics I will look for in my future career and to be more aware of opportunities outside of academia. I would highly recommend pursuing similar opportunities to work at the national labs, even outside of the SSGF program, to get this perspective.



# User Facilities

## A New Paradigm for Understanding Materials at Extreme Dynamic Compression

Washington State University ✦ PI: Dr. Y.M. Gupta (ymgupta@wsu.edu)

Understanding the real-time, atomistic-level response of materials under extreme dynamic loading conditions is central to the Stockpile Stewardship Program, to fundamental science frontiers in numerous fields, and to advances in technology. To address this key scientific need, the DOE/NNSA established the Dynamic Compression Sector (DCS), a national user facility located at the Advanced Photon Source (APS), Argonne National Laboratory. The DCS—operated by Washington State University—links state-of-the-art dynamic compression platforms with the bright, high-energy X-ray beam provided by the APS. This first-of-its-kind experimental capability (worldwide) provides real-time, microscopic measurements under high stress impulsive loading. DCS partners include the NNSA laboratories and the Army Research Laboratory. During 2018, the DCS became fully operational, and user experiments, successfully addressing long-standing scientific challenges, were undertaken in all experimental stations[1] (see Figure 1).

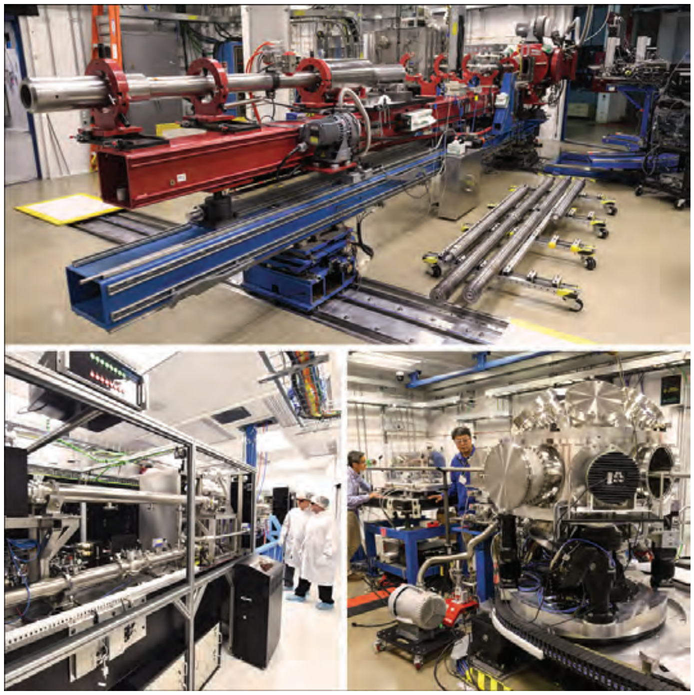


Figure 1. Impact Facility (top) and the Laser Shock Station: 100J laser system (bottom left) and target chamber (bottom right).

### DCS Laser Shock Station

The Laser Shock Station complements the Impact Facilities (plate impact experiments utilizing gas, powder, and 2-stage launchers) and the Special Purpose Station (detonation experiments, Kolsky Bar, etc.) at the DCS. The Laser Shock Station[2] houses a custom-built, 100 J (in the UV) laser system that provides highly reproducible, uniform compression loading (250 µm, 500 µm, and 1,000 µm diameters), pulse shape control, and high throughput (one shot every 30 minutes) and an extremely versatile target chamber to conduct X-ray and laser interferometry measurements. Each laser pulse (5-15 ns) can be synchronized to an individual X-ray pulse to examine structural changes and deformation at high stresses (> 350 GPa) using X-ray diffraction and imaging, and wave profile measurements. Figure 2 shows diffraction data obtained from polycrystalline tantalum (Ta) shocked to 118 GPa and the integrated diffraction data from a series of experiments on Ta shocked between 71 and 326 GPa.[2]

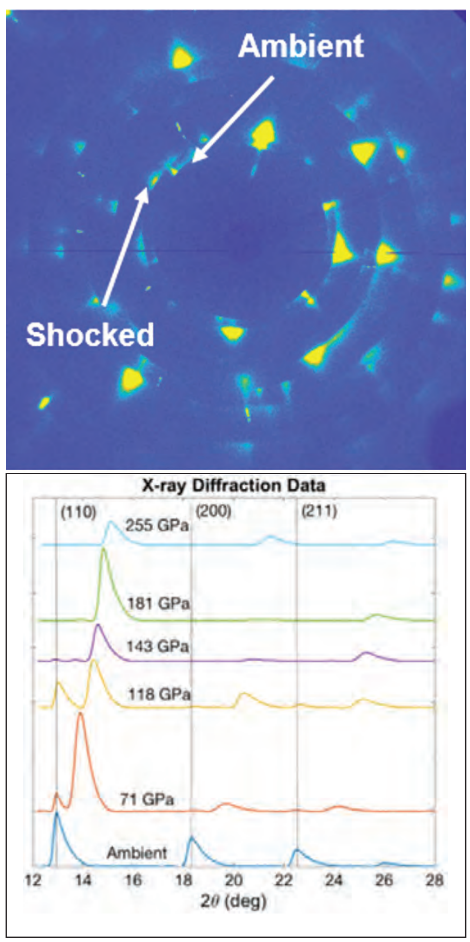



Figure 2. Raw diffraction data of Ta shocked to 118 GPa (top) and integrated diffraction data from a series of shock experiments (bottom).

### APS Upgrade

Between Spring 2022 and Summer 2023, the APS synchrotron will undergo a major upgrade to produce X-rays having higher brilliance and coherence.[3] The separation between X-ray pulses will be reduced from 154 ns to 77 ns to provide improved insight into time-dependent phenomena. The higher brilliance and beam coherence will significantly expand the scientific opportunities by permitting X-ray measurements not currently available. To maximize the benefits of the upgraded X-ray beam, the DCS will undertake complementary upgrade activities to address future scientific challenges and needs and continue as the premier user facility of its kind. The planned activities include the installation of new undulators, advanced X-ray optics, state-of-the-art X-ray diagnostics, and enhancements to the dynamic compression platforms.

### Scientific Highlights (DCS User Experiments)

#### *Shock Compression of Minerals*

Shock compression studies of minerals have broad applications to understanding planetary formation, impact cratering, and the structure of planetary interiors. Many minerals transform to new forms when shock compressed to very high pressures. With the development of the DCS, it is now possible to use X-ray diffraction to determine the atomic level structure that minerals adopt under shock loading. Silica, $SiO_2$, is a major constituent of the Earth's crust and mantle. Shock compression experiments performed on silica at the DCS (see Figure 3) revealed that it transforms to stishovite, a highly dense form of $SiO_2$ that is found at impact craters around the world. These new results by Princeton University scientists not only help constrain the pressures achieved in natural impact events, but they have direct applications to understanding stishovite's role in the

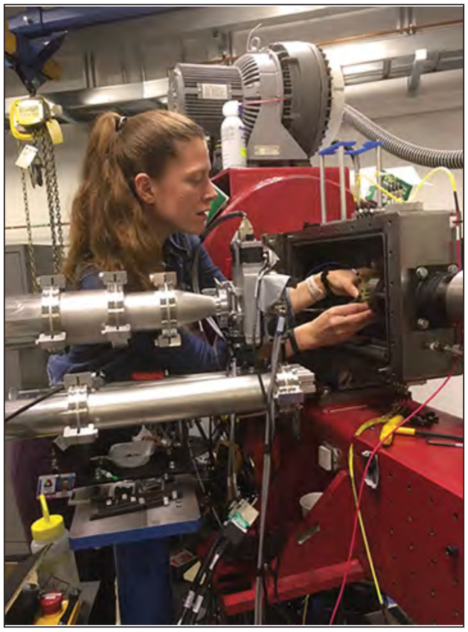


Figure 3. Sally June Tracy (Princeton University) prepares for an experiment to determine the structure of shock-compressed silica.

Earth's lower mantle more than one thousand kilometers below the surface.[4]

### *Dynamic Compression of Metamaterials*

Architected structures are gaining prominence for structural applications with the rapid growth in the additive manufacturing (AM) technologies that can enable such materials. With the expanded design space, such mesoscopic structures occupy the middle ground between granular systems and bulk materials with long-range periodicity and low relative density being the defining characteristics. These attributes enable the strong specific stiffness that have made these structures so attractive. However, studies into the deformation response of such structures (see Figure 4) are limited, particularly under dynamic compression. Utilizing the unique capabilities at the DCS, scientists are directly imaging the deformation response of such long-range periodic structures as the compression wave travels through the lattice structure. These time-resolved measurements are a part of a larger effort at Lawrence Livermore National Laboratory (LLNL) aimed at understanding the high stress, high strain rate response of heterogeneous media.[5,6,7]

### *Tracking the Kinetics of a Shock-Driven Process*

One of the unanswered questions in physics is how much time does a shock-driven phase transition require, i.e., its kinetics? And how does this time influence the end-result of the shock process?

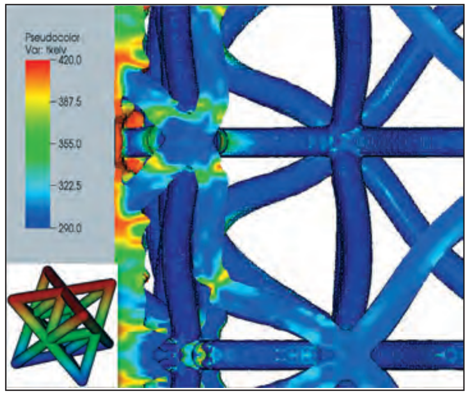


Figure 4. Finite element simulations to match the experimental response show deformation mechanisms (e.g., buckling) and stress distributions in the lattice structure.

Traditionally, phase transitions in dynamic compression are inferred from continuum data and compared to results from static compression experiments, shock-recovery, or calculations. With the combination of time-resolved, synchrotron-based X-ray diffraction and shock compression platforms (see Figure 5), this is the dawning of a new era for the field of shock physics. One now can probe atomic-scale changes *in situ* with nanosecond resolution. Recently, a team of Sandia National Laboratories (SNL) physicists leveraged the DCS capabilities to measure, for the first time, the kinetics of a shock-driven phase transition in a simple ionic solid.[8]

### *Shock Response of Granular Materials Using Advanced X-ray Diagnostics*

Understanding the compaction of granular materials under dynamic loading conditions is complex. New data are required to formulate models inclusive of particle-level physics (deformation, fracture, particle size, distribution, and morphology) that can describe the complicated response of granular systems. Initial experiments using X-ray diffraction and imaging on compressed columns (two dimensional) of aluminum (Al) and $SiO_2$ powder, conducted by Los Alamos National Laboratory scientists and collaborators (SNL and LLNL) show clear melt transition for Al, whereas the more brittle $SiO_2$ exhibits strength effects that are not observed in more traditional one dimensional geometries (i.e., plate impact). The combination of this unique loading geometry and the DCS advanced diagnostic capabilities are providing the data needed for the development and validation of current and next generation modeling capabilities by revealing unprecedented insights into the atomic

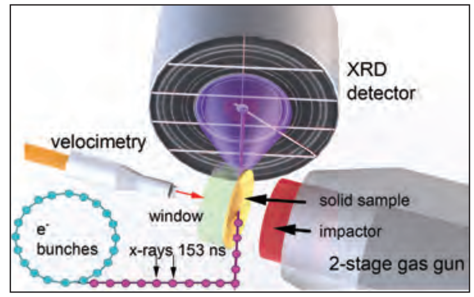



Figure 5. Time-resolved X-ray diffraction configuration.

and mesoscale phenomena responsible for compaction of granular materials under extreme conditions.

### *Structural Transformations during Shock Compression/Release of Germanium*

Washington State University researchers examined solid-solid and solid-liquid transformations in germanium (Ge) using in situ X-ray diffraction measurements during uniaxial strain compression and release. This work showed that shocked Ge transforms to a highly textured β-Sn structure on nanosecond timescales prior to melting under shock compression. A systematic change in the texture of the high-pressure phase was observed as it evolves from a single crystal to a highly textured high-pressure phase to an untextured high pressure phase near the solid-liquid phase boundary. This study demonstrated the first *in-situ* real time observation of the reverse transformation to the crystalline state of a shock melted solid upon unloading while maintaining uniaxial strain in the sample.[9]

### References

[1]These facilities were previously summarized in the 2016 SSAP Annual Report and are described on the DCS web site: https://dcs-aps.wsu.edu/

[2]X. Wang et al., Review of Scientific Instruments 90, 053901, 2019.

[3]https://www.aps.anl.gov/APS-Upgrade

[4]S.J. Tracy et al., Physical Review Letters 120, 135702, 2018.

[5]J. Lind et al., Journal of Materials Research 34, 2, 2019.

[6]H.D. Carlton et al., Acta Materialia 129, 239, 2017.

[7]J. Hawreliak et al., Scientific Reports 6, 28094, 2016.

[8]P.E. Kalita et al., Physical Review Letters 119, 255701, 2017.

[9]P. Renganathan et al., Physical Review B 99, 134101, 2019.

## A Dedicated Facility for Studying Materials at Extreme Pressure and Temperature Conditions

Advanced Photon Source, Argonne National Laboratory ✦ Authors: Nenad Velisavljevic (HPCAT-Director@anl.gov) and Maddury Somayazulu (zulu@anl.gov)

The NNSA-sponsored High Pressure Collaborative Access Team (HPCAT) at sector 16 of the Advanced Photon Source (APS), Argonne National Laboratory (ANL) is a synchrotron X-ray based facility dedicated to experimental research on materials under extreme pressure-temperature (P-T) and strain rate conditions.

HPCAT was established initially with core funding from NNSA in early 2000. More recently in 2018, HPCAT went through a management-operations transition and now is operated in conjunction with Lawrence Livermore National Laboratory (LLNL) and APS-ANL and is fully funded by NNSA. HPCAT is the largest dedicated high-pressure synchrotron facility in the world and is focused on providing cutting edge experimental techniques that serve NNSA laboratories (LLNL/Los Alamos National Laboratory/Sandia National Laboratories), NNSA Stewardship Science Academic Programs (SSAP), and the broader high-pressure scientific community.

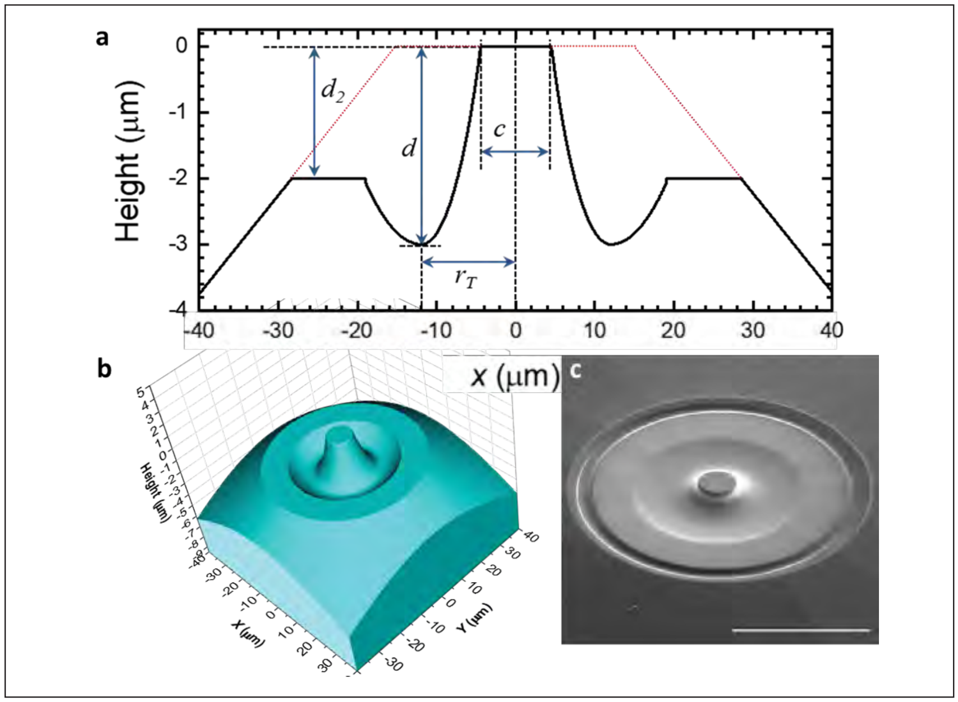



Figure 1. A focused ion beam (FIB) crafted diamond anvil for ultra-high pressure studies: (a) Cross-section of final geometry, (b) 3D model of the anvil, and (c) Scanning electron microscope image of the final anvil with scale bar length equal to 30 μm. A very small μm size X-ray beam from HPCAT was needed to study the sample and demonstrate that pressures over 500 GPa could be generated.[1]

Some key mission goals of HPCAT are: (1) research and development of synchrotron X-ray techniques for application in studying materials under extreme P-T conditions, (2) development of new devices and platforms for generating high P-T conditions, (3) supporting a diverse user community which consists of NNSA laboratories and SSAP (75%) and broader high pressure scientific community (25%), and (4) the training of students and postdoctoral researchers in support of providing next generation workforce at national laboratories.

HPCAT currently consists of four simultaneously operational beamlines. These four beamlines, 16ID-D, 16ID-B, 16BM-D, and 16BM-B, have been developed in order to provide a comprehensive array of experimental platforms that can be used for obtaining critical and fundamental experimental data in support of stewardship science and, more globally, advancing the high pressure scientific field.

An overview of beamlines, techniques, and relevant scientific impact is:

✦ 16ID-D: X-ray Raman spectroscopy, X-ray emission spectroscopy, inelastic X-ray scattering – provides key measurements of bonding and electronic structure for understanding material stability at high pressure-temperature conditions.

✦ 16ID-B and 16BM-D: X-ray diffraction and in situ laser and resistive heating – measurements can be performed over a broad range of pressures (ambient to >500 GPa) and temperatures (~10 K up to +4,000 K) with resulting pressure-volume-temperature data being applied for equation of state models and multiphase P-T phase diagram development, understanding kinetics of phase transitions and structural stability, and determining solid-melt boundary. In addition, X-ray absorption spectroscopy (XANES and XAFS) can be performed in tandem with diffraction in 16BM-D which is a unique capability that helps unravel microscopic mechanism of pressure-induced changes.

✦ 16BM-B: multi-array capabilities, including large volume Paris-Edinburg (PE) press (sample size up to ~1 mm diameter and 1 mm thick disk), and white-beam Laue X-ray microscopy. The PE press, which can generate up to ~8 GPa and ~2,500 K, can be used to obtain in situ viscosity measurements of melts/liquids, longitudinal and shear elastic moduli from a coupled piezo-transducer ultrasonic setup, and relative changes in thermal/electrical conductivity. The

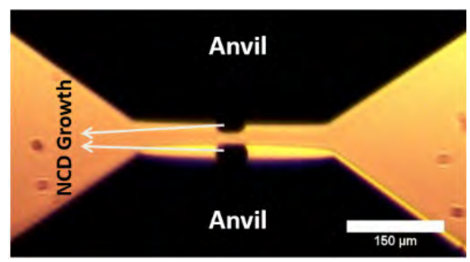



Figure 2. A state of the art Chemical Vapor Deposition (CVD) and maskless lithography setup by Professor Vohra's group at UAB was used to produce micro-anvils grown on single crystal diamond anvils. Multiple experiments were subsequently performed at HPCAT that show significant potential in using these anvils for routine generation of 300+ GPa and ultimately going to tera-pascal type pressures.[2]

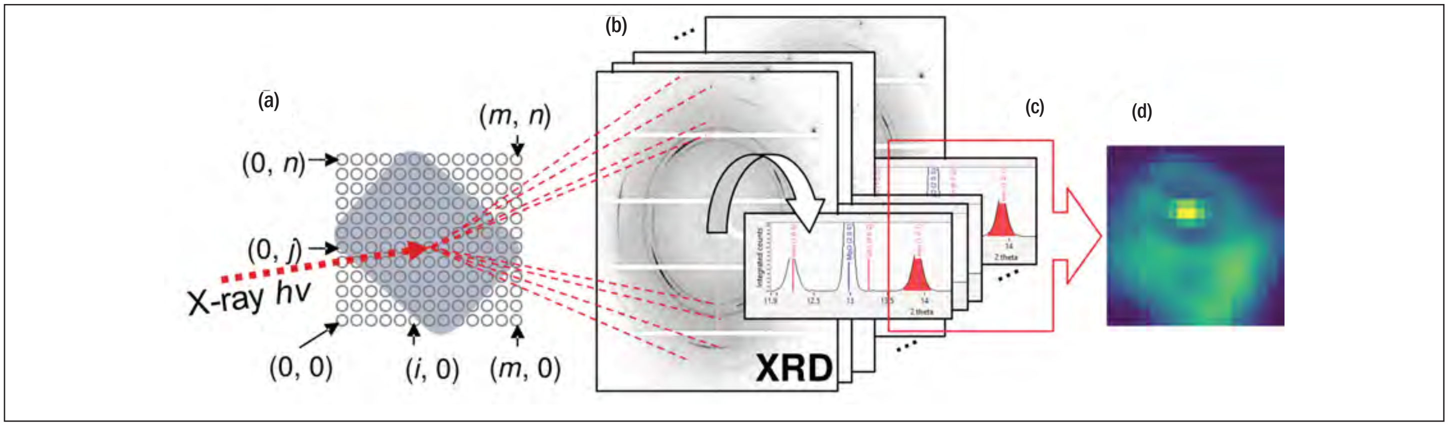



Figure 2. Schematic (a-d) showing the flowchart for high performance X-ray diffraction measurements, analysis, and visualization. (a) Sample can be separated into a systematic grid; (b) multiple X-ray diffraction patterns are collected in a pre-defined grid pattern; (c) raw images are converted into intensity patterns for analysis; and (d) a final diffraction map is reconstructed, which contains information about rheology/phase fraction/etc.[3,4]

Figure 3. Left: HPCAT hosts area students for Science Careers in Search of Women Conference 2019 at Argonne National Laboratory. Right: John Lazarz (former Northwestern University graduate student, now a postdoc at Los Alamos National Laboratory Shock and Detonation Physics Group) is working on a high-pressure, time-resolved X-ray diffraction setup at one of the HPCAT beamlines.

white-beam Laue technique is tailored for measurements with diamond anvil cells (DACs) and provides critical information pertaining to structural deformation and transformation mechanism of materials during high pressure loading/heating.

The details and scope of available techniques are communicated to our users via the HPCAT website https://hpcat.aps.anl.gov/, various workshops, and review meetings. HPCAT staff, which includes 12 beamline scientists, administrative support, and management, work closely with users in planning and coordinating experimental efforts.

HPCAT continuously strives to meet our mission goals. Some of the highlights from HPCAT staff and numerous users (over 600 annual users come to HPCAT consisting of more than 50% students/postdocs) includes:

- Report of near room-temperature superconductivity in lanthanum superhydride at megabar pressures—work done by SSAP partners from Capitol-DOE Alliance Center and HPCAT group leader M. Somayazulu.[5] Somayazulu is featured in the October issue *Scientific American*.
- Push toward terapascal pressures with diamond anvil cell—new diamond anvil design and innovative synthesis techniques by our laboratory and SSAP users are pushing the limits of extreme pressure generation. Recently, Z. Jenei et al. (LLNL) and Y.K. Vohra (UAB), have made significant strides toward generating pressures above 500 GPa (see Figures 1 and 2).
- Next generation experimental and data analysis tools are being developed by HPCAT staff in order to provide advanced measurements at high-pressure—more precise scanning stages, which allow sub-μm resolution in X-ray measurements, are essential for terapascal and other experiments. Concurrently, development of improved data processing and visualization tools are essential for aiding in understanding more complex measurements and handling large data sets (see Figure 3).

## References

[1]Z. Jenei et al., Nature Communications 9, 3563 (2018).

[2]Y.K. Vohra et al., Scientific Reports 8, 1402, (2018).

[3]R. Hrubiak, RSI 90, 025109 (2019).

[4]J. Smith et al., RSI 90, 015116 (2019).

[5]M. Somayazulu et al., Phys. Rev. Lett. 122 (2), 027001 (2019).

# 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
Carolyn Kuranz
*Center for Laboratory Astrophysics: Structure Formation and Energy Transport After the Dark Ages*

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

### Low Energy Nuclear Science

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

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

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*

Ohio University
Carl Brune
*Scattering and Reactions of Light Nuclei*

Ohio University
Zach Meisel
*Statistical Nuclear Physics and (a,n) Reactions for Applications*

Oregon State University
Walter Loveland
*The Energy Release in the Fission of Actinide Nuclei*

Rutgers University
Jolie Cizewski
*Nuclear Reaction Studies with Radioactive Ion Beams for Stewardship Science*

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

University of Kentucky
Michael Kovash
*Prompt Fission Neutrons from Pu-239*

University of New Mexico
Adam Hecht
*New Measurements of Independent Fission Fragment Yields and Energies, and Prompt and Delayed Gammas, for Stockpile Stewardship Data Needs*

University of Tennessee, Knoxville
Robert Gryzwacz
*Beta-Delayed Neutron Spectroscopy of Exotic Nuclei*

### Properties of Materials Under Extreme Conditions

Carnegie Mellon University
Robert Suter
*Towards Optimal Processing of Additive Manufactured Metals for Applications in Extreme Environments*

George Washington University
Stephen Gramsch
*Carnegie/DOE Alliance Center: A Center of Excellence for High Pressure Science and Technology*

Georgia Tech Research Corporation
Devesh Ranjan
*Detailed Measurements of Turbulent Raleigh-Taylor and Richtmyer-Meshkov Mixing at Extreme Conditions*

Harvard University
Stein Jacobsen
*From Z to Planets - Phase III*

Harvard University
Isaac Silvera
*High Pressure Metallic Hydrogen*

Johns Hopkins University
Todd Hufnagel
*Maximizing Reliability and Information Content of Ramp Compression Experiments with In Situ X-ray Characterization*

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)*

University of Alabama at Birmingham
Yogesh Vohra
*Studies on Rare Earth Metals and Alloys under Terapascal Pressures in Support of the Stockpile Stewardship Program*

University of Arizona
Jeffrey Jacobs
*An Experimental Study of Rayleigh-Taylor and Richtmyer-Meshkov Instabilities with Complex Acceleration History*

University of Nevada, Las Vegas
Pamela Burnley
*Deformation of Polycrystalline Materials under Extreme Conditions: Stress Percolation, Shear Localization and Grain Boundary Rheology*

University of Rochester
Ranga Dias
*Tuning of Competing Quantum States under Extreme Conditions*

University of Rochester
Jessica Shang
*X-ray Particle Image Velocimetry for HED Science*

University of South Florida
Ivan Oleynik
*Phase Transitions under Dynamic Compression: Carbon, Silicon, and Germanium*

University of Wisconsin, Madison
Riccardo Bonazza
*New Experimental Approaches to Study Gas Interfaces Accelerated by Shock Waves*

Washington State University
James Hawreliak
*Time-Resolved Lattice Kinetics of Rapidly Compressed Single Crystal Iron through the Alpha to Epsilon Phase Transition*

Washington State University
C.S. Yoo
*Chemistry of Dense Planetary Mixtures at Extreme Conditions*

### Radiochemistry

Michigan State University
Gregory Severin
*Aqueous-Phase Isotope Harvesting to Manufacture Radioactive Targets for Neutron-Reaction Studies*

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

University of Notre Dame
Peter Burns
*Actinide Center of Excellence*

Washington University in St. Louis
Rita Parai
*Seeing Through the Fission: Multi-Modal Analysis of Actinides and Noble Gas Isotopes in Geological Samples*

## User Facilities

Washington State University
Yogendra Gupta
*Dynamic Compression of Materials: Multiscale Measurements and Analysis*

High Pressure Collaborative Access Team
Nenad Velisavijevic, Director (LLNL)
*Argonne National Laboratory*

## 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
Pia Valdivia
*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
*Characterization of the Nonlinear Laser-Plasma Interaction in Electron-Assisted Shock Ignition*

Johns Hopkins University
Pia Valdivia
*Demonstration of Monochromatic Talbot-Lau X-ray Deflectometry (TXD) Electron Density Diagnostic in Laser Target Interactions*

Johns Hopkins University
June Wicks
*High Pressure and Temperature Polymorphism of a Key Super-Earth Mantle Material: MgO*

Massachusetts Institute of Technology
Richard Petrasso
*High-Energy-Density Physics, Laboratory Astrophysics, and Student Training on OMEGA*

University of California, San Diego
Farhat Beg
*Charged Particle Transport and Energy Deposition in Warm Dense Matter with and without an External Magnetic Field*

University of California, San Diego
Christopher McGuffey
*Driving Compressed Magnetic Field to Exceed 10 kT in Cylindrical Implosions on OMEGA*

Rice University
Edison Liang
*Collision of Two Magnetized Jets Created by Hollow Ring Lasers*

University of Chicago
Petros Tzeferacos
*Fundamental Astrophysical Processes in Radiative Supersonic MHD Turbulence*

University of Michigan
Karl Krushelnick
*The Dynamics of Strong Magnetic Fields Generated by Relativistic Laser Plasma Interactions using OMEGA EP*

University of Michigan
Louise Willingale
*Direct Laser Acceleration of Elections for Bright, Directional Radiation Sources*

University of Nevada, Reno
Roberto Mancini
*A Laboratory 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*



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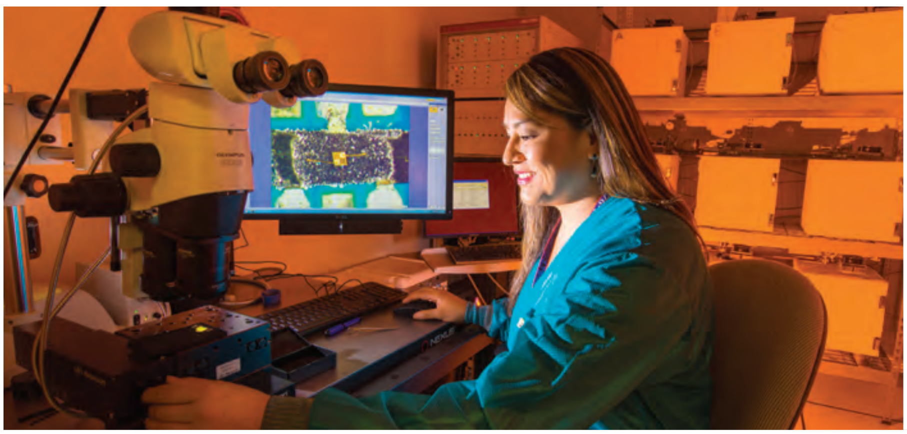
DEPARTMENT OF ENERGY
NATIONAL NUCLEAR SECURITY ADMINISTRATION

# LABORATORY RESIDENCY GRADUATE FELLOWSHIP

## APPLICATIONS DUE 3.4.2020

### BENEFITS

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- 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

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.

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*Top: Sandia's Hermes III, the world's most powerful gamma ray generator, produces a highly energetic beam to test how well electronics can survive radiation bursts similar to those nuclear weapons produce.*

*Bottom: Sandia National Laboratories researchers inspect equipment to probe how long-term aging under varying environments affects the performance of electronics inside nuclear devices.*

## FIELDS OF STUDY

**ENGINEERING & APPLIED SCIENCES**

pulsed power; particle accelerator physics and design; detector and data processing; fluid mechanics

**PHYSICS**

atomic, nuclear and plasma physics; shock physics

**MATERIALS**

additive materials; dynamic materials; energetic materials physics and chemistry

**MATHEMATICS AND COMPUTATIONAL SCIENCE**

multiscale, multiphysics theory and numerical simulation; pic/fluid hybrid simulation

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U.S. DEPARTMENT OF ENERGY

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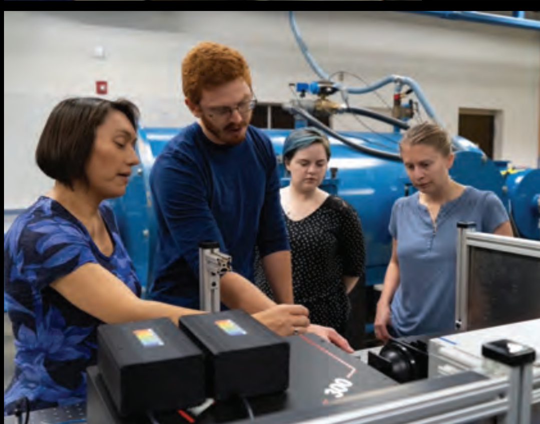
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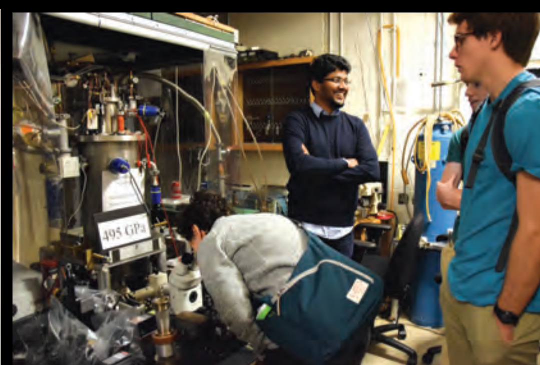
495 GPa




2019