DOE/NA-0016

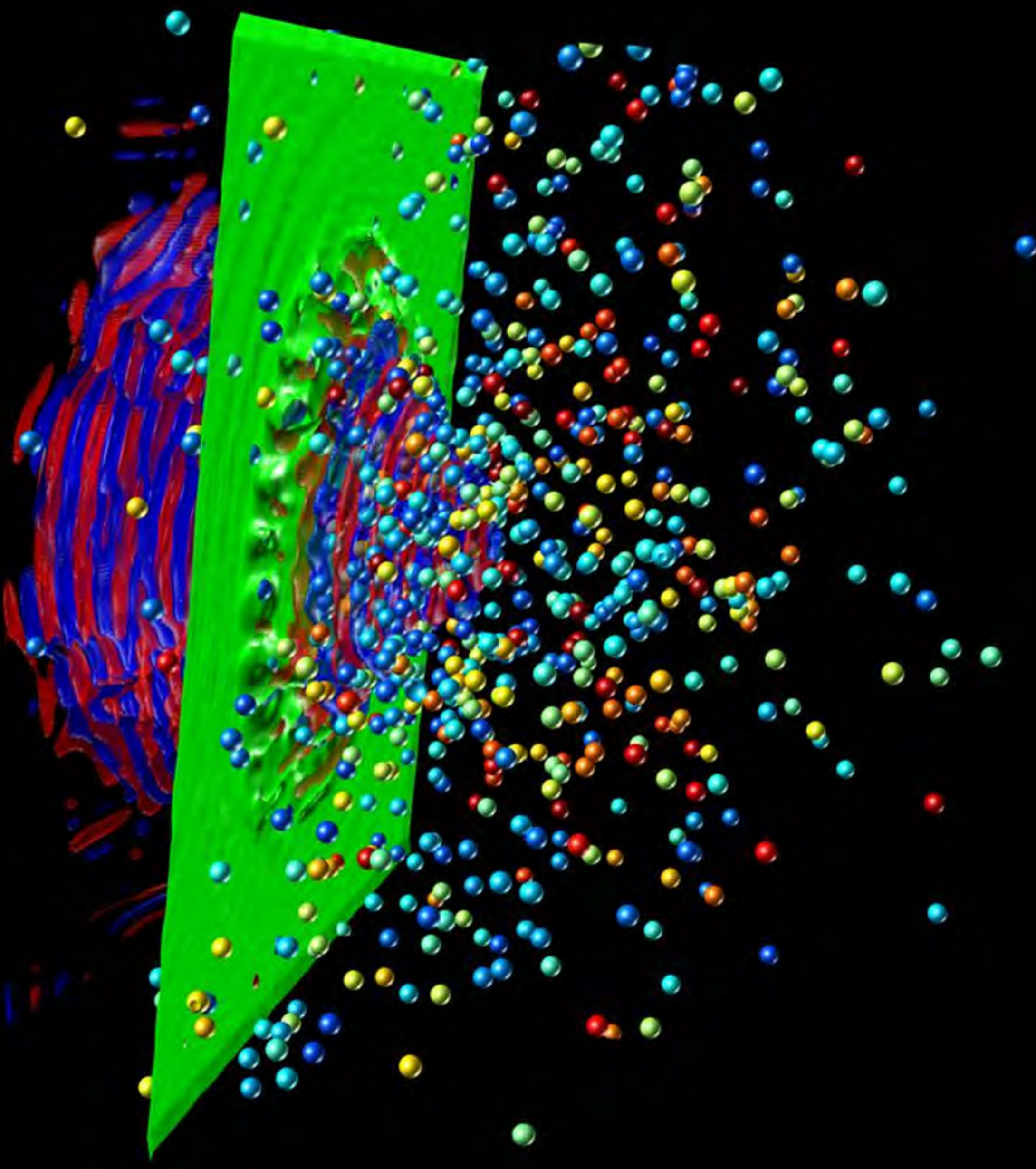
# Stewardship Science Academic Alliances Annual

2011

## Stewardship Science Academic Alliances

## High Energy Density Laboratory Plasmas

## National Laser Users' Facility



Office of Stockpile Stewardship

NNSA

U.S. DEPARTMENT OF ENERGY

## On the cover

Generation of fast electrons (spheres colored to represent different energies) from the irradiation of a fast ignition target at the critical density layer (green) by an ultra-intense laser pulse (red-blue) in a three-dimensional particle-in-cell simulation performed with the computer code, OSIRIS at Argonne National Laboratory's Intrepid.

*Image courtesy of the University of California, Los Angeles*

# Stewardship Science Academic Alliances Annual 2011

**Stewardship Science Academic Alliances**

**High Energy Density Laboratory Plasmas**

**National Laser Users' Facility**

Mission First... Through Teamwork

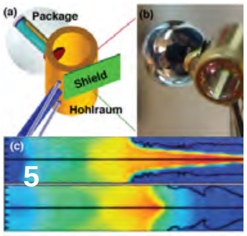
*The future of the NNSA National Security Laboratories, sites and plants has been receiving significant attention recently. As we talk about facility investments, we are well aware that people are our true resource. Their dedication, innovation and creativity make our complex strong and agile, well prepared for the challenges of the 21st Century. NNSA launched academic alliance programs more than 10 years ago, understanding that the pipeline of students with their critical skills was a key element of managing our human capital. These programs have been very successful. These academic programs have truly strengthened our stewardship program and we want to thank you all for your excellent work. Thanks to the Krell Institute, the Oak Ridge Institute for Science and Education, Terri Batuyong, and many others that continue to organize our academic alliances so well.*

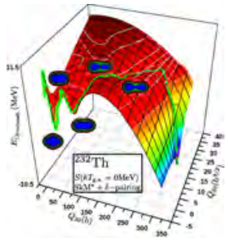
*As the new Assistant Deputy Administrator for Stockpile Stewardship, I reiterate our commitment to maintaining our academic alliances. Already these programs have resulted in many great new staff members being recruited into our laboratory complex. This is wonderful, but our academic programs are a lot more! Any reader of this SSAA Annual 2011 will appreciate the depth and breadth of the research supported by NNSA, and we are extremely proud of the excellence of this work. Students and early career scientists involved in these programs will be encouraged and inspired by the very high quality and pioneering research.*

*Enthusiastic, well-trained, and creative scientists, technologists and engineers are needed in many aspects of our modern society, and employment at our National Security Laboratories provides an ideal place to make a huge impact. Keep up the excellent work and continue to exploit all the new capabilities that we are developing. The best summary comes from Seth Root, an SSAA alumnus who is now employed by Sandia National Laboratories, "The aspect about working at Sandia that I like best is I know my research contributes directly to our national security."*

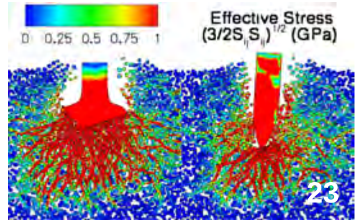
*Dr. Chris Deeney*
*Assistant Deputy Administrator*
*for Stockpile Stewardship*

# CONTENTS



18








## SSAA Annual 2011

### Publication Editors
Millicent Mischo, Terri Batuyong

### Technical Editors
Douglas Drake, Alan Wootton, Mike Kreisler

The *Stewardship Science Academic Alliances Annual* is the yearly publication of the following NNSA-supported research programs: Stewardship Science Academic Alliances, High Energy Density Laboratory Plasmas, and National Laser Users' Facility. For more information, visit the NNSA website: http://nnsa.energy.gov/aboutus/ourprograms/defenseprograms/defensescienceuniversityprograms.

Published February 2011

# Stewardship Science Academic Alliances Program

**Overview**

The National Nuclear Security Administration (NNSA) is intensely committed to supporting research vital to the Stockpile Stewardship Program. NNSA's numerous partnerships, fellowships, and grant programs are the vehicles that are used to this end. The Stewardship Science Academic Alliances (SSAA) programs are among some of the most successful. These programs afford NNSA numerous opportunities to support essential academic research important to our mission to help maintain a safe, secure, and effective stockpile without the production of new fissile material or underground nuclear testing.

The SSAA programs include the SSAA Grants Program, High Energy Density Laboratory Plasmas (HEDLP) Program, and National Laser Users' Facility (NLUF) grants program. These programs share the same primary goals. One goal is to create opportunities for scientists in physics disciplines that are overlooked by other government agencies but very important to the mission of the nation's Nuclear Security Enterprise. Another goal is to offer the highest caliber of education and hands-on training and experience to the next generation of scientists and physicists. Working with the top scientists in their fields at the NNSA National Laboratories and with SSAA academic partners accomplishes this and helps develop an exceptional pool of professionals to catapult us forward technologically and into the future.

The Stewardship Science Graduate Fellowship (SSGF) Program is another SSAA program that furthers these goals. This fellowship program trains scientists to meet U.S. workforce needs in advanced science and engineering by providing excellent financial benefits and professional development to students pursuing a Ph.D. in fields of study that solve complex science and engineering problems critical to stewardship science. The program offers a yearly stipend, paid tuition and fees, a yearly academic allowance, and the opportunity to complete a 12-week practicum at a National Laboratory. This program is expertly administered by the Krell Institute. Visit their website at www.krellinst.org/ssgf for more information.

This *Stewardship Science Academic Alliances Annual* is intended to present the SSAA program alliances and their research to the scientific community, as well as introduce the programs. Each issue of the Annual will feature research highlights from the preceding year from SSAA partners and information from the alumni who have graduated from the SSAA programs and are thriving at the National Laboratories.

This year's Annual provides information about each NNSA Center of Excellence. Three Centers and their research activities are featured; brief summaries are provided for the other six. The Centers of Excellence are committed to the highest level of scientific discovery and to training a high quality workforce to meet the nation's stockpile stewardship needs and requirements.

Selecting the research to present this year proved a difficult task so NNSA academic partners were invited to participate in the SSAA Publication Competition to facilitate the process. The competition brought specific criteria to the selection process, including quality of data, training aspects, presentation of material, writing ability, and visual appeal of the graphics and their relevance to the research. From the overwhelming response, 12 winning submissions were selected, four from each research area. Kudos to the winners for their hard work and extraordinary results!

The impressive research of the winners, along with an overview of the NLUF program research, is introduced in the pages that follow. Question and answer sessions with three alumni from the SSAA programs who now work for National Laboratories provide insights into the importance and value of the SSAA programs and the experience of working for a National Laboratory. They are representative of the more than 75 SSAA program alumni now working for National Laboratories so the future is looking bright, indeed!

**SSAA Grants Program**

Established in 2002, the SSAA Grants Program includes our Centers of Excellence and research grants. The program translates to the key pipeline of students trained in critical skills for employment at National Laboratories. The objectives of the SSAA Program are as follows:

- Support the U.S. scientific community by funding research projects at universities in the areas of fundamental science and technology of relevance to the Stockpile Stewardship Program, with a focus on those areas not supported by other federal agencies, and for which there is a recruiting need within the National Laboratories;
- Provide advanced experimental measurement techniques in the areas of condensed matter physics and materials science, hydrodynamics, fluid dynamics, and low energy nuclear science;
- Provide opportunities for intellectual challenge and collaboration by promoting scientific interactions between the academic community and scientists at the National Laboratories;
- Increase the availability of unique experimental facilities sited at the National Laboratories to the broader academic community, particularly for collaborations in areas of relevance to stockpile stewardship; and
- Develop and maintain a long-term recruiting pipeline to the National Laboratories by increasing the visibility of the NNSA scientific activities to the U.S. faculty and student communities.

Our Centers of Excellence and academic partners compete for the grant opportunities in the NNSA research areas during every solicitation period, resulting in new partnerships each cycle. Some of these partnerships are presented in the pages that follow.

**High Energy Density Laboratory Plasmas Program**

Steady advances in increasing the energy, power, and brightness of lasers and particle beams and advances in pulsed power systems have made possible the exploration of matter at extremely high energy density in the laboratory. In particular, exciting new experimental regimes could be realized by fully exploiting the scientific capabilities of existing and planned Department of Energy (DOE) facilities, as well as the relevant Department of Defense (DoD) and university facilities.

Progress in the exploration of extreme states of matter has also been facilitated by advances in computer simulation and diagnostic techniques. Other countries, e.g., Japan, China and the European Union, also have active programs in high energy density sciences.

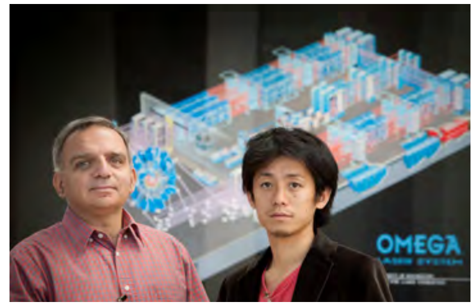
Several recent National Academies of Science reports have described the compelling scientific challenges and opportunities that exist across the field of high energy density physics (HEDP).* An interagency task force report has identified the following four research categories within the field of HEDP as critical: astrophysics, high energy density nuclear physics, high energy density laboratory plasmas (HEDLP), and ultra-fast, ultra-intense laser science. The interagency report found that stewardship of HEDLP should be improved and recommended that the NNSA and DOE's Office of Science establish a joint program in HEDLP. NNSA and the DOE's Office of Science established a joint program in HEDLP in 2008. Initially, this program was a combination of work that was funded as part of the NNSA's SSAA Program in the research area of HEDP and the Office of Science's HEDLP Program and Innovative Confinement Concepts Program. The first solicitation for this new Joint Program in HEDLP was held in 2008. A total of 128 proposals responsive to this solicitation were received, and 23 proposals were chosen for awards for projects ranging from three to five years.

**National Laser Users' Facility Grant Program**

The Laboratory for Laser Energetics (LLE) at the University of Rochester (UR) was established in 1970 to investigate the interaction of high power lasers with matter. It is the home of the Omega Laser Facility that includes OMEGA, a 30 KJ UV 60-beam laser system (at a wavelength of 0.35 μm) and OMEGA EP, a four-beam, high-energy, high-intensity, short-pulse (ps) laser capable of petawatt operation on two of the beamlines.

LLE has provided qualified researchers with a unique environment for experiments in inertial fusion and high-energy-density physics through access to the NLUF. In addition to investigations of inertial fusion physics, approved experiments have been conducted in plasma physics, x-ray laser physics, XUV spectroscopy, and instrumentation development. The NNSA's Office of Stockpile Stewardship funds the operation of NLUF, thus making it possible for researchers to conduct experiments without a direct facility charge. In addition, the NNSA provides research funds directly to users for experiments in inertial fusion and related scientific areas. The primary purpose of the NLUF is to provide NNSA's Inertial Confinement Fusion office facility time for university-led, high-energy-density experiments. The NLUF program is discussed on pages 28-30.

**Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (2003), *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science* (2003), *and Plasma Science: Advancing Knowledge in the National Interest* (2007), National Research Council of the National Academies, The National Academies Press.




Roberto Mancini and Taisuke Nagayama standing in front of a schematic of the OMEGA laser bay. Taisuke's Ph.D. dissertation extracted the 3-D spatial structure of OMEGA ICF implosions cores from data analysis using spectral (polychromatic) tomography.

### Awards and Honors

The faculty and students from the NNSA's Centers of Excellence and academic partners are leaders in their disciplines and fields of research and are frequently honored for their work and contributions. A few of their awards and honors follow.

- Carnegie-DOE Alliance Center (CDAC) Director Russell Hemley is the most recent recipient of the Bridgman Award (2009) from the International Society for the Advancement of High Pressure Science and Technology.
- Steven Jacobsen, CDAC Academic Partner from Northwestern, was awarded a David and Lucille Packard Fellowship for Science and Engineering, Presidential Early Career Award for Science and Engineering, and a National Science Foundation Faculty Early Career Development Award. He was also named a Distinguished Lecturer by the Mineralogical Society of America.
- At ICOPS-2010, two of the three student awards were given to young researchers supported by the Cornell University's Center for the Study of Pulsed-Power-Driven High-Energy-Density Plasmas. The IEEE Nuclear and Plasma Society Early Achievement Award went to E. Stambulchik, working at the Weizmann Institute of Science (Israel) under the supervision of Prof. Y. Maron. One of the two awards for the Best Student Presentation went to A. Gorenstein, undergraduate student at Cornell, for the poster presentation *Interactions Between Two Plasma Bubbles in Radial Foil Configurations*.
- Dr. Henry Kaptey and Dr. Margaret Murnane, University of Colorado, received the Arthur Schwalow Prize of the American Physical Society, 2010.
- Dr. Brian Maple, University of California, San Diego, received a Science Lectureship Award, Chiba University, Tokyo, Japan, 2010.
- Dr. Gary Mitchell, North Carolina State University, won the Division of Nuclear Physics Mentoring Award, 2010.
- Dr. N.D. Ouart, former UNR student, received an NRC Postdoctoral Research Associateship at the Naval Research Laboratory in Washington, D.C., 2010.
- Dr. Alla Safronova, UNR, received the Hyung K. Shin Award for Excellence in Research, College of Science, May 2010.

# High Energy Density Research with Connections to Astrophysics
## Center for Laser Experimental Astrophysics Research, University of Michigan

**Program Overview**
The Center for Laser Experimental Astrophysics Research (CLEAR) is focused primarily on two of the five fundamental questions of high energy density physics, as identified by the recent NNSA/Office of Science research needs workshop focused on High Energy Density Laboratory Plasmas. These questions are:

*How does the exotic behavior of dense collections of electrons, ions and photons arise?*

*What can we learn about the cosmos by creating cosmic conditions in the laboratory?*

CLEAR explores these questions by conducting research primarily in hydrodynamics and radiation hydrodynamics, sometimes taking other directions in response to the needs of the students and novel opportunities. Indeed, the primary focus of CLEAR is on training doctoral students and is graduating one Ph.D. per year on average. Their primary experimental facility is Omega at the Laboratory for Laser Energetics (University of Rochester), which is accessed through the National Laser Users' Facility program. In addition, students have recently been involved in experiments on Trident at the Los Alamos National Laboratory, on HERCULES at the University of Michigan (UM), on NIKE at the Naval Research Laboratory, and on the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL). Students benefit strongly from collaborations with scientists at each of these laboratories. The CLEAR is also fortunate to be able to coordinate its research with that of the Center for Radiative Shock Hydrodynamics (CRASH), supported by the NNSA Office of Advanced Simulation and Commuting. This enables CLEAR to also train students in predictive science, simulation, design, and algorithm development. Results of some of the CLEAR projects are highlighted below and to the right.

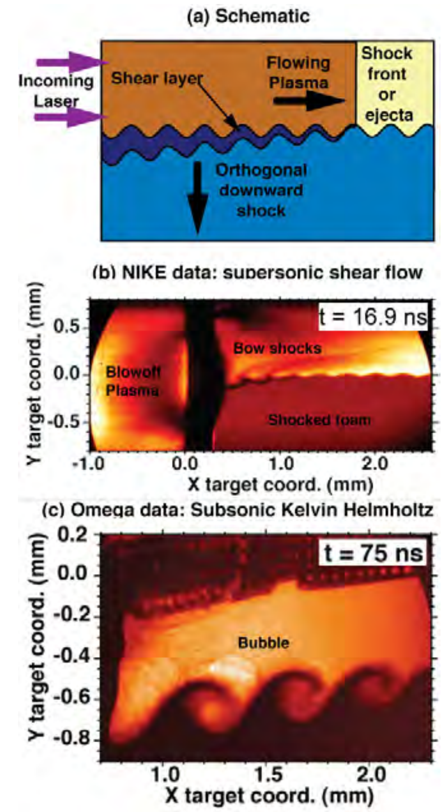
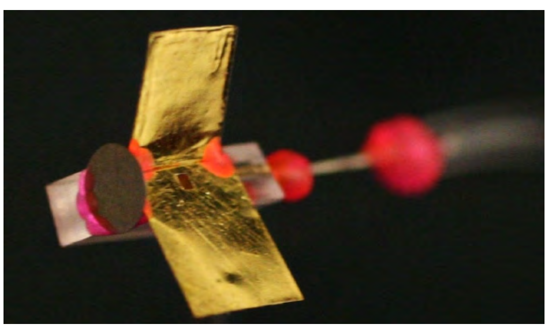



Figure 1. Shear flow experiments: (a) The essential scheme. (b) Radiograph from a NIKE experiment in which laser beams from the left drove a supersonic Al flow above a rippled surface of carbon foam. (c) Radiograph from an Omega experiment in which a blast wave in carbon foam moved from left to right across a rippled plastic surface.



*A target built at UM to measure x-rays scattered from a radiative shock wave in xenon gas.*

**Shear Flow Experiments**
Some recent experiments have explored how structure develops in shear flow at high energy density. Figure 1a shows the essential approach. A high-pressure flow across a structured interface with a second material is created. The high pressure in the flow drives a shock wave down into the second material, so that one ends up with shear across a structured interface between two fluids. Former UM graduate student Eric Harding (see Figure 2) devised experiments in which the flow was supersonic, with results shown in Figure 1b. The interaction of the flow with ripples on the interface produced bow shocks in the flow. Eric then led experiments at Omega, designed by Omar Hurricane of LLNL, which drove a blast wave across an interface to produce shear flow that was mostly subsonic. This produced classic Kelvin-Helmholtz rollups, as shown in Figure 1c, but also created some intriguing bubbles in the upper plasma that have not yet been explained.

The experiment just described is focused primarily on fundamental high energy density physics, and on the first of the two questions listed above. Even so, shear flows are present across the cosmos; these experiments will produce understanding relevant to many contexts and also will serve to provide validation data for astrophysical codes. A second experiment that is just beginning is more directly motivated by the second of the above questions and is described next.

**Radiative Reverse Shock Experiments**
In some Cataclysmic Binary star systems, matter from a donor star falls onto the accretion disk surrounding a white dwarf. The collision of the infalling flow with the accretion disk produces a reverse shock in the flow. The shock heating is strong enough that a large fraction of the incoming energy is radiated away. The emission from this radiative shock produces a bright "hot spot" in these systems, often observed. Researchers have begun an experiment developed by graduate student Christine Krauland (see Figure 3) to study the essential physics present in such systems.

The lasers strike the target shown in Figure 4a from the left, creating pressure

Figure 2. Dr. Eric Harding defended his doctoral thesis in 2010 and now works at Sandia National Laboratories.

Figure 3. Graduate student Christine Krauland.

by ablation of plastic that shocks and accelerates a thin, tin layer. The tin accelerates down the evacuated tube by expansion cooling, reaching velocities well above 100 km/s. The impact of the flowing tin on the Al end wall causes a reverse shock to form, and heats the tin sufficiently that this shock becomes radiative. In later experiments, the Al will be replaced by a tilted, flowing plasma as a surrogate for the accretion disk in the binary. Figure 4b shows a log density plot of the right end of the tube, from a two-dimensional CRASH simulation used to refine the design. One can see the thin layer of dense tin, which is radiating strongly. Figure 4c shows data from optical pyrometry. One can see the incoming plasma flow, arriving from the left at the bottom, the collision in the middle, and at the top the hot, shocked plasma flowing away from the initial Al surface.

**Radiation Hydrodynamic Instability Experiments on NIF**

The research conducted on NIF takes advantage of the early demonstration of high-temperature hohlraums by the NIF facility to do an experiment that unifies the two primary lines of inquiry. In previous experiments on Omega, the Rayleigh-Taylor instability at decelerating interfaces and radiative shocks driven into xenon or argon gasses has been explored. In the Omega Rayleigh-Taylor experiment, shock waves were driven from plastic into low-density foam while the instability produced structure on the decelerating interface between them. This experiment was well scaled to the dynamics occurring at interfaces in some supernovae. In the NIF experiment, the high-temperature hohlraum drives a faster shock wave so that the shock

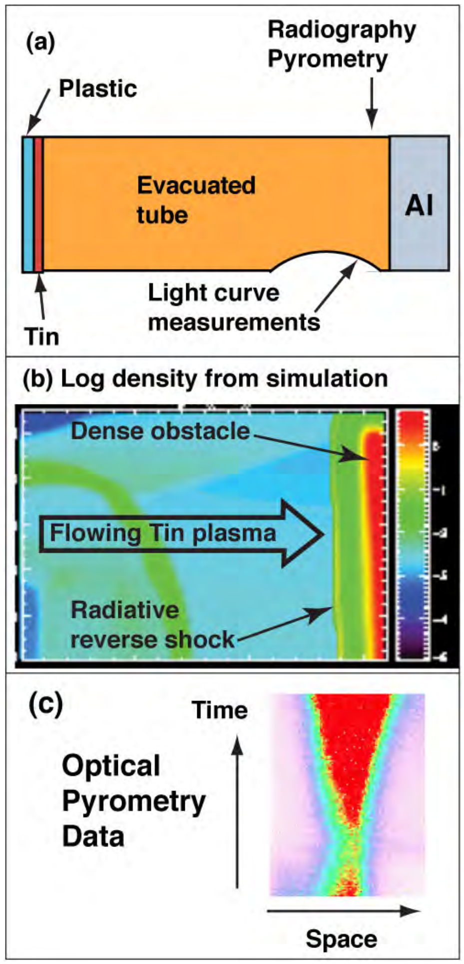



Figure 4. Reverse radiative shock experiment: (a) Sketch of target geometry. Lasers are incident from left. (b) CRASH simulation of collision region near right edge of target, by Mike Grosskopf. (c) Optical pyrometry data.

in the foam becomes radiative, and the radiation in turn affects the structure developing at the interface. Similar dynamics occur in very young supernova remnants after the explosion of red supergiant stars, in which radiation from shocks can alter the hydrodynamic evolution.

Figure 5 illustrates an experiment that is led by Dr. Carolyn Kuranz of UM (see Figure 6) and by LLNL liaison scientist Dr. Hye-Sook Park. In the experiment, about 600 kJ of laser energy will enter the hohlraum, producing a thermal environment near 3 million degrees. A shield on the hohlraum will protect diagnostics from the hard x-rays it produces. The package on the hohlraum is similar to that used in the previous UM supernova instability experiments mentioned above. The x-rays create pressure by ablation of a plastic surface, driving a shock wave through plastic and into lower-density foam. The shock

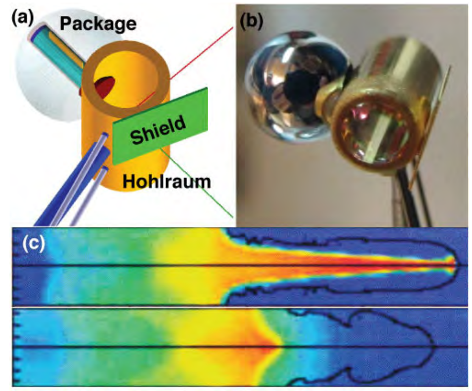



Figure 5. Radiation Hydrodynamic Instability experiments at NIF: (a) Sketch of experiment. The package contains a structured interface between plastic and foam. (b) Experimental target. The Hohlraum is gas-filled and an aluminized sphere surrounds the package to deflect unwanted laser light. (c) Log density plots from simulations by Aaron Miles of LLNL. The images show the structure produced when the shock in the foam is not radiative (upper) or radiative (lower).

Figure 6. Dr. Carolyn Kuranz leads our experiments on NIF.

wave becomes radiative in the foam. Researchers anticipate comparing conditions that would produce the same results in the absence of radiation. As Figure 5c shows, the results predicted by simulations are very different between the case in which the shock in the foam is not radiative and the case in which the shock is radiative. To date, successful shots to test the diagnostic approach and the hohlraum performance have been performed; shots intended to produce physics results during FY 2012 are planned.

For more information, contact:

Paul Drake
rpdrake@umich.edu

# Exploring Matter Under Extreme Conditions Using Pulsed Power Machines

## Laboratory of Plasma Studies, Cornell University

Cornell University's Center for the Study of Pulsed-Power-Driven High-Energy-Density Plasmas investigates the dynamics and physical properties of high energy density (HED) plasmas produced by 0.5-1.5 MA pulsed power generators. Cornell graduate and undergraduate students, faculty and staff are focused on studying the fundamental properties and potential applications of HED plasmas with densities up to $10^{22}/cm^3$ and temperatures up to 2,000,000 K produced from exploding fine metal wires and thin metal foils in various configurations. In addition, we carry out computer simulation studies and detailed atomic physics calculations to help understand the experiments and to predict interesting configurations to test. We also develop new diagnostics to determine such plasma properties as ionization state, density and embedded magnetic field, all as functions of position and time.

Graduate students Cad Hoyt (left) and Adam Cahill (right) prepare for an experiment on the 0.5 MA XP machine.

### Highlights

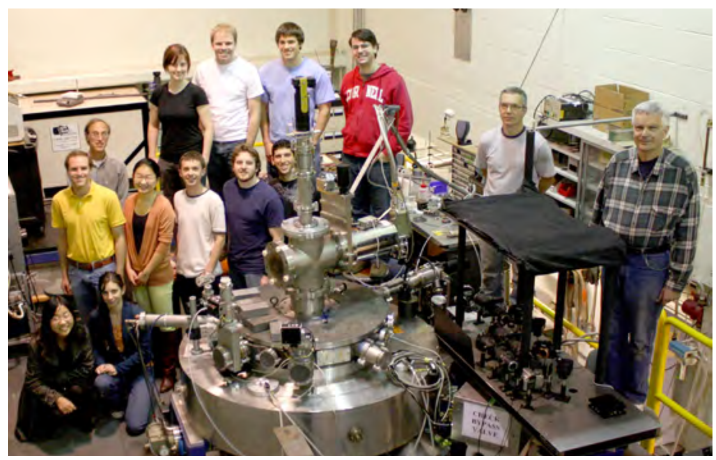
Wire array z-pinch physics is one area of focus in the Center. For example, we have shown that wire-array z-pinch experiments, including those performed on Z at 20 MA, proceed via four phases: 1) plasma initiation by current driven wire explosion, 2) ablation from stationary dense wire cores and redistribution of the array mass by global-field-driven flow of the ablation plasma, 3) snowplow-like implosion of the redistributed mass, and 4) stagnation of the imploding plasma on axis, at which time an intense x-ray pulse is generated. Center members now study the physics of plasma formation and implosion processes in detail and use wire array plasmas for HED physics studies and diagnostic development projects.

Among recent Center research projects are investigations of the dynamics and physical properties of plasmas generated by 1 MA current pulses in very thin aluminum (Al) foils in radial geometry – the current flows radially inward through the foil from a 2-3 cm radius circular electrode to a 1 mm (typical) radius metal pin at the center. Magnetic bubbles and plasma jets are formed as the foil explodes and forms plasma that is accelerated by the magnetic forces. Externally applied magnetic fields are included in some experiments to vary the magnetic configuration.

Z-pinch experiments with thin-walled copper cylinders are also in progress. X-pinch x-ray backlighting along the axis enables imaging of the plasma ablated from the inside copper surface.

Among the highlights of recent work in the Center are the following:

- Instability growth on exploding Al wires – The "fundamental mode" of a wire-array z-pinch is the end state of an instability that ceases growing due to a change in the magnetic topology.
- Cylindrical foil implosions – Very thin (3-10 μm) foils imploded by 1 MA current show ablation of material from the inner surface and piling up of material on axis long before the foil begins to move.
- Twisted wires – Experiments suggest that replacing single wires with twisted pairs or triples in wire array z-pinches produces higher x-ray yield than a conventional wire array z-pinch.



Center students and technical support staff on the 1 MA COBRA generator diagnostic platform.

- Radial Foils – Plasma focus-like implosions and plasma jets produced by radial foils appear to be useful for laboratory plasma astrophysics experiments.
- Extended magnetohydrodynamic (MHD) computer simulations – Some of the limitations of MHD computer codes have been addressed by development of an "extended MHD" code that includes a more complete Generalized Ohm's Law.
- X-ray absorption spectroscopy – Absorption of continuum radiation from a <100 ps x-pinch x-ray burst by the plasma between closely spaced exploding Al wires yields the ionization state of the plasma with submillimeter spatial resolution.

For more information, contact:

Bruce R. Kusse
brk2@cornell.edu

David A. Hammer
dah5@cornell.edu

# Proton Radiography of Electromagnetic Fields and Plasma Flows in Laser-Produced, High Energy Density Plasmas

Massachusetts Institute of Technology

To quantitatively probe laser-plasma interactions, and particularly resultant electric (*E*) and magnetic (*B*) fields, MIT has developed imaging technologies that combine a monoenergetic-particle backlighter with a matched detection system in which the backlighting protons are fusion products (14.7-MeV $D^3He$ and 3-MeV deuterium-deuterium protons) that are generated from an implosion of a thin-glass capsule filled with $D^3He$ gas. This initiative is motivated by the observation that the universe and many laboratory plasmas are embedded with spontaneously-generated fields which can strongly impact dynamics. Understanding and quantitatively characterizing the generation, evolution, and effects of such fields on inertial confinement fusion implosions and basic plasma dynamics in the high energy density (HED) regime is, therefore, of both fundamental and programmatic interest. With colleagues from the Laboratory for Laser Energetics (University of Rochester), Lawrence Livermore National Laboratory, and General Atomics, recent experiments at the Omega Laser Facility have resulted in publications (including two in *Science* and eight in *Physical Review Letters*) that have advanced our knowledge and understanding of these phenomena.

Figure 1 shows the first charged-particle radiographs of x-ray-driven implosions in gold (Au) hohlraums, made with 15-MeV $D^3He$ protons. Such images have allowed a number of important phenomena to be observed and quantitative characterization of critical aspects of indirect-drive inertial fusion to be made.

In addition, we recently demonstrated how monoenergetic proton radiography can be used in combination with Lorentz force mapping *[F = q(E + v x B/c]* for precise measurement of plasma field strengths as well as unequivocal discrimination between electric and magnetic fields. The experimental setup is illustrated in Figure 2. A pulse of 15-MeV protons from the backlighter was used to image two identical, expanding plasma bubbles, formed on opposite sides of a 5-µm-thick plastic (CH) foil by two 1-ns-long laser interaction beams; they were fired simultaneously and incident at 23.5º from the normal to the foil. To break the nearly-isotropic proton fluence into “beamlets” (~1000 protons each) whose deflections could easily be observed and quantified, 150-µm-period nickel meshes were placed on opposite sides of the foil.

Figure 2(b) is the resulting radiograph, with laser timing adjusted so the bubbles were recorded 1.36 ns after the onset of the interaction beams.

For more information, contact:

Richard D. Petrasso
petrasso@psfc.mit.edu

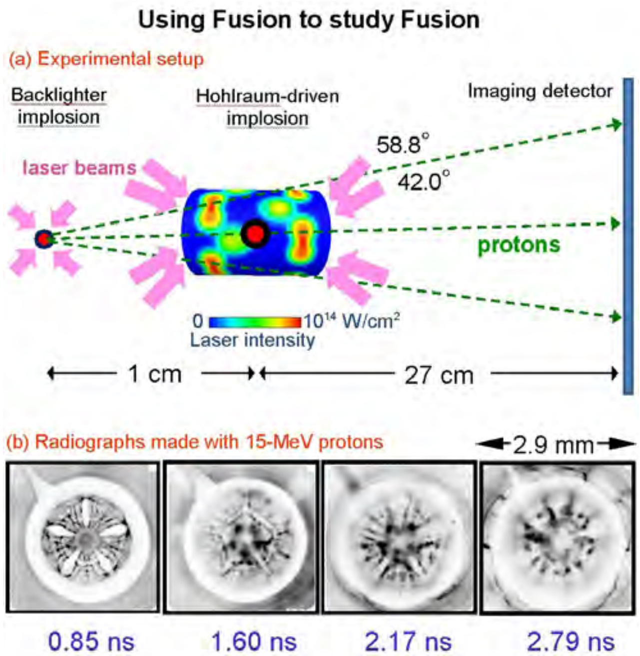



Figure 1. Fusion is used to study fusion with this monoenergetic-proton radiography setup that produces images of imploding capsules in laser-driven hohlraums, as described in *Science*, Vol. 327, page 1231 (2010). Imaging protons come from fusion reactions in a laser-imploded, $D^3He$-filled capsule with glass wall, and the imaging detector is a CR-39 nuclear track detector. Fifteen laser beams entered each end of the hohlraum at two different angles from the hohlraum axis. The colors shown on the hohlraum wall indicate the predicted laser intensity distribution. The 15-MeV backlighting protons passed through the laser-driven hohlraum, sampling plasma conditions and capsule implosions at different times. In the radiographs, the capsule is in the center, the gold hohlraum is the light-colored outer ring, and the patterns between capsule and hohlraum are due to electromagnetic fields and plasma jets. The capsule-mounting stalk is in the upper left.

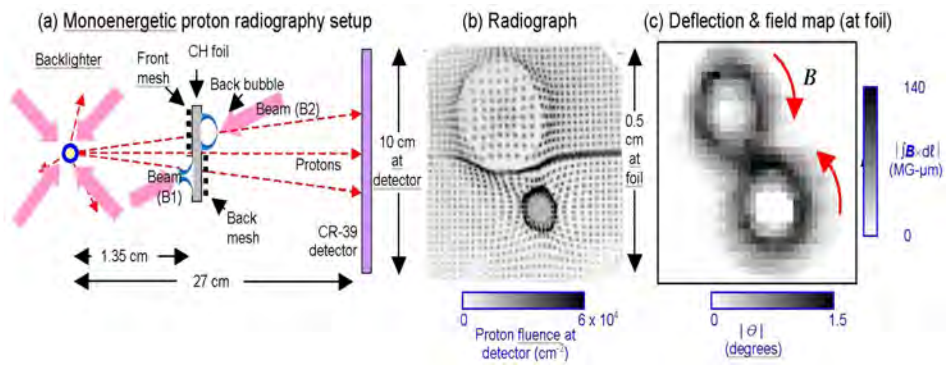



Figure 2. Proton radiography setup (a) and radiograph (b) that demonstrated identification of the type and magnitude of fields generated in laser-plasma interactions, as described in *Phy. Rev. Lett.*, Vol. 103, page 085001 (2009). Two laser-generated plasma bubbles resulted in image (b), from which a spatial map of proton beamlet deflection angle as a function of position on the foil was made (c). Mathematical analysis shows that the proton deflections are associated exclusively with a *B* field near the foil, and this means that (c) can also be viewed as a magnetic field map. Part (c) shows that the two bubbles were actually the same size even though the apparent sizes are different in the radiograph. The orientation of the images is as seen from behind the detector, looking toward the backlighter.

# Nevada Terawatt Facility/High Energy Density Physics

## University of Nevada, Reno

In recent work at the Nevada Terawatt Facility (NTF), we have continued to focus on high energy density physics and on providing a diverse array of experiments which emulate astrophysical plasmas. The NTF currently consists of a 1 MA, 2 TW z-pinch, achieving 350 shots a year, and a 50 TW, 350 fs, one micron glass laser. Experiments are undertaken in three ways: z-pinch only, z-pinch coupled with laser and laser only. Our facility generates terawatt x-ray bursts, megagauss magnetic fields, and investigates magnetized laser plasmas, including astrophysical-like plasmas. Plasma diagnostics include a multiframe laser probing, optical and x-ray imaging, particle diagnostics, and x-ray spectroscopy. Wire array pinch experiments show significant structure due to the magnetic Rayleigh-Taylor instability. Both laboratory and astrophysical plasmas interacting with magnetic fields are subject to magnetic Rayleigh-Taylor instabilities. These are modeled with nonlinear hydrodynamic modeling capable of describing a wide range of instabilities in high beta plasmas on scales of an ion Larmor radius.

Several exciting new developments have come to fruition during the last year at the NTF. First and foremost, NTF is now routinely conducting experiments that synchronize the 2 TW Zebra z-pinch with the 50 TW Leopard laser. These efforts have created novel opportunities to characterize z-pinch plasmas with laser produced x-ray backlighters and include successful absorption spectroscopy campaigns led experimentally by Vladimir Ivanov and his students with theoretical support provided by Jerry Chittenden (Imperial College) and Roberto Mancini (UNR). Simon Bott, Mingsheng Wei and Farhat Beg (University of California San Diego) also demonstrated ~6 MeV proton production in the Zebra chamber using short Leopard laser pulses (t = 350 fs) focused on thin metallic targets. Follow-on experiments will use proton deflectometry to probe z-pinch plasmas. Magnetic field structure in such exploding wire experiments is complex and difficult to measure with conventional methods. Proton deflectometry has the potential to recover details of the B-field vital to the accurate interpretation and benchmarking of magnetohydrodynamic codes. The deflectometry work will also utilize both Leopard and Zebra, and will be the first application of the technology to pulsed power experiments. Initial experiments have demonstrated focused laser intensities of 5 x $10^{19}$ W/cm$^2$ and proton spectra up to 8 MeV. The proton beam showed good reproducibility and low divergence.

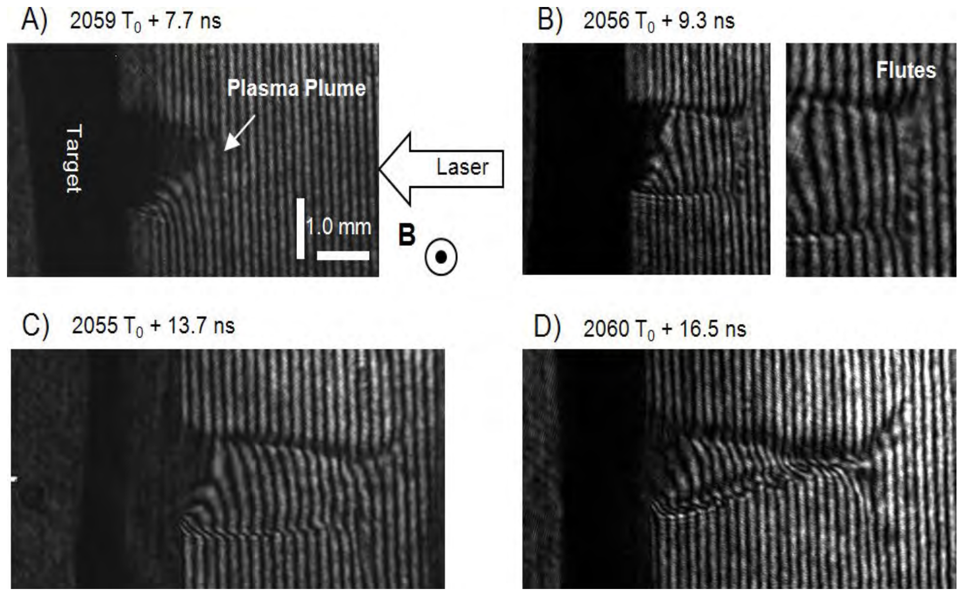



Figure 1. In these interferograms of a laser produced plasma plume entering a z-pinch produced magnetic field, the target is on the left, the electrode is on the right, and the magnetic field points out of the page. In part B) above, a magnified image of the periodic structure is shown.

Working under the guidance of Radu Presura, Chris Plechaty's dissertation research used coupled campaigns to explore the interaction of laser-produced plasma plumes with z-pinch produced magnetic fields (see Figure 1). Other campaigns were also carried out that used Zebra or Leopard alone and addressed a variety of plasma phenomena. These include studies of implosion dynamics, radiative properties of materials and instability seeding, evolution and mitigation. These experimental and modeling efforts are of fundamental interest to the HED plasma physics and astrophysics communities alike.

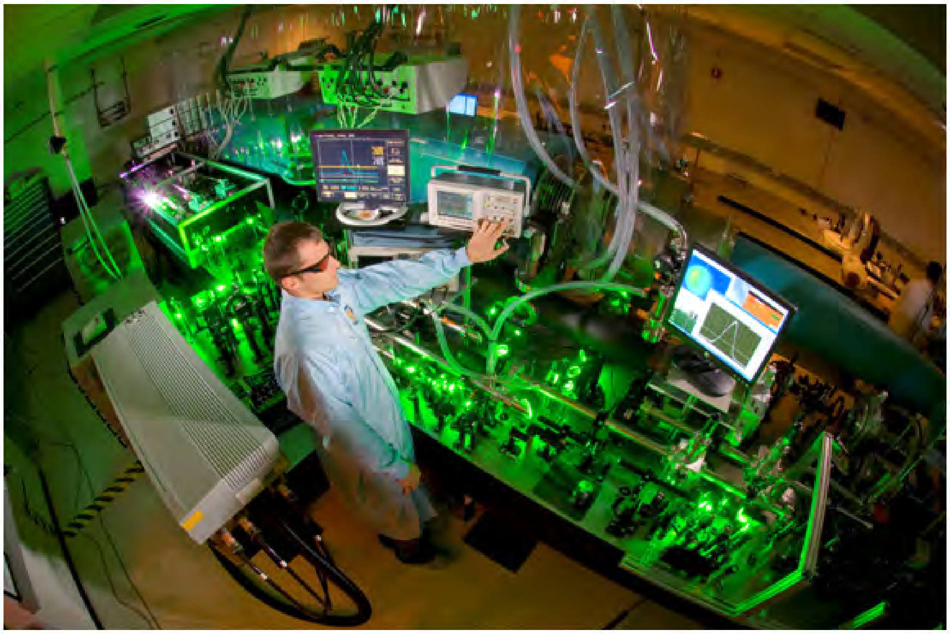
Other improvements to NTF capabilities include the successful implementation of two more generations of the Load Current Multiplier (LCM) on Zebra. The LCM is now delivering in excess of 1.8 MA to plasma loads, effectively doubling the current on Zebra targets. The LCM project was spearheaded by Victor Kantsyrev's experimental team, who worked in close concert with Andrei Chuvatin (Ecole Polytechnique), Mike Cuneo (Sandia National Laboratories) and Alexey Astanovitskiy and the entire NTF Engineering Team to realize this capability. Other NTF science highlights include fielding state-of-the-art diagnostics such as ultraviolet shadowgraphy and interferometry with ~5 micron resolution. These efforts demonstrate the effective utilization of unique capabilities that are expanding the scope of NTF science while helping us to achieve our primary mission—that of cultivating the next generation of HED scientists.

For more information, contact:

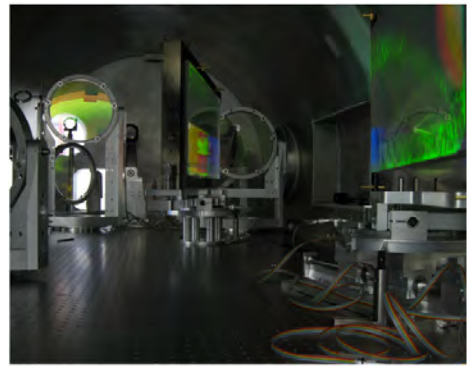
Aaron M. Covington
acovington@unr.edu

# Research on the Texas Petawatt Laser in the Texas Center for High-Intensity Laser Science

## University of Texas at Austin



The Texas Petawatt Laser (TPW)



Inside the vacuum laser pulse compressor tank of the TPW

Radiation shielding in the Texas Petawatt Laser High Bay

The Texas Center for High Intensity Laser Science (TCHILS) saw the demonstration of 1 PW from the Texas Petawatt Laser (TPW) in 2008. This achievement brought to TCHILS the highest power laser in the world and a unique tool for academic high energy density physics research. The intended use of the TPW is to perform research on topics such as intense fusion neutron generation, particle acceleration, and off-Hugoniot equation-of-state studies using ultrafast isochoric heating of solids.

During 2009, the TPW underwent a number of upgrades to improve its utility as a physics target shooter. These included the activation of a deformable mirror to greatly improve the focal spot quality and the installation of a device which corrected for the variable optical delay in the radial direction of the beam, which is now known to be a serious problem in large aperture, ultrafast lasers. The TPW can now shoot roughly 6 shots a day on experiments with a laser energy of over 180 J in a pulse duration of 130 fs.

The past year has been devoted to nearly full-time operation of the TPW in experiments. The first experimental campaigns were aimed at producing intense bursts of fusion neutrons, with the ultimate goal of using TPW-generated neutrons to study how neutrons damage materials. This experiment involved shooting the TPW laser with a long focusing optic (a capability unique among petawatt facilities world-wide) into a gas jet of deuterium molecular clusters. These clusters, when irradiated by the TPW pulses, eject fast deuterons and drive nuclear fusion.

The second major TPW research thrust involved an experiment designed to accelerate electrons by plasma wakefield generation in a gas. The goal is to use the TPW to drive plasma waves over a length of a few centimeters to accelerate electrons to energies of up to 7 GeV, an energy which is just 10% of the electron energy achieved on the entire 3 km-long linear accelerator at the SLAC National Accelerator Laboratory.

The TPW is especially well adapted for such experiments because it can operate in a unique regime with pulse duration (~160 fs) shorter than other petawatt scale systems currently in operation or under development. By focusing the 1.25 PW, 200 J, 160 fs pulses to peak intensity ~$10^{19}$ W/cm$^2$, multi-GeV electron bunches can be produced from a low density He gas jet. Because of the high power, the laser can be focused to a spot ($r_0$~100 microns) greater than the plasma wavelength ($r_0>\lambda_p$), thus minimizing radial propagation effects. Together, these properties enable the laser pulse to self-guide without the use of a preformed channel lending simplicity and stability to the overall acceleration process. Particle-in-cell simulations show the laser experiences self-focusing which, because of ultrashort pulse duration, does not lead to a collapse of the wakefield, allowing acceleration of electrons to these extremely high energies.

These two experiments are ongoing and will be followed in the coming months with experiments on proton acceleration, coherent soft x-ray production and creating positron plasmas.

For more information, contact:

Todd Ditmire
tditmire@physics.utexas.edu

# New Wave Effects in Compressing Plasma

## Princeton University

**Highlights**

- Waves in compressing or expanding plasma are shown to obey polytropic laws different from articles or photons.
- Action conservation is shown for waves in compressing plasma, with correct hydrodynamic closure equations.
- A Vlasov equation in the six-dimensional phase space is derived for arbitrarily curved spacetime, facilitating wave calculations in arbitrary metric.
- A new mechanism is predicted whereby waves in compressing plasma first grow, and then abruptly transfer energy to particles or fields.

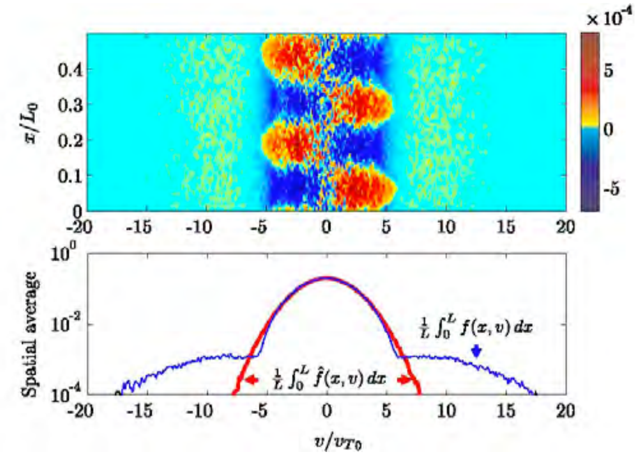



Figure 1. Top - Phase space density electrons. Bottom - Signature of abrupt damping of the Langmuir wave, forming velocity tails.

As part of the SSAA-funded project Fundamental Issues in the Interaction of Intense Lasers with Plasma, one aspect under exploration has been the wave effects, including intense laser effects, possible in compressing plasma as opposed to stationary plasma. In a variety of settings, both in nature and in the laboratory, plasmas undergo densification through compression or ionization. Conversely, plasmas undergo rarefaction through expansion or recombination. However, the wave dynamics in such plasmas are not completely understood even at a very fundamental level, so that new effects and mechanisms, possibly very useful ones, are overlooked.

When plasmas undergo densification through compression or ionization, embedded waves are affected. For compression slow compared to the wave frequency, but fast compared to collision frequencies, waves gain energy while conserving wave action. The action conservation is a fundamental constraint on densifying or rarefying plasma that has important implications to both laboratory and astrophysical plasma[1,2].

In fact, very new kinds of phenomena can be predicted to occur in densifying plasma through embedded plasma waves. For example, waves might accumulate energy and then dump it abruptly and collisionlessly on a particular species at a predetermined moment of time, thereby manipulating selectively the tail of the velocity distribution. As a result of this effect, there could be sudden particle heating leading to increased fusion events or sudden magnetic field generation leading to enhanced confinement or resistivity. Since the energy for these effects is derived from the compression, the effect can be large. Figure 1 shows a particle simulation illustrating this effect in a compressing plasma[3].

Although this is just a thought experiment at present, this switch paradigm might be useful in connection with the current groundbreaking high energy density experiments, such as those at the National Ignition Facility and Z Machine, where substantial investments are being made in the extreme compression of plasma. These built-in switches might then trigger at just the correct moment within the plasma compression history the very abrupt release of wave energy and the associated abrupt plasma heating, which might select just one species of plasma with one region of resonant velocity space. The extraordinary result could be then, in principle, the very sudden generation of electric current and associated magnetic fields at a predetermined instant of time.

**References**

[1]I.Y. Dodin, V.I. Geyko, and N.J. Fisch, *Langmuir Wave Linear Evolution in Inhomogeneous Nonstationary Anisotropic Plasma*, Physics of Plasma 16, 112101 (2009).

[2]I.Y. Dodin and N.J. Fisch, *On the Evolution of Linear Waves in Cosmological Plasmas*, Physical Review D 82, 044044 (2010).

[3]P.F. Schmit, I.Y. Dodin and N.J. Fisch, *Controlling Hot Electrons by Wave Amplification and Decay in Compressing Plasma*, Physical Review Letters 105, 175003 (October 2010).

For more information, contact:

Nathaniel Fisch
fisch@princeton.edu

# Experiments and Modeling of Photoionized Plasmas at Z

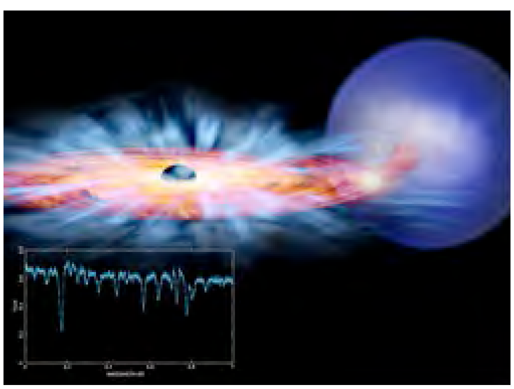
## University of Nevada, Reno

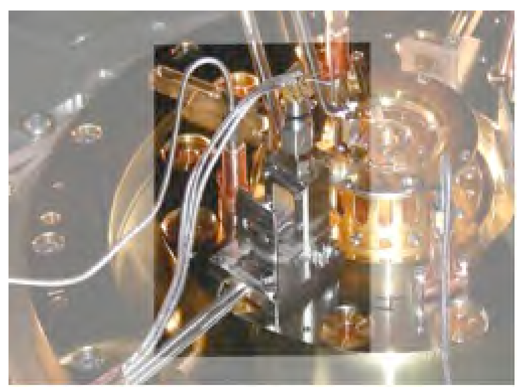
The majority of the work that has been performed on the atomic and radiation physics of high energy density laboratory plasmas pertains to collisional plasmas, i.e., plasmas where electron collisional processes are dominant. However, very little attention has been paid to investigating laboratory photoionized plasmas where both photoionization and photoexcitation driven by x-ray photons become dominant. The dearth of laboratory photoionized plasma data is due to inadequate radiation source energy. Today though, experiments at Z can fill this gap.

Photoionized plasmas occur naturally in astrophysics such as those found in accretion-powered x-ray binaries and active galactic nuclei. Figure 1 displays an artist's illustration of binary system GRO J1655-40 that is located 11,000 light-years away in constellation Scorpius. This binary system is comprised of a massive star and a black hole with an accretion disk around it. The insert in Figure 1 is an x-ray spectrum of this binary system recorded by the orbiting telescope CHANDRA that shows line absorption features in the 6 A to 7 A wavelength range produced by highly-charged ions in the accretion disk. Detailed analysis of the observed x-ray line absorption spectrum is crucial for obtaining information about the dynamics of the accretion disk formed around the black hole. In the experiments at Z (see Figure 1), we seek to recreate and study in the laboratory photoionized plasmas similar to those found in the accretion disks of black holes. To this end, the intense x-ray flux produced at the collapse of a cylindrical z-pinch implosion is used to drive and backlight gas cells, to turn them into photoionized plasmas and diagnose them using x-ray absorption spectroscopy methods. In particular, Figure 1 displays transmission data recorded from a neon gas cell photoionized plasma experiment at Z, and the comparison with synthetic spectra broken down per ion contribution. Atomic physics data and a genetic algorithm method based on the mechanics of natural selection are used to extract the atomic level populations from the data analysis. The result is independent of detailed and comprehensive atomic kinetics calculations, and can, thus, be used to test atomic models of photoionized plasmas. It can be applied to either time-integrated or time-resolved (gated) data and, in the latter case, it provides a unique window into the photoionized plasma dynamics. The nature of the photoionized plasma is inferred from the experimental observation (i.e., the presence and amount of highly charged neon ions contributing to the transmission spectrum) and a temperature estimation based on an equilibrium assumption for energy levels in the Li-like Ne ion. For the estimated temperature range, the observed charge state distribution is only possible if the plasma is photoionized.

For more information, contact:

R.C. Mancini
rcman@unr.edu





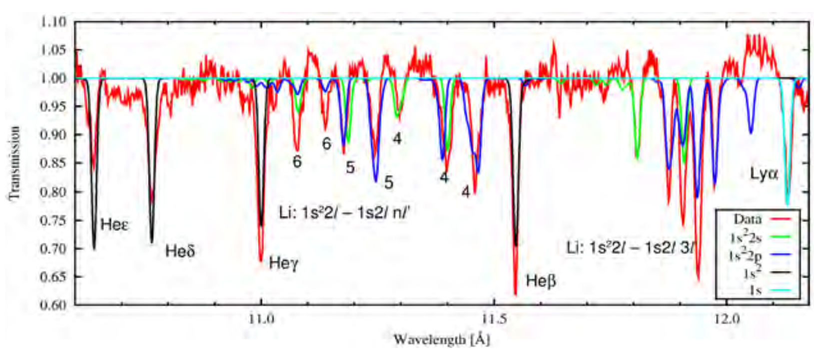


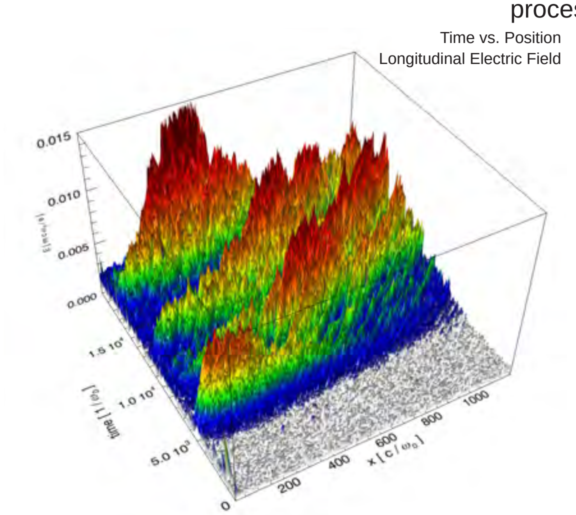

Figure 1. Upper left - Artist's illustration of binary system GRO J1655-40 (NASA website); the insert is an x-ray spectrum of this binary system recorded by CHANDRA. Upper right - Neon gas cell experimental set up at Z. Bottom - Neon transmission spectrum recorded in Z shot z1954 compared with a theoretical breakdown of total transmission into contributions from different ion stages.

# Continuation of the Application of Parallel PIC Simulations to Laser and Electron Transport Through Plasma Under Conditions Relevant to ICF and HEDS

University of California, Los Angeles

**Highlights**

- Discovery of the localization of nonlinear plasma wave packets via nonlocal wave particle interactions and its effects on stimulated Raman scattering
  J. Fahlen et al., Physical Review Letters Vol. 102, 245992 (2009), B. Winjum et al., Physical Review E 81, 045401 (2010).




The evolution of plasma wave packets generated from stimulated Raman scattering. The packets erode as they propagate to the right. Results from an OSIRIS simulation.

- Identifying a bootstrap mechanism for generating anomalously hot electrons. Electrons are towed into faster waves by first surfing on slower waves.
- Discovering a new absorption mechanism for intense lasers at a sharp solid density interface and large scale simulations of fast ignition.

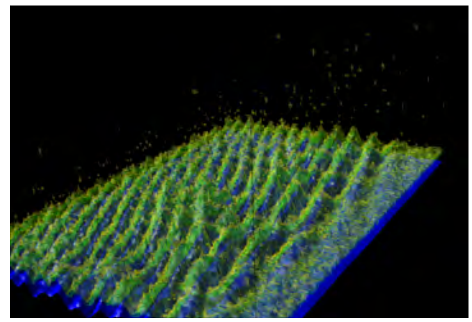
The UCLA simulation group develops and uses state-of-the-art simulation tools to study laser and beam interactions in high energy density (HED) plasmas. These tools run extremely efficiently on more than 100,000 processing cores. Understanding how a laser interacts with a HED plasma and the related generation of energetic electrons are essential for the success of the National Ignition Facility and inertial fusion energy and are of fundamental importance to the nonlinear optics of plasmas.

A laser propagating in plasma can effectively couple to plasma waves through instabilities named stimulated Raman scattering, two-plasmon decay, and the high-frequency hybrid instability. These are extremely complicated processes because they involve waves coupling to waves, particles surfing on waves, and the highly dispersive nature of plasma waves in density gradients. An ultra-intense laser provides pressures on a plasma in excess of 100 billion atmospheres and it wiggles electrons at energies in excess of 100 mega electron volts. Due to the complexity of these interactions, computer simulations that track individual trajectories of plasma particles are necessary to make sense of it all.

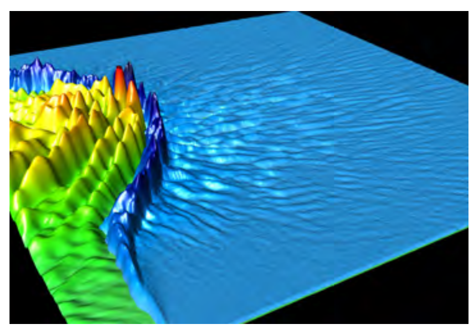
Using our massively parallel particle-in-cell (PIC) codes, we discovered that packets of plasma waves behave very differently than their idealized cousins which are infinitely long and wide. Their erosion and localization due to complex wave-particle interactions can profoundly alter the reflectivity of the laser. We also discovered that higher than expected electron energies occur when the laser scatters, both backward and forward and when this scattered light rescatters, generating a spectrum of plasma wave packets. Electrons first surf on the slower wave and then progressively bootstrap their way onto the faster waves. We found that for parameters expected in the future for inertial fusion energy that extremely strong absorption into energetic electrons can be generated near the so-called quarter critical density. We also found a new absorption mechanism for an intense laser impinging on a sharp solid density plasma interface and studied how these electrons transport forward.

For more information, contact:

Warren B. Mori
Mori@physics.ucla.edu



The white water (of energetic electrons) on top of a sea of plasma waves generated by the high frequency hybrid instability. Results from an OSIRIS simulation. Done in collaboration with Dr. B. Afeyan from Polymath Research Inc.



Electron density (blue) of a fast ignition target irradiated by an ultrahigh intensity laser (green-red) illustrating the occurrence of strong filamentation and the generation of a relativistic shock structure. Image generated from a simulation of the PIC code OSIRIS on Intrepid (ANL). Done in collaboration with IST in Portugal. Also supported by the Fusion Science Center on Extreme States of Matter and Fast Ignition Physics.

# Control of Laser-Plasma Instabilities Using (a) Spike Train of Uneven Duration and Delay (STUD) Pulses and Kinetic, Electrostatic, Electron Nonlinear (KEEN) Waves Generated by Optical Mixing

Polymath Research Inc. (PRI)

Researchers at PRI have obtained analytical and numerical results and are designing experiments that could test our findings on a new concept of laser-plasma instability (LPI) control, invented at PRI, in high energy density laboratory plasmas. This new STUD pulses technique involves breaking up the continuous laser pulse into short spikes whose durations and delays are to be adaptable to the true plasma conditions and not what is guessed at a priori. These spike trains will modulate the laser amplitude at the fastest growing instability growth timescale so as to make the possible growth of that instability be limited to a prescribed number of growth times (4-8 is advised but remains adjustable). By breaking the coherence of the drive, by allowing damping of the daughter waves to occur in between driven sections and by moving the laser hot spots around between "on" spikes, the instabilities can be strongly suppressed. Results were in the weak and strong plasma wave damping regimes (electron plasma wave (EPW) or ion acoustic wave), when the gain within a speckle, but at the average intensity, is less than 1 and up to 32 and compare our results to random or continuous phase plate (RPP/CPP), smoothing by spectral dispersion (SSD) and pseudo-STUD pulses. In pseudo-STUD pulses, the laser is modulated in time but the speckle patterns are kept fixed. The speckle patterns are fixed and nothing changes in time for an RPP/CPP.

These results will show that it is possible to use Green lasers for the driver of ICF and IFE with considerable LPI control, which is thoroughly missing in current schemes which suffer from intolerably high levels of LPI. STUD pulses also allow the control of interactions between large crossing or spatially overlapping laser beams by controlling their overlap in space-time. This has vast consequences both for direct and indirect drive laser fusion as well as shock and fast ignition schemes. Theoretical results based on the geometry of Gaussian random fields and the statistical properties of laser hot spots, with and without plasma inhomogeneity, were obtained. These theoretical analyses make predictions that could be tested in soon-to-be fielded experiments that require a few hundred psec long pulses which are psec timescale on-off modulated; psec timescale Thomson scattering and backsattering measurement capability (most likely most easily executed using Time Lenses); and short pulse optical parametric amplifiers with tunable frequency and wavenumber which can be used to drive background plasma waves to large levels by optical mixing techniques.

Researchers also further developed the kinetic electrostatic electron nonlinear (KEEN) wave resonant triad techniques of disallowing specific stimulated Raman scattering (SRS) processing from ever involving trapped electron and thus undamped EPW. This is achieved by nonlocally disrupting that delicate trapping process by the introduction of the appropriate KEEN wave at the same wavenumber but at half the frequency as the EPW. The first two harmonics of the KEEN wave work in concert, one having the same wavenumber as the EPW but half the frequency, while the other has the same frequency as the EPW but twice the wavenumber. The concomitant self-consistent electric field of all these three modes does not trap particles at the phase velocity of the EPW and feeds the KEEN wave instead. This has implications in advanced techniques of controlling SRS beyond STUD pulses, which should be the first line of attack since it is universal in scope.

*This research was conducted in collaboration with Marty Fejer and his group in the Applied Physics Department of Stanford University, Riccardo Betti and his group at the Laboratory for Laser Energetics of the University of Rochester, Thomas O'Neil and his Nonneutral Plasma Group at the University of California (UC) San Diego, Stefan Huller and his Plasma Physics Simulations and Theory group at l'Ecole Polytechnique, Josselin Garnier at the Mathematics Department of Universite' Paris VI, Jean Luc Starck at the Astrophysics group of Centre D'Etudes de Saclay, Warren Mori and his plasma simulation group at the UC Los Angeles as well as David Montgomery at P-24 and Trident at Los Alamos National Laboratory.*

For more information, contact:

Bedros Afeyan
bedros@polymath-usa.com

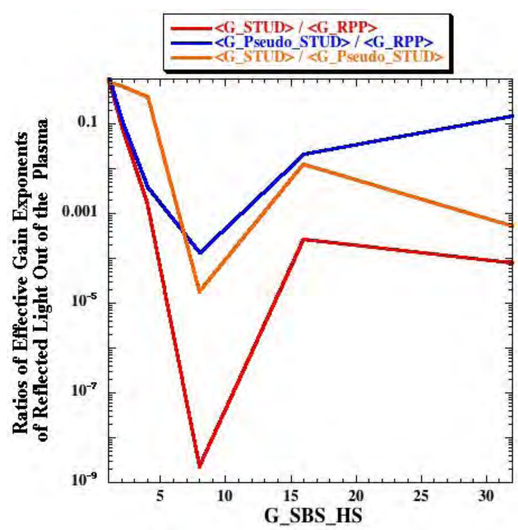



Figure 1. A comparison of the effective gain exponent of parametric instabilities driven by a STUD pulse, a Pseudo-STUD pulse and an RPP beam versus the pump strength, or the gain exponent in a single hot spot G_SBS_HS. These simulation results are for a 2-D f/8 beam, SBS in an inhomogeneous plasma in the strong damping limit. The temporal modulations are with 50% duty cycle. Note that the gain exponent is far smaller for STUD pulses even at relatively high single hot spot gains or 16 or 32.

# Radioactive Ion Beams for Stewardship Science

## Rutgers University

**Program Overview**

Low energy nuclear science is one of the forefront areas of modern science. The fundamental questions that low energy nuclear science can help to answer include: *What is the origin of the elements in the cosmos?* and *What is the origin of simple patterns in complex nuclei?* At the same time, low energy nuclear science can help provide solutions to some of the most challenging problems facing our nation, for example by developing passive and active nuclear detection systems for homeland security. Research activities in low energy nuclear science also provide the training ground for the next generation of leaders in basic research and in applications of low energy nuclear science, from nuclear forensics to homeland security to nuclear energy.

Since May 2003, the Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science (RIBSS) has worked to answer some of these questions, as well as attract and train early career scientists prepared to address the challenges that face the nation. The Center is a consortium of scientists committed to forefront nuclear science involving accelerated beams of radioactive ions of atomic nuclei. The principal investigator (PI) is Professor Jolie Cizewski from Rutgers University, joined by co-PIs from Oak Ridge Associated Universities (ORAU), Oak Ridge National Laboratory (ORNL), the University of Tennessee-Knoxville, Michigan State University, Colorado School of Mines, Louisiana State University and Tennessee Technological University.

The focus of the RIBSS Center of Excellence has been to use radioactive ion beams of fission fragments and other rare isotopes to study the reactions on, and structure and decay of, atomic nuclei far from stability. Studies with many of these short-lived isotopes can help us understand the origin of the elements. For example, the rapid neutron capture process is responsible for about one half of the elements heavier than iron. With fission fragment beams currently available at ORNL we can study the decay of some of these r-process isotopes as well as reactions on these nuclei far from stability. To realize these studies requires new theoretical approaches, new experimental tools and new rare isotope beams. The RIBSS Center has developed and fully implemented a new array of charged-particle detectors, which has inspired other efforts around the world. Currently, we are developing a new array of neutron detectors for both reaction and decay studies. To realize all of these research efforts requires a highly talented team that includes graduate students and postdoctoral scholars.

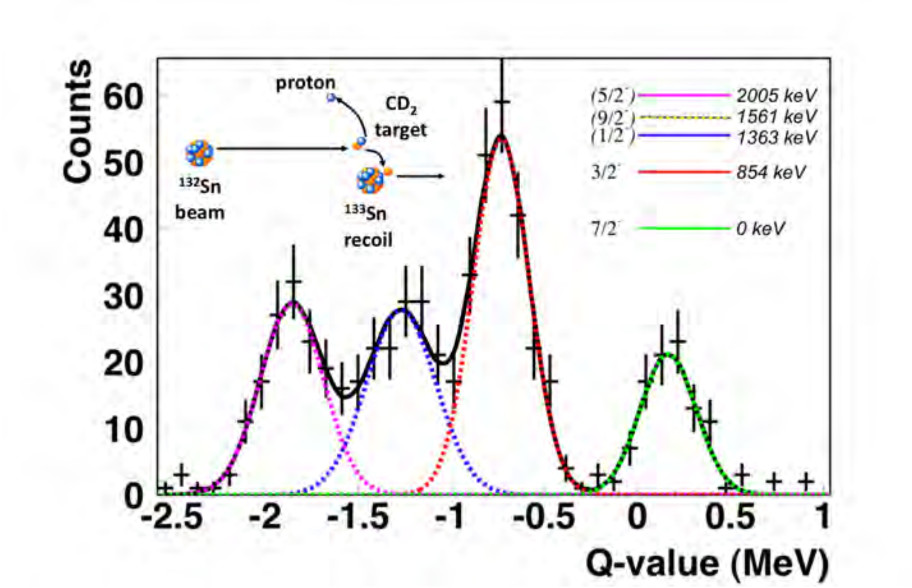



Figure 1. Center of mass or Q-value spectrum of excitations in $^{133}$Sn populated in the $^{132}$Sn(d,p) reaction. Upper left insert illustrates the interaction of the heavy $^{132}$Sn radioactive ion beam with the deuteron in a thin polyethylene, $CD_2$, target. Upper right insert displays the level energies and spin and parity quantum numbers of the excitations in $^{133}$Sn. Adopted from *Nature*.

**Research Highlight: Doubly-magic $^{132}$Sn**

We have recently completed the study of single-neutron excitations outside of $^{132}$Sn, with closed nuclear shells, or magic numbers, of both protons, Z=50, and neutrons, N=82. This effort, the cover story of the August 2010 issue of *Physics Today*, required the leadership of early career scientists as well as the implementation of new experimental and theoretical tools and techniques. The radioactive ion beams of $^{132}$Sn were produced at the Holifield Radioactive Ion Beam Facility at ORNL. These beams interacted with deuterated polyethylene foils, adding a neutron to $^{132}$Sn to populate excitations in $^{133}$Sn. By measuring the energies and angles of reaction protons, the energies and angular momenta of excitations in $^{133}$Sn were deduced. A summary of the results is displayed in Figure 1. Not only were all of the expected states with low-angular momentum, l=3 and l=1, identified, but these excitations were essentially pure configurations of a neutron coupled to the doubly-magic $^{132}$Sn core. These results show that $^{132}$Sn, 8 neutrons from stability and with a half life of only 40 seconds, is one of the best examples of a doubly-magic nucleus. $^{132}$Sn becomes a new landmark for future studies that will probe nuclei even further from stability, including those formed in explosions of supernovae or collisions of compact stars.

The study of neutron excitations outside of $^{132}$Sn required the full resources of the SSAA Center. Critical to the success was the development of the Oak Ridge Rutgers University Barrel Array (ORRUBA) of position-sensitive silicon strip detectors. ORRUBA in its full implement is displayed in Figure 2.

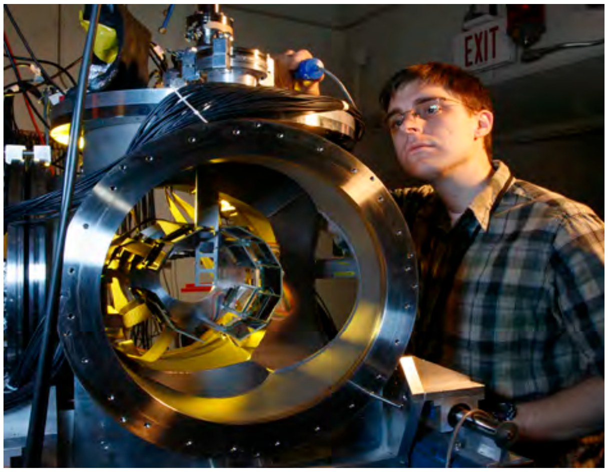


Figure 2. Stewardship Science Graduate Fellow Patrick O'Malley inspects ORRUBA.

Just as important were the SSAA resources used to attract and support the early career scientists who played leadership roles in this effort. Dr. Kate Jones, lead author of the $^{132}$Sn(d,p) study and Dr. Steve Pain who led the ORRUBA development were joined by five other physicists directly supported by SSAA.

Much of the near-term program of the RIBSS Center is focused on developing the Versatile Array of Neutron Detectors at Low Energy. Once commissioned, this array will be exploited in reaction studies and measurements of the decay of nuclei very far from stability where neutron emission, rather than just photons, follows the beta decay. The development of arrays of neutron detectors are also important for stewardship science and nuclear energy.

**Connecting Early Career Scientists to NNSA Laboratories**

The RIBSS Center has been highly successful in attracting and training low energy nuclear science undergraduate and graduate students and postdoctoral associates. All of the students and postdoctoral associates are invited every year to a workshop at one of NNSA's National Laboratories to learn firsthand about the research opportunities and introduce NNSA scientists to their research. Figure 3 was taken at the October 2009 Los Alamos workshop where participants learned about research in nuclear theory, proton radiography and isotope production. Three former RIBSS Center postdoctoral students are now staff members at Lawrence Livermore National Laboratory (LLNL). Three other former postdoctoral students are leaders in nuclear science at U.S. universities or the National Laboratories and remain closely connected to the Center's activities.

**Awards and Recognitions**

The RIBSS Center has attracted and trained some of the top early career nuclear scientists in the nation. Dr. Kate Jones, a former postdoctoral student on this project and now a Professor at the University of Tennessee-Knoxville, received the 2009 Outstanding Junior Investigator award from the Office of Nuclear Physics, DOE. The team that realized the successful $^{132}$Sn(d,p) measurements was recognized in 2010 by ORNL for excellence in scientific research. Earlier, the team led by Jeff Thomas, SSAA-supported Ph.D. student, received a similar award from ORNL. Dr. Thomas also received the Dean's Award for Excellence in Research from the Rutgers Graduate School. Current Rutgers Ph.D. student Patrick O'Malley is a prestigious Stewardship Science Graduate Fellow.

Co-PI Dr. Dan Bardayan (ORNL) has received two early career awards from the DOE, including the 2010 Early Career Research Program award. The Center's PI is a recognized national leader in nuclear science. She currently serves on the National Academies of Science decanal survey of Nuclear Physics and the Physical and Life Sciences Directorate Review Committee at LLNL.

**References**

*The Frontiers of Nuclear Science: A Long Range Plan,* DOE/NSF Nuclear Science Advisory Committee, December 2007.

K.L. Jones et al., Nature 465, 454 (2010).

S.D. Pain et al., Nuclear Instruments and Methods in Physics Research B 261, 1122 (2007).

For more information, contact:

Jolie A. Cizewski,
cizewski@rutgers.edu

Figure 3. RIBSS Center graduate students and postdoctoral students visited Los Alamos National Laboratory in October 2009.

# Cross Sections, Level Densities and Strength Functions

## Triangle Universities Nuclear Laboratory, North Carolina State University

For fields as diverse as stockpile stewardship, reactor fuel cycles, nuclear medicine and nuclear astrophysics, neutron reaction rates are crucial. One key element in predicting reaction cross sections is the nuclear level density. This is usually determined by measurement of neutron resonances. Study of the neutron capture reaction with the highly segmented gamma ray array at Los Alamos National Laboratory provides the capture cross section and the neutron resonances, as well a wealth of valuable information about the gamma ray strength function. Figure 1 shows a view of DANCE calorimeter at LANSE. Determination of the spin of the resonances provides key information, but usually requires difficult and time consuming measurements. We have for the first time applied pattern recognition theory to this problem. Sample results are presented below. Almost every experiment misses some resonances due to experimental thresholds and to resolution issues. We have developed a number of tests to determine the fraction of missing resonances. Descriptions of these various tests and accompanying computer codes are available at the International Atomic Energy Agency website. Sample results for $^{238}U$ are shown below.

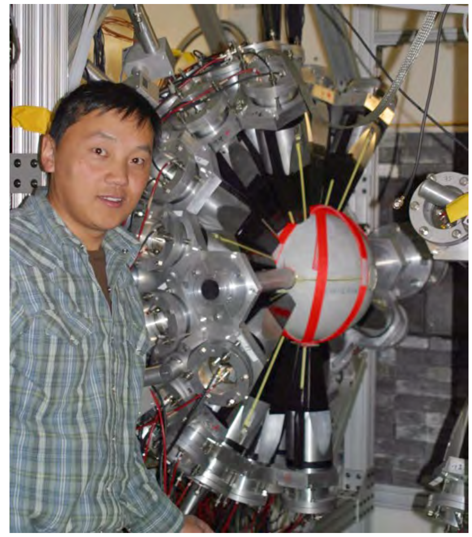


Figure 1

A classic problem in neutron resonance analysis occurs for odd mass targets (the resulting s-wave resonances have two possible spins.) DANCE, with 160 detectors, is the ideal system to determine the spin values. In Figure 2, each point represents a resonance. The two separate clusters correspond to the two possible resonance spins. Our novel approach to determine the best separation uses pattern recognition theory.

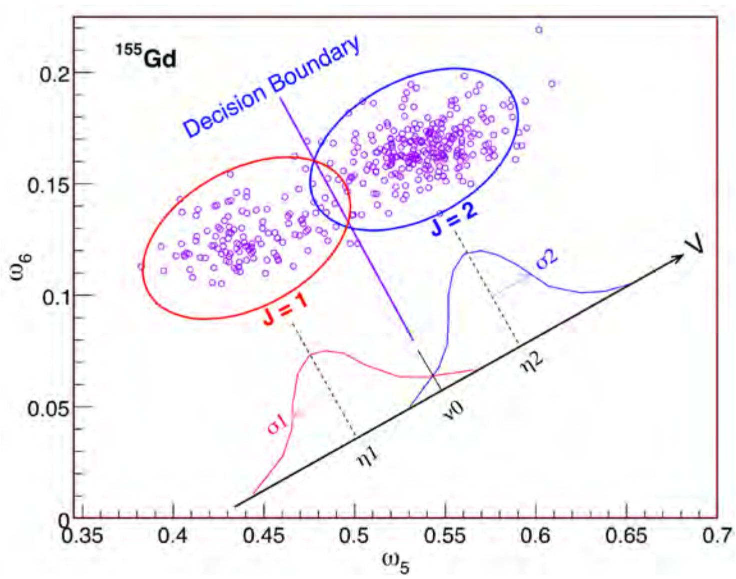



Figure 2

The determination of nuclear level densities from neutron resonances is crucial for such areas as shielding calculations, advanced fuel cycle issues, etc. A key question is whether some resonances are missing, and if so, how many?

Using several independent tests provides a more reliable determination of the missing fraction. Results for four of these tests are applied to low energy neutron resonances in $^{238}U$ and shown in Figure 3.

For more information, contact:

Gary Michell
mitchell@tunl.duke.edu

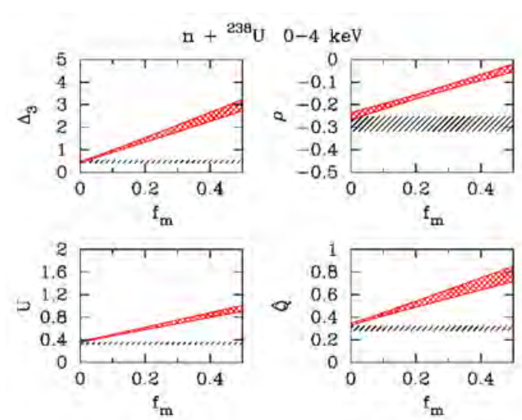



Figure 3

# Precision Photo-Induced Cross-Section Measurement Using the Monoenergetic and Polarized Gamma Beams at High Intensity Gamma-Ray Source

Duke University

**Highlights**

- First photodisintegration experiment on radioactive target using monoenergetic beams
- HIGS makes cross-section measurements possible using radioactive targets with only μγ quantities.

The aim of this work is to use the novel source of γ-radiation at the High Intensity Gamma-ray Source (HIGS) facility for precision (γ,γ') and (γ,xn) cross-section measurements on actinide nuclei. A systematic and complete survey of excited states in $^{235,238}U$ is currently being carried out at HIGS at energies below the particle emission threshold. Preparations for $^{239}Pu$ are underway. The goal of these studies is the identification of dipole states which are strongly coupled to the ground state. In addition, the activation technique is being used to obtain accurate cross sections above the neutron separation energy on stable and unstable nuclei: $^{238}U$(γ,n), $^{237}Np$(γ,n), $^{241}Am$(γ,n), and $^{241}Am$(γ,2n). This technique combined with the quasi monoenergetic (ΔE/E = 0.01 to 0.03) and intense ($10^8$ $s^{-1}$) photon beams from the recently upgraded HIGS facility, located at Duke University's Free Electron Laser Laboratory, allow us to determine unambiguously the partial cross sections for these important actinides.

**Photodisintegration Data of $^{241}Am$**

The photodisintegration cross section of the radioactive nucleus $^{241}Am$ has been obtained using activation techniques and monoenergetic γ-ray beams from the HIGS facility. The induced activity of $^{240}Am$ produced via the $^{241}Am$(γ,*n*) reaction was measured in the energy interval from 9 to 16 Me*V* utilizing high-resolution γ-ray spectroscopy. The experimental data for the $^{241}Am$(γ,*n*) reaction in the giant dipole resonance energy region are compared with statistical nuclear-model calculations.

Six electroplated $^{241}Am$ targets about 0.8 mg/cm$^2$ thick and 1 cm in diameter were chemically purified and produced at Los Alamos National Laboratory as a dried nitrate powder and used at HIGS.

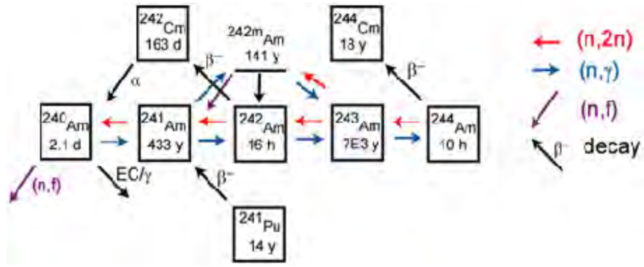



Figure 1. Nuclear reaction chain on Am isotopes.

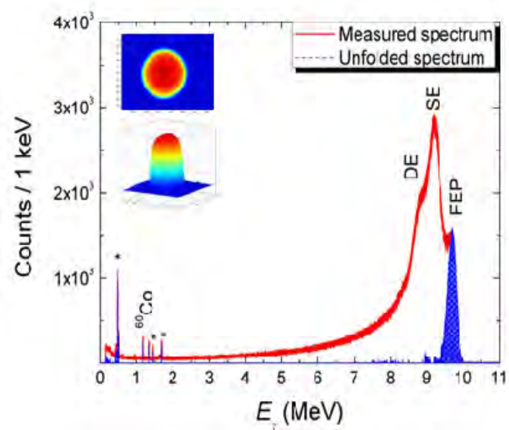



Figure 2. HIγ S γ-ray spectrum (in red) measured with a 123% HPGe detector positioned at 0° relative to the incident photon beam of 9.7 MeV. The full-energy (FEP), single escape (SE), and double escape peaks (DE) are labeled.

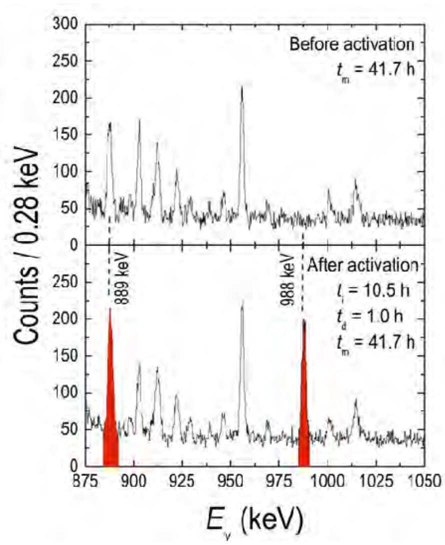



Figure 3. High-energy portion of γ-ray spectra measured before activation (top) and after activation (bottom) of the $^{241}Am$ target with Eγ = 13.6 MeV. The gamma-ray lines at 888.8 and 987.8 are associated with the decay of $^{240}Am$. The activation conditions (irradiation, decay, and measurement times) are also labeled.

Data were taken at nine beam energies from Eγ = 9 to 16 MeV. The high-energy portion of the γ-ray spectra obtained with an electroplated $^{241}Am$ target is depicted in Figure 3. Spectra from the

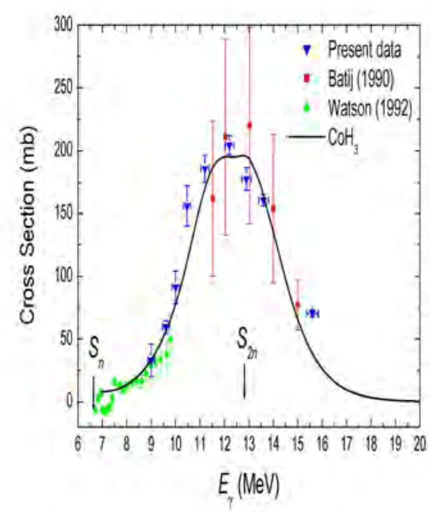



Figure 4. Cross section measurement of the $^{241}Am$(γ,n) $^{240}Am$ reaction at HIGS facility.

$^{241}Am$ target before and after activation with 13.6-MeV photons are shown in the top and bottom panels, respectively. Our results obtained from the $^{241}Am$(γ,*n*)$^{240}Am$ cross-section measurements at HIGS between 9 and 16 MeV are shown in Figure 4.

For more information, contact:

Anton Tonchev
tonchev@tunl.duke.edu

# Toward a Predictive Theory of Fission

## University of Tennessee, Knoxville

A comprehensive microscopic explanation of nuclear fission rooted in interactions between protons and neutrons, the building blocks of the atomic nucleus, still eludes us. Because of the complexity of the process, we have yet to obtain a microscopic picture of fission that is of comparable quality to what we have for ground and excited states of atomic nuclei. A predictive theory of fission is expected to yield a significant impact on our ability to computationally model components and materials for stockpile stewardship, as well as the next generation of nuclear reactor design. The pursuit of a predictive theory of fission is a challenging problem for basic research which would also impact our understanding of the synthesis of superheavy nuclei, and the astrophysical production of elements heavier than lead.

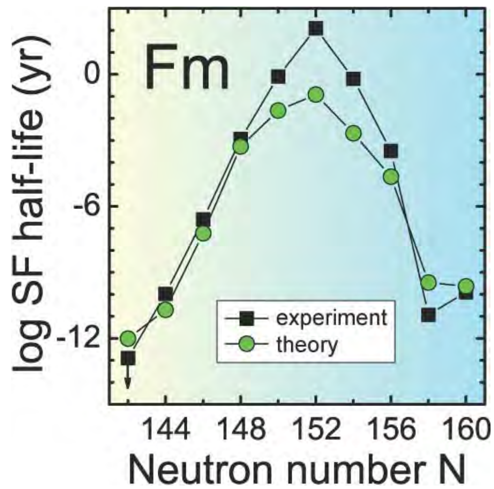



Figure 1

Quantum-mechanically, fission represents a time-dependent solution of the many-body Schrödinger equation in which all particles move in unison. Consequently, most of the essential physics should be contained in underlying self-deforming mean fields. This determines the choice of a microscopic tool to be used: the nuclear density functional theory (DFT). The advantage of DFT is that, while treating the nucleus as a many-body system of fermions, it provides an avenue for identifying the essential collective degrees of freedom.

Using the nuclear DFT and the largest supercomputing platforms currently available, we are developing a microscopic model for fission that will be predictive and extendable. We study fundamental properties of fission: half-lives and the distribution of mass, kinetic energy, and excitation energy between the fission fragments. Figure 1 shows the calculated fission half lives of even-even fermium isotopes, with 242 ≤ A ≤ 260, compared with experimental data [Staszczak et al., Phys. Rev. C 80, 014309 (2009)].

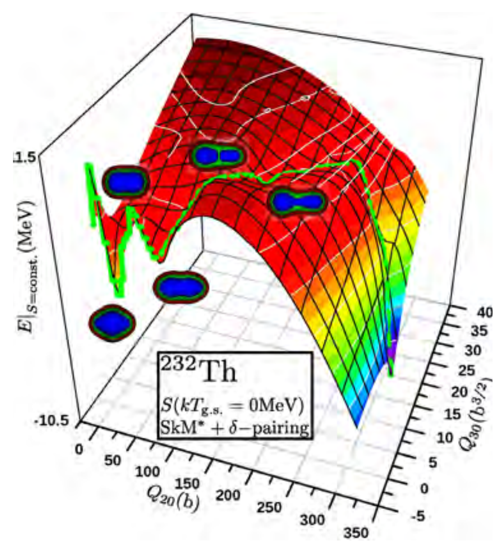



Figure 2

We are studying the fission of actinides such as $^{232}$Th as a test of theoretical predictions against experimental data. For example, as some actinide nuclei deform towards fission, they exhibit three local minima in the energy surface. Furthermore, the mass distribution of daughter products tends to be asymmetric. As seen in Figure 2, our DFT calculations successfully reproduce the three minima of $^{232}$Th, finding the third minimum to be reflection asymmetric—indicating that the division of mass between the fragments will be asymmetric, just as the data indicate.

We have extended our study to excited nuclei. We find that the third, reflection-asymmetric minimum dissolves so that the nucleus divides symmetrically (see Figure 3). Experimental data support this prediction: excited nuclei fission with a symmetric mass yield.

Extreme-scale computing affords us the opportunity to relax assumptions, so that we can calculate fission properties with increasing fidelity and, therefore, enables validation with experiments. We see this trend continuing for the next 5 to 10 years as supercomputing reaches toward the exascale.

For more information, contact:

Witold Nazarewicz
witek@utk.edu

Jordan McDonnell
jmcdonne@utk.edu

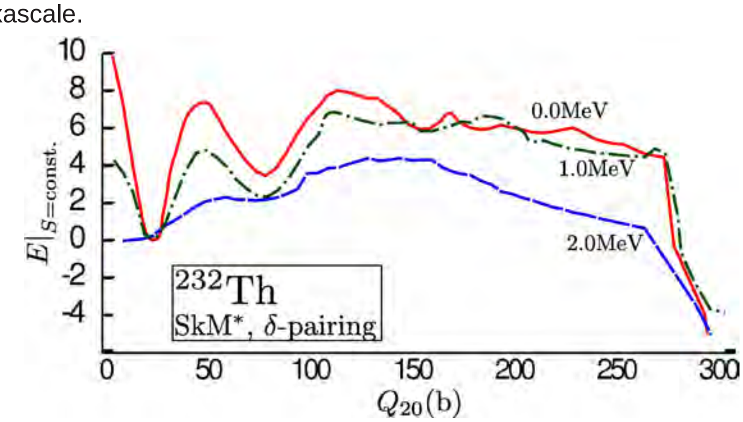


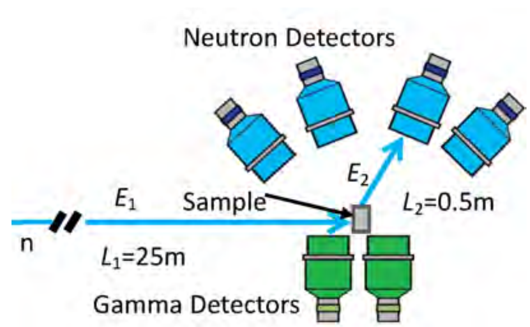

Figure 3

# Experiments with a Lead Slowing-Down Spectrometer and Fission Neutrons

## Nuclear Engineering Program, Rensselaer Polytechnic Institute (RPI)

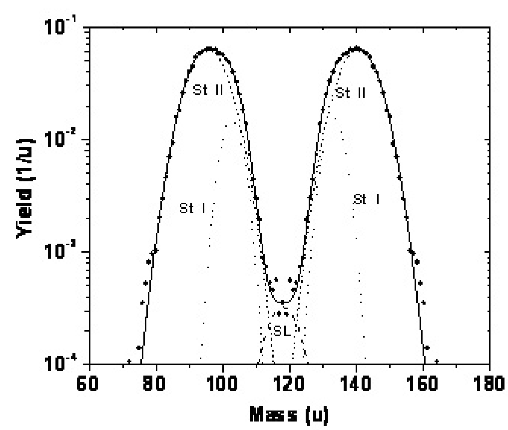
An investigation into nuclear data reveals gaps in our knowledge which can affect everything from nucleosynthesis, to neutron multiplicity, and fission product concentrations in spent fuel. RPI has one of the world's premier nuclear data centers with both time-of-flight stations and a Lead Slowing-Down Spectrometer (LSDS). This grant from the NNSA allows us to expand our knowledge of nuclear reactions to improve stellar nucleosynthesis models, criticality safety codes and nuclear fission theory. Our research is concentrated on the three topics discussed below.

Neutron-induced charged particle emission reactions are difficult to measure for materials with very low cross sections or where availability is limited to nanogram quantities (for example, due to high activity). The LSDS is a unique device providing a very high neutron flux and thus enabling cross section measurements of extremely small samples and cross sections (~1 ng/barn) between incident neutron energies of 0.1 eV and 100 keV. New methods and detectors that can measure (n,α) and (n,p) reactions are being developed. The (n,α) cross sections of $^{147}$Sm and $^{149}$Sm have been measured as proof of concepts, and measurements on the $^{64}$Zn(n,α)$^{61}$Ni and $^{50}$V(n,p)$^{50}$Ti cross sections are planned.




Accurate measurements of fission neutron multiplicity (nu-bar) and fission neutron spectrum particularly for sub 1 MeV fission neutron energies are important for accurate calculations of nuclear fission systems. The RPI fast neutron scattering detector array is being modified for coincident measurements between gammas and neutrons using a double time-of-flight experiment. The gamma tagging method allows for measurements on relatively large samples, thus increasing the count rate of the experiment. Liquid scintillators and lithium glass detectors will be utilized to allow measurements of fission neutrons with low energies. The system will be tested with $^{252}$Cf and $^{235}$U.

The high neutron flux of the LSDS enables simultaneous measurements of fission fragment mass and energy distributions as a function of incident neutron energy. Measurements on $^{252}$Cf and $^{235}$U were completed[1], and demonstrated the advantages of this method in the resonance energy region. Models for prediction of the $^{235}$U fission neutron energy spectrum and nu-bar rely on such experimental data. The measured data is used to improve the model results and analyze the uncertainties in nu-bar and the fission neutron spectrum.




Measured fission fragments mass distribution for $^{235}$U for $E_n$<0.1eV

### Reference

[1]C. Romano, Y. Danon, R. Block, J. Thompson, E. Blain, E. Bond, *Fission Fragment Mass and Energy Distributions as a Function of Neutron Energy Measured In A Lead Slowing Down Spectrometer*, Physical Review C 81, 014607 (2010).

For more information, contact:

Yaron Danon
danony@rpi.edu

# Research Directions at the Carnegie-DOE Alliance Center (CDAC)

CDAC, Carnegie Institution of Washington

The mission of the Carnegie-DOE Alliance Center (CDAC), founded in 2003, is to advance high pressure-temperature (P-T) techniques important to NNSA, to enable studies on a broad range of materials under extreme conditions and, most importantly, to train the next generation of scientists for national security science missions. CDAC focuses on fundamental experimental materials science, but also works closely with theory, modeling and simulation groups for code validation that is crucial for stockpile science.

CDAC graduate students tackle a wide variety of problems, related by the common goal of developing an understanding of the effects of extreme conditions on materials properties. Two important areas in the CDAC scientific program are the determination of accurate pressure-volume (P-V) equations of state and the measurement of transport properties of materials at high pressure. These two aspects of high pressure research were investigated together in a recent study carried out by CDAC graduate student Walter Uhoya from the University of Alabama-Birmingham. X-ray diffraction measurements of the structure of the compound $EuFe_2As_2$ showed that the material exhibits a negative compressibility up to 8.5 GPa (85 kbar). Uhoya then used “designer” diamond anvil cell technology developed within the Center (see Figure 1) for measurements of the superconducting transition temperature ($T_c$). Uhoya’s measurements also showed that $T_c$ increases rapidly in the pressure range of negative compressibility.

Cutting-edge experimental facilities are critical to the CDAC research program, and CDAC supports two synchrotron beamlines at National Laboratories. The High Pressure Collaborative Access Team (HPCAT) sector at the Advanced Photon Source (APS), Argonne National Laboratory, is specially designed for diffraction and spectroscopy experiments on materials under extreme conditions, such as static compression in diamond anvil cells. This sector is a world-class facility that has four beamlines that can operate simultaneously. Technique development projects that are crucial for stockpile science are pursued at HPCAT by members of its scientific staff. At the National Synchrotron Light Source, Brookhaven National Laboratory, beamline U2A provides state-of the-art facilities for infrared spectroscopy under extreme conditions. Both facilities have been used recently for feasibility studies of synchrotron measurements on materials under dynamic compression.

Recently, nanoscale imaging has opened up a new world of materials research, as it has now become possible to differentiate the properties of nanoscale materials from those of a bulk material. A key breakthrough in this area has been the ability to focus an x-ray beam well below one micron, which is necessary in order to resolve properties such as high-pressure strength, plasticity and texture development. As shown in Figure 2, diffraction patterns taken with a nanoscale beam allowed discrimination of components in samples at megabar pressures for the first time. Nanoscale x-ray beams also allow single crystal diffraction on nominally polycrystalline materials in cases where it is impossible to grow crystals of adequate size for traditional crystallographic analysis. This work sets the stage for future in situ measurements under dynamic compression at the APS and other facilities.

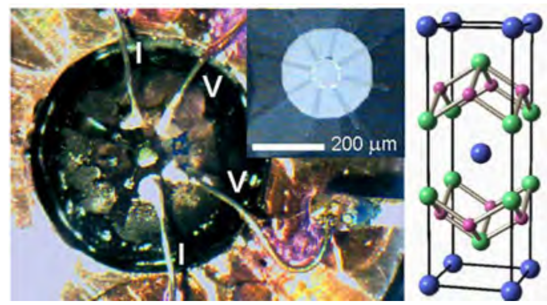



Figure 1. CDAC researchers employ many different types of high pressure devices, especially diamond anvil cells designed for the requirements of specific experiments, and improvements to the basic design are carried out in several CDAC groups. Left - Electrical leads for measuring the resistance of a sample of $EuFe_2As_2$ under pressure are embedded into the diamond anvil, allowing direct contact of the leads to the sample. Right - The crystal structure of $EuFe_2As_2$ (blue = Eu, pink = Fe, green = As).

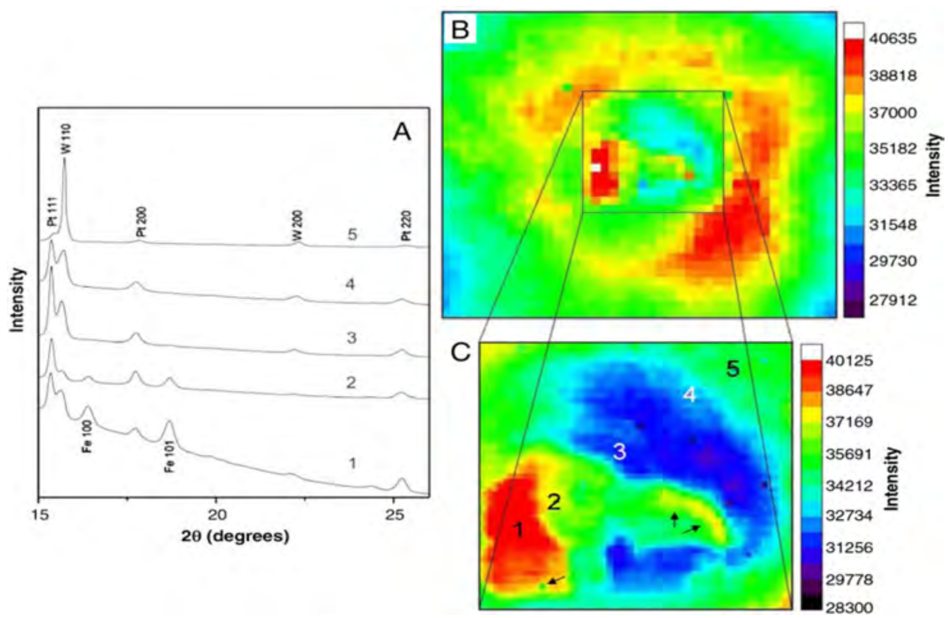



Figure 2. Right - X-ray absorption map of sample in a diamond anvil cell with 18 micron culets, taken with a tightly focused x-ray beam. The sample contains Pt, W and Fe. Darker features indicate more strongly absorbing materials (W and Pt). Top - Lower resolution (1 micron/step); bottom, higher resolution (250 nm/step). Left - Diffraction patterns taken from different components of the diamond cell sample with a 650 nm focused beam. Numbers correspond to different regions of the cell as indicated in bottom right image.

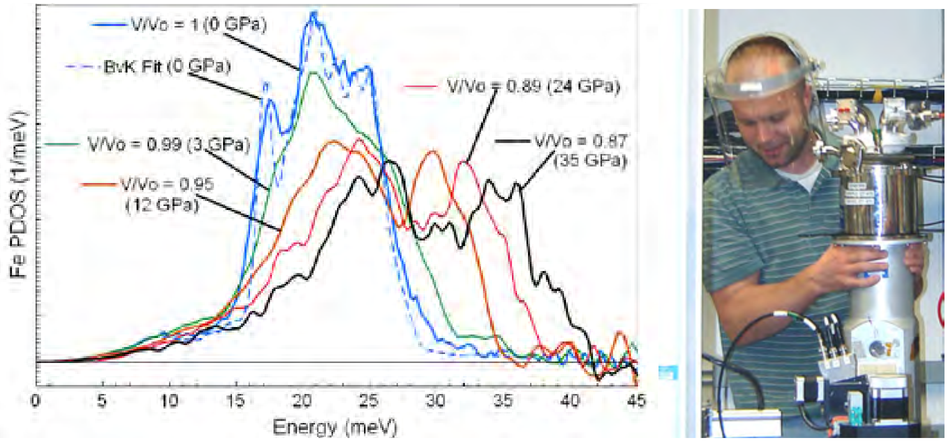



Figure 3. Left, phonon density of states (PDOS) spectra of $Pd_3Fe$ taken at increasing pressures. The marked decrease in intensity at 12 GPa and shift in energy indicate a softening of the PDOS that coincides with the onset of Invar behavior in the material. High-quality data such as these are a trademark of the spectroscopy and diffraction facilities at HPCAT. Right, Mike Winterrose assembles a cryostat at the HPCAT sector.

Mike Winterrose, a CDAC graduate student who recently completed his Ph.D. work at the California Institute of Technology (Caltech) in the group of CDAC Academic Partner Brent Fultz, used the unique capabilities of the x-ray spectroscopy beamline at HPCAT to unravel a complex problem involving the pressure-induced Invar (near-zero thermal expansion) behavior of the alloy $Pd_3Fe$ at high pressures. In the first study of lattice dynamics at pressures relevant to the pressure-induced Invar effect, Winterrose measured the $^{57}Fe$ phonon density of states (PDOS) for $Pd_3Fe$ using nuclear resonant inelastic x-ray scattering (NRIXS, Figure 3). At lower pressures, NRIXS revealed a stiffening of the $^{57}Fe$ PDOS with increasing pressure, but an anomalous softening occurred around 12 GPa. Theoretical calculations showed that the softening could result from the pressure-induced magnetic transition from a high-moment to a low-moment state. The NRIXS spectra showed that the stiffening of the $^{57}Fe$ PDOS with decreasing volume was slower from 12 to 24 GPa owing to the pressure-induced Invar transition in $Pd_3Fe$, with a change from a high-moment ferromagnetic state to a low-moment state, which was eventually observed by nuclear forward scattering, another x-ray scattering technique available at the HPCAT sector.

Educational outreach is an important aspect of CDAC. Thus far, CDAC has hosted three major events, and provided support for a number of others, in order to allow graduate students exposure to the latest work in the field of high pressure research. In June 2006, the program hosted its first Summer School, which consisted of a series of lectures by scientists at the forefront of high pressure research from the academic and National Laboratory communities. More recently, CDAC has provided students an opportunity to present their work within the workshop format. In the Winter Workshop hosted in February 2009, the lecture program featured presentations by both academic partners and National Laboratory scientists, and focused on dynamic compression, static compression, diffraction and spectroscopy. In addition, CDAC students close to finishing their graduate studies had the opportunity to discuss their work in oral presentations. In September 2010, CDAC and HPCAT co-hosted the *Fundamentals of High-Pressure Synchrotron X-Ray Techniques* workshop (Figure 4), which featured morning lectures on the fundamental science behind high-pressure work as well as afternoon lectures by HPCAT beamline staff. The afternoon lectures were designed to illustrate from a practical point of view how these experiments are carried out in the synchrotron setting. Two recent CDAC events also included poster sessions where students attending could share their work with their peers.

The variety of materials of interest to CDAC researchers continues to expand, as do the avenues for investigating these materials as new facilities are either coming online or are in the planning stages. CDAC has helped start the proposed science program at the National Ignition Facility, which will involve the participation of CDAC Academic Partners, Laboratory Partners and graduate students. Feasibility studies for the Dynamic Compression Collaborative Access Team have been carried out at the HPCAT sector, and CDAC scientists are taking part in developing a plan for dynamic compression science at the APS and other sites, including the MaRIE facility at Los Alamos. CDAC looks forward to taking the lead in combining experimental techniques and results from static compression experiments on key materials with new experimental capabilities to enhance the science of matter at extreme conditions for DOE/NNSA mission needs.

For more information, contact:

Stephen A. Gramsch
s.gramsch@gl.ciw.edu

Figure 4. At the recent CDAC/HPCAT Short Course on High Pressure Synchrotron Techniques, graduate students and postdoctoral associates listen to CDAC Academic Partner Brent Fultz (Caltech) present his lecture on *Materials Thermodynamics at High Pressure*. Professor Fultz was joined by Academic Partner Jim Shilling (Washington University in St. Louis) and HPCAT Beamline Scientist Paul Chow in presenting lectures on fundamental science that can be accomplished with the use of x-ray spectroscopic techniques.

# Scientific and Engineering Studies of Materials at High Pressures for Stockpile Stewardship

## University of Nevada, Las Vegas

Exciting research was conducted at the University of Nevada, Las Vegas during the 2009-2010 grant period. Some of this research is highlighted below.

- Shock recovery studies show that micro-turbulent mass transport in shock-generated melts and ultrafast growth and formation of high pressure phase at *P-T-t* conditions of 26 GPa, 2000-3000 K, 700 ns. This study has significant implications to understanding of dramatic meteorite impact processes in early solar terrestrial system, by Tschauner et al., Proc. Natl. Acad. Science, Vol. 106, 13691 (2009).
- Professor Chen's research group has unveiled that the wurtzite-type boron nitride (w-BN) has a greater indentation strength than naturally occurring diamond. The study also shows that another material, lonsdaleite (also known as hexagonal diamond), should be even stronger than w-BN and 58 percent stronger than diamond, setting a new record. This analysis represents the first case where a material exceeds diamond in strength under the same loading conditions. In addition, by showing the underlying atomistic mechanism that can strengthen some materials, this work may provide new approaches for designing "superhard" materials, by Pan, et al., *Harder than Diamond: Superior Indentation Strength of Wurtzite BN and Lonsdaleite*, Physical Review Letters 102, 055503 (2009).
- Our recent studies have revealed that the high pressure compels outer shell electrons to pair into higher energy levels and forces an electronic transition at 44 GPa in $FeCO_3$. The elastic contribution of neighboring clusters to the pressure-induced spin pairing of $Fe^{2+}$ *d*-electrons is demonstrated by the hysteresis of formation of spin-like domains in the $FeCo_3$. High-resolution structural analysis allowed observing the fine structural rearrangements accompanying the electronic phase transition, such as the lengthening of the bond distance of the triangular $CO_3$ unit bridging adjacent octahedra, and the sudden reduction of the amplitudes of thermal vibrations. These studies are published by Lavina et al., in Geophys. Res. Lett. 36, L23306, (2009); Phys. Rev. B 82, 064110, (2010); and High Press. Res. 30, 224-229 (2010).
- We have observed high pressure induced structural phase transition from *Cmmm to Pbnm* in the iron-based FeSe superconductor around 1.6 GPa and near $T_c$, through high resolution high-pressure/low-temperature synchrotron x-ray diffraction. Another new high pressure induced structural phase transitions of *I4mm—CmC21—P1* has been identified in $NH_3BH_3$, a highly promising potential hydrogen storage compound, by a combined x-ray, neutron, and density functional theory investigations. These two recent high pressure experimental studies on the "energy-relevant materials" are published by Kumar et al., in J. Physical. Chem. B. 114, 12597 (2010) and Chem.Phys.Lett. 495, 203 (2010), respectively.

For more information, contact:

Yusheng Zhao
Yusheng.Zhao@unlv.edu

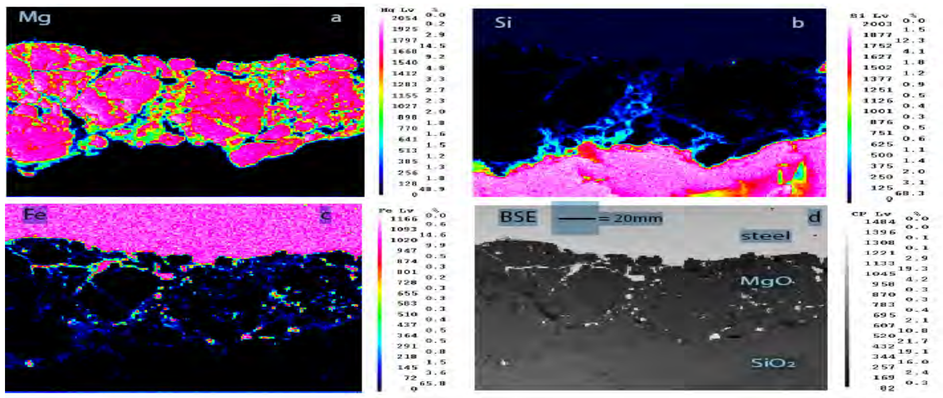



Figure 1. Images and composition mapping of shocked sample. EMP wavelength-dispersive x-ray mapping of magnesium (A), silicon (B), and iron (C) concentration in section of the shocked sample. (D) EMP backscattered electron (BSE) image of sample. Melted areas are clearly indicated by the fine scale dispersion of metal melt droplets (bright spots).

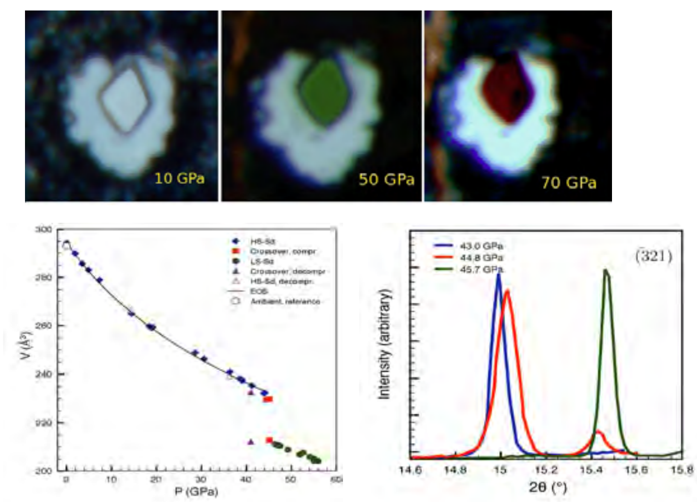
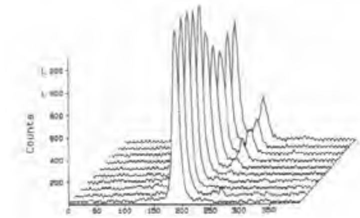



Figure 2. The spin transition in $FeCO_3$ determines a gain in absorption in the visible range, shown by the photos taken at different pressures. The transition occurs through the formation of spin-like domains evidenced by the splitting of all diffraction peaks.

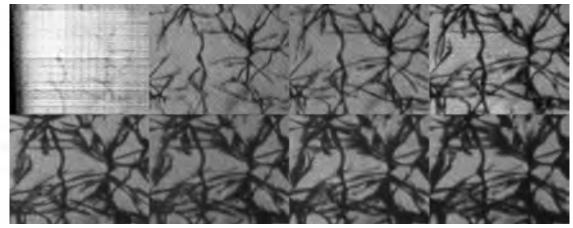
# Institute for Shock Physics
## Washington State University

Building on a more than 50-year legacy of shock wave research and educational excellence, the Institute for Shock Physics (ISP) is a multi-disciplinary research organization with a focus on understanding the real-time response of materials under dynamic compression. This focus is central to both the Stockpile Stewardship Program and the study of condensed matter dynamics at extreme conditions. Time-resolved, multiscale measurements are used to develop a continuum-to-atomic scale understanding of the following condensed matter phenomena: structural transformations, deformation and fracture, and chemical reactions. Representative examples of recent achievements include:

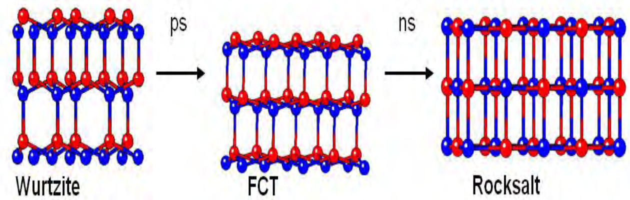
- *Real Time Microstructure of Shocked LiF Crystals: Use of Synchrotron X-Rays*, J. Applied Physics (JAP) 105: 053520, 2009.
- *Elastic Limit of X-cut Quartz Under Shockless and Shock Wave Compression: Loading Rate Dependence*, JAP 106: 053526, 2009.
- *Time-Resolved Spectroscopic Measurements of Shock-Wave Induced Decomposition in RDX Crystals: Anisotropic Response*, J. Phys. Chem., (JPC) A 114: 11560, 2010.
- *Phase Diagram of RDX Crystals at High Pressures and Temperatures*, JPC A 114: 8099, 2010.
- *Anisotropic Material Model and Wave Propagation Simulations for Shocked PETN Single Crystals*, JAP 107: 103505, 2010.
- *Equation of State and Refractive Index of Argon at High Pressure by Confocal Microscopy*, Phys. Rev. B 81: 132104, 2010.
- *Two- and Three-dimensional Extended Solids and Metallization of Compressed $XeF_2$*, Nature Chem. 2: 697, 2010.
- *Dynamic Tensile Response of Zr-based Bulk Amorphous Alloys: Fracture Morphologies and Mechanisms*, JAP 107: 123502, 2010.



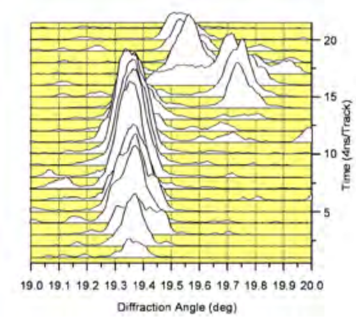

Symmetry Changes
M. Boteler, WSU Ph.D., 1993



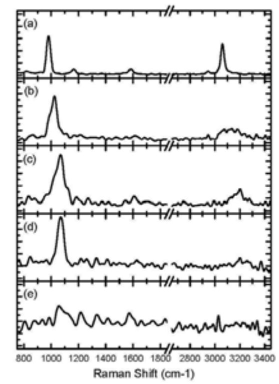
Freezing of Water
D. Dolan, WSU Ph.D., 2003




Structure Changes
M. Knudson, WSU Ph.D., 1998




Time-Resolved X-ray Diffraction P. Rigg, WSU Ph.D., 1999

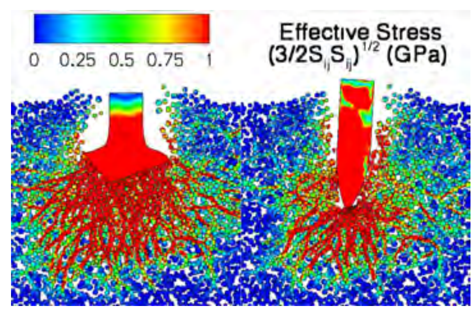



Chemical Reactions
S. Root, WSU Ph.D., 2007

- *Strength and Elastic Deformation of Natural and Synthetic Diamond Crystals Shock Compressed Along* [100], JAP 107: 113538, 2010.
- *Experimental Determination of Third-order Elastic Constants of Diamond*. (Manuscript Submitted to Physical Review).

WSU graduates and postdoctoral scholars have gone on to become leaders in this field at the NNSA's National Laboratories and elsewhere. The American Physical Society's Shock Compression Science Award, the premier biennial recognition in the field, has been awarded to WSU graduates and faculty on six occasions among the 13 awards to date.

To create a new paradigm for dynamic materials research, the Institute is leading a multi-institutional effort, in partnership with the National Laboratories, to establish a first-of-a-kind user facility dedicated to dynamic compression experiments at the




Mesoscale Modeling R. Teeter, WSU M.S., 2007

Advanced Photon Source: Dynamic Compression Collaborative Access Team (DC-CAT). DC-CAT will emphasize time-resolved in situ x-ray diffraction and imaging measurements to understand material dynamics at extreme conditions.

For more information, contact:

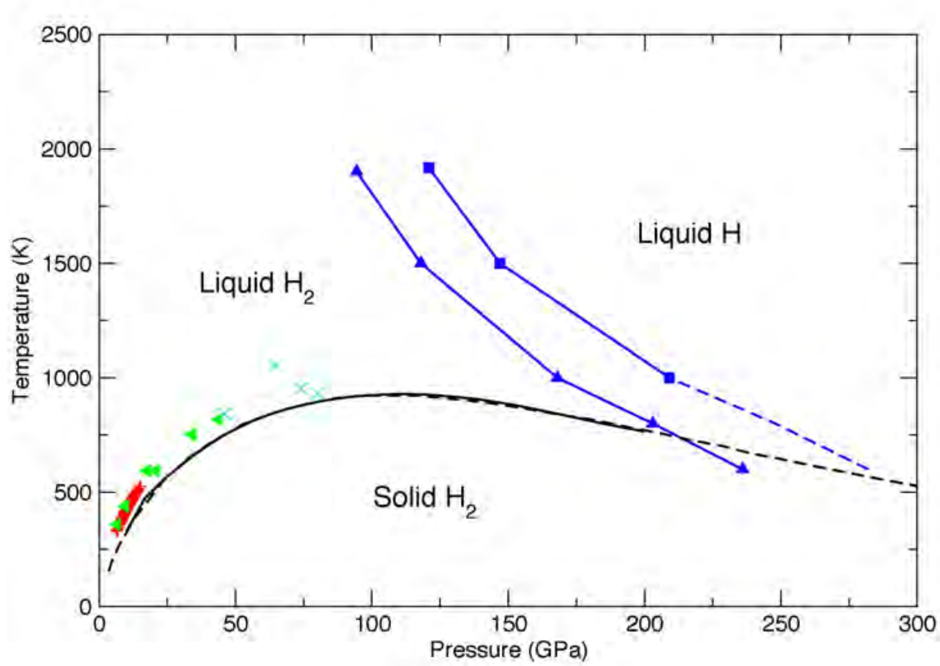
Yogendra M. Gupta, ymgupta@wsu.edu

# Quantum Simulations for Dense Matter

## University of Illinois, Urbana-Champaign

**Highlights**

- The Illinois-Livermore team found a liquid-liquid phase transition in hot dense hydrogen and determined its critical points.
- Miguel Morales was the first SSGF graduate to receive his Ph.D. He now is an employee of LLNL.




Using quantum simulation techniques based on both density functional theory and quantum Monte Carlo, clear evidence of a liquid-liquid phase transition in liquid hydrogen at high pressure was found[1]. The transition, often called the "plasma phase transition," is between a low conductivity molecular state and a high conductivity atomic state. The figure shows the phase diagram of hot dense hydrogen as determined by these calculations. The two blue lines show the estimated transition line: the left blue curve is estimated using density functional theory for the electronic energies, the right curve was estimated with quantum Monte Carlo and includes all effects of electron correlation. Using the temperature dependence of the discontinuity in the electronic conductivity, the estimated critical point of the transition is about 2000 K and 120 GPa. The melting curve of molecular hydrogen is shown as the black curve, and measurements of the melting temperature as red pluses, blue crosses and green triangles. The triple point where all three phases coexist, estimated to be at 700K and 250 GPa, is at conditions where experimental verification is feasible.

The electrical conductivity for liquid hydrogen at high pressure was also determined using Quantum Monte Carlo techniques[2]. The DC conductivity at 3000 K for several densities shows a liquid semiconductor to liquid-metal transition at high pressure in good agreement with shock-wave data.

The equation of state of hydrogen at pressures higher than molecular dissociation was also determined[3]. Good agreement with density-functional theory-based molecular-dynamics calculations for pressures beyond 600 GPa and densities above 1.4 g/cm$^3$ was found for both thermodynamic and structural properties. However, the results differ from chemical models, suggesting that a reinvestigation of planetary models might be needed.

**References**

[1]M.A. Morales, C. Pierleoni, E. Schwegler, and D.M. Ceperley, *Evidence for a First-Order Liquid-Liquid Transition in High-Pressure Hydrogen from Ab Initio Simulations*, Proc. Nat. Acad. Sc. 107, 12799-12803 (2010).

[2]Fei Lin, M.A. Morales, C. Pierleoni, R.M. Martin, and D.M. Ceperley, *Electrical Conductivity of High-Pressure Liquid Hydrogen by Quantum Monte Carlo Methods*, Phys. Rev. Letts. 103, 256401:1-4 (2009).

[3]M.A. Morales, C. Pierleoni, D.M. Ceperley, E*quation of State of Metallic Hydrogen from Coupled Electron-Ion Monte Carlo Simulations,* Phys. Rev. E 81, 021202:1-9 (2010).

For more information, contact:

David Ceperley
ceperley@illinois.edu

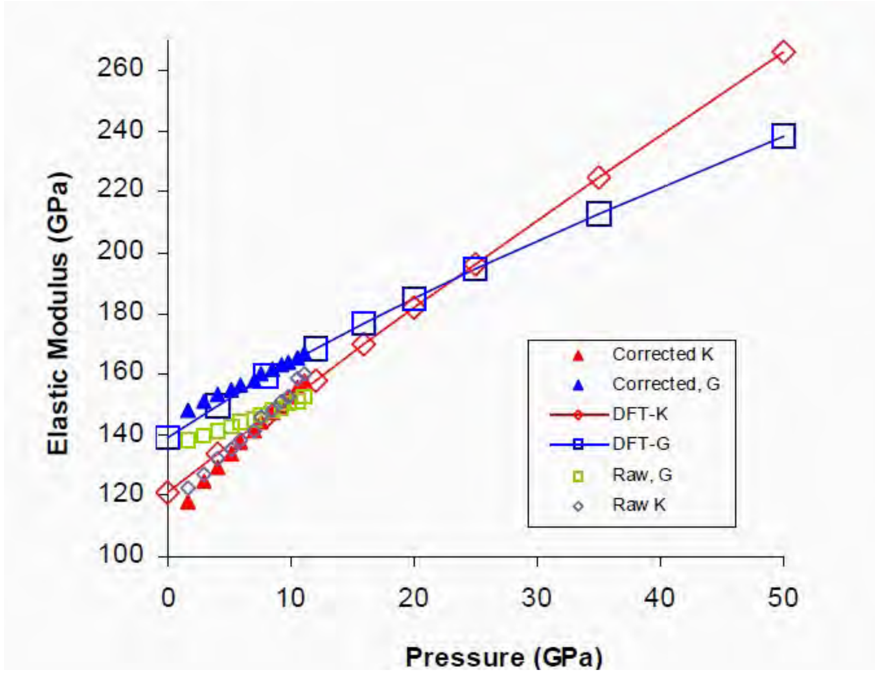
# Thermoelasticity of SSP Materials: An Integrated Ultrasonic and X-radiation Study

Stony Brook University

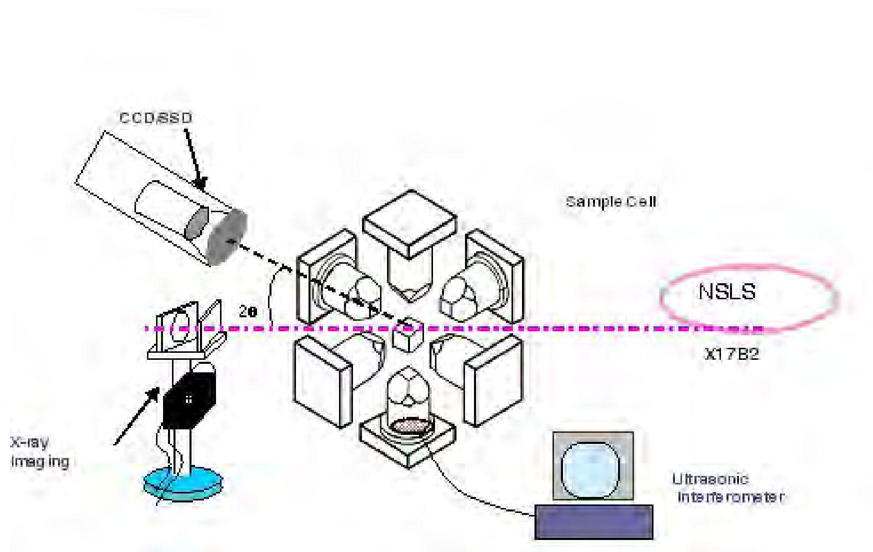
We have conducted experimental and theoretical investigations on the structural behavior and physical properties of various metals (e.g., Be, Mo, Os) that are of special interests to the nuclear Stockpile Stewardship Program. In the integrated experiments, ultrasonic interferometry is used to measure simultaneously the compressional and shear wave travel times ($t_P$ and $t_S$) inside the specimen; at the same time, x-ray diffractions are recorded for the determination of lattice parameters, allowing determination of the unit cell volume (*V*) and density (ρ). X-radiography is employed to capture the image of the specimen for a direct determination of the specimen length (*l*). Thus, compressional and shear wave speeds, $V_P = l/t_P$ and $V_S = l/t_S$, and density are determined simultaneously, from which the elastic bulk modulus $K=\rho V\rho^2-4V_S^2/3)$ and shear modulus $G=\rho V_S^2$ at all P and T conditions are directly calculated (raw data). Final results of $V_p$, $V_s$, *K* and *G* are obtained by correcting the phase shifts caused by the bonding material and interferences from spurious signals to the travel times.

Analyses of the data with finite strain equations and other thermodynamic relations (e.g., Mie-Gruneisen equation of state) yield thermoelastic parameters, including thermal expansion (α), Gruneisen parameter (γ), Debye temperature (Θ), and the respective pressure and temperature derivatives for the bulk and shear moduli ($\partial K/\partial T$,$\partial G/\partial T$). It is worth noting that these experiments determine the pressure directly from the measured K and ρ using the integrated form of K=ρ which provides a means for absolute pressure determination.

Complementary to experimental study, first principles calculations are also performed using the density functional theory (DFT), CASTEP and VASP codes. The results on Be are then compared with those from experiments at room temperature. Both experimental data and DFT calculations at high pressures suggest that the high velocities of Be hold up to the highest pressure range of the current studies (>11 GPa experiment, 50 GPa DFT) with no signs of phase transition. Despite the slight difference in the pressure dependence, the bulk and shear moduli from experiments agree well with those from DFT calculations within the experimental uncertainties (±1%).




A comparison of the elastic bulk and shear moduli for beryllium obtained from the current experiment with DFT calculation.




Schematic of the experimental setup for simultaneous ultrasonic and X-ray measurements.

For more information, contact:

Baosheng Li
Baosheng.Li@sunysb.edu

# Magnetic and Structural Properties of f-electron Systems at High-Pressure: Experiment and Theory

## University of California, Davis

Our research involves an integrated program of state-of-the-art experimental studies (modern x-ray scattering, optical spectroscopy and nuclear magnetic resonance) and advanced modeling techniques (correlated band theories) to develop a fundamental and predictive understanding of the pressure-dependent equation of state and electronic properties (insulator-metal, conductivity, superconducting transitions) of d- and f-electron systems.

### Highlights

1. Proof of principle signal to noise ratio for nuclear magnetic resonance measurements on diamond anvil cell-sized samples.
2. Unraveled unusual features of the layered ternary *sp* conductor NaAlSi.

### Research Progress 1

High-pressure science in recent years has seen dramatic advances. Modern high-pressure diamond anvil cell (DAC) techniques can achieve pressures exceeding 300 GPa, rivaling the pressure at the earth's core, and temperatures from 100 milliKelvin to 1000 K. Owing to the small sample sizes in a DAC, however, significant challenges remain to the goal of merging experimental probes like nuclear magnetic resonance (NMR) with DAC technology.

Graduate student Jim Lin has measured the Cu63 nuclear quadrupole resonance (NQR) signal to noise (SNR) ratio using custom-fabricated microcoils, in volumes ranging from V=0.15 to 10 microliters. Figure 1 shows the microcoil and indenter cell, with one of the next goals being a transition to a DAC. Theoretically, one expects SNR to vary as *V* (black line), a prediction confirmed by the data shown. In order to perform the NQR, Jim had first to tune the NMR circuit with these tiny coils, many of which he made under a microscope. Since the inductances are much smaller than conventionally sized NMR coils, we had to develop new ways to measure the Q factor, find the appropriate capacitances in order to tune the tank circuit, and apply *H*1 pulses. One of the major achievements was to demonstrate

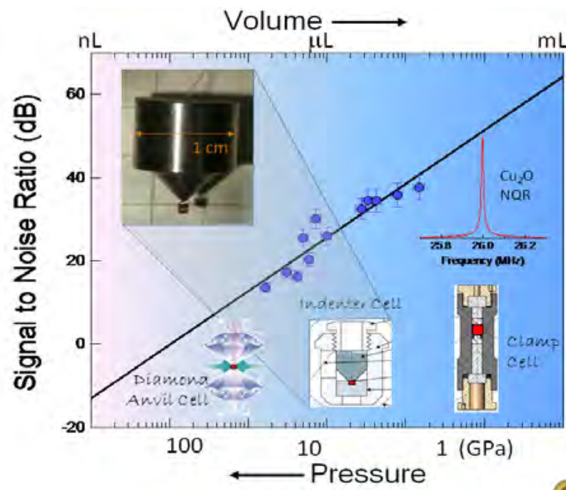



Figure 1. Upper left - Microcoils at the end of a piece of non-magnetic tungsten carbide (NMWC) - part of a custom made indenter cell in the Curro lab. The NMWC piece presses into a hole in a piece of special Ni-Cr-Al alloy, and can achieve pressures up to 5 GPa. With an upcoming upgrade to a new NMR magnet, we will be able to go to the extreme conditions combining high magnetic field, *B* = 11.8T, low temperature, *T* = 1.5K, and high pressure, *P* = 5 GPa.

tuning with microcoils and access the NMR signal. We are clearly able to see signal reliably down to the volumes available in a DAC, but we are going to use some slightly different technology (the embedded coils in the designer diamond culets) to do upcoming experiments.

### Research Progress 2

The discovery of new superconductors brings the potential to understand something deeper, or perhaps something different, about the underlying properties that favor pairing. Graduate student Hahnbidt Rhee led a theory effort (*NaAlSi: A Self-Doped Semimetallic Superconductor with Free Electrons and Covalent Holes*, arXiv:1001.0665) to understand the ternary silicide NaAlSi, an ionic and layered material that shows unexpected superconductivity at 7 K. NaAlSi introduces new interest from several viewpoints, as an *sp* electron system with high $T_c$, due to the similarity of its layered structure with Fe-pnictides, and due to connections with compounds like LiBC and CaAlSi.

Her observations include the determination of the position of the Fermi level (and therefore the superconducting carriers) in a narrow and sharp peak within a pseudogap in the density of states, the deformation potentials induced by Si and Na displacements, and insights into the (non-magnetic) pairing mechanism. Figure 2 shows the symmetry-projected Wannier functions (WFs) projected onto

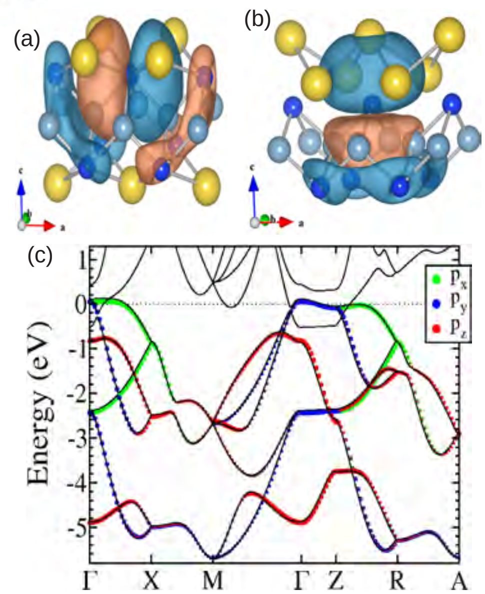



Figure 2. Isosurface of the wave-functions for (a) Si 3px and (b) Si 3pz. Na atoms are large and yellow (light) colored, Si atoms are small and blue (dark) colored. The two colors of the isosurface represent different signs. (c) The tight-binding fatbands band structure is compared to the density functional theory band structure (black lines).

Si 3p orbitals. The extension of the WFs shows considerable involvement from nearby Al and Si atoms, and in addition have some density extending into the Na layers. The positions and overlaps of the wavefunction lobes determine the ability of electrons to move through the lattice.

For more information, contact:

Richard Scalettar
scalettar@physics.ucdavis.edu

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

University of California, San Diego

Using designer diamond anvils, developed by S.T. Weir (Lawrence Livermore National Laboratory) and Y.K. Vohra (University of Alabama, Birmingham), we have recently carried out high pressure experiments on several novel *d*- and *f*-electron materials, to pressures in excess of 1 Mbar and temperatures in the milliKelvin range. We published two early papers reporting the effect of high-pressure on iron-based superconductors, the first post-cuprate materials with superconducting $T_c$'s above 50 K. For $CeFeAsO_{0.88}F_{0.12}$[1], we found that the initial $T_c$ of 44 K is suppressed with increasing pressure. On the other hand, for $LaFeAsO_{0.89}F_{0.11}$ ($T_{co}$ = 28 K) and LaFePO ($T_{co}$ = 7 K)[2], $T_c$ passes through a maximum at 41 and 14 K, respectively. This suggests that higher $T_c$'s may be achieved through chemical substitution.

We measured the electrical resistivity of high purity thorium and praseodymium metals to 40 and 120 GPa, respectively, at temperatures down to 50 mK. The superconducting critical temperature $T_c$ of Th decreases with pressure from 1.4 K to 0.7 K at 10 GPa and, remarkably, then remains nearly constant between 10-40 GPa. Praseodymium shows a large volume collapse near 20 GPa, similar to that observed in cerium metal. Unlike cerium, we find that praseodymium does not develop superconductivity in the collapsed phase.

Rare-earth tritellurides ($RTe_3$) are quasi two-dimensional layered compounds which display two orthogonal charge density waves. In collaboration with I.R. Fisher (Stanford University), we have recently found that, in addition to the magnetic ordering of the localized rare-earth ions that occurs below 10 K, a superconducting state develops below 1 K when a pressure of 1.2 GPa is applied to the samples. We are currently performing AC magnetic susceptibility and AC calorimetry measurements under pressure to determine whether the superconductivity is a bulk phenomenon[3, 4].

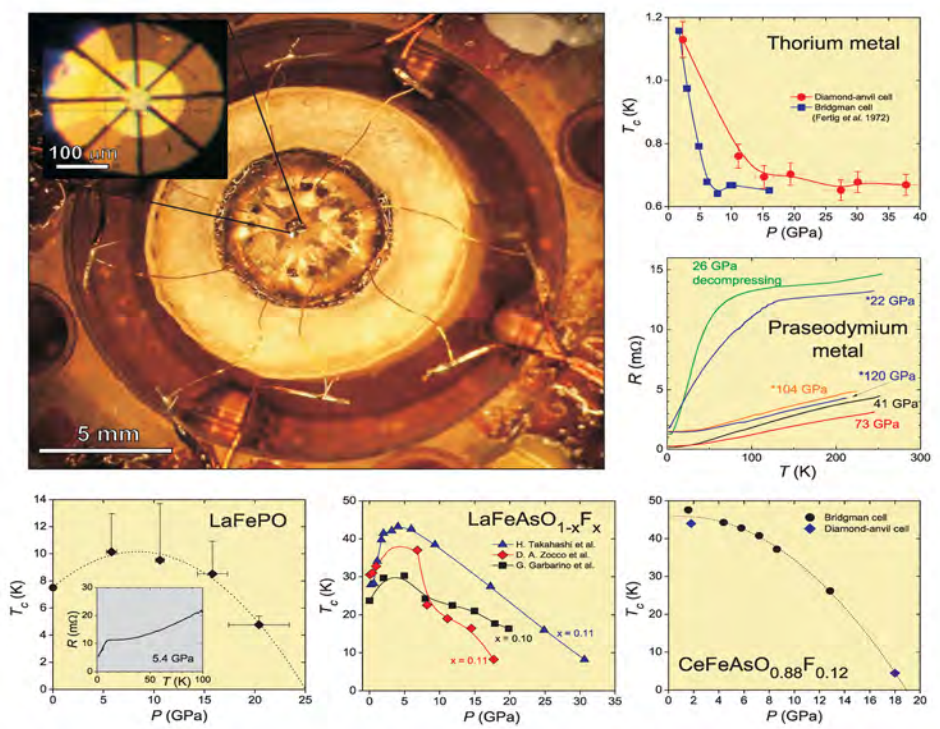



Figure 1. A "designer" diamond anvil wired for electrical resistivity measurements. The tip of this diamond is about 200 mm in diameter, allowing pressures in excess of 1 Mbar. Right - High-pressure studies of the actinide Th-metal and the lanthanide Pr-metal. Bottom - Superconducting temperature $T_c$ versus applied pressure ρ phase diagrams of three Fe-based superconductors.

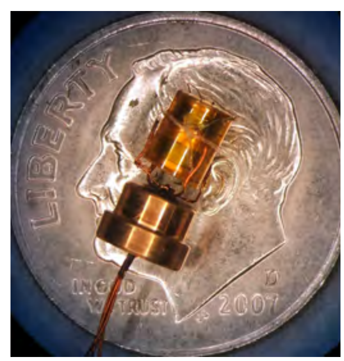


Figure 2. Miniature coil system for sensitive AC magnetic susceptibility measurements, which fits inside our hydrostatic pressure cell.

## References

[1] D.A. Zocco, J.J. Hamlin, R.E. Baumbach, M.B. Maple, M.A. McGuire, A.S. Sefat, B.C. Sales, R. Jin, D. Mandrus, J.R. Jeffries, S.T. Weir, and Y.K. Vohra, *Effect of Pressure on the Superconducting Critical Temperature of* $La[O_{0.89}F_{0.11}]FeAs$ *and* $Ce[O_{0.88}F_{0.12}]FeAs$, *Physica* C 468, 2229 (2008).

[2] J.J. Hamlin, R.E. Baumbach, D.A. Zocco, T.A. Sayles, and M.B. Maple, *Superconductivity in Single Crystals of LaFePO*, Journal of Physics: Condensed Matter 20, 365220 (2008).

[3] D.A. Zocco, J.J. Hamlin, T.A. Sayles, M. B. Maple, J-H. Chu and I. R. Fisher, *High-Pressure, Transport, and Thermodynamic Properties of* $CeTe_3$, Phys. Rev. B 79, 134428 (2009).

[4] J.J. Hamlin, D.A. Zocco, T.A. Sayles, M.B. Maple, J-H. Chu and I.R. Fisher, *Pressure Induced Superconductivity in the Charge Density Wave Compound* $TbTe_3$, Phys. Rev. Lett. 102, 177002 (2009).

For more information, contact:

M. Brian Maple
mbmaple@ucsd.edu

# National Laser Users' Facility
## University of Rochester Laboratory for Laser Energerics

**Introduction**
The National Laser Users' Facility (NLUF) was established in 1979 at the University of Rochester's Laboratory for Laser Energetics (LLE) to provide access for university and industry users to the Omega Laser Facility to conduct basic research in high energy density (HED) science. A competitive solicitation is held every two years by the DOE/NNSA for NLUF program grants. The grants provide experimental time on the Omega Laser Facility, funding for users to support their experiments, and targets fabricated by the DOE/NNSA target support contractor. Grants are awarded competitively; all proposals are independently peer reviewed by a group of highly qualified scientists. During the recent solicitation for FY 2011-12, eleven grants were awarded.

Since inception, the NLUF program has received 306 proposals and 165 have been approved. Over 120 graduate students and post-doctoral fellows have participated in the NLUF program. Currently, 15% of the Omega Laser Facility time is allotted to the NLUF program and no facility operating costs charged to the NLUF users. LLE and NNSA National Laboratory researchers are excluded from being principal investigators on NLUF grants; however, many of the experiments benefit from strong collaborations with LLE and National Laboratory scientists. This article reviews the NLUF experimental capabilities and highlights the exciting results coming from user experiments conducted during the FY 2009-10 grant period.

**Omega Laser Facility**
NLUF users have access to the Omega Laser Facility. The facility includes two of the most powerful lasers in the world: OMEGA–a 60-beam ultraviolet Nd:glass laser capable of producing laser pulses with total peak power of approximately 30 trillion watts (Figure 1); and OMEGA EP–a four-beam Nd:glass laser capable of producing infrared laser pulses with peak power in excess of 1,000 trillion watts or ultraviolet pulses with total energy in the range of 10,000 to 30,000 Joules (see Figure 2). For comparison, the peak electric power generating capability of the United States is less than a trillion watts. The Omega lasers can, therefore, produce peak power in excess of one thousand times the whole U.S. electric grid capacity.

Figure 1. Photograph of OMEGA 60-beam UV laser beamlines showing the power amplifier clusters. The final amplifiers on OMEGA are 20-cm diameter Nd:glass disk amplifiers.

Figure 2. Photograph of the OMEGA EP laser bay during a test shot with all four beam lines firing.

When focused laser light from powerful lasers strike small targets, pressures in excess of tens of millions of atmospheres can be generated with temperatures of many millions of degrees. These HED conditions provide a unique capability for a broad range of fundamental and applied scientific research, including laser-driven inertial fusion and inertial confinement fusion (ICF), carry out studies of laboratory astrophysics, measurements of the equation of state (EOS) of matter under extremely high pressures, studies of the physics of warm-dense matter, studies of relativistic plasmas, and many other HED physics phenomena.

**FY 2009-10 Experiments**

***Systematic Study of Fast-Electron Generation and Transport,* F.N. Beg, University of California, San Diego**
The aim of this experiment is to improve the understanding of the transport of high energy electrons (generated by high intensity laser-matter interactions) through dense plasmas. The ultimate application of this knowledge includes the design of advanced ignition configurations such as fast ignition targets that could achieve very high gain on the National Ignition Facility. The initial results indicate that the electrons have a relatively large divergence when they propagate through a heated foam plasma.

***Experimental Astrophysics on the OMEGA Laser,* R.P. Drake, University of Michigan**
The OMEGA laser can create systems with energy densities that are relevant to astrophysical phenomena. In some astrophysical systems, radiation can have a dominant role in the hydrodynamic behavior of the system. This project explored two types of radiative shocks, a driven radiative shock and a radiative reverse shock. They can be found in supernova remnants, where a fast-moving shock encounters a low-density gas, and in cataclysmic variables, where a supersonic plasma flow is impeded by a dense accretion disk.

***Detailed in Situ Diagnostics of Multiple Shocks,* R.W. Falcone, University of California, Berkeley**
Accurate characterization of dense states of matter is vital for understanding HED experiments, as well as the validation of EOS and plasma model assumptions. X-ray Thomson scattering was used to directly determine the temperature and density of shock-compressed matter[1]. Aluminum and Beryllium foils were shock compressed. A theoretical fit to the spectra allowed the temperature, electron density, and ionization state to be inferred[2].

***EP-Generated X-ray Source for High Resolution 100-200 keV Point Projection Radiography*, U. Feldman, ARTEP Inc.**
A transmission crystal spectrometer capable of measuring the size of the region emitting energetic 20 to 100 keV photons produced by high energy electrons was developed for OMEGA EP and recorded spectra on a number of target shots. The line spectra indicated that although the OMEGA EP beams were tightly focused (30 to 40 microns), the diameter of the hard x-ray emitting area was 350 to 400 microns.

***Development of a Platform for Laser-Ramp Compression of Planetary Materials on OMEGA*, Y.M. Gupta, Washington State University, and T.S. Duffy, Princeton University**
This project developed a high-pressure, low-temperature ramp compression drive, to permit exploration of new regions of thermodynamic space of particular relevance to material conditions found in planetary interiors. Ramp compression achieves high compression at relatively modest temperatures and can be used to extract quasi-isentropic EOS data, study solid-solid phase transitions, and compress materials in the solid state to higher pressures than can be achieved with diamond anvil cell or shock wave methods. An experimental platform for ramp loading of quartz ($SiO_2$) and iron (Fe) was established and tested.

***Measurements of the Equation of State of He/$H_2$ Mixtures Under Deep Planetary Conditions*, R. Jeanloz, University of California, Berkeley**
This project demonstrated that laboratory experiments can provide crucial data to model the interior structure of planets. The immediate goal of these experiments is to measure the EOS of hydrogen and helium warm dense fluids, and to quantify the miscibility gap in hydrogen/helium mixtures. Measurements of He, $H_2$ and $H_2$/He samples have been performed with pre-compressions up to 1.5 GPa. The Hugoniot data on helium have been published.[3,4] The Hugoniot data on $H_2$ and $D_2$ were recently measured, and their analysis is being finalized for publication (Figure 3).

***Three-Dimensional Studies of Low-Adiabat Direct-Drive Implosions on OMEGA*, R.C. Mancini, University of Nevada, Reno**
The emphasis is to develop a quantitative method for spectrally-resolved image data analysis with the goal of determining the three-dimensional (3-D) spatial structure of implosion cores in low-adiabat OMEGA direct-drive implosions. Processing the spectrally-resolved image data recorded with direct-drive multi-monochromatic x-ray imaging systems has shown that 3-D electron temperature and density distributions can be reconstructed.

***Response of BCC Metals to Ultrahigh Strain Rate Compression*, M. Meyers, University of California, San Diego**
The goal was to recover isentropically compressed Tantalum samples of various microstructures, from single crystal to nano crystal, and to measure the loading profile using Aluminum/Lithium Fluoride targets and the VISAR/ASBO instrument on the Omega laser. A total of 12 successful shots were completed resulting in 20 recovered samples and 4 successful drive measurements were obtained.

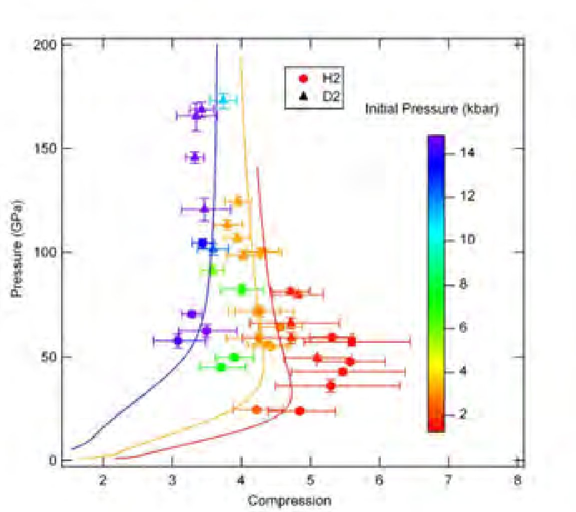



Figure 3. Summary of Hugoniot measurements (pressure versus compression (final/initial density)) collected at Omega on $H_2$ (dots) and $D_2$ (triangles), with the colour scale indicating the initial pressure of the sample. The agreement between $D_2$ and $H_2$ measurements validates the impedance matching construction based on quartz with a Grüneisen EOS of molten $SiO_2$. The full lines represent ab-initio calculations for comparable Hugoniots.

***Proton Radiography of Direct- and Indirect-Drive ICF Experiments and HEDP Plasmas*, R.D. Petrasso and C.K. Li, Massachusetts Institute of Technology**
The MIT-developed method of monoenergetic, charged-particle radiography[5] was used to study electromagnetic fields and plasmas in HED physics and in ICF physics. The team performed the first observations[6] and measurements of indirect drive ICF implosions and self-generated fields using this technique (Figure 4). Proton images are displayed to show proton fluence versus position, providing time-dependent information about field distributions, capsule compression, and hohlraum plasma conditions. A striking feature in these images is a five-pronged, asterisk-like pattern surrounding the imploding capsule, a consequence of the laser beam positions on the hohlraum wall. The spokes are formed between two expanding plasma bubbles that are generated by “nearest neighbor” laser beam pairs.

***Laboratory Experiments of Supersonic Astrophysical Flows Interacting with Clumpy Environments*, P. Hartigan, Rice University**
This project studies how strong shock waves propagate through clumpy media such as those encountered by astrophysical jets as they interact with their nascent molecular clouds. An experimental design was developed that allows the observation of a strong shock as it sweeps past a collection of obstacles in its path. The laboratory work complements new astrophysical images from the Hubble Space Telescope that were taken as part of a previous NLUF program.

***Intense Laser Interactions with Low Density Plasmas Using OMEGA EP*, L. Willingale, A. Maksimchuk, and K. Krushelnick, University of Michigan**
Propagation of high-power, short-duration laser pulses through under-dense plasma is of interest in understanding laser self-focusing, channel and blast wave formation, filamentation, soliton production, electron and ion acceleration, and x-ray generation. The formation of a channel through an under-dense plasma by an intense laser pulse was investigated using proton probing.

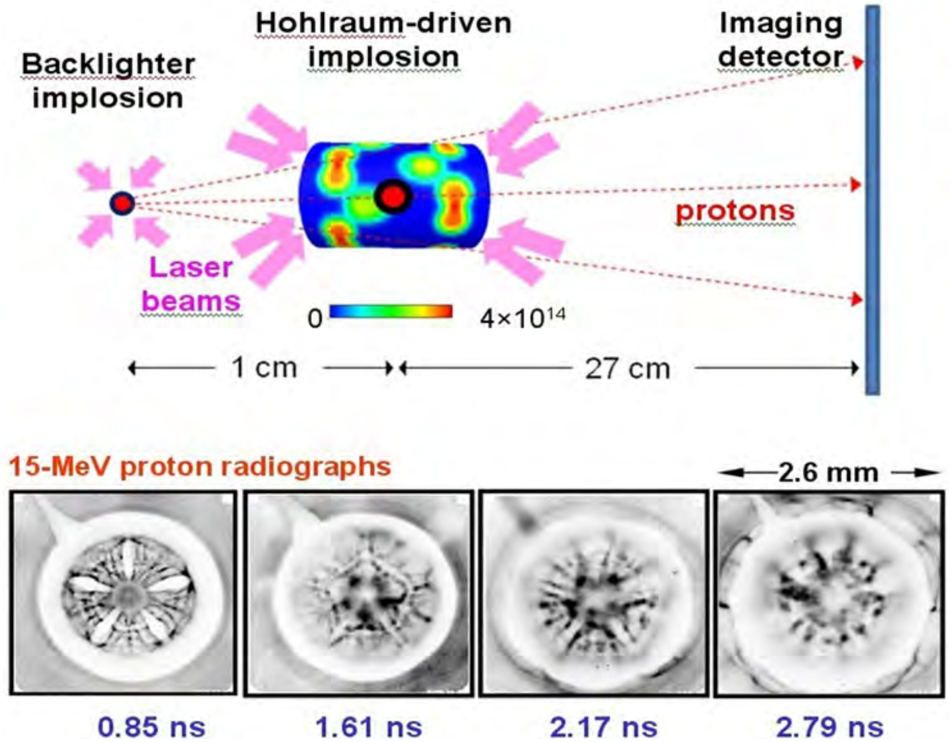



Figure 4. A laser-driven ICF capsule produced monoenergetic 3- and 15-MeV protons through fusion reactions, and the protons were used to make radiographs of another ICF capsule imploded by x-rays generated by the interaction of 30 laser beams with the inner wall of a gold hohlraum. The colors inside the hohlraum wall indicate laser intensity in units of watts per cm$^2$. In the 15-MeV radiographs shown here (recorded at different times during laser drive) the capsule is in the center, the gold hohlraum is the light-colored outer ring, and the patterns between capsule and hohlraum are due to electromagnetic fields and plasma jets. Within each image, darker means higher proton fluence. This work is discussed in *Science*, Vol. 327, page 1231 (2010).

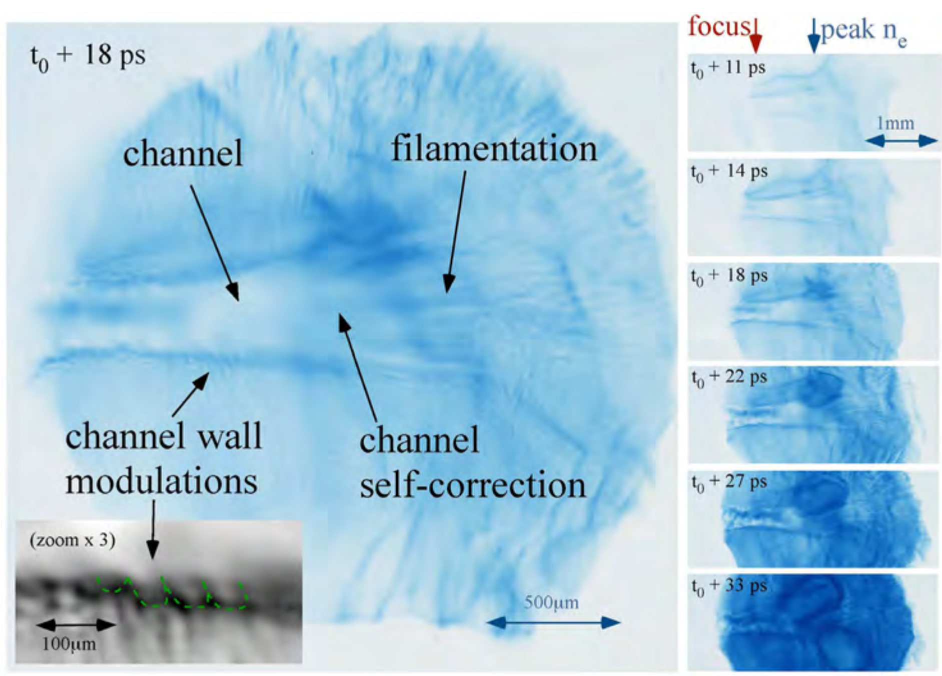



Figure 5 shows the interaction at an early time when the laser was still propagating through the plasma and the proton probe images illustrate the expansion of the channel, filamentation, and channel wall modulations. The time at which the leading edge of the pulse arrived at focus and reaches half-maximum intensity is defined as $t_0$. Self-correction of the filaments into a single channel is seen from the single shot sequence on the right side of Figure 5.

**References**


[1] S.H. Glenzer et al., Phys. Rev. Lett 90, 175002 (2003).
[2] H.J. Lee et al., Phys. Rev. Lett 102, 115001 (2009).
[3] J. Eggert et al., Phys. Rev. Lett 100, 124503 (2008)
[4] P. Celliers et al., Phys. Rev. Lett 104, 184503 (2010)
[5] C.K. Li, et al., Rev. Sci. Instrum 77, 10E725 (2006).
[6] C.K. Li, et al., Science 327, 1231 (2010).


For more information, contact:

John Soures
jsou@lle.rochester.edu

Figure 5. Proton probe images of the laser pulse propagating through the plasma from left to right. The time sequence is shown on the right-hand side and shows channel wall modulations, filamentation and channel self-correction.

## Seth Root, Senior Member of the Technical Staff

Dynamic Material Properties, Sandia National Laboratories

**Years at Sandia**: 2008-2010

**SSAA Program Years:** 2002-2007

**Awards:** ISP Graduate Scholar Award (2002-2007), NNSA Defense Programs Awards of Excellence 2010 (Xenon Equation of State Team)

**What was your Ph.D. research topic?**
My Ph.D. research was on examining physical and chemical changes in multiply shock compressed liquid benzene using optical spectroscopy. I found that benzene did not undergo a liquid-solid phase transition on the sub-microsecond timescale, and at pressures near 25 GPa, I determined that benzene likely polymerized through cycloaddition reactions. This work was performed at the Institute for Shock Physics (ISP) at Washington State University where I earned my Ph.D. in 2007. See the *Journal of Physical Chemistry A*, 113, 1268 (2009).

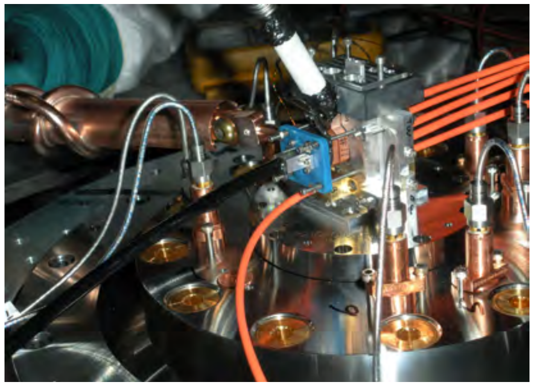
**What NNSA resources were used to perform your Ph.D. research?**
First and most importantly, without NNSA support, the ISP would not exist. It is this support that allows the Institute to maintain an excellent engineering and research staff, and graduate students that perform high quality dynamic and static compression research. Furthermore, because of NNSA's support, the ISP is able to foster the scientific excitement and the risk-taking attitude that is necessary for fundamental research. This support is essential for training graduate students who will be the future scientists at the National Laboratories. More specifically to me, NNSA funded the ISP Graduate Scholar Award I received from 2002-2007, which provided tuition and a stipend. I had access to top-of-the-line diagnostic tools, like streak cameras and framing cameras. I was able to attend the shock conferences because of NNSA as well.

**What specific opportunities were provided by the SSAA Program?**
Through the SSAA Program, the Institute maintains a close connection with scientists at the National Laboratories. The Institute has many visiting scientists give seminars, which are a good opportunity to see the research at the National Laboratories. It is also a good opportunity to meet these scientists, who were always willing to spend time talking with graduate students about the Labs and the students' thesis projects.

**Describe how the SSAA influenced your decision to work at a National Laboratory.**
The Institute's participation with the SSAA allowed me to meet people from all three Labs. I think all three Labs have excellent capabilities and people who are at the pinnacle of science research. In the end, I chose to continue my career at Sandia because I could conduct experiments on the Z machine. I think Z is the world's premier platform for performing high-precision measurements on the behavior of matter at extreme conditions.

**How did your Ph.D. research prepare you for your current responsibilities?**
My Ph.D. research is where I learned to apply my textbook shock physics knowledge. I learned about the technical aspects of experimenting too, such as the nuances of target design and building, and using and understanding the diagnostic tools. A lot of preparatory work is needed just to get one data point in a shock experiment, so you become very detail oriented because a small mistake can ruin an entire experiment that took a week or more to prepare. Also, I learned project management because my advisor gave me freedom with my research, allowing me to explore different ideas and experiments. In the end, the onus was on me to complete my research successfully by producing significant and original results.

**Describe to students what working at a National Laboratory is like and how it differs from graduate school?**
The pay is definitely better than my graduate student stipend. At the Lab, I work on several different research projects, while in graduate school I focused on one research project: benzene. For the benzene work, I did nearly everything from experimental design and building to diagnostics and



data analysis. At Sandia, I have many people helping with the experimental setup so that I have more time to design experiments and analyze data, which is good when you work on several different research projects. The aspect about working at Sandia that I like best is I know my research contributes directly to our national security.

**What is your main focus and current responsibilities now at SNL?**
My main focus is doing high quality research and producing results. I work within the NNSA Science Campaigns where I am studying the shock response of cryogenically cooled gases. I also do research as a part of the Joint Munitions Program with the Department of Defense where I am studying the response of plastic bonded explosives subjected to dynamic compression and developing equation of state models.

**How can we increase interest and encourage other students in HED research and in work at the National Laboratories?**
We need to start introducing people to HED research early in their careers. The National Science Foundation funds the Research Experiences for Undergraduates program, which is a summer research internship program. NNSA should start a similar program that gets undergraduates involved with research at the National Labs or at universities.

Contact: sroot@sandia.gov

## Amy Cooper, Physicist

NIF and Photon Science/High Energy Density Physics, Lawrence Livermore National Laboratory (LLNL)

**How many years have you been employed by a National Laboratory?**
I have been with Lawrence Livermore National Laboratory for almost 4 years.

**When did you participate in the SSAA Program?**
I attended the University of Michigan from 2001-2007, and I was under SSAA support for academic years 2003-2007, plus the summer of 2002. My advisor was Paul Drake.

**What was your Ph.D. research topic?**
My Ph.D. thesis title was "Collapsing Radiative Shock Experiments at Omega." I received my Ph.D. from the University of Michigan in 2007.

**What are your responsibilities at LLNL?**
Currently, I am an experimentalist on the Radiative Transport Integrated Experimental Team. I help plan and execute experiments on the National Ignition Facility (NIF) in a campaign that has stretched over two years. These experiments are assessing evolution of foam features as a radiation wave passes through them. My specific focus is on streaked radiography using a long-duration point-projection backlighter. I was also recently awarded time on NIF for science use experiments to explore Rayleigh-Taylor growth as it applies to the Eagle Nebula.

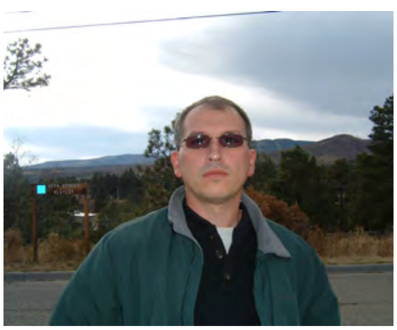
**What specific opportunities were provided by SSAA?**
Support from the SSAA allowed me many opportunities to meet and network with physicists from all over the country. I met interesting people working on stockpile-relevant physics at many conferences, in the course of my work at the Omega facility, and at the DOE/SSAA symposium in 2005. Exposure to such a wide range of interesting problems really made it obvious that I wanted to make a career at a National Laboratory.

Contact: cooper64@llnl.gov

---

## Nenad Velisavljevi, Staff Scientist

Shock and Detonation Physics, Los Alamos National Laboratory (LANL)



**How many years have you been employed by a National Laboratory?**
I've been working at Los Alamos National Laboratory for 4.5 years.

**When did you participate in the SSAA Program?**
From 2000-2005, I attended the University of Alabama at Birmingham. I participated in the SSAA Program the last three years. My advisor was Dr. Yogesh Vohra.

**What was your Ph.D. research topic?**
My research topic was on high pressure structural and electrical properties of f-electron metals, and development of designer diamond anvils for high pressure electrical resistance measurements (University of Alabama at Birmingham, 2005).

**What are your responsibilities at LANL?**
My main focus at the laboratory is on performing research experiments that help us better understand material properties at extreme pressure-temperature conditions. This includes developing new experimental techniques, conducting experiments, and delivering equation of state and pressure-temperature phase diagram on materials of interest to NNSA. Both static and dynamic high pressure techniques are used to investigate a broad range of materials, including metals, polymers, and high explosives.

**What specific opportunities were provided by SSAA?**
First, SSAA provided funding that supported my thesis day-to-day research and equipment costs. Through SSAA, our research group was also a part of the Advanced Photon Source (APS) synchrotron x-ray research facility. By having regular access to APS, I was able to conduct high pressure x-ray diffraction experiments, which cover a large portion of my research thesis work. In addition to overall research support, SSAA helped support a number of workshops and meetings. Attending these meetings and workshops provided me with the opportunity to interact with various National Laboratory and DOE/NNSA-sponsored university researchers. From these interactions, I gained a better understanding of research needs and opportunities across the DOE-NNSA complex.

Contact: nenad@lanl.gov

# SSAA Program Research Grants

## Stewardship Science Academic Alliances

### High Energy Density Physics

**Cornell University**
Bruce Kusse
D. Hammer
Center for the Study of Pulsed-Power-Driven High Energy Density Plasmas

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

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

**University of Nevada, Reno**
Aaron Covington
High Energy Density Research

**University of Nevada, Reno**
Victor Kantsyrev
Experimental Studies of Implosion Characteristics and Radiation Properties of Planar and Cylindrical Wire Arrays and X-pinches

**University of Nevada, Reno**
Alla Safranova
Theoretical X-ray/EUV Spectroscopy and Imaging Studies of Wire Array and X-pinch Plasmas

**University of Texas at Austin**
Todd Ditmire
The Texas Center for High Intensity Laser Science

**University of Wisconsin**
Ricardo Bonazza
Investigation of Rayleigh-Taylor and Richtmyer-Meshkov Instabilities

### Low Energy Nuclear Science

**Brigham Young University**
Lawrence Rees
Development and Testing of an Inexpensive Capture-Gated Neutron Spectrometer

**Colorado School of Mines**
Uwe Greife
Fission Fragment Distribution Measurements at the ALEXIS Facility of LLNL

**Duke University**
Anton Tonchev
Precision Photo-Induced Cross-Section Measurements Using the Monoenergetic and Polarized Gamma Beams at HI$\gamma$S

**Duke University**
Werner Tornow
Neutron Induced Reaction on Specific Nuclei

**North Carolina State University**
Gary Mitchell
Cross Sections, Level Densities and Strength Functions

**Ohio University**
Carl Brune
Studies in Low Energy Nuclear Science

**Rensselaer Polytechnic Institute**
Yaron Danon
Experiments with a Lead Slowing-Down Spectrometer and Fission Neutrons

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

**Texas A&M University**
Robert Tribble
Development of New Techniques to Determine Neutron Induced Reaction Rates

**University of California, Berkeley**
Heino Nitsche
Neutron-Induced Fission Cross Section Measurements on Rare Actinide Isotopes: Americium-240 and Uranium-237

**University of Cincinnati**
Henry Spitz
Design and Fabrication of a Novel, Multi-Element Scintillation Detector Exhibiting Enhanced Energy and Spatial Resolution for Measuring Low Energy Photons

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

**University of Michigan**
Sara Pozzi
Digital Waveform Sampling of Neutron and Gamma Ray Signals from Scintillation Detectors for Pulse Shape Discrimination and Pulse Height Analysis

**University of Nevada, Las Vegas**
Ralf Sudowe
Neutron Capture Measurements on $^{171}$Tm and $^{147}$Pm

**University of Richmond**
Con Beausang
Nuclear Stewardship Research at the University of Richmond

**University of Tennessee**
Witold Nazarewicz
Microscopic Description of the Fission Process

### Properties of Materials Under Extreme Conditions

**Arizona State University**
Pedro Peralta
Incipient Spall in Metallic Materials: A Three Dimensional Study of the Microstructural Characteristics of Damage Nucleation Sites

**Carnegie Institution of Washington**
Russell Hemley
Center of Excellence for High Pressure Science and Technology

**Florida State University**
Stan Tozer
Electron Interactions in Actinides and Related Systems under Extreme Conditions

**Harvard University**
Stein Jacobsen
Soft X-Ray Shock Loading and Momentum Coupling in Meteorite and Planetary Material

**Harvard University**
Isaac Silvera
Hydrogen and Its Isotopes at High Pressure

**Stony Brook University**
Baosheng Li
Thermoelasticity of SSP Materials: An Integrated Acoustic and Diffraction Study at High-P and High-T

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

**University of Alabama**
Yogesh Vohra
Structural and Magnetic Studies on Heavy Rare Earth Metals at High Pressures using Designer Diamonds in Support of the Stockpile Stewardship Program

**University of California, Berkeley**
Roger Falcone
Structure and Dynamics of Materials under Extreme Conditions

**University of California, Davis**
Nigel Browning
Enhanced Functionality for Materials Analysis in the DTEM

**University of California, Davis**
Richard Scalettar
Magnetic and Structural Properties of f-electron Systems at High Pressure: Experiments and Theory

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

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

**University of Illinois, Urbana-Champaign**
Ian Robertson
Dynamic Response of Nanostructured Single and Multilayer Metals

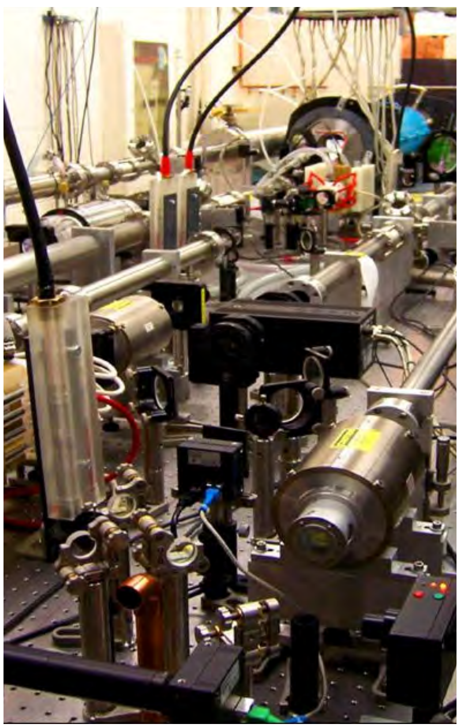
## Properties of Materials Under Extreme Conditions (continued)

**University of New Mexico**
Peter Vorobieff
Shock-Driven Multiphase Hydrodynamics Experiments for Hydrocode Validation

**University of Nevada, Las Vegas**
Zhao Yusheng
Science Based Stockpile Stewardship Collaborative Research Development

**University of Washington**
Evan Abramson
Viscosities of Highly Compressed Fluids

**Washington State University**
Yogendra M. Gupta
Institute of Shock Physics at WSU



Leopard laser at the University of Nevada, Reno (see page 9).

## High Energy Density Laboratory Plasmas (NNSA Sponsored)

**Harvard University**
Stein B Jacobsen
Planetary Science and Astrophysical Applications of Experimental Studies with the SNL Z Facilities

**Massachusetts Institute of Technology**
Petrasso, Richard
Studying Fields and Matter in HED Plasmas, Hohlraums and ICF Implosions, Using Monoenergetic Proton and Alpha Radiography and Fusion-Product Spectrometry

**Ohio State University**
Anil Pradhan
Laboratory Tests of Stellar Interior Opacity Models

**Polymath Research Inc.**
Bedros Afeyan
Optical Mixing Techniques for Taming Laser Plasma Instabilities in High Energy Density Laboratory Plasmas

**University of California, Los Angeles**
Warren Mori
Parallel PIC Simulations to Laser and Electron Transport Through Plasmas Under Conditions Relevant to ICF and HEDS

**University of California, San Diego**
Hoanh Vu
Study of Laser Plasma Instabilities Generation of Hot Electrons That Adversely Affect Fusion Target Compression

**University of Colorado**
Henry Kapteyn
Coherent Imaging Studies of High Density Femtosecond Laser Plasmas

**University of Michigan**
Paul Drake
Center for Laser Experimental Astrophysics Research (CLEAR)

**University of Nevada, Reno**
Roberto Mancini
Experiments and Modeling of Photoionized Plasmas at Z

**University of Nevada, Reno**
Yasuhiko Sentoku
Enabling Numerical Modeling of Extreme-Intensity Laser-Produced Hot Dense Plasma

**University of Texas at Austin**
Todd Ditmire
Experimental Study of the Equation-of-State in Dense, Strongly-Coupled Plasma

## National Laser Users' Facility (FY 2011-2012)

**General Atomics**
Rich Stephens
Investigation of Laser to Electron Energy Coupling Dependence on Laser Pulse Duration and Material Composition

**Massachusetts Institute of Technology**
Richard Petrasso
Charged Particle Probing of Inertial Confinement Fusion Implosions and High Energy Density Plasmas

**Princeton University**
Thomas S. Duffy
Ramp Compression for Studying Equations of State, Phase Transformations, and Kinetics on OMEGA

**Princeton University**
Anatoly Spitkovsky
Collisionless Shocks in Laboratory High Energy Density Plasmas

**Rice University**
Patrick Hartigan
Clumpy Environments and Interacting Shock Waves: Realistic Laboratory Analogs of Astrophysical

**University of California, Berkeley**
Roger Falcone
Detailed in Situ Diagnostics of Higher Z Shots

**University of California, Berkeley**
Raymond Jeanloz
Recreating Planetary Core Conditions on OMEGA

**University of California, San Diego**
Farhat Beg
Systematic Study of Fast Electron Transport in Imploded Plasmas

**University of Michigan**
Paul Drake
Experimental Astrophysics on the OMEGA Laser

**University of Michigan**
Karl Krushelnick
Intense Laser Interactions with Low Density Plasma Using OMEGA EP

**University of Nevada, Reno**
Roberto Mancini
Investigation of Hydrodynamic Stability and Shock Dynamics in OMEGA Direct-drive Implosions using Spectrally Resolved Imaging

STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP

SSGF
STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP

www.krellinst.org/ssgf

Department of Energy National Nuclear Security Administration

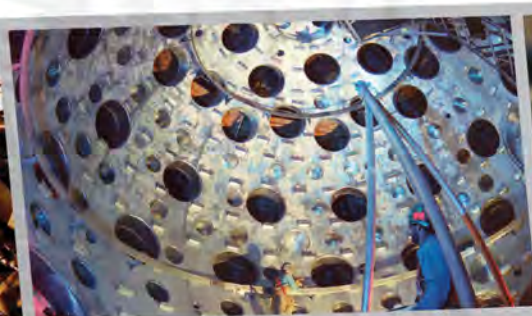
# Stewardship Science Graduate Fellowship

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

## BENEFITS

- $36,000 yearly stipend
- Payment of all tuition and fees
- $1,000 yearly academic allowance
- Yearly conferences
- 12-week research practicum
- Renewable up to four years

▲ Germanium Array for Neutron-Induced Excitations at Los Alamos Neutron Science Center - courtesy of Los Alamos National Laboratory



▲ The 10-meter diameter target chamber of the National Ignition Facility (NIF) was assembled from 10-centimeter-thick aluminum panels. Holes in the chamber provide access for the laser beams and viewing ports for NIF diagnostics - courtesy of Lawrence Livermore National Laboratory

▲ A z-pinch wire array is prepared for shooting on the Z inertial confinement fusion facility at Sandia National Laboratories in New Mexico - courtesy of Sandia National Laboratories

Krell Institute | 1609 Golden Aspen Drive, Suite 101
Ames, IA 50010 | 515.956.3696
email: ssgf@krellinst.org | www.krellinst.org/ssgf

NNSA National Nuclear Security Administration

KRELL institute

FOR MORE INFORMATION OR TO APPLY ONLINE

**www.krellinst.org/ssgf**

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


EXIT
NEVADA
NNSA
National Nuclear Security Administration