For more than 60 years, Sandia National Laboratories has delivered essential science and technology to resolve the nation's most challenging security issues. Sandia's research staff works at the forefront of innovation, collaborating in research with universities and companies and pursuing discretionary research projects with significant potential impact. The Pulsed Power Sciences Center at Sandia is the steward of pulsed power science and applications for the United States. We perform high energy density experiments on the Z facility and other facilities at Sandia and throughout the country.

Sandia offers fellowship opportunities in the following research areas:

Pulsed-power science and engineering, and accelerator design

Pulsed-power accelerators are "engines of discovery" for national security missions. Pulsed-power accelerators deliver megajoules of energy to milligrams of matter on nanosecond time scales. Such machines achieve unprecedented and extreme states of matter over macroscopic volumes, and drive a wide variety of high-energy-density-physics experiments in support of the U.S. Department of Energy's national security mission and to advance the fundamental understanding of these extreme states of matter. These accelerators have enabled access to such conditions in the laboratory, for the first time.

The Pulsed Power Sciences Center at Sandia National Laboratories develops the world's most advanced pulsed-power-accelerator technology. We apply the technology to the development of superpower accelerators; i.e., those that deliver a multi-terawatt electromagnetic pulse to an experimental assembly that serves as the electrical load of the accelerator. Various types of experimental assemblies are fielded by the user community, who conduct inertial-confinement-fusion, material-science, x-ray-radiographic, weapon-effects, radiation-physics, laboratory-astrophysics, and other experiments in support of DOE programs.

We conduct accelerator-physics experiments on Sandia's Z machine, which generates an 85-terawatt 26-megampere 100-nanosecond electrical-power pulse. (The steady-state electrical-power-generating capacity installed worldwide is 16 terawatts.) Z is – by far – the world's largest and most powerful pulsed-power accelerator. Z experiments routinely deliver megajoules of electrical energy with nanosecond precision to an experimental assembly. Z-pinch loads driven by the Z accelerator, which are among the world's most powerful x-ray sources, radiate as much as 2.2 megajoules and 330 terawatts in a 5 nanosecond pulse.

We also conduct experiments on a number of other pulsed-power machines that are owned and operated by the Pulsed Power Sciences Center. These generate peak electrical powers that range from 5 gigawatts to 500 gigawatts. The experiments are establishing the technical foundation that will be necessary to develop next-generation pulsed-power accelerators, such as Centipede, Thor, Neptune, and Jupiter.

Centipede is a four-pulse 2-kilojoule 5-gigawatt accelerator that is serving as a prototype for a future 2-MV precision electron-beam machine. The machine will serve as the injector for a 20-MeV linear-induction accelerator (LIA). The LIA will drive advanced x-ray-radiographic experiments.

Thor will be a 200-kilojoule 1-terawatt pulsed-power accelerator that generates pressures on the order of 1 megabar for advanced material-physics experiments. Neptune will be a 5-megajoule 28-terawatt machine that generates pressures on the order of 10 megabars.

Jupiter will be a 140-megajoule 960-terawatt accelerator that delivers 67 megamperes and 9 megajoules to a physics load. The principal goal of Jupiter will be to resolve fundamental questions about our ability to achieve thermonuclear fusion ignition and high fusion yields in the laboratory by achieving fusion yields in excess of 10 MJ.

In addition to conducting accelerator-physics experiments, Sandia's Pulsed Power Sciences Center develops mathematical models of pulsed-power components, systems, and accelerators, and performs analytic calculations and numerical simulations.

The principal goals of the work we do are to improve the understanding of accelerator physics; apply the understanding to the development of advanced accelerator technology; use the technology to upgrade Z and other pulsed-power machines; and establish the technical foundation for scaling to new systems, upon which we will build next-generation pulsed-power accelerators, such as Neptune or Jupiter, in support of the national-security mission.

There are a broad range of possible projects in pulsed power science or accelerator science available for the Laboratory Residency Graduate Fellowship program. Our goals include developing the science and technology to scale driver output upwards by a factor of 10, improving our understanding of, and increasing the efficiency of current delivery to HED experiments of interest, improving the performance of high voltage systems, developing new diagnostic techniques to assess high power systems, and developing highly reliable and compact pulsed power systems for multiple applications.

We publish the results of our work in premier peer-reviewed physics and engineering journals, and are committed to maintaining a strong publication record.

Several of our recent peer-reviewed pulsed-power-accelerator publications

- K. R. LeChien et al., "6.1-MV, 0.79-MA laser-triggered gas switch for multimodule, multiterawatt pulsed-power accelerators," Phys. Rev. ST Accel. Beams **13**, 030401 (2010).

- J. P. Martin, M. E. Savage et al., “Tailoring of electron flow current in magnetically insulated transmission lines,” Phys. Rev. ST Accel. Beams **12**, 030401 (2009).
- M. G. Mazarakis et al., “High current, 0.5-MA, fast, 100-ns, linear transformer driver experiments,” Phys. Rev. ST Accel. Beams **12**, 050401 (2009).
- R. D. McBride et al., “Displacement current phenomena in the magnetically insulated transmission lines of the refurbished Z accelerator,” Phys. Rev. ST Accel. Beams **13**, 120401 (2010).
- D. B. Reisman, B. S. Stoltzfus et al., “Pulsed power accelerator for material physics experiments,” Phys. Rev. ST Accel. Beams **18**, 090401 (2015).
- D. V. Rose et al., “Computational analysis of current-loss mechanisms in a post-hole convolute driven by magnetically insulated transmission lines,” Phys. Rev. ST Accel. Beams **18**, 030402 (2015).
- M. E. Savage and B. S. Stoltzfus, “High reliability low jitter 80 kV pulse generator,” Phys. Rev. ST Accel. Beams **12**, 080401 (2009).
- W. A. Stygar et al., “Analytic model of a magnetically insulated transmission line with collisional flow electrons,” Phys. Rev. ST Accel. Beams **9**, 090401 (2006).
- W. A. Stygar et al., “Energy loss to conductors operated at lineal current densities ≤10 MA/cm: Semianalytic model, magnetohydrodynamic simulations, and experiment,” Phys. Rev. ST Accel. Beams **11**, 120401 (2008).
- W. A. Stygar et al., “55-TW magnetically insulated transmission-line system: Design, simulations, and performance,” Phys. Rev. ST Accel. Beams **12**, 120401 (2009).
- W. A. Stygar et al., “Conceptual design of a 10^{13}-W pulsed-power accelerator for megajoule-class dynamic-material-physics experiments,” Phys. Rev. Accel. Beams **19**, 070401 (2016).
- W. A. Stygar, K. R. LeChien, M. G. Mazarakis et al., “Impedance-matched Marx generators,” Phys. Rev. Accel. Beams **20**, 040402 (2017).
- T. C. Wagoner et al., “Differential-output B-dot and D-dot monitors for current and voltage measurements on a 20-MA, 3-MV pulsed-power accelerator,” Phys. Rev. Accel. Beams **11**, 100401 (2008).
- D. R. Welch et al., “Optimized transmission-line impedance transformers for petawatt-class pulsed-power accelerators,” Phys. Rev. Accel. Beams **11**, 030401 (2008).
- J. R. Woodworth et al., “Compact 810 kA linear transformer driver cavity,” Phys. Rev. Accel. Beams **14**, 040401 (2011).

Radiation magneto-hydrodynamics/nuclear astrophysics

Radiation magneto-hydrodynamics and nuclear physics studies of high energy density plasmas are an ongoing and very active research effort at Sandia, in simulations and experiments. This research is essential for the inertial confinement fusion (ICF) program which relies on complex, integrated, multi-physics simulations and accurate physics models. Detailed atomic physics models and non-LTE radiation production and transport are key to the development of advanced radiation sources. These sources are developed for the radiation effects sciences program (RES) which is responsible for testing and predicting the response of materials and systems to extreme radiation environments. Fundamental research is also being performed in radiation and diffusive transport, magnetically driven plasma instability growth, and the effects of magnetic field on fundamental transport properties including charged particles in fusing plasmas.

Our current research effort in fusion includes a target concept known as Magnetized Liner Inertial Fusion (MagLIF). In MagLIF, deuterium fuel is magnetized with external magnetic field coils, heated using a multi-kJ laser, and compressed by a plasma liner with the large Z machine currents. By pre-magnetizing the fusion fuel, electron thermal conduction losses are suppressed which in turn reduces requirements on implosion velocity, target convergence, and stagnation pressure compared to traditional ICF approaches. MagLIF has already demonstrated significant fusion yields and the key principles of magneto-inertial fusion [M.R. Gomez et al., Phys. Rev. Lett. 113, 155003 (2014)]. Significant work remains, however, to better understand details of these targets and how they scale to larger fusion yields. Our goal is to create thermonuclear yields greater than the energy delivered to the fusion fuel, which simulation codes suggest may be possible on Z.

In addition to our fusion research on Z, laser propagation and heating of deuterium fuel is studied with world-class laser capabilities including the Z Beamlet and Z Petawatt lasers in dedicated experimental chambers. Sandia researchers are also performing laser heating experiments on all the largest laser facilities in the world including OMEGA, OMEGA-EP, and NIF as part of a broader collaborative effort.

There are a broad range of possible projects in large scale radiation magneto-hydrodynamic and other simulation techniques available for the Laboratory Residency Graduate Fellowship program. Our goals include developing improved codes and algorithms, developing higher fidelity simulations of existing experiments, and developing improved target designs that address the non-ideal behavior of existing targets.

Atomic physics and visible/UV/x-ray spectroscopy

Atomic Physics and Applied Spectroscopy are core elements of the High Energy Density (HED) Science and Inertial Confinement Fusion (ICF) programs at Sandia. Each area has vibrant and active research efforts within the Pulsed Power Sciences Center including theoretical, computational, and experimental activities. Spectroscopy is among the most powerful diagnostic techniques available to probe the mysteries of the HED plasma conditions at the smallest spatial and temporal scales, and under the hottest and densest conditions. Spectroscopic techniques have been used to directly measure plasma electric and magnetic fields, plasma spatial structure, and plasma fusion conditions including densities, temperatures, impurity mix, and many other properties. Plasma spectroscopy is an essential element of discovery science in HED and ICF plasmas [Rochau et al., Phys. Plasmas, 17, 055501 (2010), Rochau et al., Phys. Plasmas, 21, 056308 (2014)].

Atomic Physics. Complete atomic physics models are critical to modeling the equation of state, opacity, and detailed radiation transport in HED plasmas. Research in this area focuses on atomic processes in dense plasmas including effects on the ionization, energy level structure, and spectral line shapes. Researchers work with the international community to implement the latest models and test predictions against experimental data from HED facilities around the world. Focused experiments are also done on the Z Facility in collaboration with multiple Universities and National Laboratories to study the opacity of plasmas at stellar interior conditions [Bailey et al., Nature 517, 56 (2015)], the characteristics of photoionized plasmas like those found around black holes [Loisel et al., PRL 119, 075001 (2017)], and the effects of plasma density on spectral line shapes observed from white dwarf stars [Falcon et al., HEDP 9, 82 (2013)].

Applied Spectroscopy. Visible and x-ray spectroscopy is a key diagnostic technique for determining the characteristics of a plasma including the temperature, density, composition, ion velocity, and electric and magnetic field strength. The Pulsed Power Sciences Center has a world-leading capability to measure and interpret spectra from ICF and HED plasmas. As an example, the Z Pulsed Power Facility has over 15 spectrometers for observing x-ray and visible spectra including instruments that can achieve resolving powers of $E/\Delta E > 4000$ for the detailed study of line structure and relative line strengths. In addition to utilizing these capabilities to advance the understanding of ICF, HED, and basic atomic physics, Researchers also work with the international community to advance the understanding of spectroscopy instrumentation as published in the recent work by Loisel [Loisel et al., RSI 87, 11D613 (2016)], Harding [Harding et al., RSI 86, 043504 (2015)], and Schollmeier, [Schollmeier et al., RSI 87, 123511 (2016)]. Visible spectroscopy is being used to probe power flow physics to improve our understanding of pulsed power physics at the highest power densities [Gomez et al, PRAB, 010401, 2017)].

There are a broad range of possible projects in atomic physics or applied spectroscopy available for the Laboratory Residency Graduate Fellowship program. There may be opportunities to join an active team that is part of the Z Fundamental Science program.

Dynamic materials/shock physics

In multi-physics computer simulations, the equation of state (EOS) and transport properties like electrical- and thermal conductivity determine how energy shifts between temperature and compression and how current, heat, or magnetic fields diffuse through a system. High-fidelity equations of state and other material models are therefore necessary to model and understand a broad range of systems where matter is taken into extreme conditions, including the structure of earth- and giant planets, planetary impacts, High Energy Density (HED) and Inertial Confinement Fusion (ICF) experiments, and national security applications. *It is difficult to overstate the importance of using high-fidelity material models when performing multi-physics* *hydrodynamic simulations, a critical activity at all NNSA National Laboratories and at many academic institutions interested in shock-physics, geoscience, astrophysics, and fusion.*

In the HED Material Physics research group, we employ and develop a broad range of experimental techniques and theoretical methods to create, diagnose, and theoretically model matter under extreme conditions. At present, EOS properties are measured at multiple Sandia facilities: the STAR facility (Shock Thermodynamic Applied Research) holds several powerful gas guns/launchers and a range of diagnostics; the DICE facility (Dynamic Integrated Compression Experimental) with a small launcher and the 2.6 MA pulsed power machine VELOCE; the first next-generation pulsed power platform THOR, and finally the flagship facility Z. The Z-machine is the world's most powerful pulsed-power accelerator capable of creating many Mbars of pressure (1 Mbar is one million atmospheres pressure, the core of the earth is at 4 Mbar) and has been used for over a decade to take data with un-paralleled accuracy.

In addition to the experimental capabilities, our dynamic material properties program has a distinguished record of collaborative efforts between experiments and corresponding ab initio calculations, principally those with density functional theory (DFT). Theory is used in direct simulation of experimental conditions achieved on Z and other platforms and these calculations have been critical to developing high-fidelity physics models for the design and simulation of Z experiments. Use of DFT is now routine for calculating equations of state and electrical and thermal conductivities. Parallel to applying DFT, we also rely on Quantum Monte Carlo (QMC), QMC is an advanced method for calculating properties of materials based on the electronic structure of the material. The dramatic increase in computational capabilities has made QMC a viable method for calculating properties of real materials not only model systems.

The research in the MED Material Physics group has over the last decade resulted in a number of scientific discoveries, including the triple point of diamond/liquid/BC8 phases of carbon (M.D. Knudson, Science **322**, 1822 (2008), determination of high-pressure properties of xenon (S. Root, Physical Review Letters **105**, 085501 (2010)), quantifying the vaporization threshold of iron (R.G. Kraus, Nature Geoscience **8**, 269 (2015)), and the metallization of hydrogen (M.D. Knudson, Science **348** 1455 (2015)).

Present research activities include development of temperature and x-ray diffraction diagnostics on Z, development of a pre-compression cell capability for use on Z, experimental studies of phase-transition kinetics using the new pulsed-power facility THOR, and pioneering use of the Dynamic Compression Sector at the Advanced Photon Source at Argonne National Laboratory for time-resolved x-ray diffraction of dynamic compression. On the theory side, we are working on development of quantum monte carlo methods for studying phase-transitions in solids, perform research in time-dependent density functional theory methods for calculations of transport properties of matter under extreme conditions, and do development of equation of state tables with advanced methods including uncertainty quantification.

The HED Material Physics research group has a broad range of possible projects available for the Laboratory Residency Graduate Fellowship program. There may be opportunities to join an active team that is part of the Z Fundamental Science program.

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