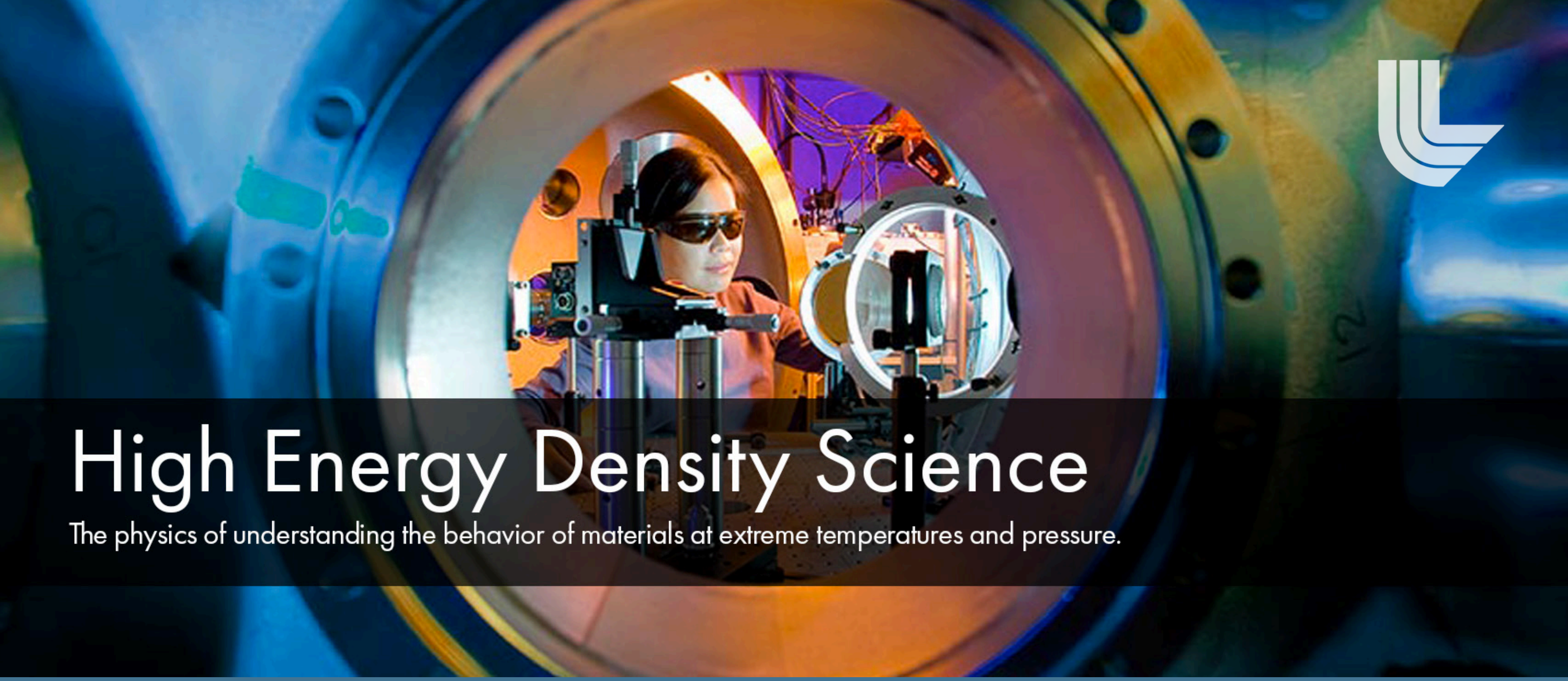


High Energy Density Science

The physics of understanding the behavior of materials at extreme temperatures and pressure.

Introduction

High Energy Density (HED) science, exemplified by the National Ignition Facility (NIF), explores matter under extreme conditions, generating temperatures higher than 180 million degrees Fahrenheit and pressures of more than 100 billion Earth atmospheres. This combination of high temperature and high pressure results in matter where energy has been concentrated in space and time.

This research reveals new frontiers in materials science by measuring properties linking the pressure, temperature, density, and structures of materials, known as the equation of state (EOS) and the transfer of radiation at unprecedented pressures and temperatures. By replicating celestial objects' properties in the lab, NIF aids in understanding stars and their energy mechanisms important to astrophysics. HED experiments yield essential data for understanding nuclear weapons' conditions, validating weapon simulation codes, advancing inertial confinement fusion, and related areas of national security.

HED research opens doors to studying unique states of matter and their applications. LLNL uses world-class facilities to advance understanding of HED physics while developing leading diagnostics, new platforms, and new theoretical and computational capabilities.

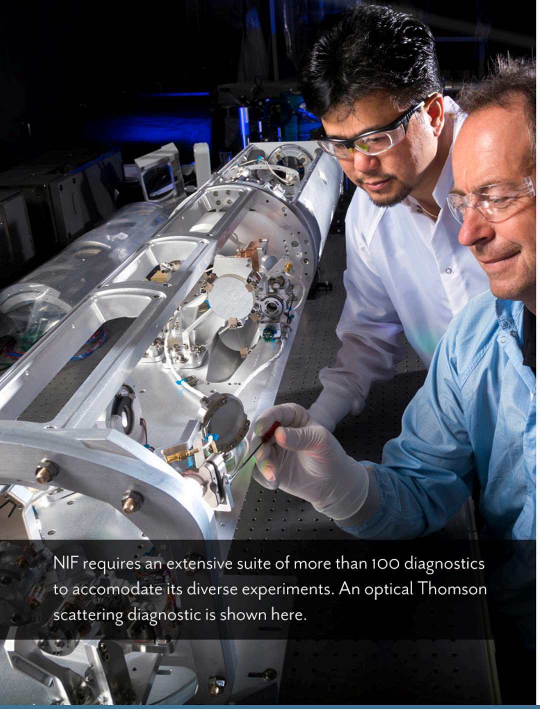
Applications

The Laboratory's heritage of expertise in HED science has led to an innovative and collaborative staff cohort, including creative and visionary laser and plasma physicists, materials scientists, chemists, computer scientists, engineers, technicians and analysts supported by health and safety experts and administrators. Their work advances inertial confinement fusion research and supports mission-critical work in nuclear deterrence and energy security.

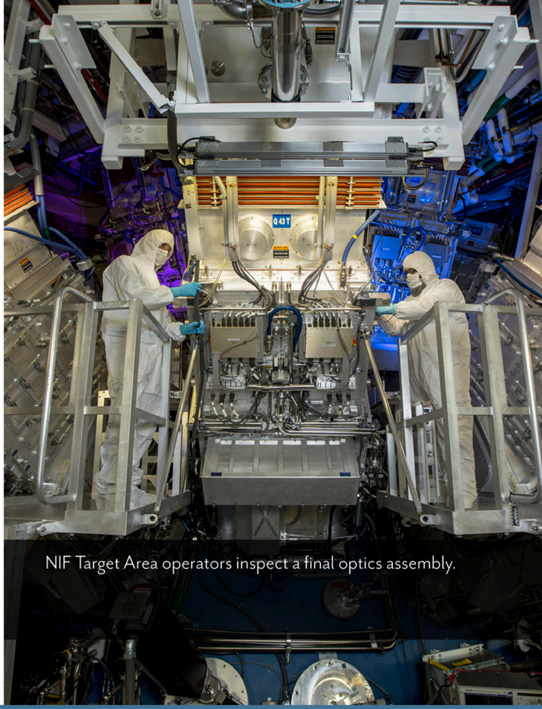
In support of the National Nuclear Security Administration stockpile stewardship mission, HED science research provides experimental data and important insights about the materials used in nuclear weapons as they age or are subjected to the immense pressures and temperatures of a thermonuclear explosion. Data from HED experiments help inform and validate 3D weapon simulation computer codes and foster a fuller understanding of weapon physics.

Further applications of HED expertise at the Laboratory include:

- Offering opportunities for scientists and engineers to access world-class experimental facilities and collaboratively explore matter and energy under extreme conditions at the High Energy Density Science (HEDS) Center. The HEDS Center engages a growing HED research community through outreach activities, including guest researchers, named fellowships, and HED programs at universities.
- Delivering leading-edge science and supporting the high energy density science research community with access to high-energy and high-power laser platforms at the Jupiter Laser Facility (JLF).
- Applying HED physics to the design and analysis of inertial confinement fusion experiments and closely related areas of astrophysics, such as stellar structure and supernovae.
- Generating ultra-short, intense x-ray and neutron sources.
- Measuring the strength of materials at extreme temperature and pressures on ultra-short time scales, including turbulent mixing between materials at high compression rates.
- Determining structural phase changes of materials, such as melting and recrystallization, or transitions between crystal lattice structures.


NIF requires an extensive suite of more than 100 diagnostics to accomodate its diverse experiments. An optical Thomson scattering diagnostic is shown here.


A cryogenic target used in NIF fusion experiments.


NIF Target Area operators inspect a final optics assembly.

Accomplishments

For more than 60 years, LLNL researchers and colleagues worked to achieve fusion ignition, one of science's most challenging goals. An experiment on Dec. 5, 2022, passed this historic milestone, opening new vistas of HED science and enabling access to new regimes relevant for future stockpile stewardship. In support of HED science, LLNL has developed multiple diagnostics necessary for measuring material properties on short time scales and at high densities and temperatures. LLNL researchers developed high-speed cameras to create"movie frames" of experiments with time resolution better than 1/10th of a nano-second using x-rays capable of probing ultra-dense materials. Instruments capable of measuring changes in material structures using x-ray scattering from crystals have allowed scientists to update models of solid transformations. Livermore researchers have also harnessed the emerging scientific areas of machine learning and artificial intelligence to advance HED simulation capabilities.

Further accomplishments from the HED team include:

- Experiments to understand the physics within planets, including the Earth's core, inside our solar system's gas giants, and in exoplanets.
- Experiments to explore astrophysics such as the interactions of supernova explosions with the surrounding interstellar gas.
- Study of the interaction of magnetic fields and turbulence as supernova shock waves propagate through space.
- Development of x-ray imaging diagnostics capable of resolving features 1/10th the size of a human hair in billionths of a second.
- Measurements of velocities and temperatures of materials and shock fronts.
- Time-resolved x-ray spectroscopy measurements at extremes.
- Quantification of energy transfer rates through materials and plasmas.
- Development of the "OPAL" radiation opacity code – part of the "Standard Solar Model."
- Development of novel machine learning algorithms for predicting yield of ICF ignition experiments.

The Future

HED research is opening new frontiers in materials science research. Researchers have developed new capabilities for measuring the basic properties of matter, such as the EOS at the highest pressures ever achieved in a controlled laboratory experiment.

The HED field continues to advance to even higher temperatures and pressures, and toward shorter time scales as advances in HED facilities enable more laser or electrical energy in shorter times.

Future improvements in measurement techniques will allow scientists to study nature in more extreme conditions, including more energetic astrophysical explosions and during more energetic phases of nuclear explosions.

The Materials Physics at Extremes (MPaX) group expects to transfer novel thermal diagnostics to the Nevada National Security Site within the next three years.

New capabilities over the next decade will include time-resolved x-ray diffraction measurements of solids such as lead and iron during compressions to feed back to physics models.

The repeated achievement of controlled fusion at NIF provides an intense source of neutrons, opening new fields of study on the effects of neutron energy deposition.

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