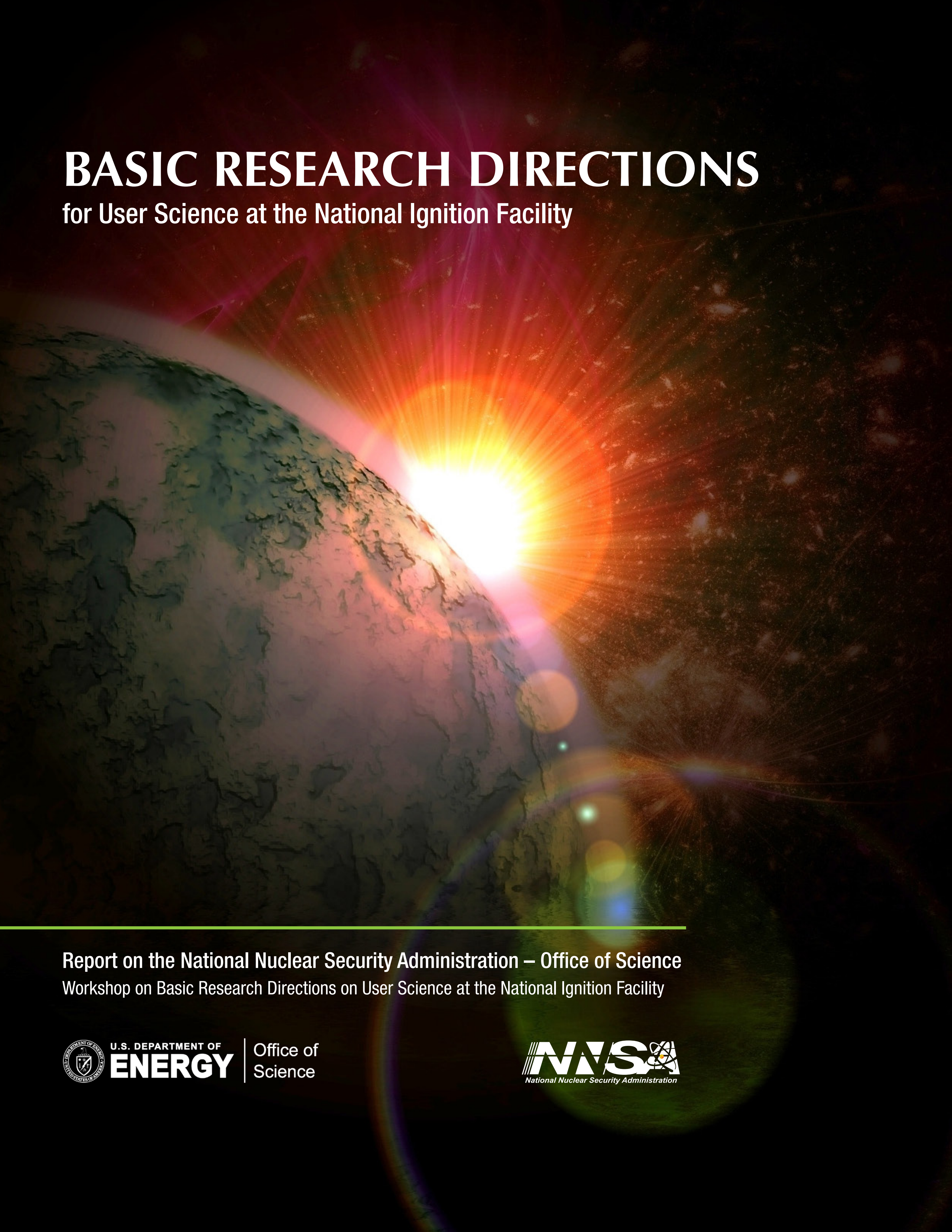
BASIC RESEARCH DIRECTIONS

for User Science at the National Ignition Facility



Report on the National Nuclear Security Administration – Office of Science

Workshop on Basic Research Directions on User Science at the National Ignition Facility

U.S. DEPARTMENT OF ENERGY | Office of Science

NNSA
National Nuclear Security Administration

BASIC RESEARCH DIRECTIONS FOR USER SCIENCE AT THE NATIONAL IGNITION FACILITY

Report on the National Nuclear Security Administration (NNSA) – Office of Science (SC) Workshop on Basic Research Directions on User Science at the National Ignition Facility

Chairs:	John Sarrao, Los Alamos National Laboratory Kimberly Budil, Lawrence Livermore National Laboratory Michael Wiescher, University of Notre Dame
Panel Chairs:	*Laboratory Astrophysics* R. Paul Drake, University of Michigan
	Nuclear Physics William Goldstein, Lawrence Livermore National Laboratory Richard Petrasso, Massachusetts Institute of Technology Michael Wiescher, University of Notre Dame
	Materials in Extremes and Planetary Physics Russell Hemley, Carnegie Institution of Washington
	Beam and Plasma Physics Chan Joshi, University of California, Los Angeles Warren Mori, University of California, Los Angeles Margaret Murnane, University of Colorado, Boulder Alan Wootton, Vector Resources
	Cross-Cut/Facility-User Issues Roger Falcone, Lawrence Berkeley National Laboratory
NNSA Contact:	Michael Kreisler
SC Contact:	James Glownia
Administrative:	Kia Williams (NNSA), Tim Ledford (ORISE)

CONTENTS

FIGURES

TABLES

ACRONYM LIST

AGB	Asymptotic Giant Branch
ARC	Advanced Radiographic Capability
ARCOS	Advanced Radiographic Coherent Optical System
BES	Basic Energy Sciences
DIM	Diagnostic Instrument Manipulator
DOE	Department of Energy
D-T	Deuterium-Tritium
DUSEL	Deep Underground Science and Engineering Laboratory
ELI	Extreme Light Infrastructure
EMP	Electro-magnetic Pulse
EP	Extended Performance
E/PO	Education and Public Outreach
EXAFS	Extended X-ray Fine Absorption Structure
FIDO	Fast Ignition Drive Optics
FRIB	Facility for Rare Isotope Beams
FRM	Faraday Rotation Measure
GA	General Atomics
GRB	Gamma Ray Burst
HED	High Energy Density
IAW	Ion Acoustic Wave
ICF	Inertial Confinement Fusion
ISAC	Isotope Separation and Accelerator
KEEN	Kinetic Electrostatic Electron Nonlinear
LANL	Los Alamos National Laboratory
LCLS	Linac Coherent Light Source
LLNL	Lawrence Livermore National Laboratory
LTE	Local Thermodynamic Equilibrium
MaRIE	Matter-Radiation Interaction in Extremes
MHD	Magnetohydrodynamics
NASA	National Aeronautics and Space Administration
NEEC	Nuclear Excitation by Electron Capture
NEET	Nuclear Excitation by Electron Transmission
NIF	National Ignition Facility
NNSA	National Nuclear Security Administration
PAH	Polycyclic Aromatics Hydrocarbons
PD	Pump Depletion
PI	Principal Investigator
PIC	Particle in Cell
QED	Quantum Electrodynamics
RBS	Raman Back Scattering
RDR	Radiation Dominated Regime

ReNeW	Research Needs Workshop
RHIC	Relativistic Heavy Ion Collider
RPP	Random Phase Plate
SC	Strong Coupling
SC	(DOE) Office of Science
SD	Spectral Dispersion
SN	Supernova
SSP	Stockpile Stewardship Program
STUD	Spike Trains of Uneven Duration and Delay
UV	Ultraviolet
VISAR	Velocity Interferometer System for Any Reflector
XANES	X-ray Absorption Near Edge Spectroscopy

EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

The National Ignition Facility (NIF) houses the world's largest laser, consisting of 192 intense laser beams that can deliver to a target nearly two million joules of ultraviolet laser pulses of nanosecond duration. Mission goals of this National Nuclear Security Administration (NNSA) sponsored facility include laboratory investigations of phenomena at extremes of temperature and pressure for stockpile stewardship, inertial confinement fusion (ICF), and fundamental basic science. With more than 50 times the energy of any previous laser system, the NIF enables scientific investigations using unique extreme laboratory environmental conditions, including

- Densities of ~ 10^3 g/cm^3,
- Neutron densities as high as 10^{26}/cm^3,
- Unprecedented areas at pressures greater than 10^{11} atm,
- Unprecedented volumes of matter having temperatures exceeding 10^8 K, and
- Unprecedented volumes of matter having radiation temperatures exceeding 10^6 K.

Only three places in the Universe have produced extremes close to such conditions: the Big Bang, when the Universe was born in a primordial fireball; the interiors of stars and planets; and thermonuclear weapons. Nothing within orders of magnitude of the neutron densities that will be produced in the NIF has been available for laboratory experiments until now. The capabilities of NIF and related smaller high-energy-density research facilities are ushering in a new era of investigative opportunities that will have a transformative impact in many fields. These fields include planetary and space physics; radiation transport and hydrodynamics; nuclear astrophysics; the science of ultradense materials and materials damage; many areas of plasma physics; laser-plasma interactions, ultraintense light sources, and nonlinear optical physics; novel radiation sources; and other topical areas involving the interplay of electromagnetic, statistical, quantum, and relativistic physics.

In particular, accelerated progress toward grand challenges in the disciplines of laboratory astrophysics, nuclear physics, materials in extremes and planetary physics, and beam and plasma physics is now possible with the advent of NIF. The ability to access and diagnose key physical observables in NIF's extremes provides unique opportunities for discovery. Further, the development of diagnostics and measurement capabilities that can perform in the NIF environment is a grand challenge that will open additional routes to innovation and discovery.

Success by a broad user community in utilizing and advancing NIF's capabilities requires not only a unique experimental tool but also a robust facility governance model and transparent user processes. Existing intermediate-scale high-energy-density facilities, as well as the broader family of Office of Science user facilities, provide a guide toward success in this area. By profiting from and partnering with these other facilities, NIF has a significant opportunity to further enhance its impact in increasingly broad areas of science.

Against this backdrop of unique capability and high scientific potential, a workshop of approximately 100 international leaders spanning the breadth of the science opportunities described above was convened in Washington, DC, in May 2011. The purpose was to explore “Basic Research Directions for User Science at the National Ignition Facility.” While a number of recent workshops have documented the challenges of high-energy-density science, far fewer have focused on the full breadth of science enabled by NIF. Therefore, the present workshop focused on a broader definition of “NIF user science” as well as specific implementation challenges and opportunities to maximize the impact of NIF in the next decade. This report documents the fruits of those efforts.

In the end, workshop attendees enthusiastically concluded that NIF science represented a broad suite of exciting opportunities and urgent research directions that span laboratory astrophysics, nuclear physics, materials in extremes and planetary physics, and beam and plasma physics. Assuming that appropriate intellectual and financial investments are made, the next decades hold bright promise for rapid progress in scientific discovery through the appropriate utilization and continued development of the NIF and related synergistic capabilities.

INTRODUCTION

BASIC RESEARCH DIRECTIONS FOR USER SCIENCE AT THE NATIONAL IGNITION FACILITY

INTRODUCTION

The National Ignition Facility (NIF) enables scientific investigation using unique extreme laboratory environmental conditions, including

- Densities of ~ 10^3 g/cm^3,
- Neutron densities as high as 10^{26}/cm^3,
- Unprecedented areas at pressures greater than 10^{11} atm,
- Unprecedented volumes of matter having temperatures exceeding 10^8 K, and
- Unprecedented volumes of matter having radiation temperatures exceeding 10^6 K.

Only three places in the Universe have produced extremes close to such conditions: the Big Bang, when the Universe was born in a primordial fireball; the interiors of stars and planets; and thermonuclear weapons. Nothing within orders of magnitude of the neutron densities that will be produced in NIF has been available for laboratory experiments until now. The capabilities of NIF and related smaller high-energy-density research facilities are ushering in a new era of investigative opportunities that will have a transformative impact in many fields. These include planetary and space physics; radiation transport and hydrodynamics; nuclear astrophysics; the science of ultradense materials and materials damage; many areas of plasma physics; laser-plasma interactions, ultraintense light sources, and nonlinear optical physics; novel radiation sources; and other topical areas involving the interplay of electromagnetic, statistical, quantum, and relativistic physics.

The purpose of this report, and the workshop from which it is derived, is to identify scientific challenges and research directions in laboratory astrophysics, nuclear physics, materials in extremes and planetary physics, and beam and plasma physics that NIF's capabilities can uniquely address, and having identified these priority directions, to identify capability gaps as well as user science processes with the maximum likelihood of achieving success on the timescale of a decade.

Approximately 100 researchers from across the scientific community, spanning domestic and international universities, national laboratories, and industry, gathered in Washington, DC, in May 2011. Specifically, the workshop emphasized research needs in the areas of laboratory astrophysics, nuclear physics, materials in extremes and planetary physics, and beam and plasma physics. Inertial confinement fusion (ICF), a scientific challenge discussed extensively elsewhere, was not a principal topic of this workshop.

A fifth panel explored cross-cutting facility governance-user issues. Workshop participants identified a series of Priority Research Directions and the capabilities required to achieve success.

The workshop began with a series of plenary talks framing the mission opportunities. Donald Cook from NNSA, William Brinkman from the Office of Science, and Under Secretary for Science Steven Koonin provided Department of Energy (DOE) perspectives on the mission opportunities. The current state of NIF as a facility and its operational experience as well as capabilities and plans for future diagnostics and targets were reviewed, as was the current state of science in key areas that NIF could potentially impact. The important work of defining discipline-specific challenges that NIF can address within the next decade that will make a difference for science was completed through many hours of discussion and debate within panels of community thought leaders. The resulting Priority Research Directions are summarized in Table 1 and are discussed in detail in the body of this report. These research directions and this report are divided into four areas of opportunity to meet discipline-specific challenges.

Table 1. NIF User Science Priority Research Directions

Panels	Priority Research Directions
1. Laboratory Astrophysics	1.1 Simulating Astrochemistry: The Origins and Evolution of Interstellar Dust and Prebiotic Molecules
	1.2 Explanation for the Ubiquity and Properties of Cosmic Magnetic Fields and the Origin of Cosmic Rays
	1.3 Radiative Hydrodynamics of Stellar Birth and Explosive Stellar Death
	1.4 Atomic Physics of Ionized Plasmas
2. Nuclear Physics	2.1 Stellar and Big Bang Nucleosynthesis in Plasma Environments
	2.2 Formation of the Heavy Elements and Role of Reactions on Excited Nuclear States
	2.3 Atomic Physics of Ionized Plasmas
3. Materials at Extremes and Planetary Physics	3.1 Quantum Matter to Star Matter
	3.2 Elements at Atomic Pressures
	3.3 Kilovolt Chemistry
	3.4 Pathways to Extreme States
	3.5 Exploring Planets at NIF
4. Beam and Plasma Physics	4.1 Formation of and Particle Acceleration in Collisionless Shocks
	4.2 Active Control of the Flow of Radiation and Particles in HEDP
	4.3 Ultraintense Beam Generation and Transport in HED Plasma
	4.4 Complex Plasma States in Extreme Laser Fields

In the first area, NIF offers unique opportunities for laboratory research to address issues that apply to the cosmos. It can create unprecedented volumes of material under conditions of astrophysical relevance by heating with lasers, intense photon fluxes, shock waves, or gradual compression. For example, one megajoule of energy deposited by NIF would heat a 70-cm cube of atmospheric gas to 10,000 K or a 7-mm cube of ice to 1,000,000 K. An important goal of the laboratory astrophysics panel was to go beyond the work of previous reports relating to astrophysical plasmas and plasma dynamics to identify novel opportunities in related fields such as astrochemistry or astrophysical dust and ice. The panel unanimously concluded that such opportunities exist and that, in general, novel phenomena that NIF can produce will be of interest for their fundamental scientific value in addition to their astrophysical relevance.

In the second area, the availability of NIF opens a new dimension of experimental opportunities for the nuclear science community and may open a new research direction for plasma nuclear physics. Probing nuclear interactions and nuclear atomic interactions in a plasma environment can address many of the questions that, owing to the complexity of the processes, have so far only been studied with rather crude phenomenological models. A hot dynamic plasma environment is a challenging medium to study, but the experience developed at existing smaller scale laser plasma facilities has generated a number of new techniques that can be used for a new generation of experiments in this novel environment.

In the third area, NIF offers unprecedented opportunities for the study of matter in new regimes of pressure, temperature, and strain rate. The conditions reachable at the facility—up to 1000-fold compression—will provide answers to fundamental questions about condensed matter and are likely to reveal entirely new phenomena in materials. Under these conditions the chemistry of the elements changes as core electrons, and not just valence electrons, participate in bonding. The nature of material strength, transport, and defects is virtually unknown in such an environment. Hence, the results will be essential for understanding the origins and evolution of planets, including the many exoplanets that have been discovered outside our solar system, as well as for characterizing the path to thermonuclear fusion: whether the transition from planets to stars, or the production of fusion energy in the laboratory. The implications span a broad range of scientific problems, from understanding fundamental interactions in dense matter to making new materials to understanding the interiors of planets, brown dwarfs, and stars.

In the fourth area, with anticipated progress in theory, in simulation tools and computers, in experimental facilities, and in diagnostics, there are many opportunities for accelerated discovery in the beam and plasma areas. Some of this accelerated discovery can only be achieved with NIF together with NIF's Advanced Radiographic Capability (ARC). Many areas for possible discovery require plasma lengths and volumes that can only be generated with NIF. Some require the energy of a NIF beam directly while others require the focusing of ARC onto a compressed plasma formed by NIF. In addition, one area for discovery is in igniting nuclear fusion in a dense plasma, and this can only be studied at NIF.

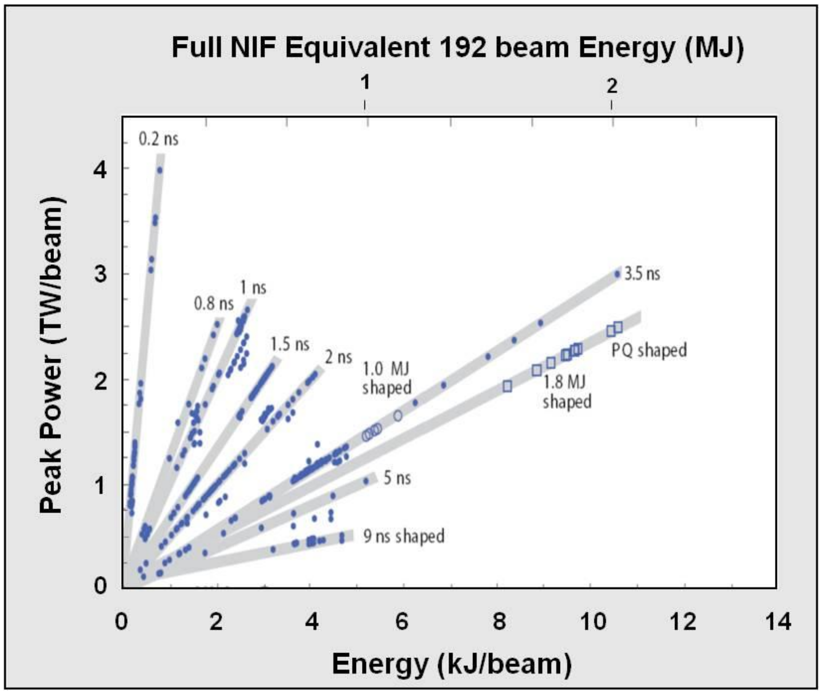
Lastly, building on this foundation of science opportunity, the cross-cutting facilities panel was motivated by three guiding principles: i) maximize the probability of success of NIF science on a decadal timescale, ii) accelerate the growth of a sense of scientific community among NIF users to enhance their collective impact, and iii) profit from best practices and lessons learned from other relevant facilities to optimize the efficiency and effectiveness of NIF as a scientific user facility. As a result of the workshop, suggestions and recommendations in the areas of facility policies and governance, facility operations considerations, and community outreach and education emerged as topics that the panel believes will contribute directly to the successful realization of the science opportunities outlined above and discussed in the body of this report.

The National Ignition Facility Today

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) is the world's largest laser, delivering 50 times more energy than any previous laser system. Construction of NIF was completed in March 2009, and today the laser is fully operational, providing 24/7 experimental access to a broad community of users. The main experimental focus is the demonstration of laboratory ignition via inertial confinement fusion in support of the NNSA Stockpile Stewardship Program (SSP). Other users from the SSP, broader national security, and fundamental science communities have also begun conducting experiments on the NIF.

NIF is made up of 192 individual laser beams grouped into four 48-beam "clusters," each of which consists of six 8-beam "bundles." To date, NIF has demonstrated a total of 1.6 megajoules of ultraviolet light (third harmonic or 3ω) on target in a pulse of 20 nanoseconds for a total power of nearly 420 terawatts. Ultimately, the laser will be capable of delivering nearly 1.8 megajoules and 500 terawatts in the ultraviolet (UV); this level of performance has been demonstrated on a single bundle. In addition, NIF could provide nearly twice this energy at the second harmonic (2ω). The laser is very flexible, capable of providing pulses of various energy, shape, and duration.

National Ignition Facility at Lawrence Livermore National Laboratory.



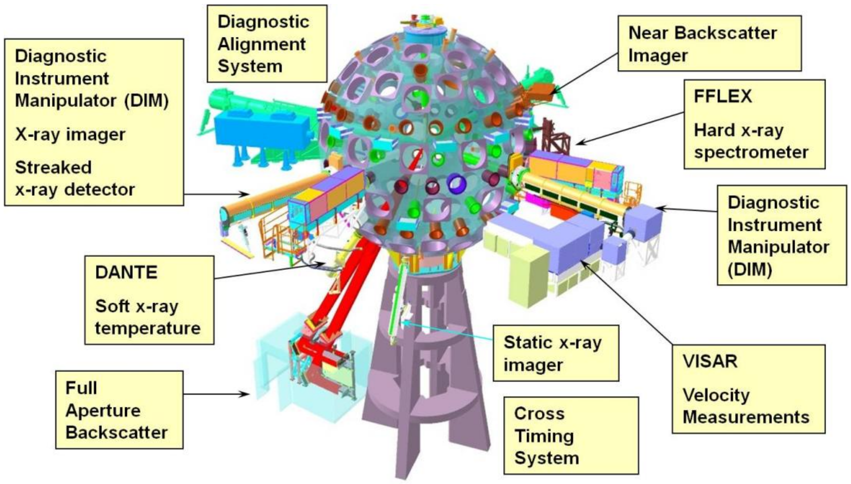
Power/beam in terawatts as a function of energy per beam for a variety of pulse durations, demonstrating the flexibility of the NIF laser system.

The National Ignition Facility Today (Cont.)

NIF provides a very flexible environment for target illumination. The target configuration for many experiments utilizes a hohlraum to convert the laser energy to an x-ray drive. Hohlraums have been demonstrated for long-duration drives at a peak radiation temperature (T_r) of 130 eV and, for shorter duration drives, at a higher peak, T_r exceeding 320 eV. In this configuration 96 beams are directed into the top of a vertically oriented gold cylinder, and the remaining 96 beams are directed into the bottom. The beams are arranged into 4 cones with angles of incidence on the hohlraum wall of 23.5°, 30°, 44.5°, and 50°, respectively. Some of the beams may also be pointed to a spot away from the hohlraum to create an x-ray back-lighter as a diagnostic probe. These beams can be independently timed and delayed relative to the main pulse, allowing for a series of diagnostic pulses to be delivered. Alternatively, the beams may be used to directly illuminate the target, again with great flexibility in pulse duration, temporal evolution, and energy. A variety of phase plates are available to provide tailored spot profiles and sizes to ensure uniform illumination.

NIF is also developing a short pulse capability called the “Advanced Radiographic Capability” or ARC. ARC converts four beams of NIF into eight “beamlets” that can be independently delayed, each beam providing pulse durations from 1 to 50 ps with energies ranging from 400 to 1700 J at 1ω. Each beam will have intensities on target of 1×10^{18} W/cm^2 at 2-ps pulse duration. Such high-intensity short pulses can be used to generate high-energy (75-200 keV) x-ray back-lighters that enable multiple radiographs of high areal density targets, such as compressed ignition capsules. Short pulse beams will also enable studies of novel ignition schemes such as fast ignition wherein the ignition capsule is precompressed with the long pulse beams to a modest compression, and then the hot spot is ignited with an injection of hot electrons into the core of the fuel.

A broad suite of diagnostics has been developed for use at the NIF to provide information on both laser and target performance. These include optical, x-ray, gamma, neutron, and charged particle diagnostics. Some diagnostics have permanent locations on the target chamber, such as instruments to measure hohlraum radiation temperatures and laser backscatter from hohlraums, while others can be configured for each shot and are inserted into the NIF chamber via diagnostic insertion manipulators (DIMs) located at (90,78), (90, 315), and (0,0). Several diagnostics have been hardened against the harsh radiation environments that will be present as fusion yields are increased in the facility. The facility also will have the capability of performing radiation chemistry measurements by both neutron activation (gaseous collection) and charged particle activation (solid collection) and neutron activation detection via witness foils. Approximately 50 diagnostics are now operational at NIF; a representative sampling of current diagnostics is listed in the table below. Additional information on NIF capabilities may be obtained by contacting the NIF User Office.



Layout of the fixed diagnostic capabilities on the NIF target chamber.

The National Ignition Facility Today (Cont.)

Diagnostic	Capabilities	Position
Streak Camera (DISC)	Time resolved x-ray camera	DIM
Static X-ray Imager (SXI)	Time integrated x-ray imager	Fixed (161, 326 and 18, 124)
Dante	Broad-band time resolved x-ray spectrometer	Fixed (143, 274 and 64, 350)
Full Aperture Backscatter Stations (FABS)	Shape, power and spectrum of reflected light back into focus lens	Fixed (150, 236 and 130, 185)
Near Backscatter Imager (NBI)	Power, spectrum and angular distribution of light back-scattered near lens	Fixed (150, 236 and 130, 185)
Gated X-ray Detectors (GXD)	Time gated x-ray detectors	DIM
Filter Fluorescer (FFLEX)	Broad-band high energy (20-400 keV) x-ray spectrometer	Fixed (90, 110)
Electro-Magnetic Pulse (EMP)	Chamber area EMP emission detector	Fixed (102, 84)
Neutron Time-of-Flight (NTOF) – 4.5 m	Neutron time-of-flight measurement for yield and bang time measurements	Fixed (64, 253; 64, 275; 64, 309; 64, 330)
NTOF – 20 m	Neutron time-of-flight measurement for yield and bang time measurements	Fixed (90, 174 and 116, 316)
Velocity Interferometer System for any Reflector (VISAR)	Time resolved Doppler velocity camera	Fixed (90, 315)
Streaked Optical Pyrometer (SOP)	Time resolved optical camera	Fixed (90, 315)
Gamma Ray History (GRH)	Time and spectrally resolved gamma emission	Fixed (64, 20)
Magnetic Recoil Spectrometer (MRS)	Neutron spectrum via neutrons converted to protons and energy analyzed by magnetic deflection	Fixed (77, 324)
High Energy X-ray Imager (HEXRI)	High energy x-ray imaging system	DIM
Wedge Range Filter (WRF) Spectrometer	Energy resolved particle emission – EMP insensitive	DIM
Neutron Imager (NI)	Image primary and down-scattered neutrons	Fixed (90, 315)

LABORATORY ASTROPHYSICS 13

LABORATORY ASTROPHYSICS

Introduction

Astrophysical systems are frequently so hot that they produce copious x-rays and are so violent that they produce ionized, turbulent matter featuring strong magnetic fields or intense radiation. Qualitatively, NIF and other large lasers produce these same elements and so can be exploited in research that is relevant to astrophysics. Quantitatively, NIF opens up some novel areas of research and pushes other areas of research into significant new regimes. This panel report describes four research directions strongly connected to astrophysics and enabled by NIF. One cannot, however, narrowly confine the astrophysical applications of NIF. They arise in all areas of astrophysics, and other panels discuss them where appropriate. This specifically includes applications of NIF to nuclear astrophysics (Nuclear Physics Panel), planets (Materials in Extremes and Planetary Physics Panel), and relativistic shock waves (Beam and Plasma Physics Panel).

Status of the Field

The application of high-energy lasers to astrophysics began in the 1990s, with work aimed at hydrodynamics during explosions and the spectral absorption of x-rays by hot matter. This work led to the growth of “high energy density laboratory astrophysics,” a field that now has two international conferences. The ability to probe properties and processes that are relevant to astrophysics is, in every case, limited by the available laser energy. By providing more than a 50-fold increase in available energy, NIF enables both novel experiments, such as the destruction of clumps of denser matter by radiative shocks, and the exploration of new regimes, such as the study of magnetic field generation in important novel regimes.

Beyond this, NIF makes possible new science relevant to astrophysics that cannot be undertaken anywhere else. The examples here relate to the evolution and chemistry of condensed matter, beginning with small grains that form from the plasmas that flow out of stars and other objects. These grains are known as “dust” and play an essential role in energy transport and chemical evolution during planet formation. Those dust grains that become covered by ice are likely locations for the photochemical interactions that produce the precursors for life. Only NIF can study dust from its inception in plasma to grain formation and to further processing by shocks or radiation. Only NIF can produce the type of x-ray bursts needed, across all relevant energies, to see the photochemistry.

Opportunities for Accelerated Discovery

In the discussion of specific Priority Research Directions, we show how in each area NIF enables novel discovery. We first provide here a brief overview of the discovery science within our scope enabled by NIF. As just described, in the fast chemistry of condensed matter, NIF will advance our ability to predict the chemical and material composition that exists during planet formation, the rate at which planets are accumulated, and thus to identify which planetary systems are most likely to develop organic life.

In the area of the interstellar and intergalactic media, NIF can uniquely address two of the grand mysteries of the cosmos: magnetization and cosmic-ray generation. Simple physics calculations readily show that magnetic fields across the Universe should be quite weak; observations, in contrast, show substantial magnetic fields. Laboratory study of magnetic field generation is limited by the need to begin with weak magnetic fields, to produce shocks or turbulent flows that can generate or amplify magnetic fields, and to avoid dissipation of the fields by plasma heating. Even computer simulations are hampered with regard to plasma heating; their numerical dissipation is too large to let them model the relevant phenomena. NIF can access the novel regime in which the dissipation is small over several orders of magnitude of structure size. In addition, some of the experiments that do this are directly relevant to the generation of cosmic rays. The "Beam and Plasma Physics" chapter discusses complementary research directions that explore other aspects of cosmic-ray generation.

Regarding the dynamics of stellar birth and death, one encounters hydrodynamic systems involving strong shock waves in which radiation often plays an essential role. The corresponding research areas of radiation hydrodynamics and compressible hydrodynamics have been active, but progress to date has been limited by the available energy to drive experiments. First, one has not been able to produce the sustained radiative shock waves that are involved in the accumulation of matter that leads to thermonuclear supernovae or in the destruction of molecular clouds (clumps) by high-Mach-number flows. Second, one has not been able to produce diverging explosions in which the long-term evolution of explosive instabilities can be followed. Third, one has not been able to observe the evolution of convective turbulence beyond its very early phases. NIF and only NIF can overcome these limitations and others, enabling substantial progress in understanding the dynamics of stellar birth and death.

In the area of the interaction of x-rays with astrophysical plasmas, which depends strongly on the atomic physics of ionized matter, NIF likewise can access new regimes. The plasmas near black holes, near neutron stars, and in many binary stars are ionized by the x-rays produced in those environments rather than by collisions, as is typical elsewhere. To interpret present and future observations one needs to understand such systems and to test one's ability to model them. Only NIF can produce values of the key physical parameter that are solidly in the astrophysical regime. In addition, stellar structure and evolution depend essentially on the transport of x-ray radiation; indeed, studies of stars were what first developed the area of radiation transport. This radiation transport, in turn, depends fundamentally on the absorption and emission properties of the matter, especially of the high-Z elements such as iron. Only NIF can produce states of matter as dense and as hot as the interior of the sun, enabling the measurement of these properties under such conditions.

In the course of identifying these research directions and identifying what might be done, we identified advances in facility capability and diagnostics that would be required to pursue them fully. Table 2 summarizes these facility needs.

Beyond the experimental capabilities listed in the table, most of these experiments require design calculations to develop the experimental configuration and to help interpret the data. Moreover, experience has shown that the intellectual center of such efforts tends to be where the design simulations happen. Correspondingly, as the national community evolves toward the emergence of collaborative teams that carry forward the work in various research directions, it is important that each team has full-time design and experimental expertise in addition to support from LLNL and/or other laboratories.

Table 2. Facility Needs for Laboratory Astrophysics

Facility Capability Needs		
Beam delays to 10 μs	Off-axis beam pointing to 10 cm	Induction coils to generate magnetic fields
X-Ray Diagnostics		
Large, field-of-view, high spatial resolution imager	Large aperture, high spectral resolution imaging spectrometer	Versatile x-ray scattering
Diverse x-ray spectroscopy		
Optical Diagnostics		
Interferometry	Faraday rotation	UV Thomson scattering
Large field imaging		
Other Diagnostics		
Particle spectrometers	ARC proton imaging	Capsule proton imaging
Surface science station		

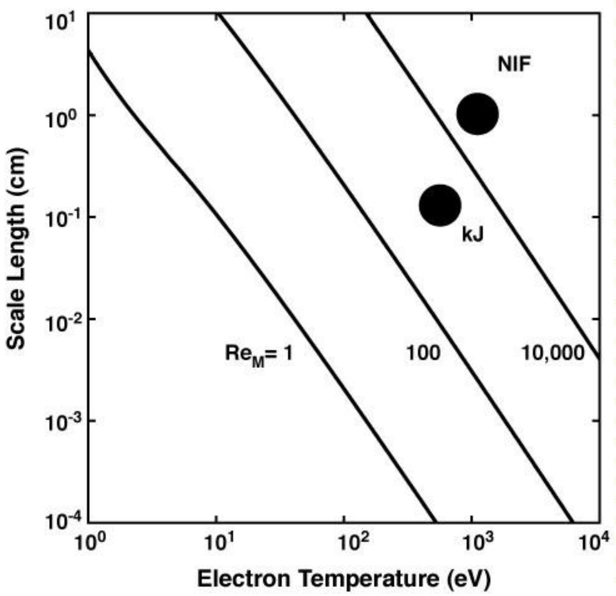
Summary

Only NIF can study dust from its inception in a plasma to grain formation and to further processing by shocks or radiation. NIF can produce the type of x-ray bursts needed, across all relevant energies, to see the photochemistry. NIF can achieve the small normalized dissipation necessary to observe turbulent magnetic-field generation. NIF can sustain steady radiative shock waves and diverging explosive hydrodynamics long enough to see long-term nonlinear behavior, enabling substantial progress in understanding the dynamics of stellar birth and death. NIF can produce values of the key physical photoionization parameters that are solidly in the astrophysical regime. NIF can produce states of matter as dense and as hot as the interior of the sun, enabling the measurement of x-ray transport under such conditions.

Magnetic Reynolds number and why it matters

Magnetic fields are present in astrophysical objects ranging from stars to galaxies, active galaxies, and clusters of galaxies. In all of these objects, the problem of understanding the origin of these fields is two-fold: (1) understanding the origins of the seed fields that magnetic dynamos require in order to operate (the "primordial field" problem) and (2) understanding the dynamo process itself, which is generally thought to involve the interaction of turbulent flows with these seed magnetic fields.

In astrophysical systems, magnetic fields dissipate slowly by comparison with the timescales on which dynamos operate. In contrast, the central difficulty in laboratory or computational studies of turbulent magnetized systems is to minimize the dissipation of the magnetic field. The magnetic Reynolds number measures the competition between dynamic behavior, which includes dynamo effects, and dissipation, which includes decay by plasma heating and by diffusion. For a system to be turbulent, it must include small structures that are no larger than 1% the size of its large structures. To produce and sustain magnetic structure over such a range of sizes, the magnetic Reynolds number must exceed 10,000.



Lines of constant magnetic Reynolds number, Re_M, for a fully stripped boron plasma. (They do not move much on such a log-log plot as materials change.) Values achievable by NIF and by kJ-class lasers are indicated. Laboratory liquid-metal-based experiments achieve Re_M ~ 100. The magnetic Reynolds numbers achievable in experiments at NIF could enable the first studies of turbulent magnetic field generation.

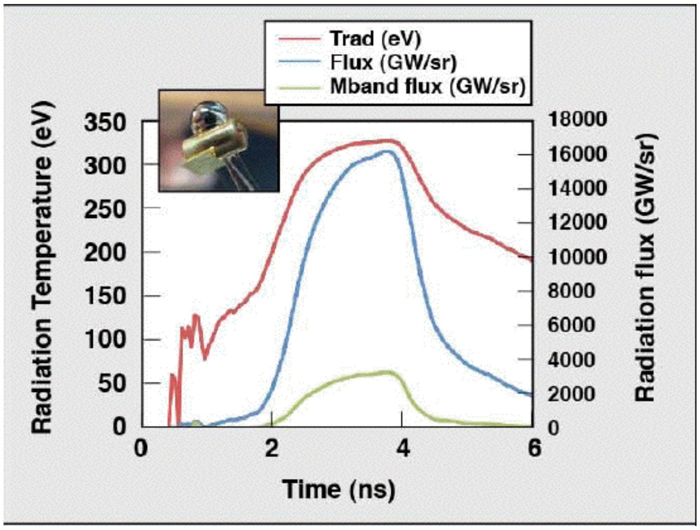
This problem has limited previous attempts to observe dynamo effects in the laboratory. These have used conducting fluids such as liquid metals. The problem is that the conductivity of typical liquid metals is so low and the maximum physical size of the experimental devices is so small that the effective magnetic Reynolds number in laboratory dynamo experiments tends to be of the order of 100 or less. In contrast, the fluid Reynolds number in such experiments can be of the order of 10^5 or larger, so these experiments can sustain turbulent fluid structure. As a result, typical laboratory experiments tend to be characterized by highly turbulent fluids but rather laminar (i.e., weakly perturbed) magnetic fields. As a result, it has so far proved to be impossible to fully explore experimentally the ideas underlying modern turbulent magnetic dynamo theory. One might hope that computer simulations could provide some insight, but in fact, they suffer the same limitation: numerical diffusion limits their effective magnetic Reynolds number to several hundred.

Laser-driven plasma experiments at NIF can achieve effective magnetic Reynolds numbers that are orders of magnitude larger than can be produced in liquid metal-based experiments or at current laser facilities like OMEGA. Estimates suggest that one could reach magnetic Reynolds numbers of the order of 10,000 (see figure). As a consequence, generation of genuine magnetohydrodyamic turbulence is possible, enabling the study of the initial phases of turbulent magnetic field generation.

Experiments on radiative alteration of Rayleigh-Taylor instabilities relevant to supernovae

Immediately after a star explodes, shock waves travel through the surrounding medium and initiate the growth of structure by means of Rayleigh-Taylor instabilities like those that produce the structure in rising cumulus clouds. When the medium is dense enough the shock waves can become radiative shocks. The intense radiation they emit as they cool can alter the evolution of the instabilities. An early basic-science experiment at NIF is exploring this type of radiation hydrodynamics. The experiment, led by the University of Michigan, involves Florida State University, the University of Texas, the University of Arizona, and personnel from LLNL and Los Alamos National Laboratory (LANL).

The experiment uses a cylindrical gold cavity, known as a “hohlraum,” to produce a source of radiation whose temperature is above 3 million degrees. The hohlraum for this type of experiment must be filled with gas to mitigate the effects of stagnation of plasma from the hohlraum walls on its axis. Experiments to date have demonstrated the diagnostic technique (a type of radiography) and have tested this hohlraum. The adjacent figure shows data from the demonstration of the hohlraum. This test for many months held the record as the hottest radiation source to date (3.8 million kelvin) from a gas-filled hohlraum.



Data from a NIF shot to demonstrate that one could produce a thermal x-ray source suitable for the radiative, supernova-relevant Rayleigh-Taylor experiment. The source temperature (Trad) of nearly 4 million degrees is shown on the left axis in units of electron volts. The figure also shows (right axis) the total radiation flux and the flux of more energetic x-rays produced by gold “M-band” emission. The target design must mitigate the otherwise adverse effects of the M-band x-rays, which is straightforward to do once their flux has been measured.

In the experiments using this hohlraum, anticipated in FY 2012, the radiation will drive a shock wave through a layer of dense plastic, the analog of an exploding star, and into a region of less dense foam, the analog of the matter surrounding the star. The shock wave in the foam will be strongly radiative, and the radiation is predicted to strongly alter the unstable structure that will develop at the boundary between the two materials. This will provide evidence of the effects that radiating shock waves can have on instabilities in flowing plasma, and will provide evidence to test the validity of astrophysical codes that simulate analogous phenomena in supernova remnants.

Simulating Astrochemistry: The Origins and Evolution of Interstellar Dust and Prebiotic Molecules

With NIF, for the first time we have the ability to recreate the evolution of a plasma to dust to prebiotic molecules under astrophysically realistic conditions.

Introduction

A precursor to the formation of planets and ultimately to life is the existence of dust grains and prebiotic (organic) molecules. The left portion of Fig. 1 shows a picture of the giant galactic nebula NGC 3603, where the National Aeronautics and Space Administration (NASA) Hubble Space Telescope captures various stages of the life cycle of stars in one single view. To the upper left of center is the evolved blue supergiant called Sher 25. The star has a circumstellar ring of glowing gas. The color of the ring and the bipolar outflows (blobs to the upper right and lower left of the star) indicate the presence of processed (chemically enriched) material. Near the center of the view is a so-called starburst cluster dominated by young, hot Wolf-Rayet stars and early O-type stars. A torrent of ionizing radiation and fast stellar winds from these massive stars has blown a large cavity around the cluster. Evidence for the interaction of ionizing radiation with cold molecular-hydrogen cloud material appears in the giant gaseous pillars to the right of the cluster. Dark clouds at the upper right are so-called Bok globules, which are probably in an earlier stage of star formation. To the lower left of the cluster are two compact, tadpole-shaped emission nebulae. Similar structures were found by the Hubble Space Telescope in the Orion Nebula and have been interpreted as gas and dust evaporation from possibly protoplanetary disks (proplyds).

The conditions in which these dust grains and prebiotic molecules form are harsh by any measure. Stellar outflows spew out torrents of high temperature plasma. As these plasmas expand and cool, they congeal into dust grains, a necessary precursor to the formation of planets around their parent star. Further, some of these dust grains eventually acquire an icy mantle outer layer, as is suggested by the grain on the lower right in Fig. 1. The persistent exposure to ionizing radiation can initiate a chemical reaction in this icy mantle. This reaction, in turn, can trigger the formation of prebiotic molecules, which is a key step toward the formation of biology and life.

Opportunity

With NIF, for the first time we have the ability to recreate this transformational evolution of plasma to dust to prebiotic molecules under astrophysically realistic conditions. By exploding a suitable target at the center of the NIF chamber, an expanding star-like plasma outflow can be created and probed as a function of position, time, and initial plasma outflow conditions. Hence, in principle the dynamics of dust condensing out of an expanding plasma, in the presence of harsh radiation fluxes and strong shocks, can be measured, modeled, and understood. Further, with the ability to dial-in specific energy bands of intense radiation

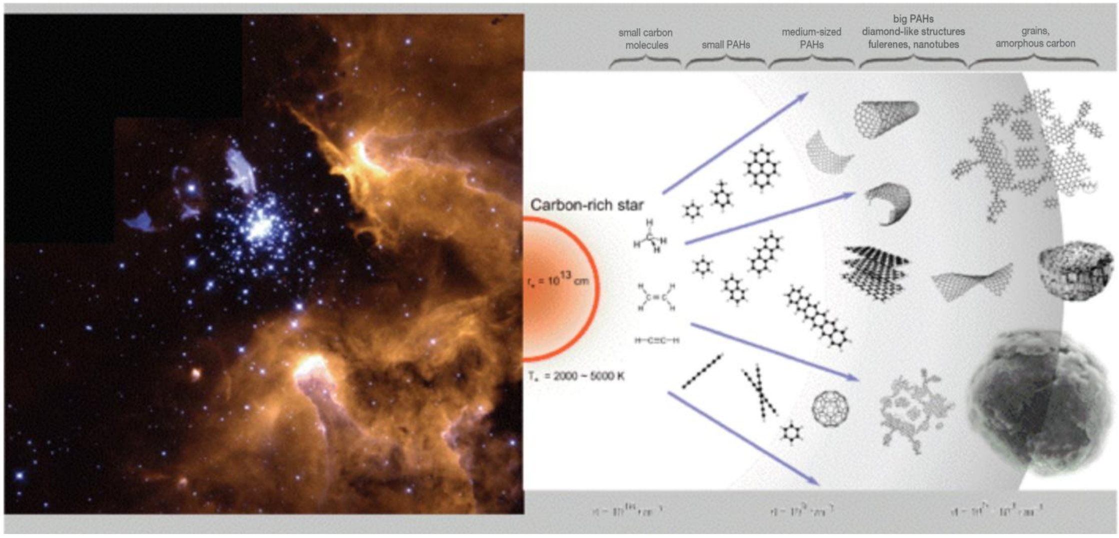


Fig. 1. Left: Life cycle of stars. True-color picture taken on March 5, 1999, with the Wide Field Planetary Camera 2 of the Hubble Space Telescope. Credit: NASA, Wolfgang Brandner, JPL-IPAC, Eva K. Grebel, University of Heidelberg. Right: Cartoon depicting the model of formation and processing of cosmic carbon-dust grain formation. Source: Adapted from Pascoli and Polleux, Astron. Astrophys. *359*, 799 (2000); Credit: Cesar Contreras (NASA ARC and NPP) and Farid Salama (NASA ARC).

fluences, the very critical radiation-driven chemistry, the key spark to the formation of prebiotic molecules (and life) can be studied as a function of a wide variety of key parameters. This proposed research is completely new, highly multidisciplinary, and transformational in the field of science. Example research directions follow.

Research Directions

Dust is an important component of the interstellar medium of galaxies. Interstellar dust grains are the building blocks of planets and a main source of radiative absorption in a range of astrophysical environments. In cold and dense environments the dust grains also provide catalytic surfaces for the formation of simple ices—water, methane, methanol, ammonia, carbon monoxide, and carbon dioxide—which through interaction with radiation can evolve into complex organic molecules, including amino acids and sugars. In protoplanetary disks these icy grains stick together, forming larger bodies and eventually comets and planets. Understanding how these grains and icy grain mantles form and evolve under astrophysically relevant conditions is, therefore, key to predict the composition of planets and especially the amount of organic material associated with the origin of life.

NIF provides unique opportunities to study grain formation from plasmas and the processing of grains and icy grain mantles by a wide range of x-rays at fluxes otherwise inaccessible in laboratory astrophysics. Carbon dust particles are thought to be primarily formed in the outflow of carbon stars through a combustion-like process, where atomic carbon and hydrogen form small carbon chains (acetylene), which form polycyclic aromatic structures

(PAHs) that nucleate into larger PAHs and, ultimately, into nanoparticles. Current experimental structures do not allow one to study the entire process in one setting. NIF offers a unique platform to generate and study dust from inception in a plasma to grain formation and further processing by shocks and radiation bursts. The NIF target chamber has a 5-m radius. Matter from an expanding plume of plasma from experiments at the chamber center reaches the wall of the chamber in 10^{-4}-10^{-3} s for typical plasma expansion velocities on the order a few tens of km s^{-1}. This timescale is considerably larger than the 10-100 ns likely required for the formation of solid particles from a plasma. As a result, dust should condense out of the expanding plasma plume in flight, in the presence of an ambient radiation field that can be controlled by secondary laser targets.

Once formed in the stellar outflows and ejected into the interstellar medium, dust grains are subjected to a harsh environment that includes photons, with energies from eV’s to keV’s and up to the gamma-ray regime, as well as energetic particles with energies ranging from hundreds of eV’s to GeV/nucleon. This irradiation processing can cause structural changes, sputtering, melting, Coulomb-driven fragmentation, or even sublimation of small dust grains. Gamma ray bursts (GRBs) are intense flashes of gamma-rays and related X-ray-ultraviolet-optical-radio emission and are considered the most energetic phenomena that dust grains encounter. No experimental studies exist of this radiation-dust interaction. Theoretical studies of the processing of dust illuminated by the radiation from GRBs have described the destruction mechanisms as resulting from either the combination of the heating of the grains leading to sublimation or evaporation of atoms off the surface of the grain, until the grain has been totally vaporized, or the charging of the grains, which occurs when X-rays eject K-shell electrons from them. This charging produces tensile stresses that exceed the yield stress of the material, triggering cracking and fragmentation or shattering (a process described as “Coulomb explosion”). It has been argued that Coulomb explosion may be the dominant effect. NIF offers a unique platform to conduct these experiments. The x-ray fluxes offered by NIF are sufficiently intense to study GRB radiation-induced dust grain destruction. NIF generates sufficiently high fluences (J cm^{-2}) and fluxes (J cm^{-2} s^{-1}) of x-rays to reproduce a scaled radiation source similar to a GRB and to allow investigating the effect on materials in the interstellar medium.

In a related research thrust, to predict where in space advanced prebiotic chemistry can be expected, the effects on ice produced by incident radiation must be understood as a function of photon flux, fluence, and energy up to at least 10 keV. Existing small laboratories have or will have the capabilities to investigate frequency-resolved, radiation-induced ice chemistry up to 10 eV. Using existing national facilities this kind of research can be pushed toward higher photon energies. This should be exploited in the near future, both to investigate an important part of the spectrum and to run proof-of-concept experiments for NIF. Both NIF and the x-ray laser Linac Coherent Light Source (LCLS) can produce useful sources from 100 eV to 10 keV, as Fig. 2 illustrates. Beyond 10 keV, only NIF has enough x-ray flux (>0.01 J cm^{-2} per photon energy bin, based on existing far ultraviolet experiments) to induce detectable amounts of ice chemistry. Higher fluences (> 1 J cm^{-2} per photon energy bin) are useful in that they enable one to follow the chemistry to a more complex level. Carrying out

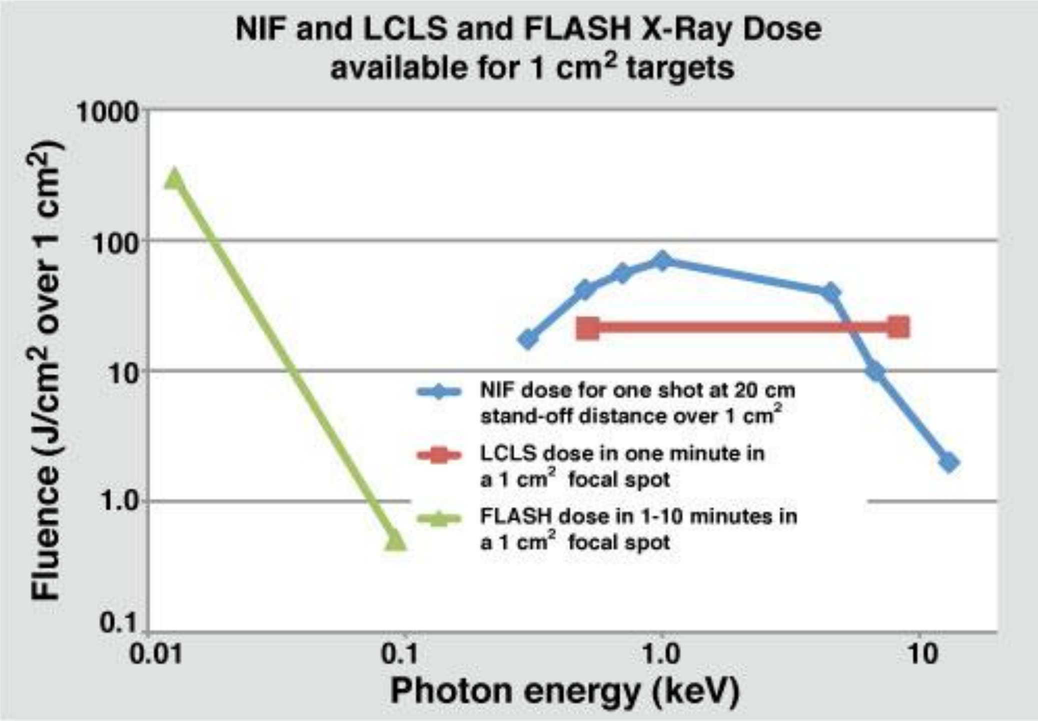


Fig. 2. Possible x-ray dose that can be delivered to a sample with an area of 1 cm^2. The NIF data (blue diamonds) are for a 200 eV hohlraum at < 1 keV, a high-Z foil target at 1 keV, a Xe gas target at 4.5 keV, an Fe K-shell target at 6.7 keV, and a Kr gas target at 13 keV. The data are based on recent measurements at NIF and OMEGA and on radiation-hydrodynamic simulations, validated on OMEGA experiments, scaled to 1 MJ of energy and 200 TW of power. The NIF dose is delivered uniformly over the 1 cm^2 test sample on a single shot; the x-ray pulse is assumed to be 5 ns wide. The LCLS points (red squares) are calculated assuming a 3 mJ energy per pulse at 0.15 nm wavelength, a 120 Hz repetition rate for the beam line, an assumed focus of the x-ray beam to a 1 cm^2 circular cross section, and a 1-min integration time. The FLASH points (green triangles) are based on 170 µJ per pulse at 13.5 nm, a 5 Hz repetition, an assumed focus of the x-ray beam to a 1 cm^2 circular cross section, and a 10-min integration time and on a fluence of 1.0 J/cm^2 at 97.6 nm, delivered at a 5 Hz repetition rate, with an integration time of one minute.

the ice chemistry experiments requires that one direct a spectrally filtered x-ray beam onto a cryogenically cooled surface under ultra-high vacuum. This can be achieved at NIF with an x-ray filter configuration that has several absolutely calibrated spectral bands. The radiation can also be further dispersed for high-resolution experiments. NIF has the advantages of being able to irradiate many sources at once and to accumulate much useful data in conjunction with other ongoing experiments, since most types of pulse lengths and fluxes will be useful (to separate the effects of photon flux and total energy dose will require a collection of experiments over a large range). The ultimate goal of the ice chemistry experiments is to provide astrophysical predictions for the chemical composition around stars during planet formation, and thus obtain data on which planets are the most likely candidates for developing life. Ices are also an interesting material on their own, because their properties and chemistry are poorly understood, and by combining photochemistry results from NIF with results from other smaller facilities we can expect to develop the first holistic model of ice photochemistry, including the formation and diffusion of radicals as a function of photon energy.

Impact

Using NIF to study the formation and evolution of dust and the radiative triggering of prebiotic molecules is truly transformational. This research will provide a unique diagnostic of dust from inception in plasma to grain formation and further processing by shocks and radiation bursts. This understanding will further allow the development of a holistic model of radiation-driven ice chemistry, which will ultimately allow the ability to predict the chemical composition during planet formation and, thus, identify the planetary systems that are the most likely to develop organic life.

Explanation for the Ubiquity and Properties of Cosmic Magnetic Fields and the Origin of Cosmic Rays

The NIF experimental environment will provide the ability to study the evolution of magnetized plasmas into highly nonlinear stages over long timescales.

Introduction

The Universe is permeated by magnetic fields, with strengths ranging from a femtogauss in the voids between filaments and galaxy clusters, to several microgauss in the intergalactic medium, to many teragauss in the vicinity of some black holes and neutron stars. For

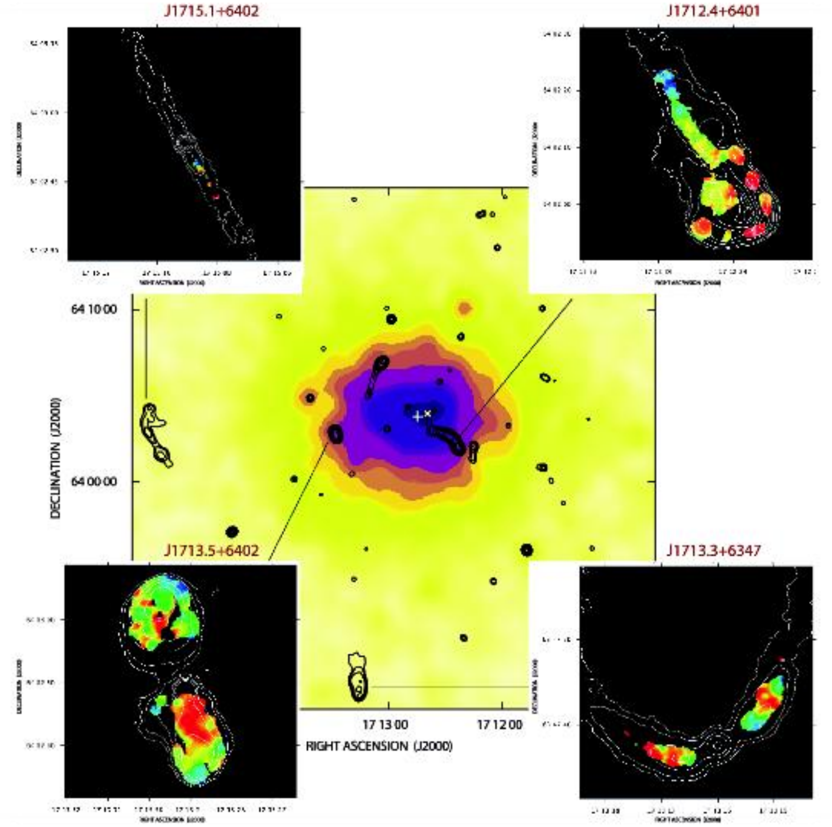


Fig. 3. Radio contours of the A255 cluster of galaxies overlaid on the ROSAT x-ray image of the cluster. The white "+" and "x" symbols show the positions of the centroid and peak of the cluster x-ray emission. The images at the corners of the figure show the Faraday rotation measure (FRM) for four radio galaxies in the cluster. The FRM of the radio halo at the cluster center and these four radio galaxies imply a magnetic field strength that declines from the cluster center outward, with a field strength of 2.6 microgauss at the cluster center and an average magnetic field strength of ~ 1.2 microgauss in the cluster core. Source: After Govoni et al., *Astronomy & Astrophysics* 260, 425 (2006). Published with permission.

comparison, the magnetic field of the Earth is near 1 gauss. Magnetic fields play a crucial role in myriad astrophysical phenomena, including the formation and evolution of stars, the generation and transport of cosmic rays, the production of relativistic jets from stellar-mass black holes and supermassive black holes at the centers of galaxies, and possibly even the formation of the large-scale structure in the Universe.

In many astrophysical objects, magnetic forces dominate the dynamics. Systems in which both fluid motion and magnetic dynamics are important are described as magnetohydrodynamic, or MHD, systems. Magnetic fields are thought to dominate the transport of angular momentum in accretion disks around white dwarfs, neutron stars, and black holes, as well as the related acceleration of relativistic jets. Astronomical observations using Faraday rotation and synchrotron emission show that large-scale magnetic fields exist in galaxy clusters (e.g., Fig. 3). These fields may come from the magnetic fields in the radio jets produced by active galaxies in the core of the cluster. The fields are then transported and amplified by turbulence in the hot gas in the cluster.

Several mechanisms have been proposed to explain the origin and strength of these magnetic fields, including field generation from the Biermann "battery" process, turbulent dynamo effects, and the growth at shocks of plasma instabilities (e.g., the Weibel instability, a non-resonant instability or return currents). However, how these mechanisms might work in various astrophysical phenomena is not fully understood.

Opportunity

During the past decade, laboratory astrophysics experiments have been developed that allow the study of dynamically evolving magnetized objects morphologically similar to those observed in the Universe. Experiments at NIF will enable scientists to study entirely new regimes. Most notably, experiments at NIF will achieve magnetic Reynolds numbers up to 10,000—well beyond those attainable in current experiments—by increasing temperature and spatial scale (see previous sidebar, "Magnetic Reynolds number and why it matters"). Such magnetic Reynolds numbers also far exceed those of current numerical simulations, which are limited to several hundred. This capability will, for the first time, permit the study of MHD turbulence and large-scale, shock-generated, magnetic fields in the laboratory. The NIF experimental environment will provide the ability to study the evolution of these magnetized plasmas into highly nonlinear stages over long timescales (~10 µs).

Research Directions

The energy deposited by NIF laser beams will allow one to drive magnetized and/or collisionless shocks at high Mach number into an initially magnetized or unmagnetized plasma. We offer three examples; others will no doubt be invented. First, a shock wave moving from a high-density target into a surrounding gas can produce turbulently generated magnetic fields through shock instabilities. Second, a laser beam striking an empty hohlraum can be expected to generate seed fields by the “battery” process. The blow-off from subsequent laser beams striking the hohlraum will produce a turbulent plasma that can be expected to amplify these seed fields. Third, NIF can be used to create a differentially rotating plasma, capable of generating magnetic fields from low-level seed fields (either self-generated from plasma instabilities or externally pre-imposed).

Because the Reynolds number is well over 1000, one can hope to see the initial field become fully turbulent and amplified in any of these experiments. The key issue is whether the turbulent plasma state can be sustained for 3-4 turbulent eddy turnover times, a requirement driven by the need to distinguish linear from exponential amplification of the magnetic fields. As an example, if the outer spatial scale for the turbulence is about 1 cm, with typical velocities of 10^7 cm s^{-1}, we will need the magnetized plasma to stay intact for at least ~ 10 × 10^{-7} s or ~ 1 µs, enabling measurements of the interior plasma parameters with a time resolution of ~ 100 ns. Diagnostics that will be needed include data on plasma density and temperature, as well as the interior magnetic field.

Connected to the problem of magnetic field generation is acceleration of high-energy cosmic rays. Recent x-ray observations have provided increasing evidence that acceleration occurs in the shocks associated with supernova remnants (e.g., Fig. 4). While there is observational, theoretical, and computational evidence that cosmic rays are primarily produced at shocks via diffusive acceleration, the specific details of the acceleration process are not understood. The coupled feedback among nonresonant amplification, jump conditions at the shock front, and the radiation field are important in determining the spectrum of the accelerated cosmic rays. NIF experiments can tackle this great puzzle in high-energy astrophysics.

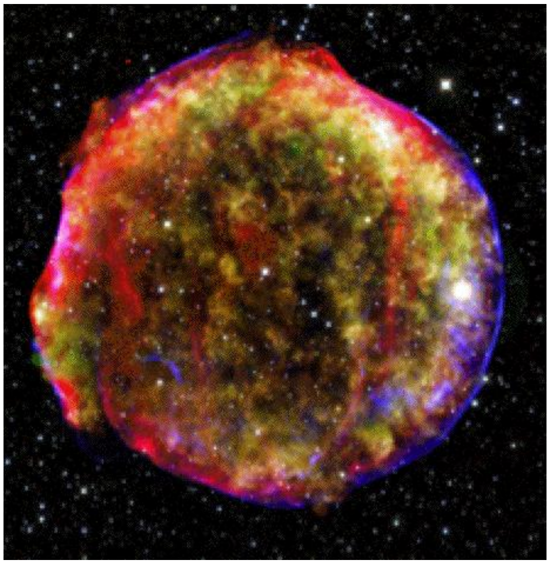


Fig. 4. Composite image of the Tycho supernova remnant in x-rays and infrared light. The blue curve surrounding the remnant shows the location of ultra-energetic electrons in the blast's outer shock wave. Credit: X-ray: NASA/CXC/SAO; Infrared: NASA/JPL-Caltech; Optical: MPIA, Calar Alto, O. Krause et al. Source: http://chandra.harvard.edu/photo/2009/tycho/

New tools and techniques will be needed for MHD experiments on NIF. In particular, large field-of-view optical and spectroscopic diagnostics will be required to characterize the properties and global topology of the plasma. Thomson scattering will be important for determining the temperature and density of the plasma locally. Magnetic field diagnostics, such as Faraday rotation, proton deflectometry, and magnetic induction coils will be required to study the distribution and the evolution of the macroscopic magnetic field driven by the turbulent flow. Measurement of the turbulent component of the magnetic field should be first developed at smaller scale facilities and then transferred to NIF. This is a long-term diagnostic objective that could have a major impact in the understanding of MHD flows. High-energy detectors and spectrometers will be needed to study the accelerated particles. The ability to design, analyze, and interpret these experiments using simulations will also be necessary.

Impact

Because it can access the unique and important regime of high magnetic Reynolds number, NIF can uniquely address two of the grand mysteries of the cosmos: magnetization and cosmic-ray generation. This will lead to new understanding of magnetic dynamo effects in turbulent plasma flows and of particle acceleration in magnetized flowing plasmas.

Radiative Hydrodynamics of Stellar Birth and Explosive Stellar Death

NIF provides new opportunities for the study of the dynamical processes involved in stellar birth and death.

Introduction

In stellar birth and death one encounters hydrodynamic systems involving strong shock waves in which radiation often plays an essential role. As a result, radiation hydrodynamics and compressible hydrodynamics have been active areas of research, but progress to date has been limited by the available energy to drive experiments. One has not been able to produce the sustained radiative shock waves that are involved in the accumulation of matter that leads to thermonuclear supernovae, or in the destruction of molecular clouds (clumps) by high-Mach-number flows. One has also not been able to produce diverging explosions in which the long-term evolution of explosive instabilities can be followed. And one has not been able to observe the evolution of convective turbulence beyond its very early phases. NIF and only NIF can overcome these limitations and others, enabling substantial progress in understanding the dynamics of stellar birth and death.

Opportunity

NIF provides new opportunities for the study of the dynamical processes involved in stellar birth and death. Past work has shown how to devise laboratory experiments in which the important dimensionless parameters, and sometimes all relevant dimensionless parameters, are well scaled between the laboratory system and the astrophysical one. Experiments at smaller facilities have produced or are producing radiative shock waves, radiative heat waves, jets, and explosive instabilities that correspond to small local regions in supernovae or supernova remnants. NIF enables several new classes of experiments. One of these experiments is already underway (see earlier sidebar, “Experiments on radiative alteration of Rayleigh-Taylor instabilities relevant to supernovae”).

Research Directions

Radiative reverse shocks form when a flowing plasma of high-enough velocity is impeded. Only NIF can drive steady shocks of this type. Such shocks will enable the creation of at least two novel radiation-hydrodynamic environments. The first is found in binary stars, where matter from a companion star is falling onto a white dwarf or other main star (see Fig. 5), which will explode when it has accumulated enough mass. Complex three-dimensional radiation hydrodynamics is at work. As a result, the morphology of, and the emissions from, the resulting structure are quite uncertain. NIF can produce well-scaled analogs of these astrophysical systems. When the star is strongly magnetized, the in-falling matter strikes the star; otherwise, it strikes an accretion disk. In the first case, observations record only radiation near the dwarf. Models suggest that the shock reaches a static position

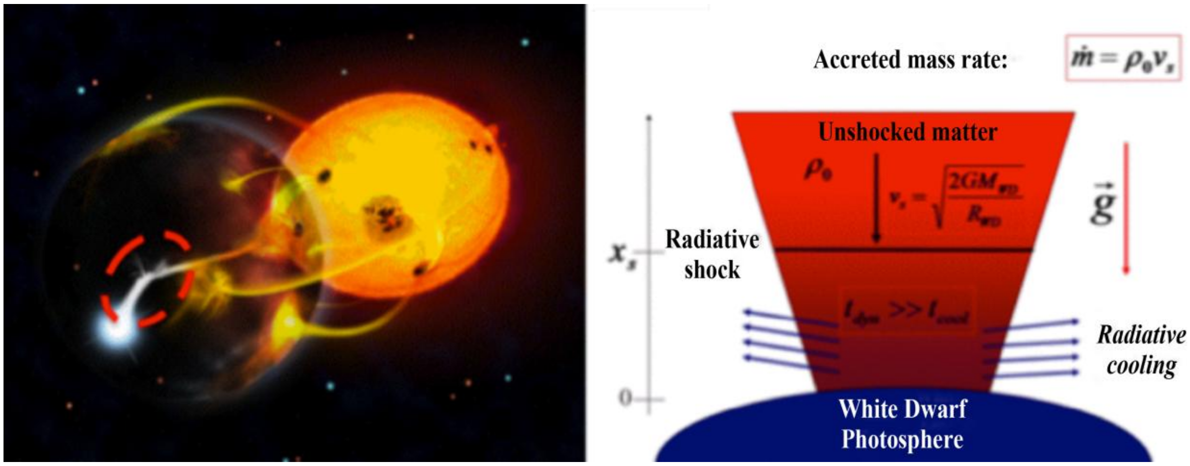


Fig. 5. Left: Image of accretion of matter from a companion star (yellow) onto a compact main star, creating local, bright emission from a radiative reverse shock at the surface of the main star. Right: Structure of the accretion column within the region encircled by red line on the left image.

Credit (left): S. Howell/ P. Marenfeld/NOAO.
Source: http://simostronomy.blogspot.com/2009_03_04_archive.html

Credit (right): S. Howell/ P. Marenfeld/NOAO.

at about 1000 km above the white dwarf surface. To confirm (or not) these theoretical models, laboratory experiments are needed in which a “continuous flow” of sufficient velocity impacts a solid obstacle that mimics the stellar atmosphere. To generate the necessary mass of flowing plasma, several hundreds of kilojoules within tens of nanoseconds are necessary, so this can only be done on NIF.

Another common role of radiative reverse shocks in astrophysics is the destruction of dense clumps (in practice, often molecular clouds). Previous experiments have observed the nonradiative limit of clump destruction, and their results have been applied to the interpretation of x-ray images from the Chandra x-ray telescope. Yet, in many cases in astrophysics, the shock that applies the pressure which destroys a clump is radiative, making it much denser, thinner, and cooler than it would be otherwise. In addition, the interplay between radiation hydrodynamics and the galactic magnetic field is important in determining the lifetime of such clouds. Only NIF can produce radiative reverse shocks that endure long enough to destroy a clump.

Such radiative clump destruction often occurs within dense, clumpy, molecular clouds illuminated by nearby bright young stars that emit intense UV ionizing radiation. The UV radiation from the stars causes a continuous ablation (by photoevaporation) of the surface of the cloud and generates a flow of ionized gas directed away from the surface. The interaction of the radiation with the structured cloud material drives radiative-hydrodynamic instabilities at the cloud surface, which are believed to cause structures such as the long pillars visible in Fig. 6. Only NIF can produce significant source temperatures (near 1 million degrees) for long enough times (near 100 ns) to directly observe, in well scaled experiments, the dynamics that occurs during the production of such structures.

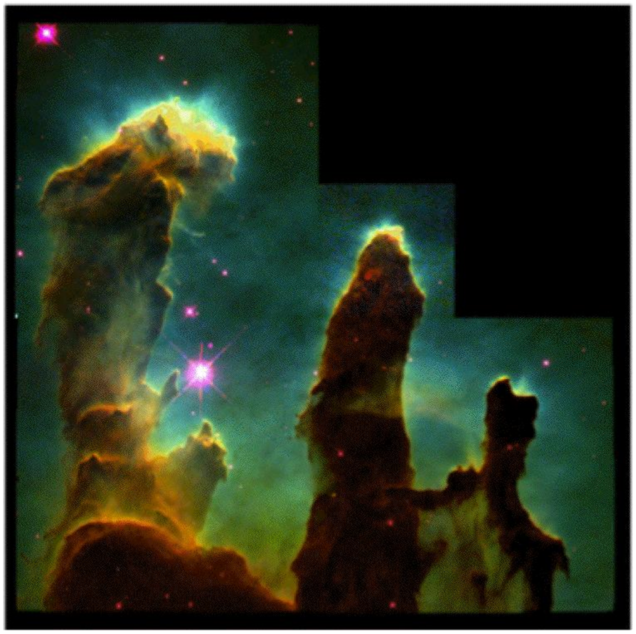


Fig. 6. Hubble Space Telescope image of the "Pillars of Creation" within the Eagle Nebula. The radiative hydrodynamics of stellar birth is prominently displayed in the tips and possibly in the clumpy interiors of the pillars of the Eagle Nebula. Credit: NASA/ESA.

Many astrophysical systems, from molecular clouds to supernova remnants, are highly structured, and much of this structure may have arisen from the Vishniac instability, which produces wrinkling of thin, dense layers created by radiating shocks. Figure 7 shows a recent scaling analysis of this instability. Only NIF can produce systems that are solidly in the regime of astrophysical supernova remnants, and only NIF can study the structure of the shocked material when this instability is driven in diverging systems.

NIF also has unique capabilities for the limit in which radiative losses play a small role, as is the case when stellar explosions occur and, in some cases, when astrophysical blast waves drive evolving turbulence. The explosion phase of core-collapse supernovae involves a diverging explosion in which unstable structure is produced primarily through the interaction of two interfaces—the inner and outer boundaries of the He-dominated layer in the star. A NIF experiment has been approved to produce an experimental system that has these three features (the diverging explosion and the two interfaces), which only NIF can do. In addition, the NIF experiment, like the astrophysical system, will have a Reynolds number that is much larger than numerical simulations can produce, opening up the potential for unexpected discoveries and the ability to test reduced-physics models that can enable more accurate simulations. In addition, there are other phenomena in compressible hydrodynamics that only NIF can access. One example is the long-term evolution of turbulence initiated by the Rayleigh-Taylor instability produced during supernovae and also by galactic shocks.

Impact

In other ways as well, NIF can bring astrophysical analogs of unprecedented realism to the laboratory. It has far more energy than any other existing devices and can sustain vastly longer laser pulses, so that much larger and hotter plasmas can be generated. Taken together, these capabilities permit many experiments to be conducted in regimes with a better scaling of key dimensionless parameters from the laboratory to astrophysics.

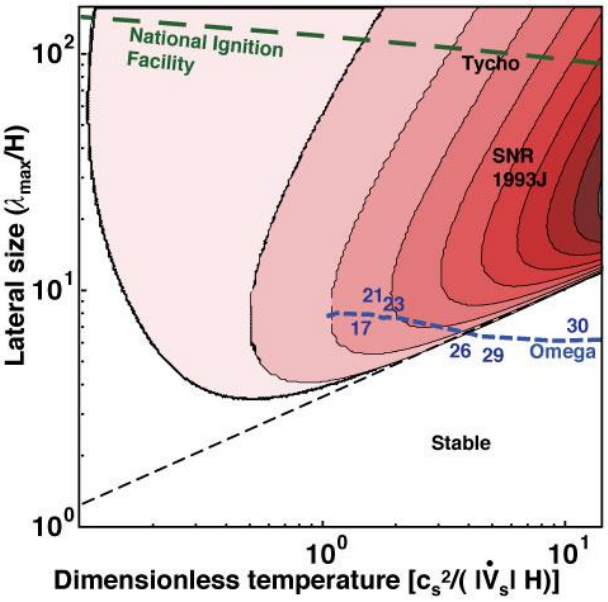


Fig. 7. Contours and shading showing the relative growth rate of the Vishniac instability, increasing toward darker colors and being stable below the lower dashed line. The numbered symbols show the regime accessed by recent experiments on the OMEGA laser. The labels represent two supernova remnants: Tycho and 1993J. NIF can access the entire region below the dashed green line. The axes represent key dimensionless variables, with the ordinate being proportional to the ratio of largest wavelength λ_{max} to dense layer thickness *H*, and the abscissa representing the normalized temperature (formally the sound speed, c_s, squared divided by the product of *H* and the magnitude of the deceleration).

Credit: F.W. Doss, Ph.D. Thesis, University of Michigan, 2011. Used with permission.

Atomic Physics of Ionized Plasmas

Laboratory experiments at NIF will provide a unique opportunity to create and diagnose astrophysical plasmas on earth at unprecedented and extreme conditions of temperature, density, and radiation flux and, in particular, will push the frontier of laboratory work on photoionized plasmas and stellar opacities to the next level.

Introduction

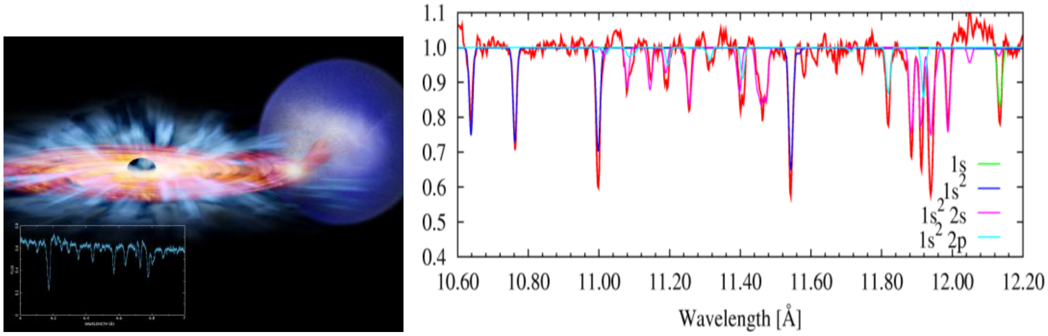
Photoionized plasmas occur naturally in astrophysics, being found, for example, in accretion-powered x-ray binaries and active galactic nuclei. Figure 8 (left side) displays an artist's illustration of binary system GRO J1655-40, which is located 11,000 light-years from Earth in constellation Scorpius. This binary system is composed of a massive star and a black hole with an accretion disk around it. Inset in Fig. 8 is an x-ray spectrum of this binary system recorded by Chandra, showing line absorption features in the 6 Å to 7 Å wavelength range produced by highly charged ions of multiple elements present 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. Furthermore, x-ray spectroscopy measurements of this and other photoionized plasmas recorded by the spectrometers aboard the orbiting telescopes Chandra and XMM-Newton clearly show the striking differences between the x-ray line spectra of photoionized plasmas and those from the more frequently encountered collisional plasmas. By collisional plasmas we mean plasmas where electron-ion collisions play the predominant role in determining the distribution of level populations and ionization states in the plasma. In contrast, photoionized plasmas are an extreme case of nonequilibrium systems where an intense x-ray flux drives the ionization atomic kinetics. The models and codes for photoionized astrophysical plasmas have been developed *only* from theory; thus, benchmarking them in well-characterized laboratory photoionized plasmas is critical to validate their application in both laboratory and astrophysical plasmas.

Opportunity

NIF can access new regimes in the interaction of x-rays with astrophysical plasmas, which depend strongly on the atomic physics of ionized matter, and the absorption and emission properties of the matter, especially of the high-Z elements such as iron. The plasmas near black holes, neutron stars, and in many binary stars are ionized by the x-rays produced in those environments rather than by collisions, as is typical elsewhere. To interpret present and future observations one needs to understand such systems and to test one's ability to model them. Only NIF can produce values of the key physical parameter that are solidly in the astrophysical regime. In addition, stellar structure and evolution depend essentially on the transport of x-ray radiation, and indeed studies of stars were what first developed the research front of radiation transport. Furthermore, NIF can produce states of matter as dense and as hot as the interior of the sun, enabling the measurement of these properties under such conditions.

Research Directions

Current experiments use either lasers or the device called "Z," a "z pinch" that implodes cylindrical arrays of current-carrying wires to produce intense x-ray fluxes. Experiments at Z (at Sandia National Laboratories) have developed diagnostics and techniques to produce and probe photoionized plasmas characterized by values of the key parameter, ξ, known as the ionization parameter, of up to 50 erg cm/s. (Figure 8, right side, shows data from such an experiment.) These experiments have already shown discrepancies with both laboratory and astrophysical modeling codes. However, astrophysical photoionized plasmas have ξ values well into the 1000 erg cm/s range, and this regime is *only* accessible in the laboratory by NIF experiments. Furthermore, NIF can develop new and well-characterized laboratory plasma sources relevant for astrophysics that are large enough, uniform enough, and long-lived enough, and thus create experimental benchmarks for theoretical models and codes.



Fig, 8. Left: Artist's illustration of binary system GRO J1655-40 and x-ray line absorption spectrum recorded by Chandra (Credits: Illustration: NASA/CXC/M. Weiss; x-ray spectrum: NASA/CXC/U. Michigan/J. Miller et al.). Right: Data (red line)/theory (lines in different colors) comparison of a transmission spectrum recorded in a laboratory; photoionized neon plasma experiment performed at the Z facility (Credit: U. Nevada, Reno/R. C. Mancini et al.).

Iron photoionized plasma experiments can be done at NIF driven by the x-ray flux of a hohlraum (see earlier sidebar, "Experiments on radiative alteration of Rayleigh-Taylor instabilities relevant to supernovae") having a radiation temperature of 300 eV. *Only* NIF can produce photoionized K-shell iron whose lines are used to infer properties of the inner accretion disk, where strong relativistic effects are important. Astrophysical simulations to date have not used validated atomic data for photoionized iron. In the NIF experiments, diagnostics would include simultaneous emission and absorption x-ray spectroscopy and optical diagnostics (Thompson scattering and interferometry) to characterize the plasma. NIF photoionized plasma experiments will provide a unique opportunity to obtain high-quality data to test x-ray photoionization theories and models under conditions relevant to astrophysics, thereby providing a critical component in the effort to understand the physics of black hole accretion and the interpretation and analysis of x-ray spectroscopic observations from Chandra and XMM-Newton.

Up until the year 2000, models of the solar structure were in good agreement with helioseismology observations, including location of the boundary between the radiative and convection zones and interior density profiles. However, revised estimations of solar matter composition with smaller amounts of metals have produced significant discrepancies. One possible source of the discrepancy is stellar opacities. Stellar structure models depend on opacities of mid-Z elements that have a myriad of atomic transitions which have never been measured in the laboratory. In this connection, the presence of partially ionized iron in the solar mixture is important since it makes a large contribution to the opacity through line transitions in open L-shell ions. Recent experiments at Z have measured the photon-energy-dependent opacity of iron for temperatures characteristic of the base of the convective zone, i.e., 190 eV. Figure 9 displays a transmission spectrum extracted from Z experiments. Magnesium K-shell and iron L-shell absorption lines are observed in the data. Detailed analysis of the magnesium lines is used to characterize the plasma conditions of the iron L-shell spectrum. These laboratory measurements are crucial to test the fidelity of state-of-the-art stellar opacity models and calculations that take into account complex atomic structure, nonideal plasma effects on equation of state and level populations, and detailed spectral line profiles.

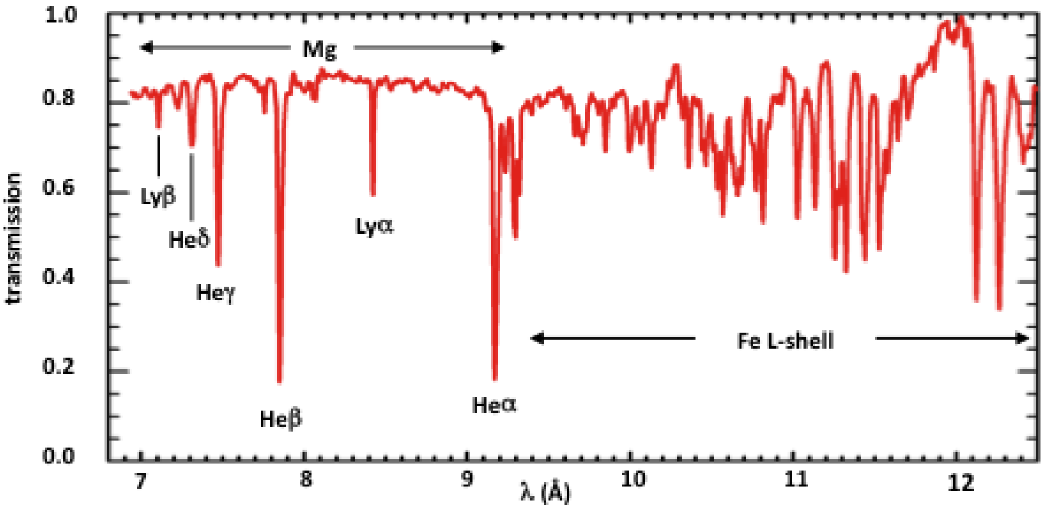


Fig. 9. Transmission spectrum extracted from data recorded in Z experiments. The wavelength range covers the K-shell lines of magnesium and L-shell lines of iron.

Credit: Sandia National Laboratories/J. E. Bailey. Souce: Reprinted with permission from J. E. Bailey et al., *Rev. Sci. Instrum.* 79, 113104 (2008). Copyright 2008, American Institute of Physics.

Impact

Opacity measurements become more challenging at temperatures above 200 eV because the heat source must supply more energy to the opacity sample, and the backlight source must be brighter to overwhelm the sample's self-emission. O*nly* NIF has the required laser energy and power to develop the next generation of opacity experiments with hot, x-ray heated samples above 200 eV, backlit with bright x-ray sources driven either by a subset of NIF laser beams or the NIF ARC petawatt-class laser. These experiments are crucial to benchmark solar iron opacity relevant to the radiative/convective boundary region and into the radiative zone, to understand solar interior structure and composition and its connection with helioseismology observations, and thus eventually to assess the impact of the sun's behavior on the earth's long-term climate history. Moreover, stellar opacity models validated with laboratory experiments are crucial for studying stellar evolution and stability, as well as supernova radiation transport. The latter will impact our understanding of the cosmic expansion and dark matter and energy in the Universe.

NUCLEAR PHYSICS 37

NUCLEAR PHYSICS

Introduction

Nuclear physicists study the fundamental building blocks of matter, and how they interact and combine to form the nucleons, elements, and exotic nuclear states that constitute the observed universe. The field is concerned with the structure of the atomic nucleus as a multi-particle quantum system, the quark structure of the nucleon, and matter at the extreme densities of neutron stars and the extreme temperatures of the Big Bang. It addresses the origin of the elements formed by nuclear interaction processes in environments from the third minute of the Big Bang to quiescent and explosive stellar systems that have evolved in the later phases of our expanding universe.

Nuclear physics has triggered a large number of applications with enormous societal implications, from the production of nuclear energy to the use of nuclear isotopes for medical diagnostics and treatment. Nuclear physics-based techniques have emerged as dominant tools in material science, geology and climatology, and the liberal arts, and in critical national security areas of nuclear forensics, nonproliferation, and counter-terrorism.

Status of the Field

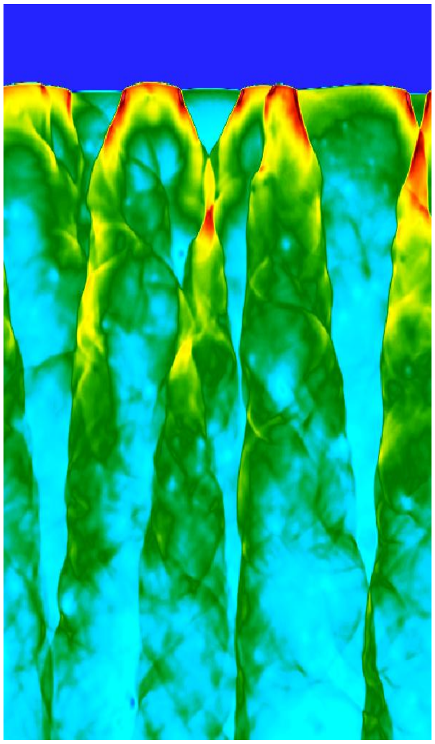
Great strides have been made in answering the riddles of the nucleus and the formation of the elements. But the strong force that binds the nucleus and dictates the symmetries and patterns observed in the elements is still not well understood: the forces between nucleons have not been directly related to quantum chromodynamics, the fundamental interaction among quarks. The same force must explain the nature of dense neutron stars, where matter is so compressed that the elements dissolve into their constituent protons and neutrons, or further, into a quark-gluon plasma. We have a good understanding of the basic principles of nucleosynthesis, the collection of processes that form the elements, but important gaps remain in understanding the complexities of chemical evolution in the Universe, predicting abundances for specific burning sites, locating the sites and contributions of specific processes, and correlating nuclear processes with the dynamics of burning and exploding stars.

These mysteries define current research directions in nuclear physics: the strong force and the structure of the nucleons, including the nature of confinement and chiral symmetry; the structure of nuclei and its impact on nuclear astrophysics, including nucleosynthesis and stellar evolution; and the implications for nuclear properties and reactions such as beta decay of new physics beyond the “standard model” of fundamental interactions. A range of existing and planned facilities is important in this research, including general capabilities such as high performance computing, astrophysical observatories, and specialized nuclear probes such as heavy ion accelerators, neutron sources, and rare isotope facilities. Several of the most prominent of these specialized facilities are described in the next sidebar.

Cosmology with precision nuclear physics

Owing to their enormous brightness—more than one billion times that of our Sun—thermonuclear supernovae can be observed to the very edge of the Universe. It has long been believed that the intrinsic brightness of these Type Ia supernovae, or SN Ia, is nearly a constant, which justified calling them “standard candles.” This property has allowed astronomers to test cosmological models by comparing their predictions for SN Ia luminosities to observations. Such comparisons provided the initial evidence that the Universe is not only expanding, but that its expansion is actually accelerating. They also offered support for the existence of a “cosmological constant,” a contribution to the laws of general relativity proposed, and then retracted by Albert Einstein. Ironically, Einstein considered the suggestion his greatest blunder. Precisely determining the cosmological constant depends on the quality of supernova observations and our understanding of their explosion mechanism: just how good is the assumption that all SN Ia explosions are equal?

As the number of supernova observations increased, astronomers realized that the intrinsic brightness of individual Type Ia events is not constant. Although the luminosity dispersion is small, it is not negligible and contributes to the error budget of parameters of cosmological models, including the cosmological constant. Theorists and modelers believe that the origins of SN Ia supernova luminosity dispersion can be traced to slight differences in the evolutionary histories of individual supernova progenitors. In this picture, characteristics of every supernova event, including its brightness, depends on a combination of several factors such as the hydrodynamic state of the stellar interior, its chemical composition, the way stellar fuel is consumed in the process of explosive burning, and, last but not least, the energetics of the nuclear reactions that power the explosion, such as carbon fusion. These factors that help define standard candles also operate in inertial confinement fusion targets. This observation suggest that the NIF can be a unique tool for studying fundamental physics processes of supernova explosions such as fusion reaction rates, Coulomb screening of nuclei by electrons in degenerate plasma, turbulent mixing, hydrodynamic instabilities, physics of thermonuclear deflagrations, and contributions from self-generated magnetic fields. These studies would offer information of critical importance to predictive supernova studies and provide improved constraints for theoretical cosmology.



The spatially heterogeneous pressure field of a thermonuclear cellular detonation, a fundamental physics process contributing to supernova explosion.

In current research plans, the study of the structure and interactions of nuclei is largely restricted to cold or ground-state nuclear systems. This limitation exists primarily because current and envisioned facilities do not have the means to populate excited nuclear states in concentrations or with lifetimes high enough for meaningful study. In addition, while nucleosynthesis typically occurs in a hot, dense plasma environment, characterized by interactions with large fluxes of free electrons and partial screening by bound electrons, reactor- and accelerator-based experiments do not reproduce these effects. Nevertheless, it is clear that the coupling of nuclear and plasma degrees of freedom can affect nuclear excited state lifetimes, reaction rates, and transport, important ingredients for understanding nucleosynthesis.

NIF presents a path to studying the interplay between nuclear and plasma processes. This can be achieved by utilizing the temperature and density conditions of the dynamic plasma environment created by NIF to probe new, as yet unachievable degrees of freedom in nuclear reaction mechanisms and nuclear-atomic interactions. If successfully applied in this way, the NIF will enable new research directions in nuclear physics and foster the growth of a new interdisciplinary field—plasma nuclear physics.

Opportunities for Accelerated Discovery

The availability of NIF opens experimental opportunities for the nuclear science community and may open a new research direction in plasma nuclear physics. Probing nuclear interactions and nuclear atomic interactions in a plasma environment addresses many of the questions that, owing to the complexity of the processes, have so far only been studied with crude phenomenological models. A hot dynamic plasma environment is a challenging medium to study, but the experience developed at existing smaller scale laser plasma facilities has generated a number of new techniques which can be utilized for a new generation of experiments in this novel environment.

The development of nuclear physics experiments at the NIF represents a transition from a well-defined accelerator environment, where the experimental parameters have well-understood or minimal uncertainties, to highly dynamic experimental conditions with as yet unknown complexities. Such experiments require extensive monitoring and modeling of the experimental conditions and development of new approaches to identify uncertainty in nuclear physics measurements. If this is successful, nuclear physics-based techniques will also add a new component to the range of diagnostic methods used to monitor and evaluate the plasma conditions through the identification and application of new signatures.

A broad range of opportunities for nuclear reaction measurements in a hot plasma environment has, in particular, been identified for the field of nuclear astrophysics, where nuclear reactions and decay processes in the hot plasma environment associated with stars or stellar explosions drive the generation of stellar energy and the synthesis of new elements. The study of these processes so far has relied on detailed measurements of reaction cross sections at low energy accelerators to map the reaction rates of the charged particle reactions, which define stellar evolution and the characteristics of the various stellar burning phases. The direct measurement of these reactions at stellar conditions has been the major goal but also a major challenge because of the extremely low reaction cross sections and the difference of electron screening effects in laboratory experiments and stellar plasmas. Studies of charged particle reactions at the NIF environment will naturally take the plasma nature of the reaction environment into account and provide new insight into the nuclear reaction processes at the interface between atomic and nuclear physics. These plasma effects can be studied best through a coordinated program of comparative measurements of light ion reactions at low energy accelerator facilities and at the NIF to identify and characterize these complex interaction processes.

Naturally occurring nuclear reaction processes such as the s-process in stellar environments depend critically on neutron capture on thermally excited states in nuclei along the reaction path. Thermal excitation of low energy states in a hot plasma can change the reaction path and alter significantly the resulting abundance distribution. There has been no satisfying way to perform direct measurements at low excited states because of their exceedingly short lifetime. At present, the entire analysis and interpretation of neutron driven reaction sequences in stellar environments rely on the assumption of equilibrium for the thermal enhancement of reaction or decay processes. Experiments in a hot plasma as provided by NIF will provide, for the first time, an opportunity to study the effects of thermal enhancement directly and explore the impact on radiative capture of neutrons and radioactive decay through these excited states. This capability opens a new window and a broad range of opportunities for s-process studies based on injecting stable and possibly even unstable long-lived nuclei into NIF targets.

The plasma environment can enhance the population of nuclear excited states through the coupling of nuclear transitions to transitions involving bound atomic states of the charged ions. The processes that result, nuclear excitation by electron transition (NEET) and nuclear excitation by electron capture (NEEC), are difficult to calculate owing to the many body physics of the atomic system and plasma effects on atomic level widths and densities. Measurements are crucial to resolving discrepant calculations. If excited state effects on nuclear reaction rates can be disentangled in NIF experiments, it should be possible to gain a handle on the effects of NEET and NEEC. Furthermore, experiments may be possible to directly observe the photo-decay of states populated by these processes.

Nuclear processes involving charged particles are also sensitive to the complex hydrodynamics that occur in NIF targets, including turbulent mixing, charged particle energy loss, and possible fractionation of light ion species. This condition comes about because particle ranges in the dense plasma are very short, making their reactions a potential probe of local conditions, particularly inhomogeneities. The interplay between nuclear and hydrodynamic processes means that nuclear measurements can provide new diagnostics for the complex physics of burning plasmas, as well as help elucidate the role of such processes in burning stars and supernovae.

To realize these opportunities, new diagnostics, target designs, and target fabrication techniques will have to be developed. For the research directions described below, these include:

- High resolution charged-particle, neutron, and gamma spectrometry techniques at low energies, especially sensitivity to neutrons below 1 keV;
- Capsule designs tailored to mimic thermonuclear reaction plasma environments in stellar and big bang nucleosynthesis;
- Capsule designs tailored to mimic neutron spectra in asymptotic giant branch (AGB) and massive stars that drive s-process nucleosynthesis;
- Capability to load radioactive elements in capsules; and
- Capabilities for radiochemical debris collection and in-situ counting.

Summary

Nuclear physicists have made major advances in understanding the origin of the elements using a suite of accelerator facilities for cross-section measurements. Many gaps in that understanding will be addressed by future facilities, including the Facility for Rare Isotope Beams (FRIB) and Deep Underground Science and Engineering Laboratory (DUSEL), which are expected to be available in the ten-year time frame. But even with these new capabilities, a full, experimentally validated picture of nucleosynthesis will be missing, because critical elements of the phenomena—interaction between the nuclear processes and the plasma environment in which they take place—cannot be accessed.

Experiments at the NIF will certainly manifest these interactions. Work underway now—including diagnostic development, experimental design, and preliminary measurements—suggests that NIF experiments can be designed to observe and measure this interaction and its effects. Such a program of nuclear physics at NIF would be complementary, and possibly equally important, to programs planned at FRIB and DUSEL in solving the problem of nucleosynthesis. Without such plasma-based experiments, our increased understanding from these future facilities will remain incomplete.

NIF will offer the only opportunity for direct measurements in a plasma undergoing thermonuclear burning—just as occurs in stars. Hydrodynamic phenomena in these systems, such as turbulent mix and charged particle transport, also couple to nuclear processes, and the NIF should be able to explore this interface as well. The sensitivity of nuclear interactions to hydrodynamics may, in turn, lead to new diagnostics applicable to the goal of achieving a controlled thermonuclear burn in the laboratory through inertial confinement fusion.

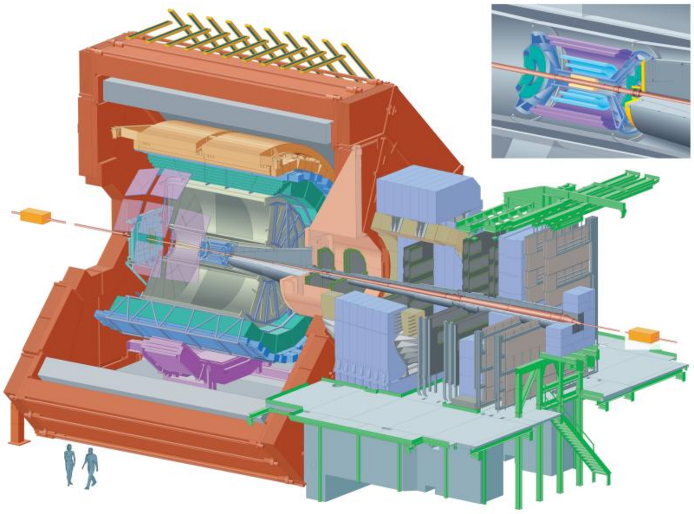
The opportunity to explore the interface between nuclear and plasma physics at the NIF suggests that a new research direction—plasma nuclear physics—is opening. Success in meeting this opportunity can be expected to lead to new insights—not available from other facilities—into nuclear astrophysics, the origin of the elements, the lifecycle of stars, and the properties of burning plasmas.

Nuclear physics facilities

Nuclear physics research is carried out at a suite of accelerator and reactor based facilities around the world. In the U.S., the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is used to study nuclear matter at extreme densities characteristic of the primordial universe, just after the Big Bang. At the Jefferson Laboratory 12 GeV accelerator, high-energy electron collisions probe the quark structure of the nucleus. Smaller accelerator and reactor based facilities are used currently to study weak and strong interactions, the structure and properties of the atomic nucleus as a many body quantum system, and the charged particle and neutron-induced reactions relevant to the Big Bang and stellar nucleosynthesis to understand the origin of the heavy elements.

New facilities, under development or in construction, will push the frontiers in density, energy, and stability. The ALICE experiment, at the CERN Large Hadron Collider, will access extreme nuclear densities and temperatures. The Facility for Rare Isotope Beams (FRIB), under construction at Michigan State University, will explore the structure and properties of nuclei at the limits of radioactive stability. By producing short-lived nuclear isotopes in flight and analyzing their interactions, the FRIB accelerator will expand our understanding of the nuclear reaction chains that occur in stellar explosions on sub-second timescales, shorter than the typical beta decay lifetimes. The Deep Underground Science and Engineering Laboratory (DUSEL), presently under development, will allow nuclear physicists to escape the cosmic ray backgrounds that limit the study of charged particle reactions at low energies comparable to stellar environments.

The NIF presents complementary and unique opportunities. With NIF, a portal is opened to plasma nuclear physics, the direct study of nuclear processes in the presence of an atomic plasma. In NIF plasmas nuclei are affected by large fluxes of electrons and neutrons, just as they are in burning and exploding stars. This interaction between a nucleus and the plasma is expected to lead to phenomena that can affect timescales of nuclear interaction and the pathways of nucleosynthesis, influencing the processes of stellar evolution. The NIF plasma represents a new degree of freedom in nuclear physics, beyond those being explored by other existing or planned facilities.



Dedicated heavy-ion detector built by the ALICE collaboration to exploit the unique physics potential of nucleus-nucleus interactions at Large Hadron Collider energies.

Stellar and Big Bang Nucleosynthesis in Plasma Environments

Determining the rates of the light-ion fusion reactions that initiate nucleosynthesis and power the early stages of stellar evolution requires the study of reaction rates in plasma environments that only NIF can create.

Introduction

Once the Universe had cooled down enough for stable protons and neutrons to form, the creation of the elements began through a sequence of nucleosynthesis processes. During the first few minutes, the primordial elements of hydrogen, helium, and lithium were created. But because there are no stable nuclei with five or eight nucleons, elements heavier than A=8 were not synthesized in the rapidly expanding early universe. The formation of heavier elements—^{12}C and beyond—required the long-lived, high-density plasma conditions of stars, which evolved in the first billion years after the Big Bang. Nucleosynthesis through many generations of stars led to a slow buildup of the elemental and isotopic abundance distribution observed today.

Stars are stabilized against gravitational collapse by the energy produced in nuclear reactions. Light ion fusion processes create heavier nuclei, which serve as the fuel for subsequent burning sequences. The evolution and final fate of stars depend on their initial mass, which determines the temperature and density conditions in the stellar core. Low mass stars end as white dwarfs—heavily compressed degenerate material at very high density; massive stars end in violent explosions as core collapse supernovae, with rapid nucleosynthesis occurring in an expanding shock front, feeding on the seeds of previous quiescent burning phases. Despite the differences in temperature, density, and timescale, the synthesis of the elements is unified by the sequences of nuclear reactions in a plasma environment.

The stellar reaction rates, which drive the burning processes, are determined by the nuclear reaction probability (cross section) at stellar energies and by the screening effects of the free floating electron gas of the plasma, which reduces the Coloumb barrier between the interacting positively charged ions. The screening effects increase dramatically with density in the plasma and can lead to a substantial enhancement of the reaction rate. An example is density-driven pycnonuclear fusion in white dwarf stars, where enhancement of ^{12}C+^{12}C fusion by electron screening triggers SN Ia explosions. Modern reaction rate and nucleosynthesis calculations rely on a phenomenological description of electron plasma screening motivated by observation and analogy rather than direct experimental investigations.

Opportunity

The dynamic evolution of plasma conditions at the NIF provides new opportunities to directly study charged-particle reactions important to stellar and Big-Bang nucleosynthesis.

For example, electron-screening corrections to fully ionized reaction rates will be small in the weakly coupled plasmas produced in exploding pusher targets. In contrast, accelerator-based reaction studies at low energies require large corrections to account for the interaction of the incoming beam particles with the atomic shell electrons. These screening effects are also not well understood and contribute substantial systematic errors to the measurements. A direct measurement of light ion reactions in a hot plasma at the NIF can provide, for the first time, the opportunity to correlate accelerator-based experimental results with quasi-stellar plasma conditions. It will test both the extrapolation techniques developed by nuclear reaction theory and the theories of atomic and plasma screening, which are primarily based on phenomenology (Fig. 10).

Research Directions

The first light-ion reaction experiments, observing reactions such as T+T, D+^{3}He, and ^{3}He+^{3}He, have already been performed at the OMEGA laser facility at the University of Rochester. In some cases, the results indicate substantial deviations from the predictions based on accelerator experiments. While the reason for these deviations must still be explored, the observations point to the existence of phenomena that may affect nuclear reactions in plasma environments and alter our present interpretation of stellar burning phenomena. Initially, experiments at NIF can leverage existing particle detection diagnostics developed for the National Ignition Campaign to build on the OMEGA results. A broader suite of highly resolving detector technologies over a wider range of energies will be required to fully exploit the information present in these brief, intense implosions. Such experiments can be expanded toward a broader range of light ion studies to map specific nuclear atomic effects, or to study critical reactions in the pp-chains and CNO cycles of hydrogen burning, which have unique signatures. The development of radiochemical methods, in particular, would open up new possibilities. These studies would complement ongoing efforts to probe the very low-energy nature of stellar fusion processes with accelerators at underground laboratories.

In the future, we can hope to obtain higher plasma temperatures through, for example, the operation of NIF at longer laser wavelength. With higher temperature studies, reactions on radioactive isotopes, such as ^{18}F(p,α)^{15}O, can be envisioned with long-lived ^{18}F material injected into the capsule. This is a critical reaction in nova explosions, driven by the hot CNO cycle, and determines the amount of ^{18}F produced by the nova thermonuclear runaway and the extent to which the nova luminosity curve is driven by the decay of the rather long-lived (2 hours) ^{18}F isotopes. This experiment would be complementary to radioactive beam studies performed at facilities such as Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory and the TRIUMF Isotope Separator and Accelerator (ISAC), and would address the impact of the hot dense plasma conditions at the surface of accreting white dwarfs where nova explosions occur. Longer term, we can envision the possibility to study reactions in moderately or strongly coupled plasmas. Clearly, such experiments to probe nuclear reactions in dense matter will entail new experimental designs and new techniques to sift through the debris of implosions to identify reaction products caught up in the dense plasmas produced.

Impact

Observed isotopic abundances are perhaps the best probes of what the early universe was like, and how stars evolve. But our ability to exploit observations is compromised by uncertainties in the effects of plasma conditions on charged particle reactions. NIF offers the possibility of resolving this question through direct laboratory measurement of light-ion fusion reactions in a plasma.

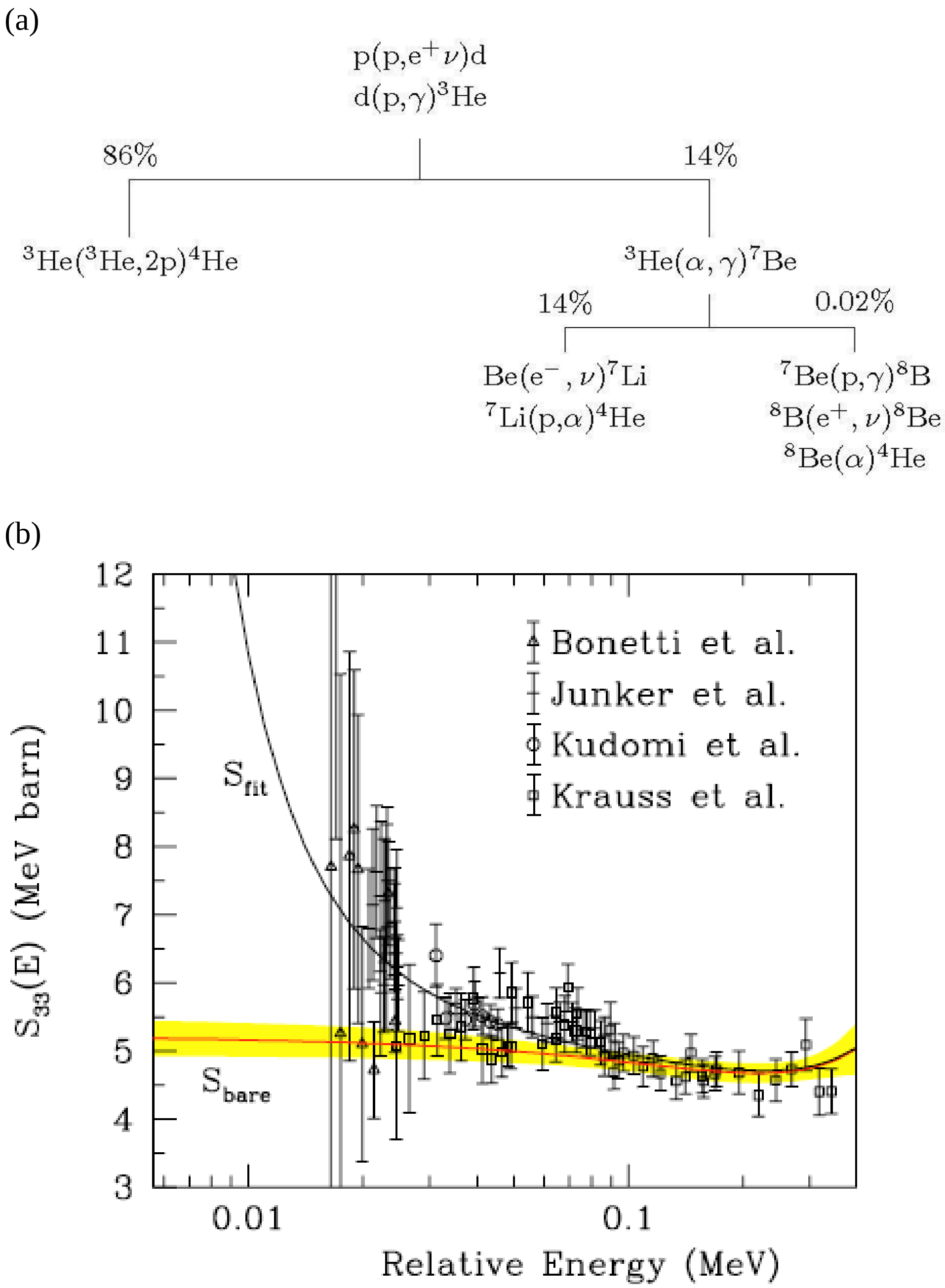


Fig. 10. (a) Schematic of proton-proton (p-p) chain, which is the primary mechanism for burning hydrogen into helium in stars like the sun. The ^{3}He(^{3}He,2p)^{4}He reaction sets the ratio between high and low energy solar neutrinos, and determines the sun's core temperature. It should be possible to measure the ^{3}He+^{3}He cross section on NIF without the bound electron screening effects that hamper experiments at accelerator facilities. (b) Graph of cross section data, where the fit to data, S_{fit}, must be corrected to yield the bare quantity, S_{bare}, relevant to stellar interiors. Here, S is related to the cross section (σ) by

$$\sigma(E) \cong \frac{e^{-\sqrt{E_C/E}}}{E} S(E)$$

Formation of the Heavy Elements and Role of Reactions on Excited Nuclear States

The effects on nucleosynthesis and nuclear lifetimes of excited states populated through interactions with the stellar plasma environment can only be directly studied at NIF.

Introduction

The heavy elements in the Universe were formed by nuclear reactions in both burning and exploding stars. In stellar burning, a relatively low rate of neutron captures (s-process) leads to the buildup of heavier nuclei as stable nuclei absorb a neutron and then decay back to stability before undergoing a subsequent capture. In supernovae, neutron fluences become so large that a rapid series of neutron captures (r-process) leads to very neutron-rich nuclei, and the buildup to heavier elements takes place far from stability. The distribution of isotopic abundances produced in the s-process is of particular importance for understanding nucleosynthesis since it represents the seed for subsequent processes. S-process abundances are used to define the "observed" r-process abundance distribution, the main signature for r-process model studies. The s-process depends sensitively on neutron flux and temperature conditions at the s-process site. An accurate description of these environments, s-process reactions, and beta-decay half-lives is required to understand the s-process path and resulting abundances.

In the exotic environments where heavy elements are created, nuclei need not be in their ground-state configurations but can be excited due to atomic processes that couple into the nucleus. Several nuclear decay and excitation processes are mediated by atomic electrons. In cold matter, neutral atoms have no inner-shell vacancies; hence, the only process that can occur is internal conversion, where the nuclear decay energy is transferred to a bound electron, which is ejected into the continuum. However, as the temperature in the plasma environment is increased, other processes are possible as there are both free electrons and many inner-shell and outer-shell vacancies. For example, nuclear decay can excite a bound electron to an unoccupied bound state (bound internal conversion). The inverse processes of internal conversion can also occur. The inverse of bound internal conversion occurs when the electron goes from a higher atomic level to a lower level and resonantly transfers the energy to excite the nucleus (Fig. 11). At even higher temperatures, the dominant electromagnetic coupling to the plasma environment is to the radiation field, and photons are directly absorbed at nuclear resonant frequencies. Nuclear rates responsible for heavy element generation can be substantially modified by nuclear excitation, leading to tremendous differences in the production and decay of specific isotopes.

Opportunity

NIF can create conditions that lead to this complex plasma-nuclear coupling, enabling for the first time detailed experimental studies of these processes and their effect on nucleosynthesis.

Low-lying states in heavy nuclei are thermally accessible even in the relatively modest temperatures (~300 MK) for s-process nucleosynthesis. The population of these states can significantly modify the neutron capture rate relative to the ground state component, changing the capture timescale, which translates into a different abundance distribution. Thermal enhancement of long-lived radioactive isotopes along the s-process path can also dramatically change the effective lifetime of the isotope and will lead to a new branch in the reaction path, which again meaningfully alters the final abundance distribution. Assuming that the excited nuclear states are in thermal equilibrium with the ground state, reactions will proceed along the most rapid reaction path while maintaining a fixed excited-to-ground-state ratio, effectively converting all of the material to the state with the most rapid reaction path. Present estimates for this enhancement in neutron capture rates in stellar environments are based on theoretical calculations. These effects provide a new tool for the astronomer to measure the stellar temperatures at the actual s-process sites in AGB stars and also in massive stars. The most critical reaction uncertainties in the s-process network involve unstable or thermally modified reaction branches.

Research Directions

Neutron capture measurements for the s-process are typically performed at spallation neutron source facilities, such as the Neutron Time-of-Flight Facility at CERN and the Los Alamos Neutron Science Center, but these measurements can only access the ground-state capture component. The NIF is a neutron source of unique strength. By choice of design and fuel selection, the low-energy neutron flux can be tailored for sensitivity to stellar neutron reactions. One nucleus that would be interesting to study in NIF implosions that mimic s-process conditions is ytterbium-170, which is produced solely via the s-process. Further, its destruction cross section due to neutron capture is estimated to be modified by as much as 30% in a stellar environment due to the role of capture in excited states. By performing a neutron capture measurement in the NIF plasma at varying temperatures, the effect of excited state capture on ^{170}Yb could be measured to improve the stellar uncertainties in a region where the ground-state cross sections are known to better than 5%. The new opportunity made possible by NIF is to directly measure the neutron capture component on excited states in experiments in a hot plasma environment not accessible at existing facilities.

The few experimental attempts to measure the excitation via internal conversion of nuclei in a plasma environment have not yet succeeded. There are two experimental configurations that could result in nuclei being driven to high-temperature local thermodynamic equilibrium (LTE) conditions: either a short intense laser pulse incident on a target that is confined by surrounding material, or in a NIF-type implosion. Short pulse heating leads to high temperatures at solid density, but for short times: $t < 40$ ps. Implosions offer the possibility of reaching higher densities ($\rho \sim 300$ g/cc) and significantly longer time scales ($t < 200$ ps), with larger numbers of dopant nuclei, but will have lower temperatures. In both cases, the basic strategy would be to create LTE conditions at a temperature sufficient to populate low-lying nuclear excited states, and then seek to observe late time fluorescence of the “pumped” nuclei that remain in excited states after the plasma heating environment has been rapidly removed. A second variant on this experimental idea is to pick a nucleus in which the pumped isomeric state leads to a second nuclear decay branch with a distinct radiochemical signature. Initial experiments to look for evidence of nuclear-plasma induced excitation might investigate the first excited state in ^{73}Ge (13.9 keV) and ^{169}Tm (8.41 keV). Simulations indicate that the X-ray background in the NIF chamber this late in time is low enough to allow observation of the de-excitation of these states.

The hot plasma conditions provided by the NIF also offer an opportunity to study the effects of the plasma environment on the lifetimes of long-lived radioactive nuclei. The lifetimes and decay modes of radioactive nuclei and their excited states are studied at radioactive beam storage ring facilities, like the GSI Helmholtz Centre for Heavy Ion Research GmbH in Germany, and in beam-target experiments at advanced accelerator laboratories, like the National Superconducting Cyclotron Laboratory at Michigan State University. The NIF offers an alternative approach for analyzing the decay properties of these nuclear states by utilizing the short pulse characteristics of the shot as an additional timing signature.

The lifetime of ^{210}Bi is illustrative of the challenges that could be uniquely addressed at the NIF. Bismuth-210 is created at the end of the s-process in metal-poor, low-mass AGB stars as long-lived ^{210m}Bi ($t_{1/2} = 3 \times 10^6$ y) and short-lived ^{210gs}Bi ($t_{1/2} = 5$ d). If the states are in thermal equilibrium, all of the ^{210}Bi created will decay back to ^{206}Pb via the short-lived ground state decay before further capture can take place. If the states are not in thermal equilibrium, then the metastable state might undergo an additional capture before decay, recycling back to ^{207}Pb. These plasma-driven effects control the ^{206}Pb and ^{207}Pb abundance ratios. By tuning the plasma temperature of NIF shots loaded with ^{210m}Bi and looking for the decay of ^{210gs}Bi post-shot, the thermal equilibration timescale might be measured as a function of plasma temperature. Selenium-79, a branch point in the *weak* s-process, shows similar effects. The change in lifetime between terrestrial and stellar conditions is approximately five orders of magnitude. The decay rate in a stellar plasma is sufficiently high to undergo noticeable decay *during* the NIF plasma, opening the door to a test of modification of the decay rate due to the plasma.

These efforts will require mature diagnostics at the NIF, including the ability to accurately diagnose the plasma temperature and duration, the neutron fluence down to extremely low energies—approximately 1 keV—and reproducible shots. In addition, efficient, prompt radiochemical debris collection of both solids and gases will be needed for many of the reaction studies of the effects of the plasma and temperature on excited states. The study of neutron capture reactions will also benefit from an approach to measuring the gamma-ray decay cascade following capture. The current Gamma-Ray History diagnostic provides an initial handle on this information by measuring a gamma-ray time history during and after the implosion.

Impact

Heavy stars, supernovae, and other dynamic, transient astrophysical phenomena are largely responsible for the production of the heavy elements. Nucleosynthesis in these environments often involves an interplay between enormous particle fluxes that drive the production of nuclei far from stability and spontaneous decay back to stability. In dynamic environments where abundance distributions are not driven to equilibrium, the effect of excited nuclear states on neutron capture rates and decay half-lives is intrinsically important to an understanding of the observed abundances. NIF opens the door to studying some of these effects in a laboratory setting. Exploring these effects at NIF will require significant steps forward in creating and diagnosing a broad set of plasma environments.

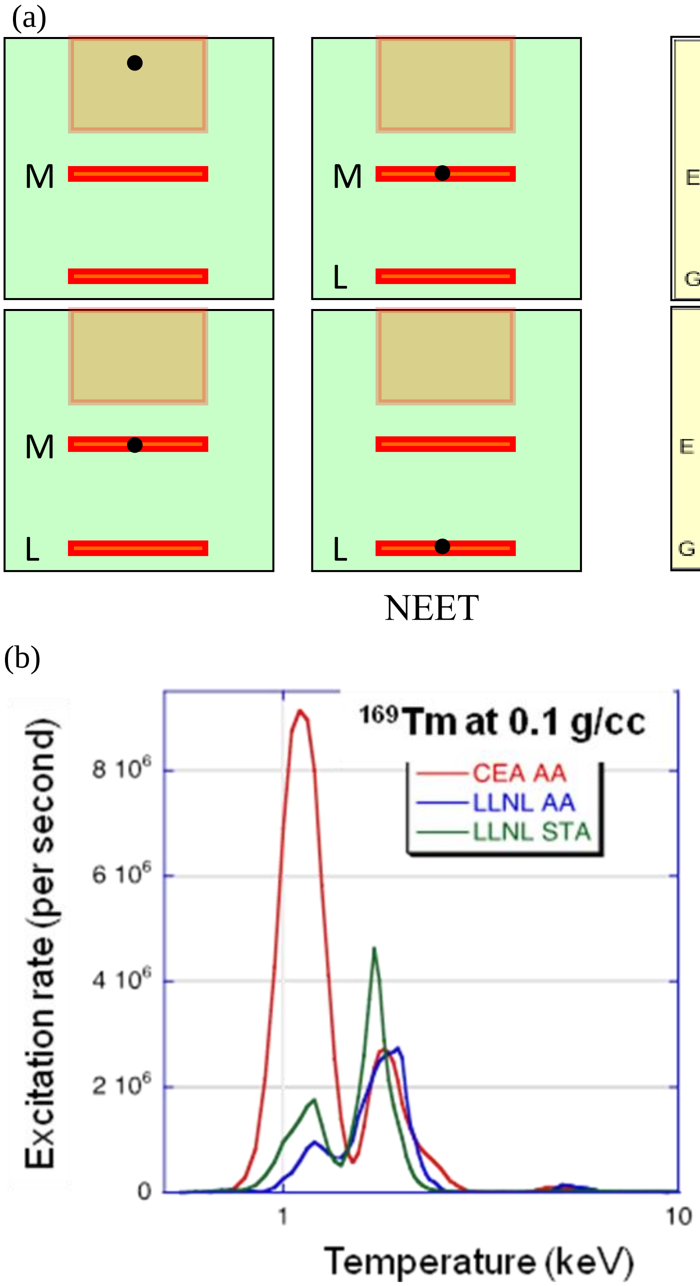


Fig. 11. (a) Two virtual photon exchange processes thought to dominate the coupling of plasma excitations to nuclear excitations: nuclear excitation by electron capture (NEEC), in which an electron in the continuum is captured into a bound atomic orbital, and nuclear excitation by electronic transition (NEET), a resonant process involving the transition of a bound electron to a lower atomic orbital. In both processes, the energy of an electron excites the nucleus from the ground state (G) to an excited state (E). (b) Different calculations for nuclear excitation rates in ^{169}Tm (private communications from Mau Chen and Stephen Libby of LLNL and from Gilbert Gosselin, P. Morel, and Vincent Meot of CEA). These calculations are complicated, and the relevant degrees of freedom for accurate and computationally efficient models need to be worked out, leading to a need for experimental measurements of these processes to test these models.

Thermonuclear Hydrodynamics and Transport

Nuclear reactions can be a sensitive probe of complex plasma dynamics, including mix, charged-particle energy loss, and mass flows. NIF experiments involving nuclear measurements will allow the development of new understanding of these phenomena.

Introduction

To fully exploit the potential of NIF for exploring science at the interface between nuclear and plasma physics, we must face the challenge of better understanding the interaction between hydrodynamics and thermonuclear energy release. Progress in this direction will extend and expand the utility of NIF for nuclear physics, help elucidate stellar evolution, and lead to new ways of studying burning plasmas. Complex phenomena such as turbulent mix in convergent flows, energy and charge transport via high-energy particles, and the possibility of isotopic fractionation in a burning plasma can be explored through nuclear measurements.

Opportunity

The extreme conditions available at NIF offer a unique opportunity to probe the interplay between hydrodynamics and burn. To date, there exists only a phenomenological understanding of this complex physics. A joint theoretical and experimental NIF program could accurately characterize the physics of mix and its associated effects on thermonuclear burn, as well as bring unique insights to bear on compelling astrophysical mix-based conundrums, such as Supernova (SN) 1987a (Fig. 12).

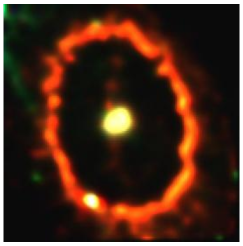


Fig. 12. NASA image of SN 1987a. One of the outstanding conundrums of SN 1987a involves the early emergence of ^{60}Co light emissions, an effect which is conjectured to be related to 3-D turbulent mix effects. Such effects could be studied in proposed experiments at NIF.

The unique sensitivity to hydrodynamical mix arises because reactions of charged particles are sensitive probes of spatial information in burning NIF capsules, since the range of these particles is typically a small fraction of the radius of the compressed capsule. Thus, charged-particle reactions probe the location of materials, making them ideal probes of the hydrodynamical mix at small scales.

A related opportunity afforded by the combination of thermonuclear (TN) burn and convergent hydrodynamics is the study of the interaction of energetic charged particles with partially or fully degenerate plasmas. The energy loss of the particles is a direct probe of the plasma degrees of freedom and mechanisms for transferring energy to the plasma, a problem of fundamental interest, with applications to ignition. For example, how does the energy couple into the different plasma components, ions versus electrons? Can energy be transferred to collective modes that involve material motion, but not thermal excitation, and how long does it take for collective modes to dampen? With current NIF technology and diagnostics, unique opportunities exist today to explore this issue; farther into the future, studies on this topic could be greatly expanded with advanced NIF technologies that will become available.

Finally, it has recently been realized that dynamical plasma effects may alter nuclear reactions in ICF implosions. Anomalous reaction yields have been observed at the OMEGA laser facility, first by Rygg et al.,[1] then by Hermann et al.,[2] associated with the use of multispecies fuel mixtures in ICF implosions. Rygg et al. discovered that directly driven capsules filled with different mixtures of D_2 and ^{3}He gas show an unexpected density scaling of experimental reaction yields. Implosions with a 50:50 mixture of D:^{3}He by atom consistently showed measured reaction yields that are about half of that anticipated by density scaling from measured yields of hydroequivalent implosions with pure D_2 and nearly pure ^{3}He. Although some differences were observed in the Rygg et al. and Herrmann et al. data sets, both experiments showed similar anomalous reaction-yield trends. Similar effects were also seen in other high-Z campaigns in which dopants such as Ar and Kr resulted in anomalously low reaction yields, as well as for Ar-doped deuterium fuels on NOVA.[3]

A satisfactory explanation to these results has not yet been found, but recent work by Amendt et al.[4] on plasma barodiffusion appears promising. Barodiffusion (or pressure gradient-driven diffusion) in a plasma that incorporates electric fields might explicate the reported reaction-yield anomalies. According to this theory, the lighter deuterium (and tritium) ions diffuse away from fuel center in D(T)^{3}He implosions, leaving the implosion core slightly rich in ^{3}He. This condition leads to a reduction in fusion neutrons, a result qualitatively consistent with the anomalous yields observed in experiments with D^{3}He, DT^{3}He, and high-Z doped deuterium fuels.

In addition, recent and initial measurements of the TT and DT reaction yields conducted at OMEGA also indicate that the reactivity of TT vs. DT fusion is greater than what is expected based on existing knowledge of the fusion cross sections, implying that species fractionation may be significant even in DT plasmas. This issue may have implications for DT hot-spot ignition at the NIF.[5] Barodiffusion theory also predicts that H_2 added to D_2 or DT fusion fuels (such as THD employed at NIF) might have the opposite effect: scaled yield could actually increase due to the hydrogen diluent diffusing out of the hot core. These and other closely related effects of multispecies fuel mixtures can be definitively studied at the NIF, utilizing its unique and versatile high-convergence implosion platforms.

Research Directions

An experimental mix program would include the design of innovative NIF capsules and the development of diagnostics. The diagnostics needed to enable a mix program at NIF include gamma-reaction history with a time resolution of 10 ps, 14.1 MeV neutron-imaging with 10-µm spatial resolution, prompt solid-debris radiochemistry, and high-resolution Compton gamma-ray spectrometry. This diagnostic suite would enable the design and fielding of a full experimental mix program at NIF.

Experiments that use initially separated reactants (e.g., a very thin deuterated shell within an “inert” ablator) would probe the details of mix morphology as the deuterated layer mixes into, and then burns with, the tritium (Fig. 13). A second class of experiments would measure the reaction of high-energy alphas and knock-on tritons and deuterons with the shell material. Together these two classes of experiments could probe mixing lengths, the evolution from chunk to atomic mix, and the effect of mix on burn. Such NIF experiments would provide ideal environments capable of validating mix models for compressible, converging flows with TN burn. In addition they would provide critical experimental insights to outstanding astrophysical mix problems, such as illustrated by SN 1987a, where the early emergence of ^{60}Co light curve remains a challenging mystery.

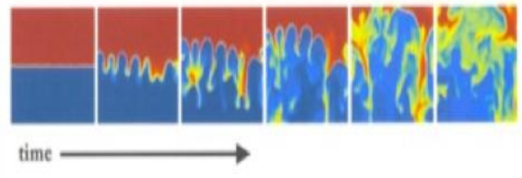


Fig. 13. Image derived from calculations for the spatial distribution of mass fraction and for evolution of chunk to atomic mix in NIF capsule. The shell (red) and fuel (blue) are initially separated. Turbulence causes the interface to become initially distorted, then the two fluids evolve into an atomically mixed field. A small amount of pristine fluid remains.

NIF possesses today four critical elements to immediately undertake the study of charged particles stopping in partially or fully degenerate plasmas. First, monoenergetic protons (14.7 and 3.0 MeV), alphas (3.7 MeV), and tritons (1.0 MeV) can be, and in fact already have been, generated at the NIF (Fig. 14). This has been accomplished by imploding exploding-pusher capsules filled with D^{3}He fuel. When D^{3}He fuses, it generates 14.7 MeV protons and 3.7 MeV alphas. In addition, the fusion of DD generates 3.0 MeV protons and 1.0 MeV tritons. As these particles are monoenergetic, any energy loss that results from their passage through the target can be directly related to the stopping power. The second element is charged particle spectrometers to accurately measure the energy loss after passage through the target plasmas. In one form or another, these already exist at the NIF and have been utilized in several experiments (Fig. 14). The third element is the capability to generate large uniform plasmas that are highly compressed. NIF has the capability to uniformly and quasi-continuously compress materials to pressures of ~30 to ~1000 Mbar, from which unique and suitable target plasmas can be generated with areal densities of order 10 mg/cm^2 to 50 mg/cm^2. The fourth element is adequate diagnostics to characterize the target plasmas, and many of these diagnostics, if not all, are present at today’s NIF.

In the future, NIF ARC will be able to generate proton energies of ~100 MeV. These protons will be able to penetrate degenerate target plasmas of spherically imploded capsules that have areal densities of ~ 2 gm/cm^2. Only at NIF could such target plasmas be both generated and diagnosed with the goal of uniquely furthering our fundamental understanding of stopping power in partially or fully degenerate plasmas.

Experiments to reproduce, and further study, the effects of fuel mixtures and the possible presence of barodiffusion hinted at in OMEGA measurements could be implemented at NIF almost immediately.

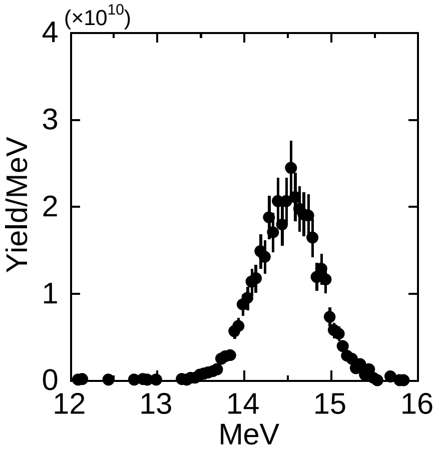


Fig. 14. The 14.7 MeV proton spectrum from D^{3}He exploding pusher. The proton line, a result of the fusion of D and ^{3}He and obtained with a NIF ("wedge") proton spectrometer, would be used to measure, through accurate energy loss of the protons from their birth energy, the stopping effects of degenerate plasmas.

Impact

Thermonuclear ignition and many other phenomena depend on the details of how matter and energy are transported in high-energy density plasmas. NIF's energy and yields will enable us to study transport mechanisms in new ways, specifically with charged-particle reactions as a probe of turbulence on short length scales, and to measure stopping power. These experiments have the potential for a deeper understanding of ignition in inertial confinement fusion and may shed light on astrophysical anomalies such as the light curve of SN 1987a.

References

1. Rygg, J. R., J. A. Frenje, C. K. Li, F. H. Séguin, R. D. Petrasso, J. A. Delettrez, V. Yu. Glebov, V. N. Goncharov, D. D. Meyerhofer, P. Regan, T. C. Sangster, and C. Stoeckl, Tests of the hydrodynamic equivalence of direct-drive implosions with different D2 and ^{3}He mixtures, *Phys. Plasmas* **13**, 052702 (2006).
2. Herrmann, H.W., J. R. Langenbrunner, J. M. Mack, J. H. Cooley, D. C. Wilson, S. C. Evans, T. J. Sedillo, G. A. Kyrala, S. E. Caldwell, C. S. Young, A. Nobile, J. Wermer, S. Paglieri, A. M. McEvoy, Y. Kim, et al., Anomalous yield reduction in direct-drive deuterium/tritium implosions due to ^{3}He addition, *Phys. Plasmas* **16**, 056312 (2009).
3. Lindl, J.D., P. Amendt, R. L. Berger, S. G. Glendinning, S. H. Glenzer, S. W. Haan, R. L. Kauffman, O. L. Landen, and L. J. Suter, The physics basis for ignition using indirect-drive targets on the National Ignition Facility, *Phys. Plasmas* **11**, 339 (2004).

4. Amendt, P., O. L. Landen, H. F. Robey, C. K. Li, and R. D. Petrasso, Plasma barodiffusion in inertial-confinement-fusion implosions: Application to observed yield anomalies in thermonuclear fuel mixtures, *Phys. Rev. Lett.* **105**, 115005 (2010).
5. D. Casey et al., to be submitted to *Phys. Rev. Lett*. (2011).

MATERIALS AT EXTREMES AND PLANETARY PHYSICS 59

MATERIALS AT EXTREMES AND PLANETARY PHYSICS

Introduction

NIF offers unprecedented opportunities for the study of matter in new regimes of pressure, temperature, and strain rate. The conditions reachable at the facility—up to 1000-fold compression—will provide answers to fundamental questions about condensed matter and are likely to reveal entirely new phenomena in materials. Under these conditions the chemistry of the elements changes as core, and not just valence electrons, participate in bonding. The nature of material strength, transport, and defects is virtually unknown. Hence, the results will be essential for understanding the origins and evolution of planets, including the many exoplanets that have been discovered outside our Solar System, as well as for characterizing the path to thermonuclear fusion, whether the transition from planets to stars or the production of fusion energy in the laboratory. The implications span a broad range of scientific problems, from understanding fundamental interactions in dense matter to making new materials to understanding the interiors of planets, brown dwarfs, and stars.

Status of the Field

Recent advances in static and dynamic compression experiments have, in combination with theory and computation, opened a new world on the nature of materials at high pressures and temperatures.[1] Static compression experiments have revealed a broad range of remarkable findings to several megabar and low to high temperatures (10^{-3} K to 10^{4} K).[2] Myriad transformations in materials provide new insight into their chemical and physical properties, opening a window on their energy landscapes. Novel electronic, magnetic, and superconducting phases, including the highest temperature superconductivity, have been discovered. Fundamental transformations in hydrogen and other low-Z quantum systems have been identified and provide sensitive tests of theory. These advances take advantage of developments in a broad spectrum of x-ray, neutron, and laser sources, in particular, diamond-anvil cells achieving the highest pressures.

Dynamic compression experiments provide information on the properties of materials at high strain rate and, in principle, to higher pressures (e.g., to ~10 Mbar, with selected studies having reached much higher pressures). These experiments use gas-gun, magnetic (Z pinch), and laser drives. Hugoniot and ramp-compression methods have been developed and exploit an increasing number of diagnostics. These developments have yielded important recent results for materials, documenting metallization of fluid hydrogen, helium, and silica; melting of diamond; and phase transformations in iron.[3-6]

Despite these advances, many questions remain because we lack the ability to study materials over the required range of pressures, temperatures, and densities. For example, the notion that pressure can ionize—“smear out”—atoms, taking materials across the great divide between insulators and metals, has been a fundamental tenet since the birth of quantum mechanics (Fig. 15).[7-9] Recent research has turned past theoretical understanding on its head, with the finding that a "simple metal" like sodium becomes a novel type of electride at high pressures: a transparent, electrically insulating solid with ionic bonding.[10-12] There could be important implications for developing new materials, but much work is needed to understand the origin and generality of such phenomena.

These findings challenge current theory and are driving the development of new theoretical approaches. Indeed, theory has suggested even more profound changes at higher compressions, such as the pressure-induced quantum melting—a liquid ground state for simple materials at high pressures—predicted a half a century ago.[13] More recent theoretical work points to combined superconductivity and superfluidity in dense hydrogen, which would be an altogether new state of matter.[14] Access to the "atomic pressures" ($\frac{e^2}{2a_0{}^4}$ = 147 Mbar) required to explore this regime requires a major leap in experimental capabilities.

Opportunities for Accelerated Discovery

Recent advances in studies of materials at extreme conditions, in inertial fusion experiments, and in planetary astronomy set the stage for major breakthroughs.[1,15,16] A central focus concerns characterizing the nature of matter at 10- to 100-fold and even greater compressions—unexplored territory for physical science. The capabilities of NIF allow orders of magnitude increases in the pressure and density range available for investigating materials behavior. The energy scale associated with compression to Mbar pressures corresponds to eV's, the range of conventional chemical bonds; Gbar pressures accessible with NIF correspond to keV energy changes, an altogether new regime (Fig. 16). As the recent observations of transparent alkali metals now show, the traditional view of transforming an insulator to a dense "plasma" state under pressure through smearing of electron orbitals is demonstrably wrong. Collective electronic effects come into play. Rich phenomena involving bonding, electronic structure, new quantum states of matter, and emergent collective behavior of atoms remain to be uncovered.

Central to many problems is the behavior of element one—hydrogen—the starting point and testing ground for much of modern physics. At low and modest temperatures, different forms of metallic hydrogen have been theoretically predicted over a broad range of conditions, including the quantum many-body states discussed above.[8,14,17] At higher temperatures, one enters the domain of warm dense matter (1-10 eV) (i.e., of planetary interiors), extending to the regime of dense burning plasmas (keV and above) of stars and fusion energy. Exploration throughout this pressure-temperature range will close the gap between normal condensed matter and the stuff of which stars are made, establishing a materials science of condensed matter undergoing thermonuclear fusion. This will provide the foundation for translating the first successful ignition experiments into practical means of energy production by thermonuclear fusion.

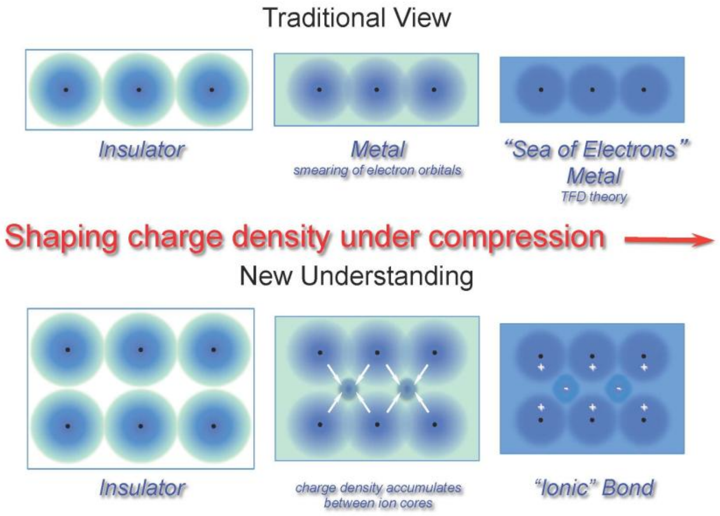


Fig. 15. Representation of the charge density and its impact on structure and bonding in materials as a function of compression.

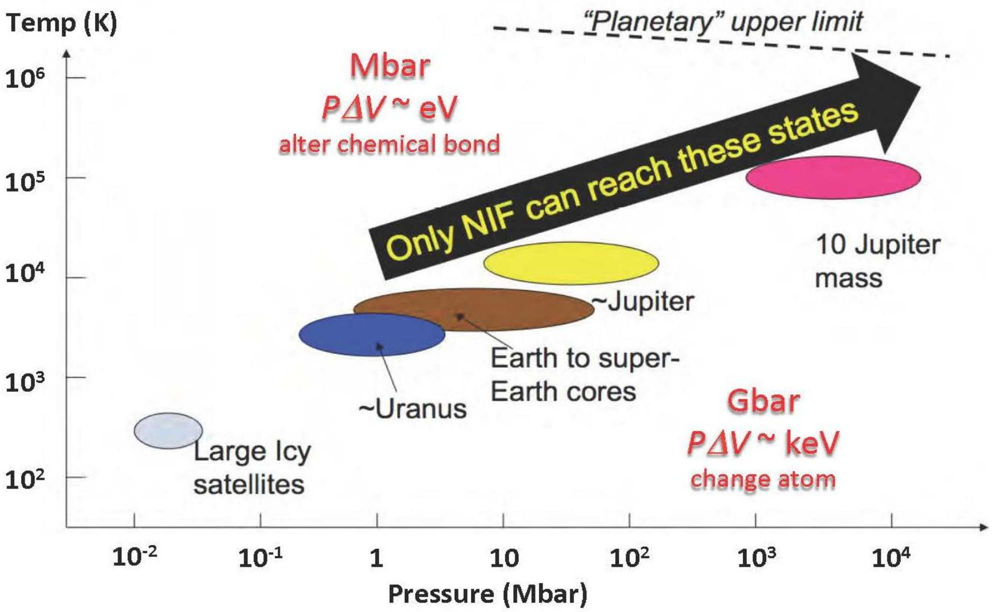


Fig. 16. Range of interior pressures and temperatures of classes of planets and the corresponding effects of the compression on bonding energies of the component materials (Credit: D.J. Stevenson, 2008).

Joining the fields of condensed-matter and plasma physics—based for the first time on high-density measurements made under controlled laboratory conditions—represents a major intellectual breakthrough in the science of materials and energy.

Studies of materials at atomic pressures will open up new chemistry at ultrahigh compression, including “kilovolt” chemistry involving core electrons and new physical properties of which there are glimmerings in recent experiments at more modest pressures.[10-12] In short, this will lead to an entirely new view of the periodic table, as well as novel conditions for nuclear chemistry (e.g., pressure-induced electron capture). There is also an opportunity to characterize the dynamics of materials at the microscopic level, including the time dependence of phase transformations, and new regimes of strength and damage. Measurements of transport properties will provide a basis for understanding and controlling metastability, leading to the creation of new materials that may be recoverable.

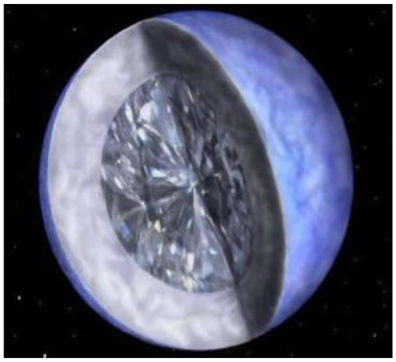


Fig. 17. Artist rendition of the interior of the white dwarf BPM 37093, dubbed Lucy in the popular press. Material at the center of this massive object is thought to be solid even though the outer surface temperature is in excess of 1 eV.

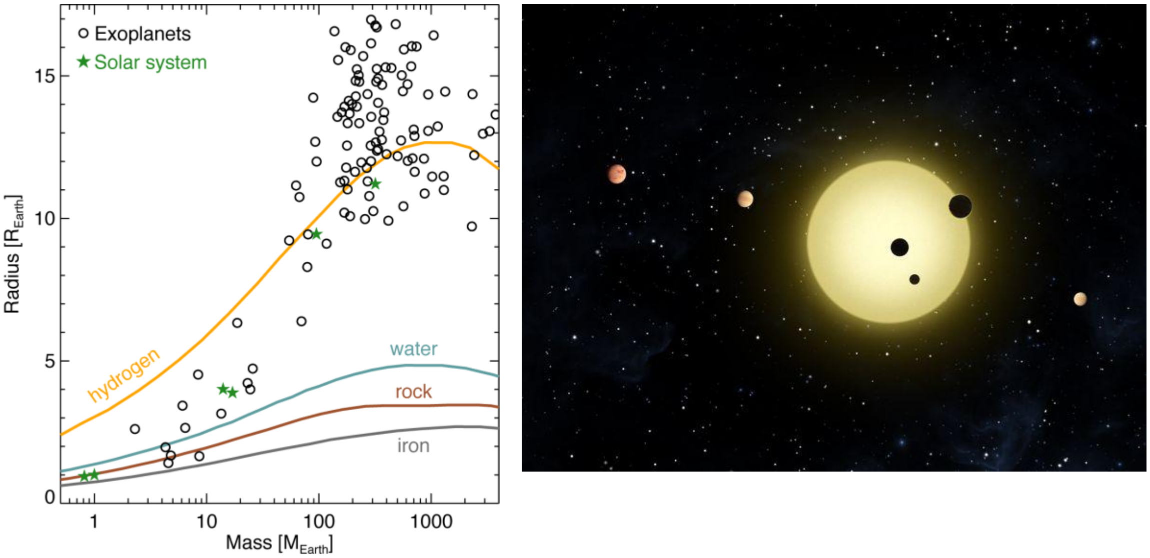
NIF will provide the essential bridge between observational astronomy and a fundamental understanding of the massive objects in the universe or even a predictive astronomy (Fig. 17). Recent observations of myriad exoplanets, including super-Earths with potential for harboring life, have opened a broad frontier (see next sidebar). NIF is uniquely poised to provide materials data essential for understanding the nature of the interior structure, composition, evolution, and even origins of these bodies. Understanding the nature of super-giant planets further motivates studying warm condensed matter into the Gbar regime, including highly accurate equations of state of hydrogen, the nature of hydrogen/helium mixtures, and the behavior of the more complex chemistries necessary to understand differentiating planetary bodies. NIF will provide the energy density needed for simulating the conditions associated with the giant impacts of planet formation, such as the one that led to creation of the Earth’s moon. In addition, NIF will allow x-ray impulse loading of asteroid-type materials to address the technical challenge of deflection of celestial bodies on Earth-crossing orbits and thus contribute to mitigation of rare but potentially catastrophic hazards of impacts.[18]

These studies require the continued development and refinement of diagnostic and target-preparation techniques at NIF. For the studies of condensed matter, one of the main challenges will be the accurate measurement and control of temperature (off-Hugoniot) at conditions approaching isentropic compression (i.e., able to produce cold dense) matter, which has never before been explored experimentally above several Mbar. This will require accurate pulse shaping to achieve shock-less loading through ramp compression. The exceptional control of pulse shape at NIF that has been developed for the National Ignition

Campaign provides a basis for extending this capability to a wide variety of materials (sidebar on next page). Ramp compression is not only essential for reaching super-dense, relatively cool (non-nuclear) states of matter, it will also inform future approaches for achieving ignition with enhanced efficiency (e.g., generalization of the fast-ignition concept, obtaining as high a density as possible before inserting the energy for ignition). Pre-compression experiments with diamond anvil cells also extend the range of Hugoniot measurements to keep samples cool (hence dense) and help match planetary interior pressure-temperature profiles. Finally, x-ray and other imaging experiments can provide the means to measure the dynamics of composite or otherwise complex materials.

The exoplanet frontier

One of the remarkable findings in 21st century science is the realization that planets are everywhere. More than 1500 planets have now been identified outside of our solar system, and the number is growing rapidly. Recent results from the Kepler mission indicate that Earth-like planets are common in our galaxy. These bodies are roughly classified as super-earths, ice giants, and gas giants, but we presently know little about their composition, formation, or potential for life. Currently, NIF is the only facility that will allow scientists to subject materials to the full range of interior conditions of the largest of these astrophysical objects and probe the nature of planetary materials under such extreme conditions.

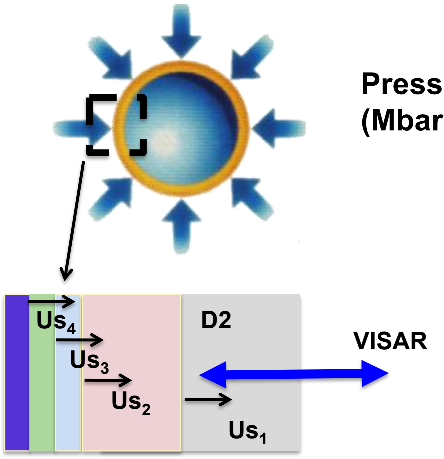


Left. **Mass-radius relationship for transiting exoplanets compared with planets in our solar system. (Source: Adapted from Winn et al., *Astrophys. J. Lett.*, in press.). *Right.* Schematic of the six-planet system around Kepler-11. All are ice and gas giants with orbits within half the Sun-Earth distance. (Source: Lissauer et al., *Nature* 470, 53-58, 2011. Credit: NASA/Tim Pyle.)**

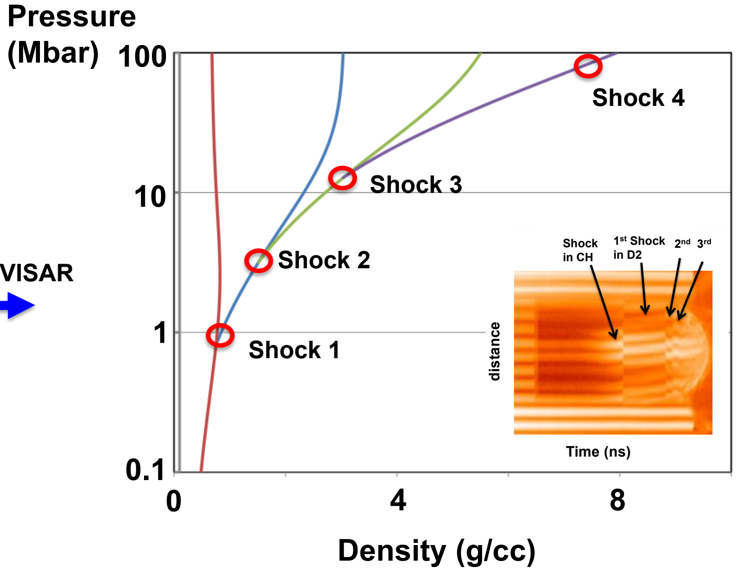
There will be important synergies between these new experiments at extreme conditions and the improvement of theory, simulation, and modeling of materials. New theoretical approaches will be needed, starting with extending first-principles (quantum-mechanics) theory on dense matter at “warm” conditions (<1 eV). Exploring the effects of temperature will provide a check on theory, including our understanding of the underlying electron states such as hybridization of core electrons and implications for phase stability. The identification of new physical and chemical phenomena is likely to emerge and lead to new materials and materials behavior.

Exploring materials using unique compression paths

The initial precision tuning of multiple shocks in an ICF implosion allows the first stage of compression of hydrogen. This compression path is largely 1-D compression and is followed by the spherical convergence of the capsule, compressing the hydrogen another >100 fold in density. The inset image shows the raw data record from a NIF experiment where three shocks were used to compress heavy hydrogen in a spherical capsule. In addition to launching multiple shocks, NIF can generate shock-less compression by ramp compression. For example, early NIF user experiments were used to ramp compress diamond to 50 Mbars, recreating conditions comparable to the most extreme planetary core conditions in our solar system.



Multiple shocks are tuned to lower the entropy of the fuel for ignition implosions



Summary

Over the next decade, a major science program built around NIF could potentially alter our understanding of materials and condensed matter in profound ways. NIF will extend the range of materials studies in pressure by at least three orders of magnitude, thereby allowing the tuning of external pressures into the atomic regime for the first time. This capability could facilitate the identification of altogether new forms of matter on Earth. It could also provide a new dimension to the periodic table leading to: i) novel materials; ii) enhanced understanding and control of dynamical processes in high-density materials; iii) enhanced understanding of nonequilibrium and potentially self-organizing behavior of matter at extreme pressures; iv) support for the wealth of new astronomical observations regarding planets outside the solar system; and v) enhanced routes to inertial fusion energy.

We close with a grand challenge: *Can we create and control star matter on Earth?* That is, can we create the dense-plasma state undergoing thermonuclear fusion, as within stars, and can we then study and understand it so as to control its properties? Doing so will inform us about our origins on Earth and—perhaps—a key source of energy to sustain our presence here.

References

1. Takemura, K., ed., *International Conference on High Pressure Science and Technology, Joint AIRAPT-22 & HPCJ-50, 26–31 July 2009, Tokyo, Japan*, J. Phys.: Conf. Ser., 215 (2010).
2. Hemley, R. J., Percy W. Bridgman's second century, *High Press. Res.* **4**, 581-619 (2010).
3. Bradley, D. K., J. H. Eggert, R. F. Smith, S. T. Prisbrey, D. G. Hicks, D. G. Braun, J. Biener, A. V. Hamza, R. E. Rudd, and G. W. Collins, Diamond at 800 GPa, *Phys. Rev. Lett.* **102**, 075503 (2009).
4. Eggert, J. H., D. G. Hicks, P. M. Celliers, D. K. Bradley, R. S. McWilliams, R. Jeanloz, J. E. Miller, T. R. Boehly, and G. W. Collins, Melting temperature of diamond at ultrahigh pressure, *Nature Phys.* **6**, 40-43 (2010).
5. Hicks, D. G., T. R. Boehly, J. H. Eggert, J. E. Miller, P. M. Celliers, and G. W. Collins, Dissociation of liquid silica at high pressures and temperatures, *Phys. Rev. Lett.* **97**, 025502 (2006).
6. Knudson, M. D., M. P. Desjarlais, and D. H. Dolan, Shock-wave exploration of the high-pressure phases of carbon, *Science* **322**, 1822 (2008).
7. Fowler, R. H., On dense matter, *Mon. Not. R. Astron. Soc.* **87**, 114-122 (1926).
8. Wigner, E., and H. B. Huntington, On the possibility of a metallic modification of hydrogen, *J. Chem. Phys.* **3**, 764-770 (1935).
9. Bridgman, P. W., The breakdown of atoms at high pressures, *Phys. Rev.* **29**, 188-191 (1927).
10. Gregoryanz, E., L. F. Lundegaard, M. I. McMahon, C. Guillaume, R. J. Nelmes, and M. Mezouar, Structural diversity of sodium, *Science* **320**, 1054-1057 (2009).
11. Ma, Y., A. Oganov, Z. Li, Y. Xie, and J. Kotakoski, Novel high pressure structures of polymeric nitrogen, *Phys. Rev. Lett.* **102**, 065501 (2009).
12. Lazicki, A., A. F. Goncharov, V. V. Struzhkin, R. E. Cohen, Z. Liu, E. Gregoryanz, C. Guillaume, H. K. Mao, and R. J. Hemley, Anomalous optical and electronic properties of dense sodium, *Proc. Nat. Acad. Sci. U.S.A.* **106**, 6525-6528 (2009).
13. Abrikosov, A. A., Some properties of strongly compressed matter, *Sov. Phys. JETP* **12**, 1254-1259 (1961).
14. Babaev, E., A. Sudbø, and N. W. Ashcroft, A superconductor to superfluid phase transition in liquid metallic hydrogen, *Nature* **421**, 666-668 (2004).
15. *APS March Meeting, Materials Physics at Gbar Pressures*, accessed at http://meetings.aps.org/Meeting/MAR08/SessionIndex3/?SessionEventID=82505 (2008).
16. *American Association for the Advancement of Science Annual Meeting - Our Planet and Its Life: Origins and Futures*, Chicago, IL, February 12-16, 2009.

17. Ashcroft, N. W., Metallic hydrogen: A high-temperature superconductor? *Phys. Rev. Lett.* **21**, 1748-1749 (1968).
18. *Defending Planet Earth: Near-Earth Object and Surveys and Hazard Mitigation Strategies,* National Academies Press, Washington, DC (2009).

Quantum Matter to Star Matter

NIF offers a unique opportunity to achieve terapascal pressures in hydrogen, testing predictions of novel quantum many-body states.

Introduction

Hydrogen has been the essential element for the development of modern physics,[1] and helium has played a central role in the discovery of quantum many-body states in condensed matter at low temperature.[2] However, the properties of these two systems at very high density remain largely unknown. Given the rich physics that has been observed in these two systems in the ambient pressure regime, one can only anticipate fascinating physics to be revealed as pressure is increased to the 10 TPa range. In particular, important theoretical predictions remain to be realized, with profound implications for our fundamental understanding of matter, astrophysics, and ICF.

Opportunity

The current limit of static compression studies of hydrogen is 0.3 TPa,[3] below the 0.5 TPa pressure necessary to observe the predicted low-temperature metallic hydrogen, including its novel superconducting and superfluid phases. Dynamic shock compression of cryogenically cooled liquid hydrogen and deuterium has reached pressures in the 0.3 TPa range,[4] but at much higher temperatures due to the large dissipation associated with shock compression. Cumulative shocks could also be used to achieve similar thermodynamic states at the expense of an absolute determination of the equation of state. More recently, the approach of coupling static and dynamic compression has been demonstrated, thereby offering the possibility to access a much wider region of phase space between the Hugoniot and the cold compression curve.[5] However, in all cases the peak pressures attainable have been limited by the energy available to couple into the system. Achieving the TPa pressure range requires that a few 100 kJ of energy be coupled to the system. NIF offers a unique opportunity to achieve such conditions. Dynamic compression using NIF is, to date, the only approach to measure the properties of hydrogen and helium above 0.5 TPa (Fig. 18).

The large energy available from NIF is a necessary but not sufficient condition for success in observing new and interesting physics in very dense hydrogen/helium systems. First, one has to achieve in a controlled way the thermodynamic conditions of interest. NIF offers a large energy reservoir, but more important, this energy can be delivered through precise laser pulse shaping. Combining this pulse shaping with cryogenic planar targets, cryogenic spherical targets, and pre-compressed diamond anvil cell targets allows various compression paths to be followed, enabling a wide region of phase space to be accessed. Second, accurate pressure, temperature, and density measurements must be performed. A whole set of measurements could be performed on NIF so as to produce a redundant determination of these thermodynamic variables. Third, the properties of the system have to be characterized

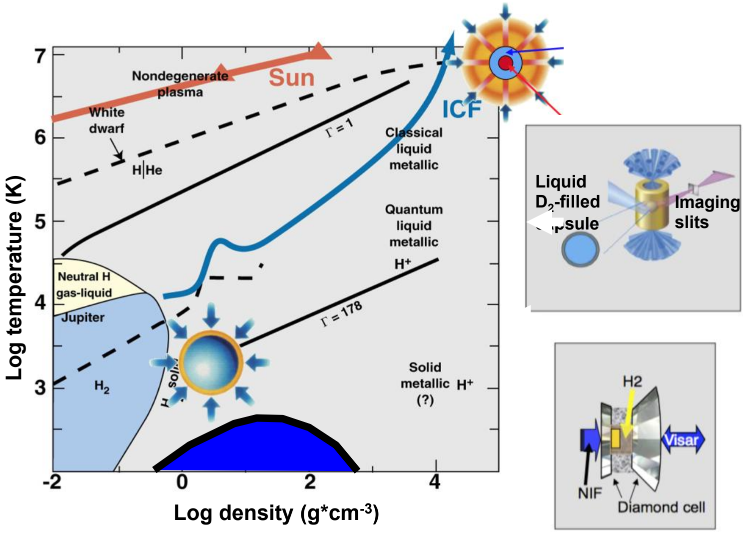


Fig. 18. Part of the hydrogen phase diagram accessible with NIF together with the path of one particular section of dense hydrogen in an ignition implosion on its way to thermonuclear fusion. Once ignition begins, the previously bottled thermonuclear energy stored in heavy hydrogen is used to further compress hydrogen to even more extreme conditions.

from the microscopic to the macroscopic level. Different diagnostics are already employed to measure various properties: Velocity Interferometer System for Any Reflector (VISAR) for the shock velocity; reflectivity at the shock front; Thomson scattering for the Fermi density of state and indirectly the temperature; optical pyrometry for temperature; and x-ray radiography for the density. Additional diagnostic will need to be employed to obtain specific microscopic information: Raman spectroscopy for the bonding and lifetime of molecules, and magnetic and electrical measurements to characterize the superfluid/superconductor states.

Research Directions

Important theoretical predictions remain to be realized in the study of hydrogen and helium in the pressure-temperature range possible at NIF. Predicted phenomena include solid metallic hydrogen;[6] a plasma phase transition in the fluid phase for hydrogen and helium;[7] a maximum of the melting curve;[8] the melting of hydrogen at $T = 0$ K; a Wigner crystal state for hydrogen; and a superconductor and/or superfluid phase of hydrogen.[9] All these predicted phenomena should either be observed to be correct—or proven wrong—if one can measure the properties of hydrogen and helium at pressures of a few TPa and temperatures below ~0.3 eV. At pressures of ~10 TPa, it should be possible to excite nuclear reactions via pure quantum tunnelling, thus reaching the domain of pycnonuclear reaction.[10] Finally, given that hydrogen and helium are the main constituents of many astrophysical objects, measurement of the equation of state of hydrogen-helium mixtures and, in particular, the thermodynamic conditions of their miscibility gap would have a profound impact on the understanding of planetary interiors.

A major challenge is to characterize the nature of the superfluid state, as well as to test for superconductivity mechanisms in a range of temperatures where these super states of matter have not been observed before. From the point of view of equation of states modeling, theory will face the challenge of generating global equations of states for fluids that take into account all sorts of critical points, including liquid-gas, liquid-liquid, and liquid-plasma.

Current strategies for achieving and controlling fusion burning plasmas in the laboratory use heavy hydrogen at extreme densities and temperatures. NIF is first pursuing “hot spot ignition,” where a hydrogen shell is compressed from 0.25 g/cm^3 and 20 degrees above absolute zero temperature (20 K) to a shell more than 1000 g/cm^3 dense (100 times the density of lead) surrounding a hot hydrogen plasma at a temperature of 50 million K. Understanding the behavior of hydrogen at these conditions and the paths leading to these extreme conditions will be crucial for optimizing and controlling fusion in the laboratory or industry. The equation of state for hydrogen from 0.1 g/cm^3 to many kg/cm^3 will provide insight into the optimum path for compression. Transport properties guide how energy redistributes in fusion experiments and will be critical for any advanced fusion concepts.

The sidebar titled “Exploring materials using unique compression paths” (p. 64) shows some of the transport paths important for hot spot ignition. For example, thermal conduction from a hot ablator to dense hydrogen fuel helps set the stability of implosions; thermal conduction from the dense fuel to the hot plasma in the central region (potentially in the presence of large magnetic fields) is important for controlling both the confinement time and stability of the final assembly; the efficiency at which hydrogen can stop fusion-produced particles helps set the length scale for any optimized design; the rapidity with which electrons and light hydrogen ions equilibrate partially sets limits on how long one can keep a fuel assembly hot; and the list goes on. With a deep understanding of these hydrogen properties, can we come up with altogether new and more efficient paths to fusion?

Impact

The potential scientific impact of these measurements is significant. On par with recent achievements in low temperature physics such as the observation of Bose-Einstein condensation by laser cooling instead of by conventional low-temperature approaches, observation of low-temperature metallic hydrogen—the holy grail of high pressure physics for decades—could be realized through a dedicated research effort using NIF. Microscopic measurements revealing a coupled superfluid and superconducting state would be the first observation of a novel quantum many-body state of matter. The plasma phase transition could be unambiguously crossed, manifested by discontinuities in such quantities as density, temperature, reflectivity, and molecular bonding, akin to a first-order phase transition. Such evidence would be clear confirmation of the metallic nature of the very dense hydrogen plasma and would confirm the Landau school predictions. Observation of fusion events at very low temperature and their increased probability in the 10 TPa pressure range would provide fundamental information on the effect of electron screening of the coulomb repulsion between two deuterons and on the many-body contribution to the nuclear cross section. Such understanding of this pycnonuclear regime would prove to be useful for our ability to enhance the efficiency of ICF. Finally, the determination of the equation of state of hydrogen-helium mixtures, their miscibility, and the existence of first-order transitions would have a broad impact on the modeling of planetary interiors and would greatly improve our understanding of the formation mechanisms of gas giant planets.

References

1. Rigden, J. S., *Hydrogen, The Essential Element*, Harvard University Press, Cambridge (2002).
2. Volovik, G., *The Universe in a Helium Droplet*, Oxford Press, Oxford (2003).
3. Loubeyre, P., F. Occelli, and R. LeToullec, Optical studies of hydrogen to 320 GPa and evidence for black hydrogen, *Nature* **416**, 613-617 (2002).
4. Collins, G., L. B. Da Silva, P. M. Celliers, D. M. Gold, M. E. Foord, R. J. Wallace, A. Ng, S. V. Weber, K. S. Budil, and R. Cauble, Measurements of the equation of state of deuterium at the fluid insulator-metal transition, *Science* **281**, 1178-1181 (1998).
5. Eggert, J. H., S. Brygoo, P. Loubeyre, R. S. McWilliams, P. M. Celliers, D. G. Hicks, T. R. Boehly, R. Jeanloz, and G. Collins, Hugoniot data for helium in the ionization regime, *Phys. Rev. Lett.* **100**, 124503 (2008).
6. Wigner, E., and H. B. Huntington, On the possibility of a metallic modification of hydrogen, *J. Chem. Phys.* **3**, 764-770 (1935).
7. Morales, M. A., 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. Sci. U.S.A.* **107**, 12779-12803 (2010).
8. Bonev, S. A., E. Schwegler, T. Ogitsu, and G. Galli, A quantum fluid of metallic hydrogen suggested by first-principles calculations, *Nature* **431**, 669-672 (2004).
9. Babaev, E., A. Sudbø, and N. W. Ashcroft, A superconductor to superfluid phase transition in liquid metallic hydrogen, *Nature* **421**, 666-668 (2004).
10. Pollock, E. L., and B. Militzer, Dense plasma effects on nuclear reaction rates, *Phys. Rev. Lett.* **92**, 021101 (2004).

Elements at Atomic Pressures

Research into extreme and metastable states of matter accessible only through NIF will lead to a new view of the periodic table in which complexity rather than simplicity and periodicity dominates our understanding.

Introduction

The traditional view of highly compressed matter and materials is that the valence electrons, the electrons that control chemistry and the behavior of solids and fluids on Earth, are pushed into the continuum to form a near-free electron gas surrounding ions, which are packed like billiard balls into a simple close packed structure.[1] This view has been extremely successful in understanding "high-pressure" material behavior for many materials at up to a million times atmospheric pressure (1 Mbar), which is roughly equivalent to the energy scale of chemical bonds. Thus, at 1 Mbar, we expect the structure of matter to be significantly different from that at standard conditions on Earth. At significantly higher pressures, say, 100 Mbar, this simple picture breaks down. There is mounting evidence that at such conditions, the core orbitals occupy most of the volume in a solid or fluid, forcing a localization of the gas-like electrons. This condition appears to push atoms into complicated arrangements, where periodicity, one of the underpinning concepts of solid-state physics, is no longer every other atom but every hundred atoms or more.

Opportunity

This new long-range organization of atoms has myriad impacts, such as dramatically changing the melt temperature of materials or perhaps making the mechanical difference between a solid and a liquid indistinguishable, and changing metals into insulators. This hyper-organized assembly of atoms may also have somewhat profound implications on our understanding the nature of how atoms self-organize. How does extreme pressure drive atoms to exhibit intelligence about sister atoms over extraordinarily large distances? How does such an assembly of atoms evolve to find such highly correlated stable or metastable structures? This new scientific frontier, which is crucial for understanding the structure and evolution of planets and many low mass stars, is now accessible on NIF.

Research Directions

When the pressure limit accessible in the lab was a few Mbars, there was not much of a push to improve theory above this limit. New experimental evidence, however, is providing mounting evidence that matter and materials above these pressures behave quite differently.[2] At least 23 metals have complex structures at the highest pressures obtained experimentally (Fig. 19).[3] Sodium, an archetypal ambient free-electron metal, adopts the most complex structure ever observed in an elemental solid, with over 500 atoms in the unit cell near

1 Mbar,[4] and becomes a transparent insulator with an open ionic structure near 2 Mbar.[5] The presence of 500 atoms in a unit cell means that, somehow, at high pressure, each atom has an intimate knowledge of the behavior of other atoms, many atoms away in any direction. Moreover, the geometry for packing these atoms in three dimensions is excruciatingly complex. Theory too is finding that the traditional view of high compression is insufficient. Theory suggested significant structural complexity in sodium and lithium prior to experiment,[6,7] but the richness of the phenomena from the low melting temperatures, diversity of complex structures, and insulating behavior were not anticipated.[4,5,8] It has been argued that the primary driving force for these new results is the emergence of strong quantum mechanical constraints in the electronic wave functions due to the Pauli-exclusion principle, the necessity to orthogonalize the wave functions of all electrons, valence and core, and the narrowing of the available interstitial space at high compression.[9]

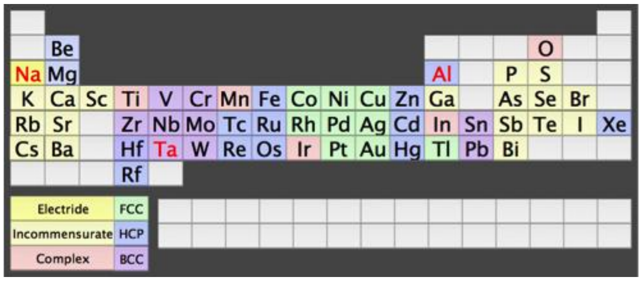


Fig. 19. Structures reported at the highest pressure obtained experimentally. (Source: after Ref. 3.)

A new paradigm for high-compression science is required. The need is further illustrated when even higher compression predictions are made. Transparent sodium has a predicted band gap of about 1 eV at 2.20 Mbar, rising to about 3.5 eV at 4.2 Mbar (Fig. 20). As compression increases, sodium appears to become a large band-gap insulator with no end in sight.[10] Diamond, long predicted to transition to a simple cubic phase at 30 Mbar, is now found to have several extraordinarily complex metastable phases, including a monoclinic structure with eight atoms in the unit cell.[11] Finally, aluminum has been predicted to retain very complex structures to above 300 Mbar and to adopt an incommensurate phase at 30 Mbar and an open electride structure with localized d-electrons near 100 Mbar.[12]

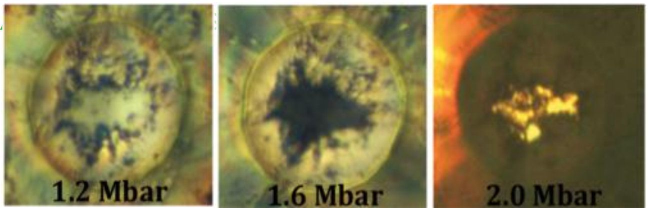


Fig. 20. Transition of sodium from a reflecting metal to a black semiconductor to a transparent insulator. (Source: from Ref. 14.)

As we continue to explore this new regime of extreme compressed matter we may find surprising results (Fig. 21). The phase transitions in aluminum at 30 and 80 Mbar are predicted to entail 2-3 % volume discontinuities, and the electronic density of states shows dramatic shifts of roughly 10 eV.[12] There are no current predictions or measurements of the melting curve for any of these new materials, but it seems possible that the solid phases may be very stable. However, as the unit cell continues to increase with pressure, on a local scale, it becomes difficult for neighboring atoms to know the difference between a random assembly of atoms such as in a fluid.

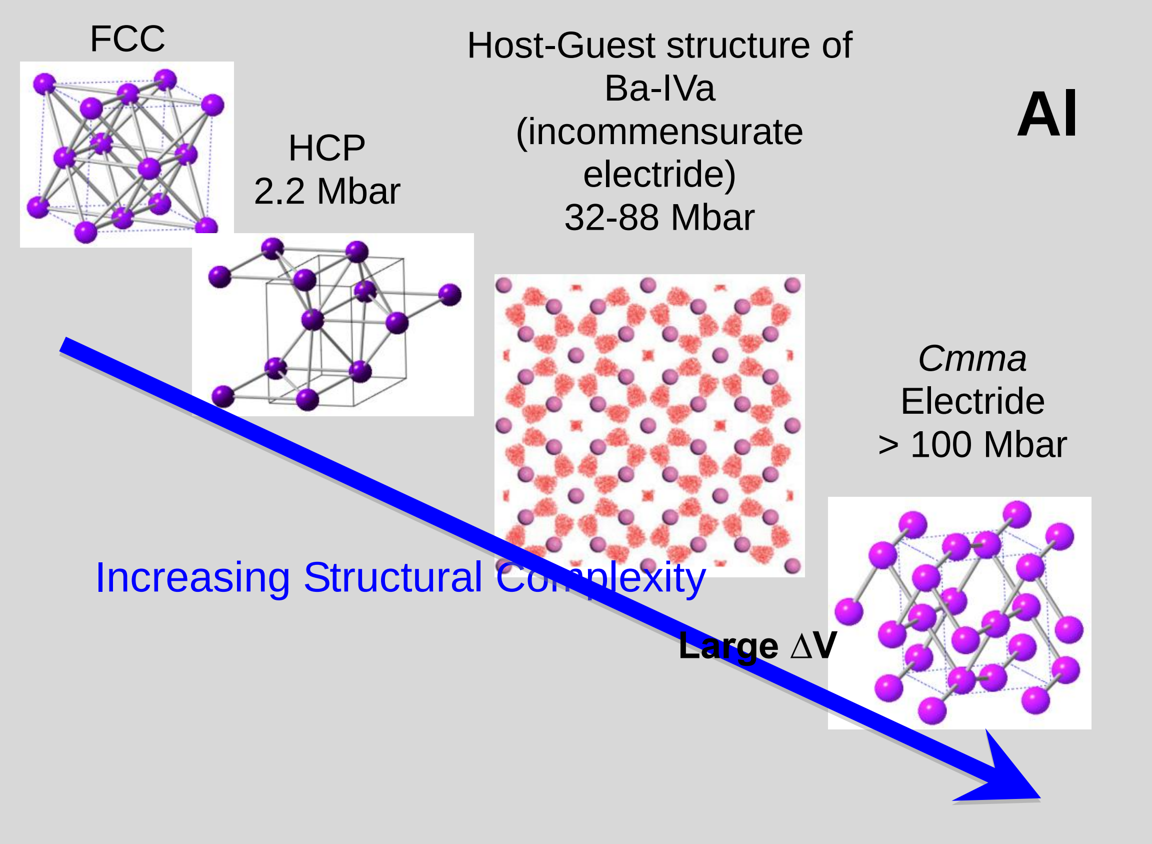


Fig. 21. Theoretical predictions of structural complexity and unusual physical properties at ultrahigh pressures in Al. (Source: from Ref. 15.)

The NIF offers a unique opportunity to explore this new frontier in science. The ability to temporally shape the laser energy versus time with unprecedented fidelity and the high energy available enable the compression of matter to high density and over a wide variety of temperatures. Several compression techniques need to be pursued to optimize the regimes accessible with NIF. Using techniques developed at the OMEGA facility,[13] ramp compression of materials in planar geometry on NIF has already achieved 50 Mbar pressures in diamond. This technique may be able to reach the 100 Mbar range, depending on the material. The final-state temperature will likely be set by the material strength or viscosity and will be bounded at the lower end by the isentropic temperature. Shock waves in planar geometry can access fluid states into the several hundred Mbar regime. Convergent experiments offer significantly higher densities and pressures. For example, an ICF implosion compresses hydrogen to >1 kg/cm^3 (4000-fold compression) and several hundred billion atmospheres (Gbar). Finally, by creatively using the thermonuclear reactions expected to be accessible with NIF, pressures in excess of many trillion of atmospheres (Tbar) are possible. How temperature modifies the auto-organization of matter at such pressures is sure to be important. While temperature is adjusted through the volumetric work performed or viscous heating, the temperature can be increased isochorically through x-ray, proton, or electron heating from either the short pulse capability expected to be on-line at NIF or by the large flux of radiation emitted during a high-yield fusion implosion. Finally, in addition to adjusting density and temperature we can potentially modify materials by bathing them with extreme electric and magnetic fields through flux compression or other field manipulation schemes.

These advanced compression schemes will require advanced diagnostics to probe both the thermodynamic and atomic to mesoscale physics driving this new extreme correlation regime. The mainstay for determining pressure and, in some cases, density in many of the planar experiments is through high-fidelity velocity measurements (VISAR). X-ray diffraction at high photon energy (1 to 100 keV) with high resolution/dynamic range detection will be crucial for determining the structure, long-range order, phase, equations of state, and strength of solids and fluids. Extended x-ray absorption fine structure (EXAFS) and x-ray absorption near edge structure (XANES) measurements will be important to determine short-range order and details of how perturbed deep electron shell levels are at extreme conditions. Coupling elastic and inelastic x-ray scattering with high-resolution radiography, phase contrast radiography, and potentially, diffractive imaging will provide absolute equation-of-state measurements and mesoscale structure in both planar and convergent experiments. This capability will be increasingly important as we compress matter to pressures where there are no standards for making comparative measurements. Optical and potentially x-ray spectroscopy (Raman and x-ray Thomson scattering) must be developed to determine bonding, and to measure temperature and electron-ion scattering time. Proton scattering can provide information on field generation in these dynamic compression experiments. Finally, magnetic flux rejection or transmission will be useful in determining if material becomes superconducting.

Impact

Focused research into these extreme states and metastable states of matter will lead to a new view of the periodic table and the discovery and control of new material properties both at extreme and potentially standard conditions. This research will provide important insight into the synthesis of new materials both stable and metastable. The unprecedented long-range correlations driven by pressures capable of producing intersecting core electron states will potentially drive noncarbon-based complex sequences, where auto-organization of elements will open a new field of ultra-dense matter research.

References

1. Ross, M., High pressure equations of state: Theory and applications, *High Pressure Chemistry, Biochemistry and Materials Science*, Acquafredda di Maratea, Italy (1993).
2. Hemley, R. J., Percy W. Bridgman's second century, *High Press. Res.* **4**, 581-619 (2010).
3. McMahon, M. I., and R. J. Nelmes, High-pressure structures and phase transformations in elemental metals, *Chem. Soc. Rev.* **35**, 943-963 (2006).

4. Gregoryanz, E., L. F. Lundegaard, A. K. McMahan, C. Guillaume, R. J. Nelmes, and M. Mezouar, Structural diversity of sodium, *Science* **320**, 1054-1057 (2008).
5. Ma, Y., M. Eremets, A. P. Oganov, Y. Xie, I. Trojan, S. Medvedev, A. O. Lyakhov, M. Valle, and V. Prakapenka, Transparent dense sodium, *Nature* **458**, 182-185 (2009).
6. Neaton, J. B., and N. W. Ashcroft, Pairing in dense lithium, *Nature* **400**, 141-144 (1999).
7. Neaton, J. B., and N. W. Ashcroft, On the constitution of sodium at higher densities, *Phys. Rev. Lett.* **86**, 2830 (2001).
8. Gregoryanz, E., O. Degtyareva, M. Somayazulu, R. J. Hemley, and H. K. Mao, Melting of dense sodium, *Phys. Rev. Lett.* **94**, 185502 (2005).
9. Rousseau, B., and N. W. Ashcroft, Interstitial electronic localization, *Phys. Rev. Lett.* **101**, 046407 (2008).
10. Gatti, M., I. V. Tokatly, and A. Rubio, Sodium: A charge-transfer insulator at high pressures, *Phys. Rev. Lett.* **104**, 216404 (2010).
11. Sun, J., D. D. Klug, and R. Martoňák, Structural transformations in carbon under extreme pressure: Beyond diamond, *J. Chem. Phys.* **130**, 194512 (2009).
12. Pickard, C. J., and R. J. Needs, Aluminum at terapascal pressures, *Nat. Mater.* **4**, 624-627 (2010).
13. Bradley, D. K., J. H. Eggert, R. F. Smith, S. T. Prisbrey, D. G. Hicks, D. G. Braun, J. Biener, A. V. Hamza, R. E. Rudd, and G. W. Collins, Diamond at 800 GPa, *Phys. Rev. Lett.* **102**, 075503 (2009).
14. Ma, Y., M. Eremets, A. R. Oganov, Y. Xie, I. Trojan, S. Medvedev, A. O. Lyakhov, M. Valle, and V. Prakapenka, Transparent dense sodium, *Nature* **458**, 182-185 (2009).
15. Pickard, C. J., and R. J. Needs, Structure of phase III of solid hydrogen, *Nature Phys.* **3**, 473-476 (2007).

Kilovolt Chemistry

Previously unobserved chemical structure and bonding are anticipated when matter is compressed beyond its ionization limit, at compression levels comparable to those in the deep interiors of the largest planets.

Introduction

Chemistry at ultrahigh pressures is a new frontier. Starting even below 1 Mbar unusual chemical bonding, speciation, electronic structure/ionization, charge transfer/ disproportionation phenomena are found.[1] but they remain poorly understood from the standpoint of predictive science. Moreover, at even higher pressures altogether new kinds of chemical phenomena are anticipated, with the participation in bonding of deep electronic levels. NIF will provide the capability to create compression states comparable in energy with the energies of these deep electronic levels in the kilovolt range. This capability provides a unique opportunity to explore entirely new regimes of chemistry. These experiments will also probe materials at the compression levels comparable to those in the deep interiors of the largest planets.

Opportunity

NIF capabilities allow creating material states in a broad pressure-temperature-time range. To perform studies of chemical reactivity in a wide pressure range (1 Mbar to 1 Gbar) using the ramp compression platform at NIF, new diagnostics need to be developed or improved. These include ultrafast laser technique of broadband optical and stimulated spectroscopies (e.g., coherent anti-Stokes Raman scattering), which probe electronic and vibrational properties to provide unambiguous information about the electronic state and bonding. X-ray spectroscopy techniques (EXAFS and XANES) provide unique information about the local atomic structure. Changes in equation-of-state quantities associated with changes in heat capacity can be used as evidence of new chemical phenomena, including temperature-dependent chemical equilibrium between reactants and products, as well as phase transitions. Moreover, the material state created may be temporally/spatially inhomogeneous, providing further opportunities to probe the chemical kinetics, nanostructures, interfaces, and mesoscopic structures.

Research Directions

Planetary ices (H_2O, NH_3, CH_4) and their mixtures (e.g., CH_4-H_2O) are predicted to exist in a superionic state at moderate compressions (>0.5 Mbar); at further compression/heating they are expected to ionize at high temperatures (>5000 K), but lower temperature behavior remains unknown (Figs. 22 and 23).[2-4] Moreover, the effect of mixing of different ices on the ionization is unknown, but theoretical predictions indicate that ionization is milder at these conditions. The full range of conditions is important for understanding the behavior of these

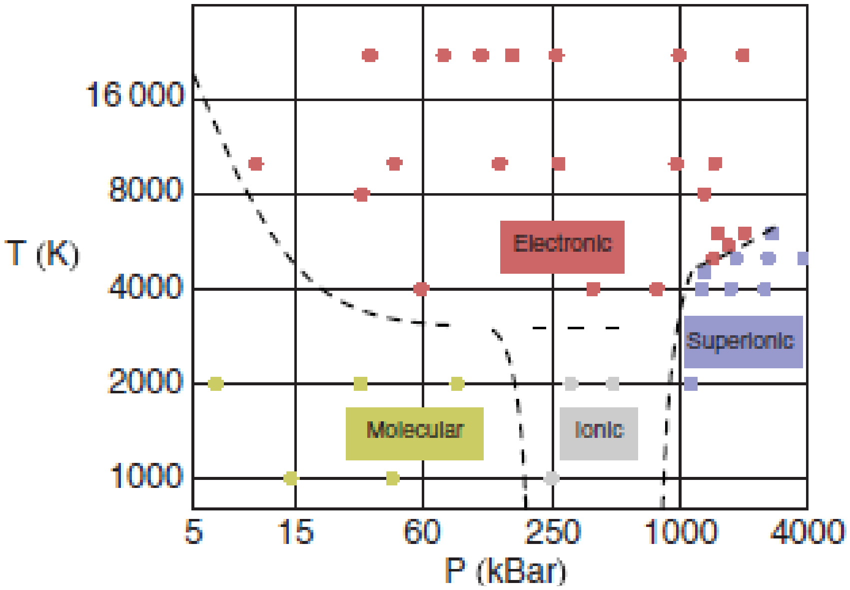


Fig. 22. Behavior of water at high pressures and temperatures. (Source: from Ref. 3.)

complex mixtures as a function of depth in planets, especially super-Earths and super-Neptunes outside of our solar system. In addition, it will be important to examine the extent to which "plasma" compounds form at very high pressures and temperatures when core electrons can hybridize to form bonds.

Noble gases are conventionally considered inert, unreactive; yet new highly unusual compounds are emerging even below 1 Mbar (Fig. 24).[5] For these systems, the nature of the bonding is not understood, and subjecting them to even more extreme conditions is expected to unleash additional electrons to form new kinds of chemical bonds. Such studies could form a benchmark or reference point for this new ultrahigh pressure chemistry, where new chemical reactions arise from the participation of the core electrons.

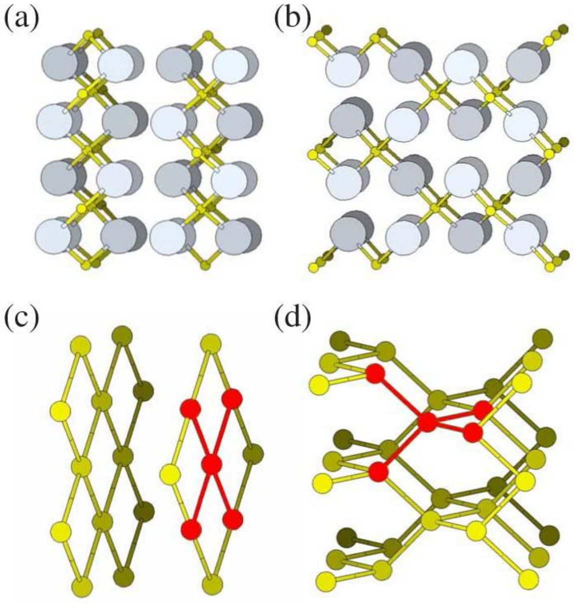


Fig. 23. Predicted structures of ultradense CO_2 at 2-9 Mbar. Novel layered structure (a) and b-cristobalite structure (b), where the larger spheres represent oxygen atoms and the small spheres represent carbon atoms; (c) and (d) show the carbon sublattice in the two structures. (Source: from Ref. 7.)

The high-pressure behavior of ionic salts has shown similarities with isoelectonic rare-gas solids as their equations of state converge in the limit of high compression, where they both crystallize in effectively the same hexagonal-close-packed structure.[6] Moreover, both classes of materials become metallic under these compressions, thus demonstrating similar chemical bonding in spite of a great initial difference in bonding (ionic versus van der Waals). Unraveling the further similarity or disparity in behavior in the range of compression, which affects the core electrons, would present a major challenge for the proposed studies.

Another question is the extent to which electron-capture radioactive decay can be accelerated substantially under very high pressures. This process is controlled by the electronic density at the nucleus, which is a function of compression and gives rise to changes in decay rate of certain unstable isotopes, such as ^{7}Be. However, studies to date have been largely inconclusive because of the inability to reach sufficiently high compressions. These studies could have a profound implication for understanding planetary heat production, as well as the isotopic and elemental composition of our and other solar systems.

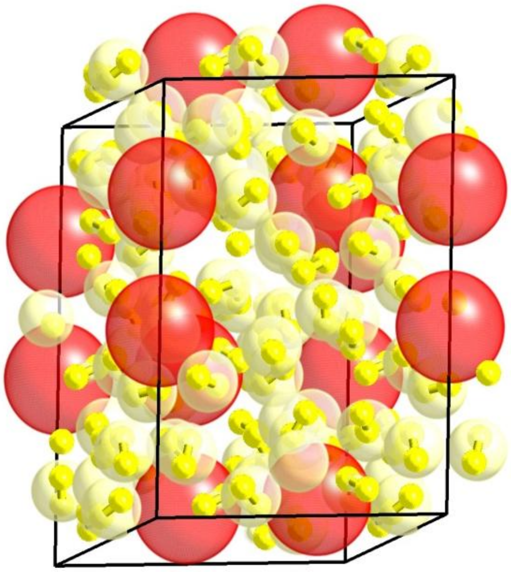


Fig. 24. Structure of novel high-pressure compound $Xe(H_2)_7$ that is stable to Mbar pressures and <300 K. The chemistry of such systems in the new pressure-temperature regimes accessible by NIF remains unexplored. (Source: from Ref. 5.)

The emerging new ultrahigh pressure chemistry will drive the development of new theory. This effort must begin with "all electron" methods in which the core electronic states are explicitly considered in chemical bonding. Core states are subject to a large "on-site" interaction; therefore, Coulomb and exchange interactions will have to be also explicitly considered in the simulation methods. Even more fundamental is the need to treat the nuclei and electrons on the same quantum mechanical footing; this capability will be essential for systems containing low-Z elements (e.g., hydrogen).

Impact

The outcomes of this study have multidisciplinary implications. These Priority Research Directions will result in new predictive chemical correlation models governing the structure and composition of materials compressed beyond their ionization limits. This work will provide first-hand information about the forms of matter in planetary interiors by direct observations of their properties under the relevant conditions. The knowledge gained will ultimately be useful for the synthesis and recovery of new materials with unique properties (e.g., high energy density).

References

1. Grochala, W., R. Hoffman, J. Feng, and N. W. Ashcroft, The chemical imagination at work in very tight places, *Ang. Chem.* **46**, 3620-3642 (2007).
2. Lee, K. K. M., L. R. Benedetti, R. Jeanloz, P. M. Celliers, J. H. Eggert, D. G. Hicks, S. J. Moon, A. Mackinnon, L. B. Da Silva, D. K. Bradley, W. Unites, G. W. Collins, E. Henry, M. Koenig, A. Benuzzi-Mounaix, J. Pasley, and D. Neely, Laser-driven shock experiments on precompressed water: Implications for "icy" giant planets, *J. Chem. Phys.* **125**, 014701-014707 (2006).
3. Mattson, T. R., and M. P. Desjarlais, Phase diagram and electrical conductivity of high energy-density water from density functional theory, *Phys. Rev. Lett.* **97**, 017801 (2006).
4. Schwegler, E., M. Sharma, F. Gygi, and G. Galli, Melting of ice under pressure, *Proc. Nat. Acad. Sci. USA* **105**, 14779-14783 (2008).
5. Somayazulu, M., P. Dera, A. F. Goncharov, S. A. Gramsch, H. P. Liermann, W. Yang, Z. Liu, H. K. Mao, and R. J. Hemley, Pressure-induced bonding and compound formation in xenon-hydrogen solids, *Nature Chem.* **2**, 53 (2010).
6. Hemley, R. J., and N. W. Ashcroft, The revealing role of pressure in the condensed matter sciences, *Physics Today* **51**, 26-32 (1998).
7. Lee, M. S., J. A. Montoya, and S. Scandolo, Thermodynamic stability of layered structures in compressed CO_2, *Phys. Rev. B* **79**, 144102 (2009).

Pathways to Extreme States

NIF will allow us to access regimes of the pressure-temperature-time phase diagram previously unreachable through a variety of loading pathways.

Introduction

The creation of novel states of matter and materials at very high compressions requires an understanding of the physical principles that underpin exactly *how* such states are reached, including the roles of metastability and material inhomogeneities. This research direction thus addresses fundamental questions associated with the response of materials to extreme dynamic compression.

Opportunity

The NIF offers unprecedented opportunities to create and diagnose novel states of matter at extreme densities and temperatures (and at very short timescales), allowing us to access parts of the pressure-temperature-time diagram hitherto unreachable. This capability is largely a result of the high (MJ) laser energy in combination with exquisite pulse-shaping possible, which provides a range of loading rates (and shapes) such that material compression to a given pressure can be produced at a rate that does not steepen the compression wave into a shock. The resulting compression is referred to as “ramped” or “shock-less” compression (also sometimes termed “quasi-isentropic compression”).[1-6] In this manner, high pressures (multiple tens of Mbar) can be achieved while keeping a material below its melting curve, leading to the creation of matter in uncharted regions of the phase diagram or thermodynamic states previously inaccessible in laboratory experiments. Furthermore, NIF provides the means to diagnose such matter via the plethora of new diagnostic techniques under development.

Research Directions

The science opportunities afforded by the capabilities of NIF in this area are widespread. For example, a question that has eluded answer for many decades can essentially be stated as “What is the difference between a shock and an isentrope?” or in the new parlance, “What is the difference between shock and shock-less compression?” Our inability to answer this question at present is a keen reminder of our lack of understanding of how materials respond to uniaxial compression at high pressures, such that the transient shear stresses are relieved, and how the pressure-volume curve at high pressures compares with the high temperature hydrostat. In essence, we wish to understand how a solid “flows” at high pressures, that is, what is the relationship between the solid and liquid state at ultrahigh compression (Fig. 25)?

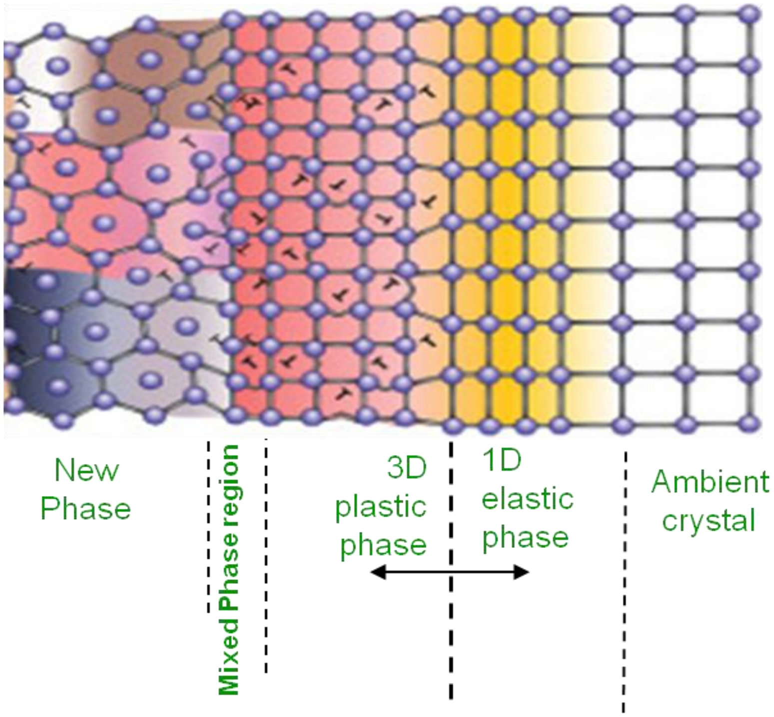


Fig. 25. A schematic representation of how a material evolves under extreme compression.

Recent studies[7-8] have highlighted a long-standing problem related to material deformation at extreme loading rates: the inability to reconcile the calculated and measured defects in materials. Experiments have yet to provide definitive information on the microstructure present at and behind a shock or ramp-compression front. In this area, there is a strong synergy between the national laboratory mission needs and basic science research on materials. How defects are generated and then propagate to relieve shear stress underlies how materials resist deformation; these same mechanisms determine how much plastic work is performed along a given loading path. The latter dictates how close to an isentrope can be achieved along a loading path in practice, thus limiting the pressure-temperature range that can be explored for a given material on NIF (Fig. 26).

However, the response of materials to compression is not merely encompassed by asking how a solid can behave like a liquid. The complexity of the potential response is such that the opposite question (how liquids can behave like solids) is also one that arises at ultrahigh strain rates, as material response becomes highly time dependent. The physics of the time dependence of phase transitions and inelastic deformation ensures that time (or rate) itself will be one of the areas of parameter space that needs to be explored, as well as compression, deformation, and temperature. Understanding these processes will lead to accessing not only new stable, but also metastable states (Fig. 27). Our knowledge of the transport properties (e.g., electrical and thermal conductivity), as well as optical properties, is also poorly

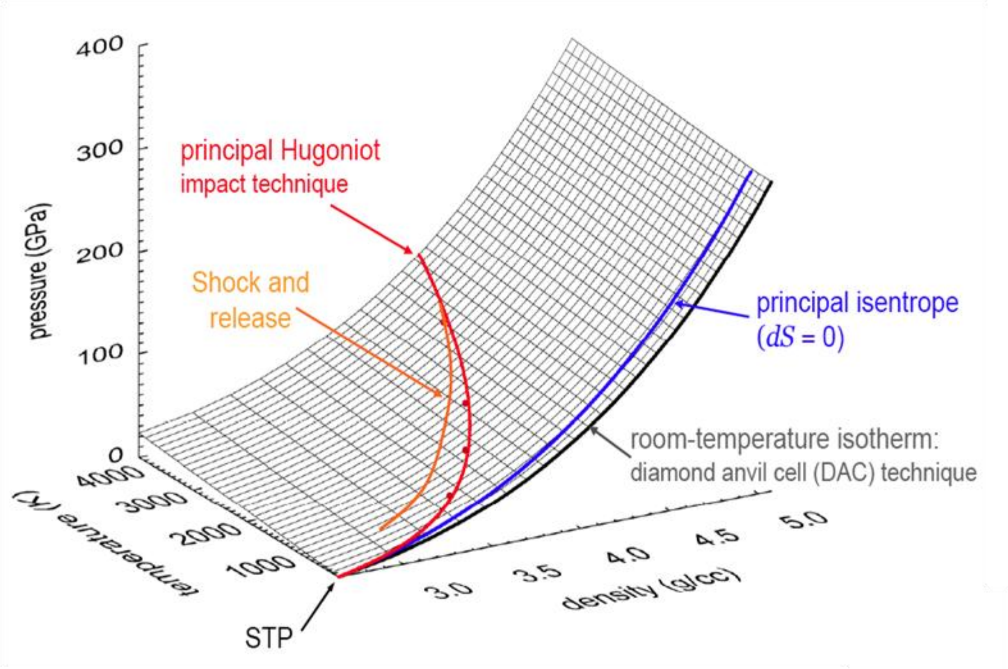


Fig. 26. Different pressure-temperature trajectories including the principal Hugoniot, isoentrope, and isotherm that can be explored with NIF.

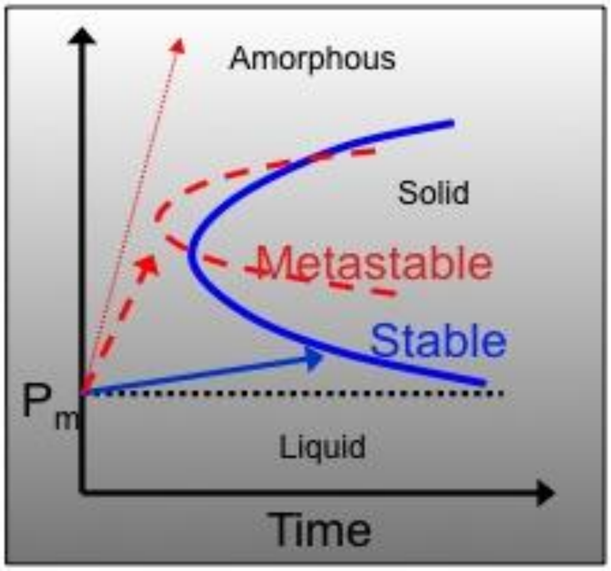


Fig. 27. Stable and metastable states of solid, liquid, and amorphous solids in different pressures as a function of time that can be explored with NIF.

developed for extreme states, and one of the greatest challenges will be to develop experimental techniques that allow us to probe these parameters.

The extreme states created by the NIF will be transient—lasting perhaps a few nanoseconds at most—and in conjunction with development of loading paths, the development of new and improved diagnostic capabilities will be of paramount importance. The measurement of phase (solid or liquid), resistance to deformation, and structure will be amenable to study via x-ray diffraction. Developmental work in this area has already been undertaken on a number of laser and other platforms around the world.[9-13] Implementing and optimizing this technology at NIF will be challenging but essential. Furthermore, the optimum diffraction geometry (for example, divergent beam, white-light Laue, or Debye-Scherrer) must also be chosen with care.

Taking a longer view, we note that x-ray scattering can also provide information on the microstructure of a material (scattering from defects), which may provide a link in our understanding between the physics that is occurring across a variety of length scales (micro/meso/macro). X-ray diagnostics will need to be complemented by a suite of other diagnostics, including possible broadband reflectivity measurements in conjunction with electrical conductivity measurements to develop transport properties. Diagnostics for accurate measurements of temperature for solid matter under these extreme conditions, potentially challenging at lower temperatures, will need to be developed.

Impact

The exploration of new paths to extreme states of compression is an exciting area of science that will impact a number of areas. In particular, the new states reached will allow improvement in our understanding of other events in the universe where extreme compression of condensed matter occurs, for example, during the impacts that lead to the formation of planets and their moons. One of the most useful forms of condensed matter in our everyday experience is itself the result of the extreme states reached within our planet—diamond at the Earth's surface is a result of a metastability that may itself be mirrored by at least some of the extreme states achievable on the NIF. The potential recovery of new classes of materials from ultrahigh pressures (e.g., the BC8 form of carbon predicted to have a large range of metastability) will require understanding behavior up to extreme states and back again. Finally, information on material strength at high pressures, required to understand the temperatures reached within such matter, is also of direct relevance to a number of important NNSA priorities.[14]

References

1. Davis, J. P., Experimental measurement of the principal isentrope for aluminum 6061-T6 to 240 GPa, *J. Appl. Phys.* **99**, 103512-103517 (2006).

2. Lorenz, K., M. Edwards, A. Jankowski, S. Pollaine, R. Smith, and B. A. Remington, High pressure, quasi-isentropic compression experiments on the Omega laser, *High Energ. Dens. Phys.* **2**, 113-125 (2006).
3. Smith, R., S. Pollaine, S. J. Moon, K. Lorenz, P. M. Celliers, J. Eggert, H. S. Park, and G. Collins, High planetary x-ray drive for ultrafast shockless-compression experiments, *Phys. Plasmas* **14**, 057105 (2007).
4. Bradley, D. K., J. H. Eggert, R. F. Smith, S. T. Prisbrey, D. G. Hicks, D. G. Braun, J. Biener, A. V. Hamza, R. E. Rudd, and G. W. Collins, Diamond at 800 GPa, *Phys. Rev. Lett.* **102**, 075503 (2009).
5. Hall, C. A., J. R. Asay, M. D. Knudson, W. A. Stygar, R. B. Spielman, T. D. Pointon, D. B. Reisman, A. Toor, and R. C. Cauble, Experimental configuration for isentropic compression of solids using pulsed magnetic loading, *Rev. Sci. Instrum.* **72**, 3587-3895 (2001).
6. Hayes, D. B., C. A. Hall, J. R. Asay, and M. D. Knudson, Measurement of the compression isentrope for 6061-T6 aluminum to 185 GPa and 46% volumetric strain using pulsed magnetic loading, *J. Appl. Phys.* **96**, 5520-5527 (2004).
7. Meyers, M. A., F. Gregori, B. K. Kad, M. S. Schneider, D. H. Kalantar, B. A. Remington, G. Ravichandran, T. Boehly, and J. S. Wark, Laser-induced shock compression of monocrystalline copper: Characterization and analysis, *Acta Mater.* **51**, 1211-1228 (2003).
8. Bringa, E. M., K. Rosolankova, R. E. Rudd, B. A. Remington, J. S. Wark, M. Duchaineau, D. H. Kalantar, J. Hawreliak, and J. Belak, Shock deformation of face-centered-cubic metals on subnanosecond timescales, *Nat. Mater.* **5**, 805-809 (2006).
9. Wark, J. S., R. R. Whitlock, A. A. Hauer, J. E. Swain, and P. J. Solone, Subnanosecond x-ray diffraction from laser-shocked crystals, *Phys. Rev. B* **40**, 5705-5714 (1989).
10. Kalantar, D. H., J. Belak, G. W. Collins, J. D. Colvin, H. M. Davies, J. H. Eggert, T. C. Germann, J. Hawreliak, B. L. Holian, K. Kadau, P. S. Lomdahl, H. E. Lorenzana, M. A. Meyers, K. Rosolankova, M. S. Schneider, J. Sheppard, J. S. Stölken, and J. S. Wark, Direct observation of the a-e transition in shock-compressed iron via nanosecond x-ray diffraction, *Phys. Rev. Lett.* **95**, 075502 (2005).
11. Rigg, P. A., and Y. M. Gupta, Real-time x-ray diffraction to examine elastic-plastic deformation in shocked lithium fluoride crystals, *Appl. Phys. Lett.* **73**, 1655-1657 (1998).
12. d'Almeida, T., and Y. M. Gupta, Real-time x-ray diffraction measurements of the phase transition in KCl shocked along [100], *Phys. Rev. Lett.* **85**, 330-333 (2000).
13. Turneaure, S. J., and Y. M. Gupta, Real-time microstructure of shock-compressed single crystals from x-ray diffraction line profiles, *J. Appl. Cryst.* **44**, 574-584 (2011).
14. Knudson, M. D., M. P. Desjarlais, and D. H. Dolan, Shock-wave exploration of the high-pressure phases of carbon, *Science* **322**, 1822-1825 (2008).

Exploring Planets at NIF

NIF will provide us with the ability to test planetary formation models in ways that were not previously possible.

Introduction

A major scientific opportunity for NIF research over the next decade is to address fundamental questions about the origin of planetary systems and the structure and evolution of planets in our own and other solar systems. These problems require a new level of understanding of the complex, multiphase systems that exist under the extreme conditions found within planets and during the giant collision phase of planet formation.

Opportunity

What is the interior structure and evolutionary pathways for planets both within and outside the solar system? The observation of over a thousand planets and planet candidates outside our solar system is one of the most exciting scientific discoveries of this generation. It is estimated that at least one-fifth of all stars possess an ice giant and one-tenth of all stars are orbited by an Earth or super-Earth planet.[1] Many of the newly discovered planets have no analogs within our solar system (see sidebar titled "The exoplanet frontier" on p. 63).[2-3] Understanding the interior properties and evolution of such bodies is a major challenge, beginning with the gas giants of our own solar system (Fig. 28). Pressure and temperatures in the much larger "super-Jupiters" may extend up to ~1 Gbar and ~10^5 K, conditions under which there are almost no current experimental constraints on equation of state, thermodynamic properties, melting curves, and transport properties.

What is the role of impacts in shaping planets and their evolution? Giant impacts between proto-planets punctuate the end stage of planet formation (Fig. 29). The final collision plays a key role in sculpting the final state of a planet; such impacts are invoked to explain the high density of Mercury, the lack of water and retrograde rotation of Venus, and the origin of the moons around Earth and Pluto. At present, the moon-forming impact hypothesis is under active debate and suffers from a lack of understanding of the basic physics and chemistry governing the merger of two planetary-scale bodies. Such impacts create transient states at extreme conditions of pressure, temperature, and strain rate that are very poorly understood. The physical, chemical, and dynamical processes during planetary collisions can be addressed using the new tools enabled by NIF.

What controls the formation and diversity of planets? NIF will provide us with the ability to test planetary formation models in ways that were not previously possible. One of the major unsolved problems in planetary science is identifying conclusively the mechanism by which Jupiter formed. There are two main competing ideas for the formation of this gas giant: the core accretion model and the disk instability model. The predicted interior structure of Jupiter differs greatly in these two formation scenarios. Unfortunately, our understanding of the equation of state of hydrogen under Jovian conditions is too crude to rule out either of these two formation scenarios. The equation of state of hydrogen must be known to better than 2% to resolve a rocky core. Thus, improvement in our knowledge of equations of state under planetary conditions will be one of the most important outcomes of NIF research on planets.

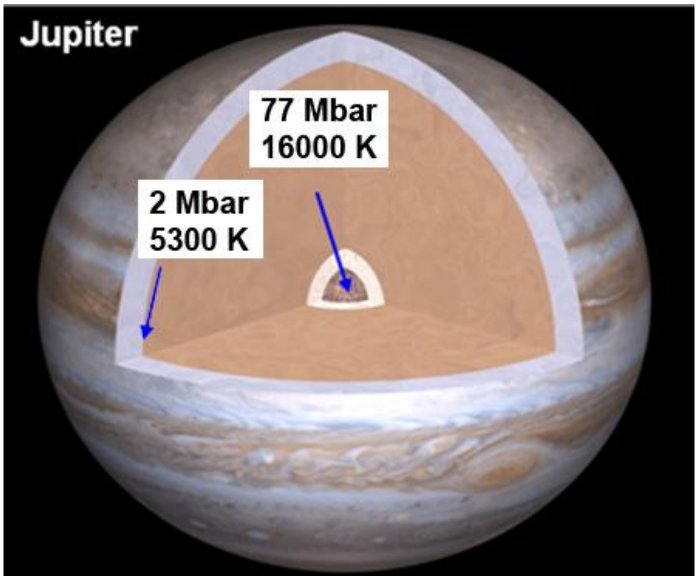


Fig. 28. Cut-away view of the interior structure of Jupiter showing the transition from molecular to metal hydrogen and the possible 10-Earth-mass core of rock, metal, and ice at the planet's center. The entire range of pressure-temperature conditions of a Jupiter-sized planet will be experimentally accessible for the first time using NIF.

Research Directions

NIF will enable us to probe unexplored regimes of pressure-temperature-density-strain rate for condensed matter. Tailored compression paths will enable us to achieve the interior conditions of gas and ice giants and super-Earths. High-precision equation of state measurements for hydrogen, helium, and their mixtures are of fundamental importance. This capability will require developing platforms to cover a wide range of states, including shock compression, ramp compression, pre-compressed or pre-heated samples, and combinations of shock and ramp loading. In addition to the planetary gases, such measurements will also be needed for planetary ices (H_2O, NH_3, CH_4, etc.), silicates (SiO_2, $MgSiO_3$, and MgO), and iron and its alloys. Measurements of crystal structures and bonding using x-ray diffraction and spectroscopy at multi-megabar pressures will advance both fundamental physics and planetary science. Solid-solid phase transitions and melting curves are of particular interest for planetary interiors.

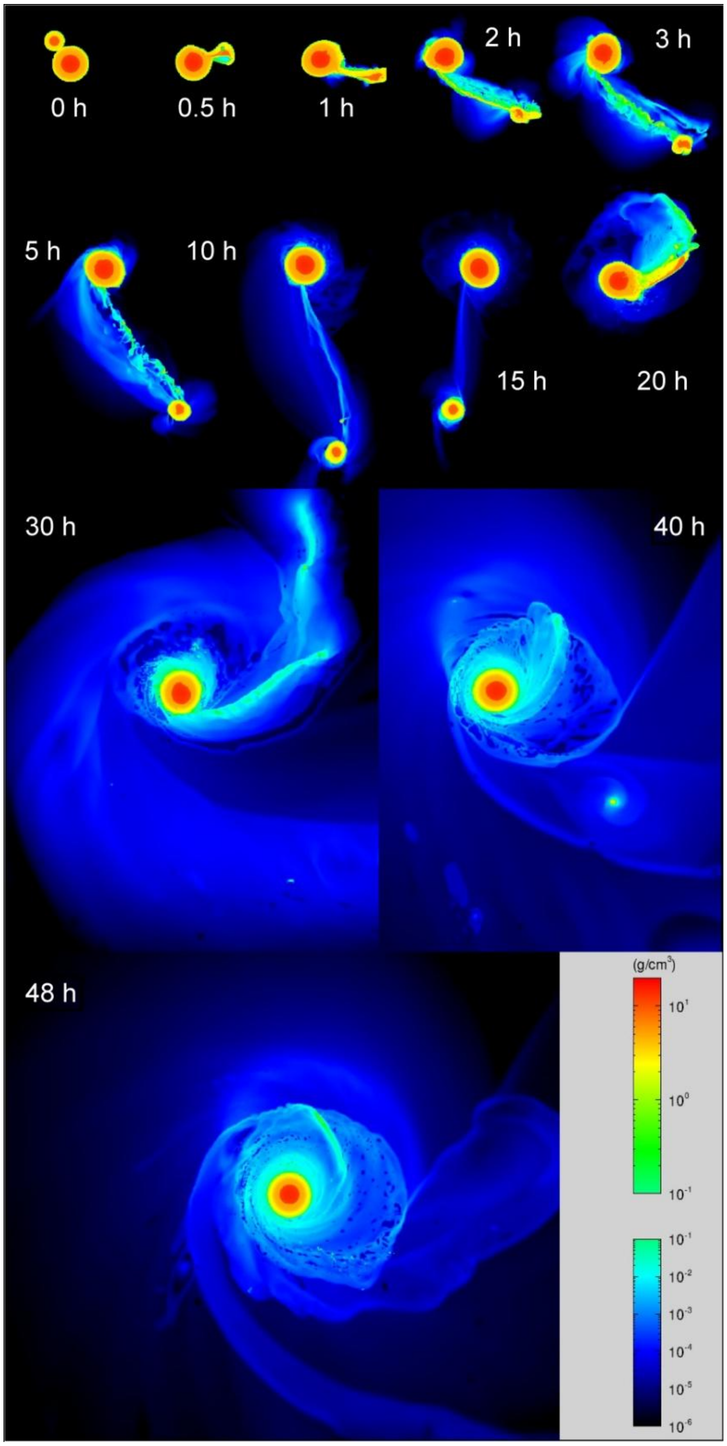


Fig. 29. High-resolution hydrocode simulation of a candidate moon-forming impact. This scenario involves an initial impact that slows the projectile. The second impact ejects material from both the proto-Earth and the projectile into a vapor-rich disk. (Source: from Ref. 4.)

Ultimately, NIF data will lead to the development of global/multiphase models for equations of state as a function of pressure, volume, and temperature that can be used by the astrophysics and planetary science community for interpretation of exoplanet observations and development of evolutionary models.

Experiments to study the physics of giant impacts and core formation also need to be developed. These include studies of shock-induced melting and vaporization and the hydrodynamics of mixing and phase separation. Development of methods to carry out in-situ and recovery experiments on large volumes (centimeter scale) of material is also crucial for understanding heterogeneous materials and mixtures, chemical mixing, and phase separation.

Impact

Within our own solar system, NIF experiments will enable fundamental advances in understanding the origin and chemistry of the Earth and moon, the formation of Jupiter, and the anomalous luminosity of Saturn. Better understanding of planetary materials at the extremes of pressure and temperature will guide development of models for formation and evolution of extrasolar planets. Understanding the dynamics of planet formation and the structure of planets from the surface to the core is fundamental to determining the formation pathways for Earth-like planets.

References

1. Borucki, W., D. G. Koch, G. Basri, et al., Characteristics of Kepler planetary candidates based on the first date set, *Astrophys. J.* **728**, 117 (2011).
2. Winn, J., J. M. Matthews, R. I. Dawson, D. C. Fabrycky, M. J. Holman, T. Kallinger, R. Kusching, D. Sasselov, D. Dragomir, D. B. Guenther, A. F. J. Moffat, J. F. Rowe, S. Rucinski, and W. W. Weiss, A super-earth transiting a naked-eye star, *Astrophys. J. Lett.*, in press.
3. Lissauer, J., D. C. Fabrycky, E. B. Ford, et al., A closely packed system of low-mass, low-density planets transiting Kepler-11, *Nature* **470**, 53-58 (2011).
4. Crawford, D., CTH simulations of candidate moon forming impacts, *Lunar and Planetary Science Conference*, Abstract 2112 (2011).

BEAM AND PLASMA PHYSICS 91

BEAM AND PLASMA PHYSICS

Introduction

For the purposes of this report, the term “high energy density (HED)” beam and plasmas covers the interaction of a laser or particle beam and a plasma when the energy density of the plasmas corresponds to pressures exceeding a Mbar and/or when the energy density of a particle or photon beam exceeds a pressure of ~10 Gbar. The plasma parameter, which is essentially a measure of the number of electrons within a Debye sphere (and the ratio between the average kinetic energy to the potential energy of free electrons to the two-thirds power), can be written as, $\Lambda = (4\pi/3)n\lambda_d^3 = 2.1 \times 10^3 (T_{keV})^2/(P_{MBar})^{1/2}$. When the plasma parameter is very large, the plasma is essentially collisionless. However, for high energy densities, i.e., pressures exceeding a Mbar and nonrelativistic temperatures, the plasma parameter is finite and can even be less than unity. In this domain the discrete nature of the plasma cannot be ignored. Understanding plasmas whose properties span collisionless to collisional and continuum to discrete phenomena is intellectually challenging and rich in possibilities for many new discoveries to be made. When a laser beam has an energy density of 1 Gbar (10^9J/cm^3) or its own electric field is large enough, it will accelerate individual plasma electrons to relativistic energies and exceed the binding field of hydrogen by more than an order of magnitude. At even higher beam energy densities, the fields of the laser exceed the binding fields of inner shell electrons for high Z atoms and radiation reaction, and electron-positron pair production becomes important in the plasma dynamics.

Status of the Field

The current status of beams and plasmas is well described in several recent reports, including a Fusion Energy Sciences Advisory Committee report entitled *Advancing the Science of High Energy Density Laboratory Plasmas* and a Research Needs Workshop (ReNeW) report for HED physics. In these reports six fundamental research areas for HED laboratory plasmas were identified. The topic of HED beams and plasmas overlaps two of these topics, “the nonlinear optics of plasmas and laser plasma interactions” and “relativistic HED plasmas and intense beam physics.”

The nonlinear optics of plasmas is an old topic but one with many exciting and recent new ideas. When laser light propagates into a HED plasma, many multi-wave, coherent interaction processes can occur. The photons can self-focus, filament, bend, coherently scatter off of collective electron plasma waves and ion acoustic waves, and be absorbed into two plasma waves. Electron plasma waves can generate energetic electrons, they can decay resonantly into other plasma waves and ion waves, and they can self-organize into nonlinear, nonstationary kinetic structures. In addition, unlike other nonlinear optical media, seemingly small changes to the free electron or ion distribution functions can lead to large changes to the amount of scattering. Electrons can freely move large distances and “remember” from whence they came, thereby leading to nonlocal interactions and transport. The scattered light can also rescatter into multiple secondary instabilities, which make regulating the primary instability quite difficult. All of these processes lead to a plasma that consists of a rich spectrum of light waves, plasmas waves, and ion acoustic waves (including nonlinear, nonstationary kinetic modes). New understanding of these processes is being achieved through theory, simulation, and experiment. Complex simulation tools have recently been developed that can study the details of nonlinear plasma waves, including tools that can run on leadership-class computer facilities. These tools enable new ways to study the interaction of multiple beams for meaningful spatial and temporal scales while including the details of the distribution functions. Experiments are being performed at mid-scale facilities to study with precision some of these phenomena in controlled and reproducible settings, and new experimental diagnostics are also being developed. The challenge for experiments is that the plasma must have a high energy density, and it requires significant laser energy to produce such a plasma.

When a HED laser (intensities exceeding 10^{19} W/cm^2) propagates through an “underdense” plasma (where the laser frequency is above the plasma frequency) or impinges on a solid or higher density plasma, a different set of nonlinear-optics-of-plasma processes can occur. The laser can self-modulate due to the formation of plasma wakefields (plasma waves with phase velocities near the speed of light). The plasma wakefield modifies the index of refraction at a phase velocity that keeps up with the laser. This condition leads to spot-size modulations, self-focusing, laser hosing, and asymmetric spot-size evolution as well as filamentation. In addition, when an ultra intense laser hits solid density plasmas, it accelerates single electrons to relativistic energies (as high as 100 MeV). These electrons move forward into the plasma, causing a complex current structure to form that itself leads to current driven instabilities. The nonlinearity of each process as well as the means by which they couple together makes it difficult to develop proper theoretical models. In addition, the relativistic electrons that are generated collide with high Z ions, producing positrons. Currently, numerous experiments are being performed at mid-scale facilities of both underdense and overdense laser-plasma interactions. These experiments have demonstrated many of the processes that have been indentified above, as well as GeV-class electron beams and 50 MeV proton beams. High intensity lasers have until recently been limited to tens of joules, and they have not been near other lasers that could preform HED plasmas. Complex simulation tools that are critical to understanding these collective and complex systems now exist, and they are able in some cases to model the full spatial and temporal scales of experiments in three dimensions (e.g., a ~50 fs laser propagating through a meter of underdense plasma).

Opportunities for Accelerated Discovery

With anticipated progress in theory, in simulation tools and computers, in experimental facilities, and in diagnostics, there are many opportunities for accelerated discovery in the beams and plasmas area. Some of this accelerated discovery can only be achieved with NIF together with ARC. As described in the Priority Research Directions, many areas for possible discovery require plasma lengths and volumes that can only be generated with NIF. Some require the energy of a NIF beam directly, while others require the focusing of ARC onto a compressed plasma formed by NIF. In addition, one area for discovery is igniting nuclear fusion in a dense plasma, and this can only be studied at NIF. In the recent ReNeW report, several questions for opportunistic research were identified:

- How can we control and manipulate the intense flow of energy and matter in extreme states?
- How can we control and tailor nonlinear optical processes in HED laboratory plasmas?
- How does coherent radiation drive self-organized states in plasmas?
- How do multiple nonlinear processes co-evolve?
- How do overlapping laser pulses interact via common plasma modes?
- How does intense coherent radiation alter the behavior of HED plasmas, and how do plasmas modify coherent radiation?
- How can ultra-intense beams be used to ignite nuclear fusion reactions in hydrogen fuel?
- How can a plasma’s tolerance for huge transient fields be used for energy transfer far beyond conventional material limits?
- What new collective behavior and fundamental physics will be found at the relativistic limits of HED physics?

The Priority Research Directions described in the next four sections address how the unique capabilities of NIF and ARC can be used to answer these questions.

Summary

The availability of a facility such as NIF whose capabilities are unlikely to be matched for some time is quite attractive and compelling. The precision diagnostics, the reproducible conditions, and the massive computational and engineering resources made available to design and execute a well planned experimental campaign will attract the best and the brightest to be involved. Due to the coherence of the radiation field and its massive energy scales, many nonlinear interaction processes thrive and manifest their deepest secrets in such a vast setting. In addition, the ability to focus an intense laser or lasers from ARC into plasmas formed by the large energy NIF beams provides unique abilities to study the interaction of intense lasers with preformed HED plasmas. We will exploit these capabilities by scaling up from smaller experiments on intermediate-scale facilities with respect to the NIF to answer compelling questions that plague our understanding of fundamental mysteries of the universe, relating to gamma-ray bursts, the origin of cosmic rays, the nature of taming turbulence and coherence control, synchronization and exploitation of nonlinear coherent processes, and new states of self-organization of nonlinear order emerging from chaos. The relativistic frontier, extreme energy densities, the controlled amplification of desirable radiation and particle beams, combined with the development of predictive capability of matter interacting with radiation coherently under extreme conditions, will constitute a gateway to a new appreciation of collective behavior of many body systems and to the creation of order out of chaos, turbulence, nonstationary equilibria, and far-from-equilibrium steering of energy and information. These are high concept arenas where the NIF will play a crucial goal.

Formation of and Particle Acceleration in Collisionless Shocks

NIF will allow the study of collisionless shocks in unprecedented environments, allowing the full range of microphysics and leading to the study of shock formation.

Introduction

Collisionless shock waves are a classic phenomenon in plasma physics, ubiquitous in many space and astrophysical scenarios.[1] By definition, in collisionless shock the mean free path is much longer than the shock thickness. Thus, the dissipation mechanisms, required to sustain the nonlinear structure of the shock, are determined by collective wave-particle and wave-wave plasma processes rather than collisions. Collisionless shocks are believed to play a critical role in the acceleration of cosmic rays, but many questions associated with their formation, the wave-particle mechanisms underlying the self-consistent fields in the shock, the acceleration mechanisms, and the feedback of the accelerated particles on the shock properties remain unanswered. While there is a wealth of experimental observations for shocks in space plasmas, there is only indirect observations for astrophysical plasmas, and these are limited to nonrelativistic shocks. However, progress in understanding relativistic shocks, which are believed to be associated with some of the most violent events in the Universe, is being made through advances in kinetic simulations.[2,3]

Figure 30 shows the electron density and magnetic field upstream and downstream from a shock generated by a relativistically flowing plasma reflecting off a wall. This progress in experimental observation and simulations is making it possible to enunciate compelling science questions, spanning many disciplines and topics, including fundamental plasma physics and relativistic astrophysics, and encompassing novel technologies such as laser-driven ion accelerators closely connected with collisionless shocks. Questions to be addressed include the following:

- What are the physical mechanisms and plasma micro-instabilities responsible for excitation of collisionless relativistic-like shocks in a broad range of conditions?

- What are the ion acceleration mechanisms in collisionless shocks? How do these accelerated ions modify the shock features through driving plasma instabilities in the upstream region?

- What are the signatures (radiation, particle spectrum) for different shock structures and shock dynamics?

- Can Fermi acceleration or other shock acceleration mechanisms be observed in the laboratory plasma?

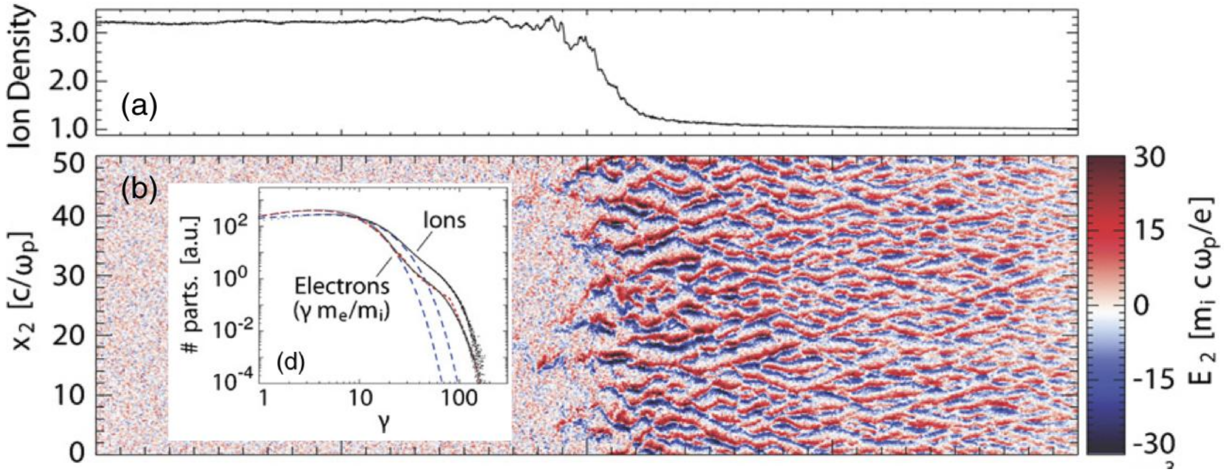


Fig. 30. (a) Transversely averaged ion density (versus laser propagation direction) and (b) structure of the magnetic fields (with the same x-axis scale) illustrating the formation of a relativistic-like collisionless shock arising from counter-streaming plasmas. In the simulations the plasma is bounced off a reflecting wall (located on the left) which mimics the contact discontinuity. The inset in (b) illustrates the spectrum of accelerated particles in the downstream region. (Source: Ref 5.)

These questions are also closely associated with the 60-year old history of cosmic rays and their acceleration. NIF could provide a unique setting to generate and to probe collisionless shocks, with unprecedented detail, for conditions yet to be realized in the laboratory. These conditions could range from nonrelativistic shocks to relativistic-like (electron temperature > 1 MeV) shocks, to shocks propagating in unmagnetized or moderately magnetized plasmas, and to the collision of shocks.

Opportunity

Collisionless shocks can be generated via several mechanisms, including counter-streaming flows and strong localized heating in near transparent plasmas, or with a laser piston in solid targets. For precise measurements of collisionless shocks in plasmas, it is desirable to drive planar shocks, close to a one-dimensional configuration, with a minimum amount of transverse inhomogeneity. It is necessary for the shock to propagate distances more than an order of magnitude longer than the shock formation distance and the shock thickness. The shock width must also be more than an order of magnitude larger than the shock thickness in order to generate planar-like shocks. Simulations of Weibel-mediated shocks driven by lasers show that the shock thickness scales with the ion Larmor radius, and that this thickness is close to the ion collisionless skin depth (c/ω_{pi}, where c is the speed of light, and ω_p is the ion plasma frequency) when the self-generated magnetic fields saturate.[2-4] If one assumes that the laser must push inward at least one shock thickness ($\sim 1c/\omega_{pi}$), the shock width is many shock thicknesses ($\sim$ 10's c/ω_{pi}), the plasma is solid-density hydrogen, and the electron temperature is ~1 MeV behind the shock, then one needs ~ 1 kJ of drive laser energy if there is 10% efficiency. Larger energy lasers will be needed if the shock propagation distance is to be large enough to study the acceleration of ions due to multiple shock crossings.

Experiments are already planned on NIF for exciting shocks from the counter streaming of two ablated plasmas. The use of counter-streaming ablated plasmas and laser pistons in NIF will allow studying collisionless shocks in background densities in the range of $n_e = 10^{20}$ - 10^{24} cm^{-3}, flow velocities in the range of v_{flow} ~ 1000-10000 km/s, and electron temperatures in the range of T_e ~ 10’s eV–1 MeV. With these parameters, the full range of microphysics leading to shock formation can be explored, including the unique possibility to excite Weibel-mediated relativistic-like collisionless shocks.

The combination of extreme (kilojoules) and higher laser energies and laser intensities above 10^{20} W/cm^2 together with a broad suite of diagnostics further strengthens the uniqueness of NIF and NIF-ARC to address the science questions connected with collisionless shocks. For a single-shot experiment, radiation and particle beams coming out of plasmas would be analyzed by using Thomson scattering and x-ray spectroscopy with a picosecond resolution as well as plasma density interferometry, proton radiography, and ion spectra simultaneously.

Research Directions

A stepwise strategy for the systematic study of collisionless shocks excited by lasers with an increasing energy of 100’s J to 10’s kJ to100’s kJ is already in progress. Electrostatic collisionless shock studies are now in progress in several laser facilities worldwide, including the Institute of Laser Engineering (Japan), Laboratoire pour l'Utilisation des Lasers Intenses (France), Rutherford Lab (UK), and Chinese Academy of Sciences in Shanghai (China) (e.g., Ref. 5). Medium-scale experiments, using OMEGA and OMEGA-Extended Performance (EP) for counter-streaming plasmas, are now addressing measurements of the plasma parameters (T_e, T_i, n_e, and v_{flow}) using 2ω Thomson scattering, and of the magnetic field using proton deflectometry and B-dot probes. Ion acceleration in shock waves is also being explored at lower laser energies. The UCLA Neptune Laboratory of monoenergetic recently reported 22 MeV protons accelerated by collisionless shocks.[6,7] Recently, large-scale and high-fidelity kinetic simulations have also predicted that NIF-ARC parameters can drive relativistic-like shocks in solid targets.[4] Sample results are shown in Fig. 31.

The natural next step will be to increase the energy for the laser driver to 10’s kJ and eventually bring it up to 100 kJ, which should generate Weibel-mediated shocks and possibly will allow for long-enough shock propagation distances to explore the mechanisms for particle acceleration in the shock structure. This step will also require the development of plasma diagnostics with picosecond resolution and the capability to counter-propagate laser beams with different f-numbers, e.g., using plasma mirrors. For magnetized plasma experiments, the generation of external B fields with plasma magnetization $\sigma = B^2/8 \pi n_i m_i c^2 (\gamma_{flow} -1)$ in the range $\sigma \sim 10^{-4} – 10^{-1}$ will also be important. An increase in laser intensity beyond 10^{23} W/cm^2 might lead to new exciting physics (including strong synchrotron losses, pair production, and gamma-ray generation) that can affect the shock formation and the shock dynamics. The experimental effort should be complemented by a vigorous theoretical and computational effort. To understand the complicated plasma physics, multidimensional multiscale modeling capabilities must be developed and improved to cover the kinetic scales

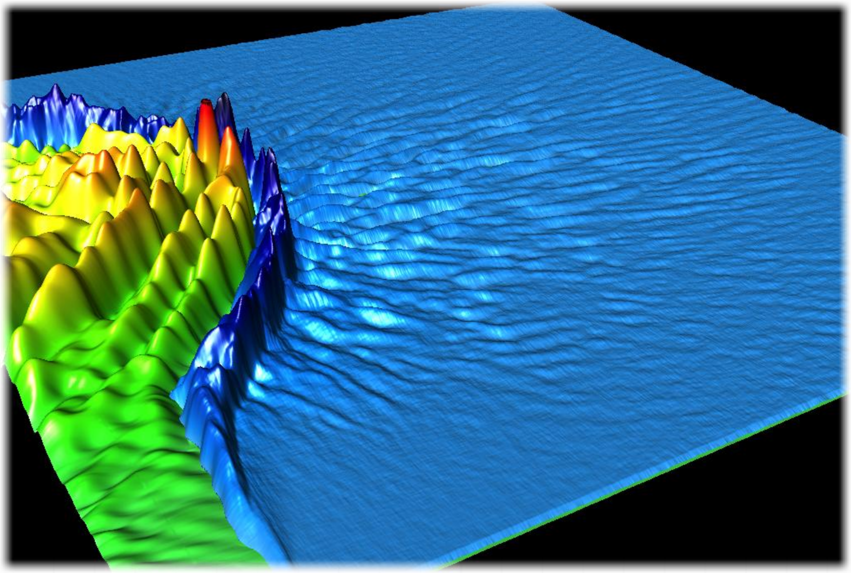


Fig. 31. Interaction of a finite width intense laser with an overdense plasma ($n_e = 100\ n_c$) (blue), showing the formation of a relativistic-like shock due to the Weibel instability of the return current (filaments in front of the density pile-up). (Source: Ref 4.)

over more than four orders of magnitude, ranging from the timescale of electron dynamics to the particle acceleration in the shock timescale.

Impact

A successful program may resolve a 60-year old mystery associated with the formation of collisionless shocks and particle acceleration in the universe, associated with, for example, supernova remnants and gamma-ray bursts. We aim to identify the main acceleration mechanisms leading to both power-law spectra (with direct evidence for Fermi acceleration) and to monoenergetic particle beams.

References

1. Sagdeev, R. Z., and C. F. Kennel, Collisionless shock waves, *Sci. Am.* **264**, 106 (1991).
2. Spitkovsky, A., On the structure of relativistic collisionless shocks in electron-ion plasmas, *Astrophys. J. Lett.* **673**, L29 (2008).
3. Martins, S. F., R. A. Fonseca, L. O. Silva, and W. B. Mori, Ion dynamics and acceleration in relativistic shocks, *Astrophys. J. Lett.***695**, L189 (2009).
4. Fiúza, F., et al., Weibel mediated collisionless shock in laboratory with ultraintense lasers, submitted for publication (2011).
5. Kuramitsu, Y., Y. Sakawa, T. Morita, C. D. Gregory, J. N. Waugh, S. Dono, H. Aoki, H. Tanji, M. Koenig, N. Woolsey, and H. Takabe, Time evolution of collisionless shock in counterstreaming laser-produced plasmas, *Phys. Rev. Lett.* **106**, 175002 (2011).

6. Haberberger, D., et al., Shocks in a laser produced plasma generate monoenergetic 20 MeV proton beams, submitted for publication (2011).
7. Fiúza, F., et al., Laser-driven shock acceleration of mono-energetic ion beams, in preparation (2011).

Active Control of the Flow of Radiation and Particles in HEDP

NIF has the opportunity to advance the frontiers of plasma instability suppression through the prospect of achieving burning plasmas and studying high-yield and high-gain burning plasma environments by using green light as opposed to UV light.

Introduction

A grand challenge in HED physics is performing specific tasks such as instability suppression or coherent radiation generation and amplification by controlling the flow of energy and momentum in coherent radiation and particle beams. The nonlinear optics of plasmas is a rich field where numerous waves can self-organize, mutually organize, or synchronize to each other. This condition can cause undesirable or runaway effects that can set very high upper bounds on the intensity, thereby preventing the use of high intensity lasers for inertial fusion. If properly controlled, however, such instabilities may act as instigators and amplifiers and serve as temporary storage media for ultrahigh energy density particles or radiation energy, which can then be redirected and harnessed as desired. Both extremes of this problem, namely, understanding how to suppress instabilities and how to enhance them and steer them, are opportunities for use of the NIF.

Controlling these instabilities requires a radically new idea. A recent idea discussed here is called STUD pulses (spike trains of uneven duration and delay).[1,2] It involves the use of NIF for adaptation of ultrafast optics techniques to stretch and compress in time, using nonlinear optical processes in waveguides and arbitrary laser waveforms at different wavelengths (such as the UV region, called the blue or green option). Then, with the addition of spatial scrambling of the intense portions of a laser beam (the speckle patterns), the incoming laser beams' ability can be suppressed to trigger or sustain undue self-organization in the plasma, and can do so orders of magnitude more effectively than the slower phase-altering methods. In STUD pulses, the incoming laser beams are modulated at the fastest instability growth time, which is of the order of picoseconds, and the speckle patterns or hot spots between unevenly spaced laser spikes are scrambled so as to limit the coherent accumulation of parametric growth, which is replaced with the incoherent superposition of small growth spurts. The new optimal and sectionally adaptive control of parametric growth reduces an exponential dependence on the number of laser spikes (or laser pulse duration) down to a mere linear scaling, which is significantly better than explosive and exponentially growing instabilities.

Another grand challenge is the exploitation of a three-wave instability such as Raman scattering in pump-probe geometry or the creation of other novel nonlinear kinetic states such as kinetic electrostatic electron nonlinear (KEEN) waves[3] to mediate the interaction between an energetic, high-energy, nanosecond-wide pump beam and turn it into an orders-of-magnitude shorter probe beam amplified by a few orders of magnitude. Many instabilities must be suppressed while only the desired process must be isolated, making this a demanding and challenging task. The possibility is, however, exciting. Using an HED plasma to create ultra-intense laser pulses by stacking their energies and channeling them to a short-pulse, a high-intensity beam may open the door to many high concept applications in pure and applied physics.

Opportunity

The science and technology opportunities with NIF resulting from instability suppression lie in the prospect of achieving burning plasmas and studying high-yield and high-gain burning plasma environments by using green light as opposed to UV light. This capability will allow the use of up to 4 MJ of laser energy, more than double the current energy available with UV light. Developing the ability to modulate and scramble lasers on picosecond timescales may also allow diagnosing plasma conditions (including the distribution function) by a pump-probe STUD pulse setting. It could also potentially allow hotter hohlraums to be accessible by avoiding laser-plasma instabilities in an adaptive manner. Figure 32 shows the results from stimulated Brillouin scattering, where orders of magnitude reduction in backscattering is achieved with a scrambled beam in space-time, driven by STUD pulses,[1,2] compared with a traditional beam smoothing technique such as random phase plates, or one-dimensional smoothing by spectral dispersion.

The same techniques being proposed to tame instabilities can be used in pump-probe geometry to diagnose the intricate and fast changing properties of the electron velocity distribution function with picosecond time resolution for the first time and reveal to what extent our so-called “first principles” theoretical models can follow the nonlinear evolution of instabilities and their mutual coupling. If successful, this access to the kinetic details of the plasma could lead to a dramatic improvement in the understanding of HED plasmas and their interaction with intense sources of coherent radiation. The successful implementation of these techniques could lead to advances to the fundamental science of nonlinear optics of plasmas and to the achievement of high-gain and high-yield burning plasmas.

Well-controlled Raman amplification in plasmas offers the potential for achieving high power (above 10 petawatts) and short pulse (sub-100 femtoseconds) lasers. Proof-of-concept experiments have been performed at Princeton University,[4,5] and a comprehensive series of large-scale multi-dimensional particle-in-cell simulations of this process has demonstrated that multi-petawatt peak powers can be reached using Raman amplification, but only in a narrow parameter window in which deleterious instabilities are avoided.[6] This window can be characterized as the nonlinear Raman amplification regime, as the seed pulse intensity at the start of the interaction is sufficiently high to avoid linear growth of the seed pulse, which ordinarily requires much longer interaction lengths. A multitude of nonlinear effects has been encountered and needs to be avoided, such as probe saturation due to Raman forward scattering and wakefield generation, wave breaking of the Raman back scattering (RBS) Langmuir wave that couples pump and probe, and parasitic pump RBS and transverse filamentation of both pump and probe pulses. The detailed kinetic evolution of the nonlinear electron plasma wave (or perhaps KEEN waves)[3] used for this amplification must be

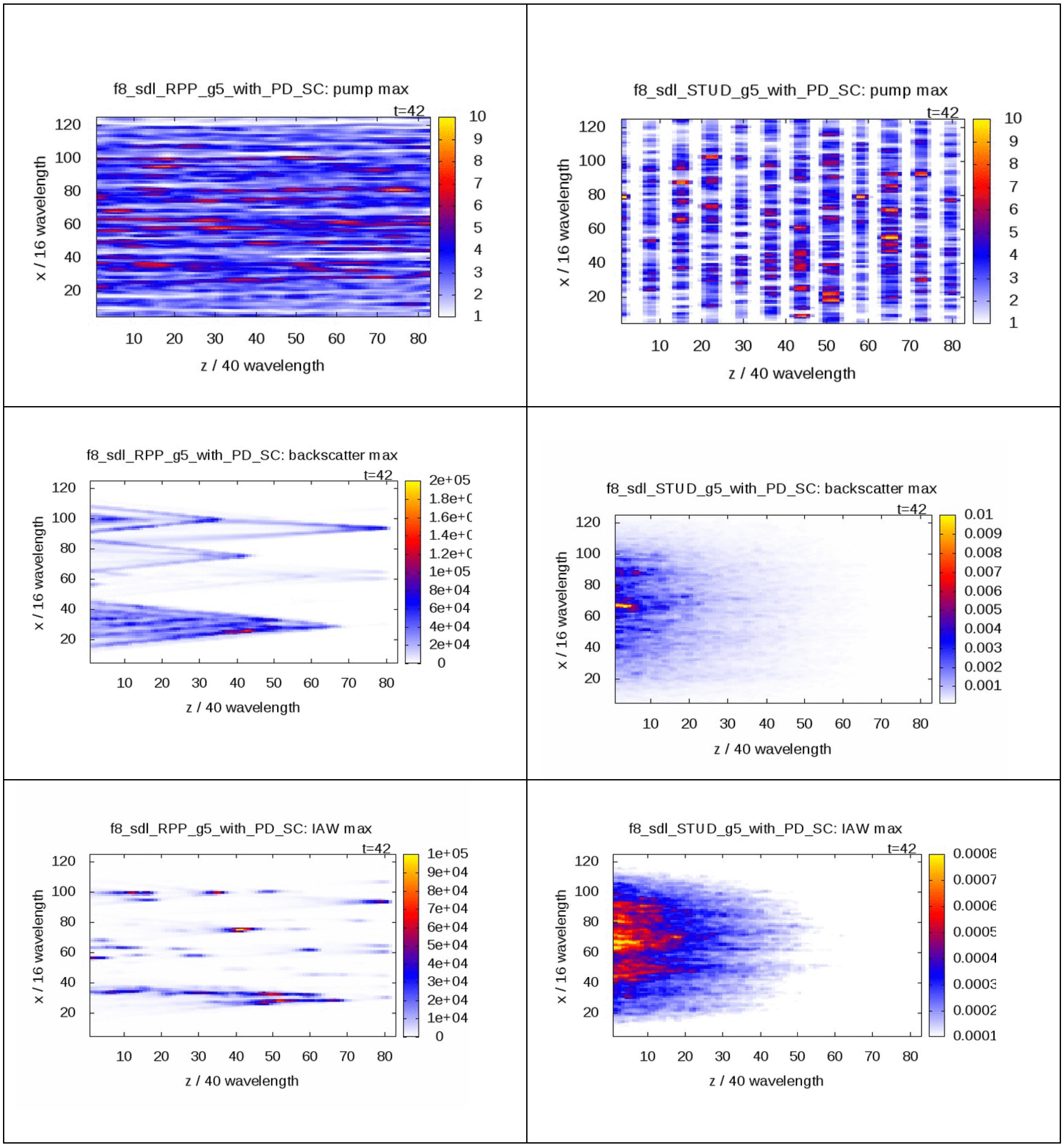


Fig. 32. (Left graphs) Pump and the stimulated Brillouin back-scattered light and the driven ion acoustic wave (IAW) amplitude distributions in random phase plate (RPP) or smoothing by spectral dispersion (SD). (Right graphs) Spike train of uneven duration and delay (or STUD pulse) at 42 ion acoustic periods. The maximum value in a 40 x 16 wavelength squared region is plotted. Note the many orders of magnitude reduced reflectivity and IAW generation with a STUD pulse when compared to RPP or smoothing SD. In both cases, the gain for the average laser intensity in a single laser hot spot of this f/8 beam is 5 (g5 in the heading for each frame). The effects of pump depletion (PD in heading), strong coupling (SC in heading), inhomogeneous flow, and strong IAW damping are all included. The laser propagates in the z direction, and x is the transverse direction.

thoroughly understood and monitored to establish just how much energy can be pumped into the signal without disruption. NIF might achieve power (and energy) ranges approaching exawatts, provided that these instabilities are understood and controlled.

Research Directions

We envisage a staged research program, using the Trident laser at LANL then the OMEGA facility at Laboratory for Laser Energetics in Rochester, and then the NIF, to determine the efficacy of STUD pulses, which consist of a sequence of on-off laser spikes. STUD pulses, via the generation and adaptive modulation of laser pulses, and the scrambling of laser hot spot patterns in space, between spikes, can be used to tame stimulated Raman and Brillouin scattering. We will measure the reflected light on the picosecond timescale by nonlinear optical techniques that require four-wave mixing in waveguides to stretch optical pulses and render them easily. These are known as "time lenses" or time telescopes and microscopes.[7] We will learn how HED plasmas evolve kinetically over very short timescales via the slope of the electron velocity distribution function. We will fine tune the spike sequences to achieve minima in reflectivities of the fastest growing instability for a given set of laser and plasma parameter conditions. We will test to what extent codes can predict the proper evolution of instabilities when the kinetic Landau damping rates or particle trapping signatures are measured and tracked in time. New models are likely to emerge from this process. Instabilities of other (uncontrolled or insufficiently controlled) beams mutually interacting and influencing each other's evolution will be tracked by these novel techniques as well. Chaos control or stochasticity management will become an integral part of the arsenal available to the nonlinear optics of HED plasmas.

The window in relevant parameter space (plasma density, pump intensity, probe intensity, and interaction length) for successful Raman amplification is predicted to be narrow. Exploring this space requires careful experimentation and diagnosis. Simulations indicate a limit to the peak laser intensity of the seed pulse; therefore, to increase the output power, the spot sizes of both the pump and seed pulses will need to be increased in proportion to power. The table below shows the output power targeted at different facilities, including the Advanced Radiographic Coherent Optical System (ARCOS) facility of NIF operating at 30 ps and one-half of NIF operating at 88 ps.

Facility	**Pump energy (J)**	**Pump pulse length (ps)**	**Intensity (W/cm^2)**	**Focal spot dia. (mm)**	**Probe pulse length (fs)**	**Probe energy (J)**	**Length (mm)**	**Output peak power (PW)**
Vulcan	300	30	1.35×10^{15}	0.92	25	0.25	4	4
EP	1000	30	1.35×10^{15}	1.8	25	0.8	4	12
EP	2000	80	1.0×10^{14}	5.6	25	0.625	12	24
NIF	7500	30	1.35×10^{15}	4.86	25	6.25	4	90
NIF	5000	88	2.5×10^{13}	17.8	25	6.25	12	264

Experiments need to be conducted on smaller-scale facilities such as OMEGA at Rochester to confirm the veracity of the numerical simulation. Further, additional research and development is needed to evaluate fully operation of NIF at the below spot sizes. In particular, operation of NIF at 88 psec with a large spot may require overlapping beams.

Impact

Achieving control over parametric instabilities or nonlinear optical processes in laser-produced plasmas has been a grand challenge problem for the last forty years. All attempts to tame such instabilities have met with limited success (going from red to blue light helped). The techniques outlined above will, if successful, allow the use of green light for driving laser implosions and producing burning plasmas. This capability, in turn, could profoundly improve the reach in parameter space accessible to HED physics, laboratory astrophysics, and nuclear astrophysics.

If controlled, the rich physics potential of laser-plasma interactions can be harnessed to provide the next generation of ultraintense laser pulses. NIF is in a unique position to deliver exawatt laser capability. Such lasers could open the window to many new science topics and applications for strong field physics.

References

1 Afeyan, B., STUD pulses: Spike trains of uneven duration and delay for the control of laser-plasma instabilities in ICF, IFE and HEDP, accessed at http://meetings.aps.org/link/BAPS.2009.DPP.TO5.7.

2. Afeyan, B., STUD pulses for shock ignition and LPI control, accessed at http://www.lle.rochester.edu/media/publications/presentations/documents/SIW11/Session_3/Afeyan_SIW11.pdf.
3. Afeyan, B., et al., Kinetic electrostatic electron nonlinear (KEEN) waves and their interactions driven by the ponderomotive force of crossing laser beams, Proc. Inertial Fusion Sciences and Applications, Monterey, CA, American Nuclear Society (2004).
4. Ren, J., W. Cheng, S. Li, and S. Suckewer A new method for generating ultraintense and ultrashort laser pulses, *Nature Phys.* **3**, 732–736 (2007)
5. Suckewer, S., Ultra-intense lasers beyond a petawatt, *Nature Phys*. **7**, 11 (2011).
6. Trines, R. M. G. M., F. Fiúza, R. Bingham, R. A. Fonseca, L. O. Silva, R. A. Cairns, and P. A. Norreys, Simulations of efficient Raman amplification into the multipetawatt regime, *Nature Phys.* **7**, 87-92 (2011).
7. Reza Salem, M. A. Foster, A. C. Turner, D.F. Geraghty, M. Lipson, and A. L. Gaeta, Optical time lens based on four-wave mixing on a silicon chip, *Opt. Lett.* **33**, 1047-1049 (2008).

Ultraintense Beam Generation and Transport in HED Plasma

The combination of NIF and the short-pulse ARC Quad provides a unique capability for studying the physics of ultraintense beam generation and transport in a high-density ignition-scale plasma.

Introduction

The combination of high-energy (greater than 1 kJ) , long-pulse (greater than 1 ps), and high-intensity (greater than 10^{19} W/cm^2) short-pulse lasers at today's next generation laser facilities is opening new, exciting research directions in HED plasma physics. A ubiquitous feature of high-intensity laser-matter interactions is the rapid, directional acceleration of particles—electrons and ions—to energies of several million to billions of electron volts. Laser energy can be coupled to particle energy with high efficiency (a few to tens of percent) resulting in the generation of ultrahigh flux relativistic (electron) and sub-relativistic (proton and ion) beams. The acceleration can occur through a wide variety of physical mechanisms, including direct acceleration in the electric field of the laser, ponderomotive force, radiation pressure, and electrostatic field acceleration.

Understanding the transport of such ultra-intense particle beams through dense plasma presents a scientific challenge. With present-day multi-kilojoule short-pulse lasers, relativistic electron current densities can exceed giga-amperes, many orders of magnitude greater than the Alfven limit. The beam interacts strongly with the dense plasma, drawing a return current and creating strong resistive electrostatic fields and multi-megagauss magnetic fields. The beam is subject to collective instabilities such as resistive filamentation and Weibel instability. The particle beam couples energy to the plasma, through both collisional and non-collisional processes, heating it to keV temperatures. The ability to control the generation and transport of these intense beams has practical application in the creation of plasma states with unprecedented energy densities, ultimately reaching that required to trigger thermonuclear fusion and propagating burn in a dense deuterium-tritium fuel. This is the fast ignition approach to ICF, which allows for high overall energy gain by separating out the phases of fuel compression through a high-mass low-velocity implosion, and almost instantaneous heating a small region of that fuel through an ultraintense short-pulse particle beam.

Once understood and characterized, these beams can be used to generate unique probes to explore a wide range of plasma and HED physics states that can be assembled in NIF. For example, intense laser-plasma interactions at 10^{21} W/cm^2 will be capable of generating ultra-bright harmonics with many tens of thousands of orders (≥10 keV). This unique X-ray source with simultaneously produced harmonics (in addition to being in close proximity to NIF) will allow one to study unique features of the structure of warm dense matter—the temperature regime between the solid and plasma states. The intensity of the scattered x-ray radiation from warm dense matter is dependent upon the ion-ion structure factor, and there are a number of different ways of calculating this intensity, e.g., molecular dynamic models using unscreened Coloumb potentials. Strong coupling may affect rates of energy transfer, particularly as momentum can be taken up by more than one ion. For example, gold is expected to have a face-centered-cubic-like structure that persists for many picoseconds when heated to a few eV's. Sub-picosecond probing of these high temperature and pressure states of matter should allow one to investigate their evolution. This example is just one indication of the wide range of applications in fundamental plasma physics, materials science, astrophysics, and nano-sciences (nano-crystal formation, strain, domain formation, dynamics, etc.) that will benefit from the development of these femtosecond and attosecond probe capabilities.

Opportunity

The combination of NIF and the short-pulse ARC Quad provides a unique capability for studying the physics of ultraintense beam generation and transport in a high-density ignition-scale plasma. ARC Quad consists of 8 beamlines delivering a total of 650J in 2 ps in a 280-µm diameter spot, with a peak intensity of mid-10^{18} W/cm^2. The relativistic laser absorption and particle acceleration mechanisms described here require the ARCOS adaptive optics upgrade to ARC, which concentrates the laser energy into a 50-µm spot and increases the peak focal intensity by a factor of 10-20X, to near 10^{20} W/cm^2. Coherent addition of the full quad could lead to peak intensities of 10^{21} W/cm^2 and enable generation of intense high-Z ion beams through, for instance, radiation pressure acceleration.

Research Directions

Four major research components are required to address the above scientific opportunities:

(i) *Configuration of initial plasma state*—NIF provides the capability for creating plasmas over a wide parameter space of density and temperature. Fundamental studies of particle beam-plasma interactions will first require techniques such as x-ray heating or shock compression for creating plasma configurations with given initial values of density and temperature. The highest densities, relevant to fast ignition of >300 g/cm^3, will require new isochoric compression schemes, in either indirect- or polar direct-drive geometry, that can implode a capsule shell to a uniform high density state.

(ii) *Relativistic laser absorption and beam generation*—Experiments would be performed to study the interaction of the high-intensity ARC/ARCOS pulse with underdense and overdense plasmas and characterize and optimize the production of fast electron, proton, and ion beams. Figure 33 shows a simulation result from a particle-in-cell code, demonstrating the complicated physics of a laser propagating through a short underdense plasma before the critical surface. Close coupling between experiments and simulations will be important.

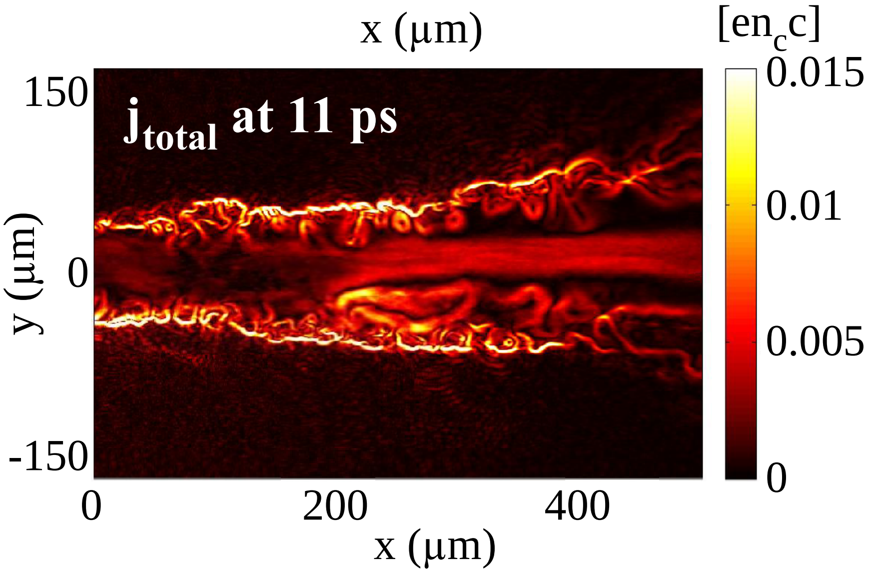


Fig. 33. Particle-in-cell (PIC) simulation of a kilojoule-energy, picosecond laser pulse propagating through near-critical density plasma. The map of electron current density shows the complex nature of the laser-plasma interaction, including beam channeling, hosing instability, and excitation of surface waves.

(iii) *Ultraintense beam-plasma interaction*—Experiments would study the transport of intense beams through plasmas spanning density-temperature space, including beam-plasma instabilities, self-generated electrostatic and magnetic fields, the dynamic response of the background plasma, and the coupling of energy from the beam to the plasma. Experiments would progress to investigating methods to control and concentrate energy flow into the plasma (and thus maximize the plasma energy density), for instance, by tailoring the spatio-temporal-energy characteristics of the beam, or though designing suitable spatial gradients in material resistivity, temperature, magnetic field, etc., in the initial plasma configuration. Importantly, because the return current characteristics will affect the relativistic absorption and beam generation, advanced simulations will be required to make progress. In Fig. 34, filamentation of the incoming electron beam is seen in a hybrid simulation.

(iv) *New probes for high energy density plasmas*—One can envisage a wide range of unique probe capabilities being developed, in addition to the x-ray harmonics described above for HED plasmas. These include 3D-tomographic reconstructions using charged-particle radiography/deflectometry, 3D-tomographic reconstructions using hard-x-ray radiography sources (K_α x-rays, Compton radiography, and betatron oscillations in laser wakefields), and others.

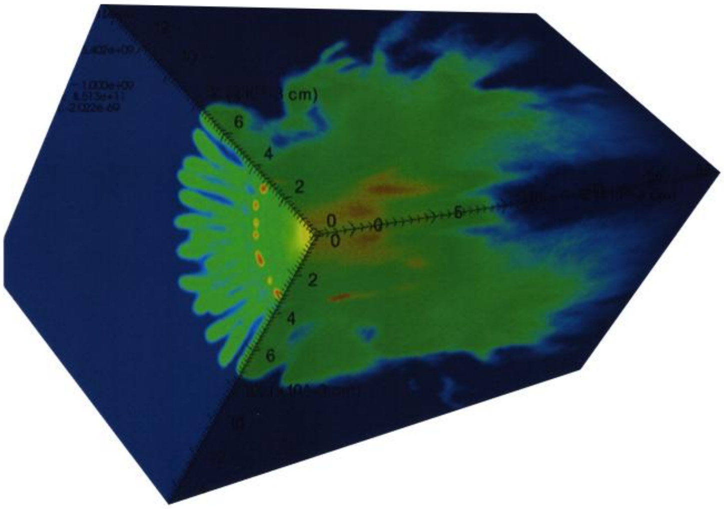


Fig. 34. Three-dimensional simulation of an intense relativistic electron beam propagating through a high-density compressed DT fuel. The simulation couples a hybrid-PIC electron transport code (Zuma) with a radiation-hydrodynamics code (Hydra). The map of energy density shows the beam, initially gaussian in space and propagating from left to right, breaking into multiple filaments through the resistive filamentation instability.

Current research at laboratory petawatt-class laser facilities (Titan, Trident, Vulcan, etc.) and at the OMEGA-EP facility provides the groundwork for studies on NIF, including the development of experimental and diagnostic techniques. In parallel, major advances are being made in theory and modeling of relativistic laser-matter interaction, as well as beam generation and transport in dense plasma.

Impact

The greatest potential impact is in establishing the underlying physics of fast ignition and extrapolating, with high confidence, to a robust high-gain fusion target design. This capability will require developing an understanding, and a degree of control, of intense particle beam generation and transport in an ignition-scale dense plasma, validated through experimental measurement and predictive simulation capability. An attractive, competitive design could lead to a program for demonstration of high-gain ignition with >100 MJ yield, a major milestone on the path to inertial fusion energy.

Complex Plasma States in Extreme Laser Fields

NIF, including the development of the full ARC system, provides a unique capability for studying ultra-relativistic extreme field physics.

Introduction

Ever increasing laser intensities are leading to a dramatic change in the character of laser-plasma interactions, with significant implications for many processes of scientific and practical interest that are under active study today. Specifically, as laser intensities increase, new physics-like radiation damping (including nonlinear Compton scattering), pair production, and the generation of HED high-Z plasmas could all occur simultaneously. Several planned ultrahigh intensity laser facilities, e.g., the European Extreme Light Infrastructure (ELI), will have the capability to study some aspects of this new extreme field physics. However, the NIF in conjunction with a fully developed ARC (ARCOS, Phase III) could provide the first facility capable of entering this new physics regime in a hot-dense plasma regime. This will allow the first studies of macroscopic, relativistic plasma states at extreme intensities.

To unravel the interactions in such a complicated regime, it is also useful to understand some processes in isolation. For example, a fundamental problem is “radiation reaction”: a charged particle that is accelerated by an external field emits radiation, and this emission changes the motion of the electron (Fig. 35). While the classical Lorentz force describes the motion of the particle and the Lamor equation gives the rate of the radiated energy, multiple perturbative approaches exist, like Lorentz-Abraham-Dirac, Landau-Lifshitz, or Caldirola, but it is difficult to experimentally verify them. In addition, when the energy of the radiated photon is near the total radiated energy, quantum electrodynamics (QED) effects have to be included.

Opportunity

The development of the full ARC system, including full adaptive optics and phase locking of multiple beams, in combination with advanced pulse cleaning techniques and plasma optics, provides a unique capability for studying ultra-relativistic extreme field physics. In combination with the NIF, this regime can be reached in a HED environment of an ignition-scale plasma, allowing, for example, surrogate experiments for radiation creation and transport of interest to astrophysical situations. Phase III ARC consists of eight coherently added and phase-locked beamlines, delivering a total of 8 kJ in 10 ps at peak intensities of $>10^{20}$ W/cm^2. Additionally, the use of focusing plasma mirrors might increase the intensity further, to well beyond 10^{22} W/cm^2.

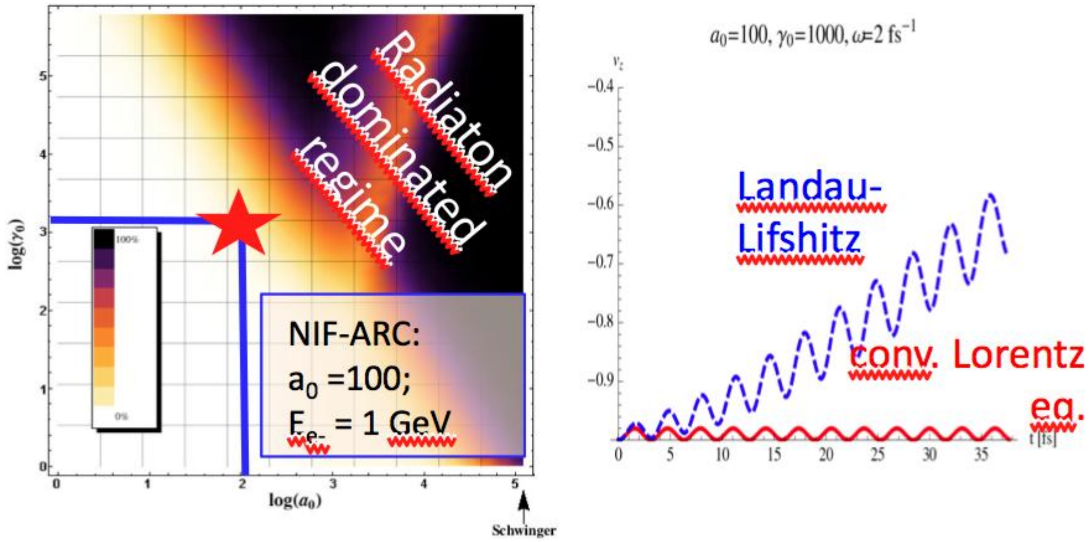


Fig. 35. The radiation-dominated regime (RDR) as predicted by the Landau-Lifshitz model of radiation reaction. NIF-ARC using plasma optics and a 1 GeV electron beam created with one-half of the available beams barely reaches the RDR, and effects are on the percent level.

Research Directions

This research direction is less mature than the others. While some exciting opportunities exist for basic research, it is recommended that a separate workshop be held in which experts in HED plasmas, lasers, and field theory gather to discuss if NIF in conjunction with smaller staging facilities can be used to address these fundamental issues and test the models and theories required to understand and predict the physics of extreme fields. Whereas other ultrahigh intensity lasers will reach ultra high intensities (>10^{22}W/cm^2) by going to ever shorter and shorter pulses and thus increasing the intensity and field strength, ARC could potentially do the same by increasing the pulse energy. This approach allows the existence of ultrastrong fields for picoseconds instead of femtoseconds; as a result, the laser-matter interactions continue much longer at the same rate. As many signals depend ultimately on the energy content of the system, this approach allows single-shot experiments instead of the long accumulation periods required by low energy facilities, resulting in completely different interaction geometries.

Possible topics to be discussed at the proposed workshop include:

> *Experimental validation of radiation reaction models*—Can ARC/ARCOS be used together with a well-defined electron beam in the 100 MeV to 1 GeV range to create distinct radiation signatures that will allow the validation and development of radiation-reaction models and nonlinear QED rate equations. Can lower energy lasers be used? Can the copious amounts of hard x-rays produced in these studies be used to interact

> with the dense high-Z plasma created by one or more arms of NIF to create interesting plasma states?
>
> *Extreme field interactions in NIF-created target plasma*—Combining the developed technologies of extreme field creation with a NIF-created target plasma gives us the opportunity to study extreme field physics in a plasma environment. At high laser intensities and high laser energies, it may be possible to produce a plasma with the simultaneous interaction between electron-positron plasmas, hard x-ray transport and absorption, and high-Z, high-atomic-number ions. The laser intensities and energies needed to create such exotic plasmas need to be quantified, and the unique properties of such plasmas need to be analyzed.

Depending on the outcomes of the proposed workshop, research at laboratory petawatt-class laser facilities (Titan, Trident, Vulcan, etc.) and at the OMEGA EP facility could provide the groundwork for studies on NIF, including the development of experimental and diagnostic techniques. In parallel, major advances can be made in theory and modeling of relativistic laser-matter interaction, including radiation reaction, pair creation from vacuum and electron collisions with high Z atoms, and proper local thermodynamic equilibrium models for the ionization states of the high Z ions.

Impact

The first and most immediate potential impact is in further exploring the century-old problem of radiation reactions and establishing a semi-classical solution for it or a full (non-linear) QED treatment if required. Furthermore, we will develop a fundamental understanding of extreme field interactions, essential to experiments both on full NIF-ARC and on future facilities.

SCIENCE ON NIF: CROSSCUTTING AND FACILITY PANEL

The crosscutting and facility panel was motivated by three guiding principles:

- Maximize the probability of success of NIF science on decadal timescales.
- Accelerate the growth of a sense of scientific community among NIF users to enhance their collective impact.
- Profit from best practices and lessons learned from other relevant facilities to optimize the efficiency and effectiveness of NIF as a scientific user facility.

As a result of their deliberations, suggestions and recommendations in the areas of

- Facility policies and governance,
- Facility operations considerations, and
- Community outreach and education

emerged that the panel believes will contribute directly to the successful realization of the science opportunities discussed earlier in this report.

Policy and Governance

A clearly defined user policy and governance model defines the ways in which the scientific user community will interact with and access the facility. It contains elements to ensure open and fair access, as well as safe and efficient utilization of the facility. The goal is to maximize scientific productivity and societal benefit.

Access modes

DOE facilities often encompass a range of user access modes that should be examined for applicability to NIF science. These modes include both “general users” and special relationships, including “approved programs” or “partner users.” These special relationships encompass users who can bring additional resources (diagnostics, staff, skills, program interests, etc.) or useful collaborations to a facility (such as industries). All users are expected to submit written proposals for evaluation by independent panels under peer review.

Team formation

It is expected that experiments will be conducted by teams of scientists, including those from both outside and inside NIF. A strong motivation exists for self-organization of researchers, due to inherently limited resources (shots on NIF are few, and experiments are complex and expensive). Early standup of a User Group and associated meetings will expedite coordination among researchers with shared interests. A principal investigator to represent each team is required and will be expected to be on-site for experiments; some team members may be off-site.

Advisory bodies

Best practices based on operation of current Department of Energy (DOE) Office of Science (SC) facilities should inform the development of an organizational structure that advises NIF leadership. Such structures typically involve three committees: Science Advisory Committee (for long term scientific vision), Proposal Review Committee (for peer review of proposals), and User Executive Committee (for user input).

Stewardship

There should be a primary steward (for NIF it's NNSA) of a facility. However, successful precedents exist for shared funding of science at many major facilities. For example, the Basic Energy Science (BES) Facilities Division is the steward of DOE's light source facilities, while BES science program offices, as well as DOE's Biological and Environmental Research, National Institutes of Health, and others, support individual principal investigators (PIs) that use synchrotrons. Additionally, multi-agency support is available for HED science at UK laser facilities. Today, there is already international support for activities at NIF (e.g., Commissariat à l'énergie atomique, France, and Atomic Weapons Establishment, England). An additional example of co-funded science and facility activity is structured under a memorandum of understanding between NNSA and SC involving the Los Alamos Neutron Science Center; importantly, this joint work is actively monitored by a multi-agency council. An attempt to expand the resource base for HED science is discussed in the ReNeW report, which endorsed the joint program between NNSA and SC (Fusion Energy Sciences) as a way to define additional agency funding beyond the NIF steward of NNSA; this is a viable concept that expands the number of agencies and thus the scientific missions that could be supported using NIF. Multiyear commitments by science agencies to support research that falls within their various missions are clearly essential to enable experiments, and we encourage consideration by the multiple federal agencies that could exploit the unique capabilities of NIF so as to leverage this large investment in facilities and instrumentation. At present no agency has issued a call for proposals within the past three years that included support for research on NIF within its scope.

Calls for proposals

Calls for proposals should be periodic, predictable, and widely distributed. Points of contact for detailed information and timelines should be clear. Timely notifications should be made of the disposition of the proposal at relevant stages. Any constraints on breadth of calls (e.g., facility limitations) should be made clear.

Review processes

In the initial call for experiments on NIF, a combination of written proposals and in-depth presentations and discussions with the review team worked well. Additionally, this mechanism facilitated the combining of different groups with similar goals. Going forward, review processes should involve a sufficiently large group of independent reviewers with diverse skills; appropriate turnover of reviewers over time is expected to ensure a fair process. Feedback should be given to encourage successful future proposals.

Coordination and integration with other (midscale) facilities

Coordination with other facilities is a laudable goal but is difficult in practice, and it may be difficult to formulate a general policy on this topic. Experience suggests that coordination of “warm-up” experiments, which in an optimal situation would lead to good science on both a midscale facility as well as set the stage for a more successful NIF experiment, can be addressed by close communication among facilities and the proposing PIs and perhaps the sponsor. It should be noted that successful users at the largest facilities, like NIF, generally have a record of success at midscale facilities. It is also true that there are some experiments at NIF that have no analogue on smaller facilities.

Internal LLNL scientists' roles

An appropriate balance must be struck between science led by internal LLNL scientists (including those who might assume a role of “instrument scientist,” “user support scientist,” or “liaison scientist”) and external scientists. Transparency of the review process, including submission of all proposals to the review process, will be key to affecting this correct balance. Career paths and expectations for internal scientists, as well as opportunities for external collaborations, need to be clarified. The unique capabilities of internal scientists (physics, experimental technique, or instrument) require particular attention to the appointment of points of contact for teams.

Data handling and availability

The scientific community, government agencies, professional societies, and publishers are studying issues surrounding the availability of data beyond that which is published. Additionally, examples of policies surrounding proprietary work exist for DOE’s light sources. Furthermore, complications exist for NIF regarding potential classification issues. We expect that NIF will subscribe to norms being developed by the broader communities, will allow users to have access to their experimental data in a timely way, and will benefit from the experiences and practices at existing midscale facilities.

Export control

If NIF is designated a "DOE User Facility," users will sign the DOE standard user agreement that clarifies roles and responsibilities.

Operations

Experiments at NIF pose a unique set of challenges due to its large scale; these include a limited number of shots, high cost of targets, need for sophisticated simulation and modeling, and a potential need for significant engagement of NIF personnel in any experiment. However, experience at both current and past large scale facilities, as well as large facilities in other nations, can guide consideration of recommendations for future science at NIF.

Capacity

High scientific productivity implies that the number of shots per day on NIF be maximized; these shots will be limited by many factors, including laser cooling times, target availability and insertion, debris, activation, resources for staff, etc. Additional mechanisms for enhancing the shot rate, as well as ride-along shots for many users, and appropriate sequential scheduling, should be exploited. The possibility for 5 to 10 shots per (24 hour) day seems plausible. Furthermore, the community should participate in the discussion of the appropriate allocation fraction of shots for fundamental science.

Access to simulations, design, and theoretical support

Successful experiments on NIF will require significant design and simulation of target conditions. The most advanced tools for this work, and the expertise to utilize these tools, will in large part reside within the NIF organization and the broader national laboratory complex. A transparent and accessible methodology for pairing outside researchers with the people and tools needed for simulation and design, and more broadly, theory, will be required. An example of other resources for users is the FLASH Center for Computational Science at the University of Chicago for astrophysical hydrodynamics.

Access to target fabrication

Timely fabrication of targets, including initial specification and the associated research and development, will be essential to a successful NIF science program. The sophisticated targets expected to be utilized under the program will require early and extensive discussions among the team, target fabricators, and NIF personnel to determine the cost of R&D on the targets, as well as fabrication, so as to avoid each investigator having to invent his or her own solution. Costs associated with fabrication of NIF targets are typically $50K but can exceed that in special circumstances. Assembly is often done through a combined effort by a private company, such as General Atomics (GA), and a national laboratory. For the National

Laboratory Users Facility program, a supplementary funding program provides resources to GA for target fabrication. We envision a range of solutions to the problem of paying for targets, ranging from costs being covered by NIF operations, to costs being covered under a grant provided by the science sponsor. Increasing demand for target design and fabrication will require a rampup of national capability, thus a program, in this area.

Staff and Resources

Dedicated staff and sufficient resources are essential to the success of a user facility. This includes both operations and user support staff, and resources for simulation, design, fabrication, and execution of experiments. It will be important for the steward of the facility to maintain sufficient operations budgets to provide the necessary staff and resources to ensure the science program on NIF, with due consideration for staff career growth and succession planning.

Training

Responsibility for providing training rests with the NIF facility. It is expected that extensive use will be made of on-line training to allow for early and complete training to ensure safe and productive experiences for users.

Badging and student and foreign national access

A central user office and point of contact for users will expedite the throughput of the broad range of users expected in a NIF science program. Experience at other facilities (especially HED facilities) suggests that early submission of applications for admission to national labs will provide smoother operation. Concepts associated with the Livermore Valley Open Campus, including discussions on open temporary offices and computer access, are a good indicator of a potential solution.

Outreach and Education

The roles of NIF in outreach and education will include educating the general scientific community, publicizing NIF capabilities, sending scientists to appropriate professional society meetings, engaging other facilities (e.g., midscale laser facilities), and holding workshops to flesh out Priority Research Directions identified elsewhere in this report.

An active program in outreach and education will support the mission of NIF by providing fundamental training and networking opportunities for young scientists and by broadly distributing and explaining the results of cutting edge science at NIF.

NIF should actively include students and postdoctoral researchers in the user community. Young scientists may be supported in several ways, including summer research opportunities at both the undergraduate and graduate level, training workshops for researchers, and invitations to present and speak at user and science meetings. Office and housing accommodations should be considered for long-term visits to NIF as part of active collaborations. NIF research opportunities should also be highlighted among existing graduate student programs in the NNSA Stewardship Science Academic Alliance program and other DOE fellowship programs.

NIF should also target K-12 educators and the general public as part of a broader program to convey the experimental results and the unique characteristics of the facility. Suggested activities include partnering with science museums to develop traveling exhibits based on NIF research, producing podcasts and partnering with radio and online-based public science web sites (e.g., popular science magazines), contributing materials to teacher training workshops in physical sciences, scheduling visits by students from area schools and summer programs, and sponsoring science competition events in topical areas related to NIF research. NIF users should be invited to participate in disseminating their research results through these structured avenues; in addition, funds may be budgeted for education and public outreach (E/PO) proposals (to follow successful NIF proposals). We note that outreach may be accomplished with relatively modest funds by forming strong partnerships with existing E/PO avenues set up by established programs (e.g., NASA as a nationwide network of E/PO contacts).

Users' Group

A Users' Group is essential for engaging the broadest community, providing forums for discussions of science, holding workshops and schools, and forming teams and other interactions among scientists and students as well as technical and facility staff. This Users' Group will organize an Annual User Meeting and, importantly, provide feedback to NIF and DOE. It can also serve as strong advocate for NIF by joining the National User Facility Organization. It is expected that such a Users' Group will be governed by bylaws developed by its members. The leadership of a Users' Group should be elected by users. A model exists in the Omega Laser Facility Users Group as well as user organizations at the light source and neutron facilities. A NIF Users' Group should be formed now.

Centers of intellectual effort

The natural evolution of NIF science will support development of a broad set of intellectual centers. We expect that universities (U.S. and international) will take advantage of opportunities to hire faculty engaged in NIF science, and thus they would leverage NIF. Important vehicles for leveraging such investments in science include joint appointments (between LLNL or other national labs and a university); focused grants under DOE's Stewardship Science Academic Alliance and joint programs, Defense Threat Reduction Agency, National Science Foundation, and NASA; formation of institutes for collaborative NIF science; and internships and visiting faculty programs. However, this natural evolution will only be possible if various agencies and offices take advantage of the opportunity NIF represents by making funding available to support such centers.

Success of Office of Science User Facilities

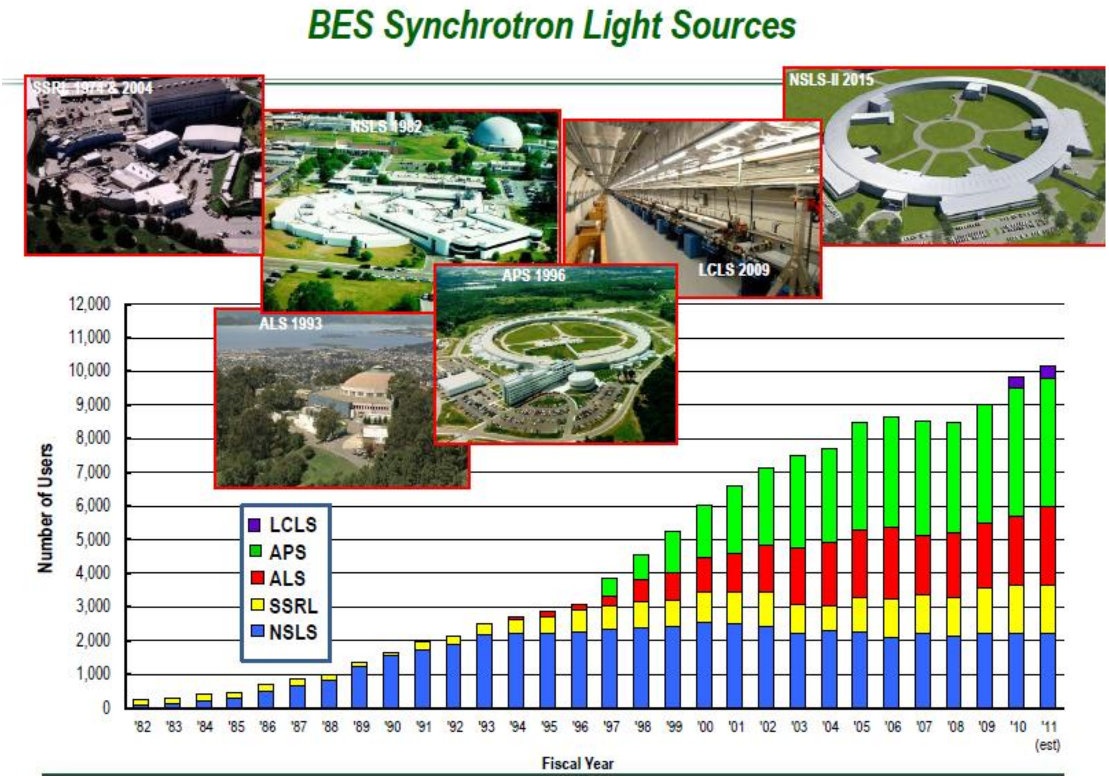
The DOE SC operates many large-scale user facilities, ranging from accelerators for high energy physics, nuclear physics, high-end scientific computing facilities, to neutron and synchrotron sources. These facilities are typically utilized by large, vibrant scientific user communities that produce world-leading science. For example, the five light sources operated by the basic energy sciences together support close to 10,000 users and publish thousands of high quality papers annually. Research at these light sources has also led to several Nobel Prizes. This tremendous success is due to a clearly articulated access policy, and the commitment of SC and the facility management to support the user community to perform the best science.

The user access policy defines the ways in which the scientific user community can access the facility. It contains elements to ensure open and fair access to the facility, as well as safe and efficient utilization of the facility with the goal of maximizing the scientific productivity and societal benefit. First and foremost, each facility administers a peer review process to evaluate scientific proposals for access. The proposals are evaluated for scientific merit by independent proposal review committees or panels and for feasibility and safety by the facility, with those that are most compelling being accepted and allocated time. There is no charge for users who are doing non-proprietary work, with the understanding that they are expected to publish their results. Access is also available on a cost-recovery basis for proprietary research that is not intended for publication. In addition, the user community is also encouraged to partner with the facility to develop new or enhance existing capabilities and engage in outreach activities to develop new user communities.

Each facility also has established mechanisms to receive advice and input on its activities. Typically, a scientific advisory committee is established to advise the Director of the facility on issues related to long-term scientific directions, development of scientific programs, and scientific productivity of the facility, as well as planning and construction of new facilities. Each facility also has a user executive committee or similar user organization to facilitate the communication between the user community and the facility. User organizations also work closely with the facilities to organize annual user conferences and topical workshops to provide input to facility on facility upgrades, explore new scientific opportunities, and educate and train new users. Each facility also conducts a survey of user satisfaction and solicitation of suggestions for improvement regularly.

Finally, the SC program office conducts regular operations review of the facility with external experts to provide oversight of the facility operation.

Success of Office of Science User Facilities (Cont.)



Number of users at DOE light sources:

LCLS	Linac Coherent Light Source
APS	Advanced Photon Source
ALS	Advanced Light Source
SSRL	Stanford Synchrotron Lightsource
NSLS	National Synchrotron Light Source

Taking the OMEGA Users Group Experience to the National Ignition Facility

The OMEGA Facility Users Group consists of 262 scientists from 31 universities, from 23 centers and national laboratories, and from 13 different countries. It meets twice yearly. At the annual 2-½ day OMEGA users workshop in April 2011, the objectives were, as in past workshops, to:

1. Present ongoing and proposed research at the OMEGA Facility and at the NIF.
2. Promote the research of students and postdocs working in HED laboratory science.
3. Establish diagnostic and experimental platforms that could be, and are, transferred from OMEGA to the NIF, and to other HED facilities.
4. Formulate findings and recommendations that will improve the OMEGA Facility.
5. Establish the framework for working with the OMEGA management, during the course of the year, in implementing the findings and recommendations of the users.

At this year's workshop, 50 students and postdocs attended and made 37 presentations. Most of the students and postdocs receive travel-expense assistance from a grant from NNSA. In all, 79 wide-ranging presentations were made by the 115 workshop attendees, and the topics covered the spectrum of ongoing and proposed research at OMEGA and NIF. Also, facility talks helped to update the users on the latest facility changes from the last workshop, and to introduce to new users the complexities and experimental procedures of OMEGA. Many of these changes are a direct result of the findings and recommendations of the previous year's workshop.

A critical element of the workshop is the student-postdoc panel/town meeting, in which these users formulate findings and recommendations for the facility, based on their experience. These, in turn, become part of the overall set of recommendations of the users to the OMEGA management.

A full day of the workshop is devoted to discussions and town-meeting sessions regarding the findings and recommendations. These discussions were led by eight users, and they focused on three general areas: (1) OMEGA 60-Beam Facility, (2) OMEGA EP Facility, and (3) general user issues. Details of these findings and recommendations can be found in the *Annual Workshop Proceedings*.

The last half-day of the workshop involved dialog between users and the OMEGA management in working to formulate a set of recommendations that are both forward-looking and achievable within available facility resources. These final findings and recommendations then form the grist for year-round discussions between the users and the OMEGA management, as work proceeds toward their implementation. Success to date in implementing the user recommendations is due to the working relationship between users and the OMEGA management. To assess progress, six months later, at the annual American Physical Society Division of Plasma Physics meeting in the fall (this year November 15, 2011), an evening OMEGA users meeting will convene to evaluate and discuss progress and possible mid-course corrections in implementing the users findings and recommendations. This is a joint meeting held by the users and the OMEGA management.

As the NIF users group is in its formative stages, the working model of the OMEGA users could prove useful in helping the NIF users community form their own cohesive users group.

Taking the OMEGA Users Group Experience to the National Ignition Facility (Cont.)

Attendees at the annual OMEGA Users Group Workshop of 27-29 April 2011

Students and postdocs that attended this year's OMEGA Users Group Workshop.

CONCLUSION

CONCLUSION

NIF is the world’s largest laser system. Its 192 beams can reliably deliver nearly two million joules of ultraviolet laser pulses of nanosecond duration on a target. With more than 50 times the energy of any previous laser system, the NIF enables scientific investigations under unique extreme laboratory environmental conditions, including exceptionally high matter and neutron densities as well unprecedented extremes of pressure and temperature.

While construction of the NIF was completed in 2009 and exciting results have already appeared, the full scientific potential of NIF will be realized over the next decades. To assess this potential, approximately 100 researchers from across the scientific community, spanning domestic and international universities, national laboratories, and industry, gathered in Washington, DC, in May 2011 for a workshop. The goals were to identify scientific challenges and research directions in laboratory astrophysics, nuclear physics, materials in extremes and planetary physics, and beam and plasma physics that NIF’s capabilities can uniquely address, and having identified these priority directions, to identify capability gaps as well as user science processes with the maximum likelihood of achieving success on the timescale of a decade. The following summarizes the main conclusions:

- For laboratory astrophysics, NIF offers unique opportunities for laboratory research to address issues that apply to the cosmos. It can create unprecedented volumes of material under conditions of astrophysical relevance by heating with lasers, intense photon fluxes, shock waves, or gradual compression.

- For nuclear physics, the availability of NIF opens new research directions for plasma nuclear physics. Probing nuclear interactions and nuclear atomic interactions in a plasma environment can address many of the questions that, owing to the complexity of the processes, have so far only been studied with rather crude phenomenological models.

- For materials in extremes and planetary physics, NIF offers unprecedented opportunities for the study of matter in new regimes of pressure, temperature, and strain rate. The conditions reachable at the facility—up to 1000-fold compression—will provide answers to fundamental questions about condensed matter and are likely to reveal entirely new phenomena in materials.

- For beam and plasma physics, there are many opportunities for accelerated discovery that require plasma lengths and volumes that can only be generated with NIF. Some of these can only be achieved with NIF’s Advanced Radiographic Capability (ARC). Many areas are open for possible discovery.

Specific Priority Research Directions (PRDs) in each of these areas were identified during the workshop and are discussed in detail in this report. These PRDs are summarized below.

Summary of Workshop Priority Research Directions

Panels	**Priority Research Directions**
1. Laboratory Astrophysics	1.1 Simulating Astrochemistry: The Origins and Evolution of Interstellar Dust and Prebiotic Molecules
	1.2 Explanation for the Ubiquity and Properties of Cosmic Magnetic Fields and the Origin of Cosmic Rays
	1.3 Radiative Hydrodynamics of Stellar Birth and Explosive Stellar Death
	1.4 Atomic Physics of Ionized Plasmas
2. Nuclear Physics	2.1 Stellar and Big Bang Nucleosynthesis in Plasma Environments
	2.2 Formation of the Heavy Elements and Role of Reactions on Excited Nuclear States
	2.3 Atomic Physics of Ionized Plasmas
3. Materials at Extremes and Planetary Physics	3.1 Quantum Matter to Star Matter
	3.2 Elements at Atomic Pressures
	3.3 Kilovolt Chemistry
	3.4 Pathways to Extreme States
	3.5 Exploring Planets at NIF
4. Beams and Plasma Physics	4.1 Formation of and Particle Acceleration in Collisionless Shocks
	4.2 Active Control of the Flow of Radiation and Particles in HEDP
	4.3 Ultraintense Beam Generation and Transport in HED Plasma
	4.4 Complex Plasma States in Extreme Laser Fields

In addition to its focus on PRDs, the workshop also considered specifically the means to realize this potential and impediments to progress. Exploring these issues and identifying solutions was the mandate of the cross-cutting facilities panel. This panel was motivated by three guiding principles: i) maximize the probability of success of NIF science on a decadal timescale, ii) accelerate the growth of a sense of scientific community among NIF users to enhance their collective impact, and iii) profit from best practices and lessons learned from other relevant facilities to optimize the efficiency and effectiveness of NIF as a scientific user facility. As a result of the workshop, suggestions and recommendations in the areas of facility policies and governance, facility operations considerations, and community outreach and education emerged as topics that the panel believes will contribute directly to the successful realization of the science opportunities outlined above and discussed in the body of this report.

In the end, workshop attendees enthusiastically concluded that NIF science represented a broad suite of exciting opportunities and urgent research directions that span laboratory astrophysics, nuclear physics, materials in extremes and planetary physics, and beam and plasma physics. Assuming that appropriate intellectual and financial investments are made, the next decades hold bright promise for rapid progress in scientific discovery through the appropriate utilization and continued development of the NIF and related synergistic capabilities.

Appendix A: Workshop Agenda

Appendix A: Workshop Agenda

Basic Research Directions Workshop on User Science at the National Ignition Facility
Hyatt Crystal City
May 9-12, 2011

Final Agenda

Monday - 5/9/11

6:00 pm	Registration/Arrival Reception – Cinnabar (2nd flr)	All
7:00 pm	Organizers Dinner – Potomac 1	Panel Leads/Chairs only

Tuesday - 5/10/11

7:30 am	Continental Breakfast	All

Plenary Session – Potomac 3/4

8:30 am	Workshop Opening	Kim Budil
8:45 am	NNSA Perspective on NIF Science	Donald Cook, NNSA
9:00 am	Office of Science Mission Drivers	William Brinkman, SC
9:30 am	NIF Science Opportunities	Steven Koonin, DOE
10:15 am	Coffee Break	
10:30 am	NIF Current Capabilities/Future Directions	Chris Keane, LLNL
11:30 am	Panel Introduction and Charge	John Sarrao
11:40 am	Lab-Astro Intro	Paul Drake
11:50 am	Nuclear Physics Intro	Michael Wiescher
12:00 pm	Materials Intro	Raymond Jeanloz
12:10 pm	Beams and Plasma Intro	Warren Mori
12:20 pm	Facilities Intro	Roger Falcone
12:30 pm	Lunch	

Parallel Panel Breakout Sessions

Room Assignments:

Lab Astro – Potomac 1; Nuclear Physics – Potomac 2; Materials – Potomac 5;
Beams and Plasmas-Potomac 6; Cross-Cutting – Potomac 3/4

1:30 pm	Discussion of Candidate Research Directions	Panels
3:30 pm	Coffee Break	
3:45 pm	Refinement /Distillation of Research Directions	Panels
5:30 pm	Panels Adjourn	

6:00 pm	Dinner	
Facility Considerations Town Hall		Plenary Session
7:00 pm	Future Diagnostic Opportunities at NIF	Joe Kilkenny, LLNL
7:20 pm	“A month in the life of NIF”	Warren Hsing, LLNL
7:40 pm	Future Target Considerations at NIF	Alex Hamza, LLNL
8:00 pm	Taking the OMEGA User Experience to the NIF	Rich Petrasso
8:20 pm	Discussion	Roger Falcone
9:00 pm	Adjourn for day	

Wednesday-5/11/11

7:30 am	Continental Breakfast	
8:30 am	Prioritization of Research Directions	Panels
10:15 am	Coffee Break	
10:30 am	Prioritization of Research Directions/Presentation Refinement	Panels
12:00 pm	Lunch and Initial Panel Outbriefs (10 min each)	Plenary Session
	Lab-Astro	Paul Drake
	Nuclear Physics	Rich Petrasso
	Materials	Rus Hemley
	Beams and Plasma	Margaret Murnane
	Facilities	Roger Falcone
1:30 pm	Integration of Research Directions	Panels
3:30 pm	Coffee Break	
3:45 pm	Integration of Research Directions	Panels

Thursday – 5/12/11

7:30 am	Continental Breakfast	
8:30 am	Panel Wrap Up and Writing Assignments	Panels
9:45 am	Coffee Break	
Closing Plenary Session		
10:00 am	Introduction and Goals	John Sarrao
10:10 am	Lab-Astro Summary	Paul Drake
10:30 am	Nuclear Physics Summary	Bill Goldstein
10:50 am	Materials Summary	Rus Hemley
11:10 am	Beams and Plasma Summary	Warren Mori
11:30 am	Facilities Summary	Chi-chang Kao

11:50 am	Reflections/Next Steps-SC	Patricia Dehmer, SC
12:05 pm	Reflections/Next Steps-NNSA	Ralph Schneider, NNSA
12:20 pm	Workshop Closing	John Sarrao
1:30 pm	Writing Session	Panel Leads

Appendix B: Workshop Participants

Appendix B: Workshop Participants

Last Name	First Name	Organization
Afeyan	Bedros	Polymath Research Inc.
Aprahamian	Ani	University of Notre Dame
Bahukutumbi	Radha	Laboratory for Laser Energetics, University of Rochester
Bingham	Robert	STFC Rutherford Appleton Laboratory
Boger	John	US DOE
Budil	Kimberly	LLNL
Buitano	Lois	NNSA/DOE
Cauble	Robert	LLNL
Cizewski	Jolie	Rutgers University
Collier	John	Central Laser Facility, STFC
Collins	Gilbert	Lawrence Livermore National Laboratory
Correa	Alfredo	Lawrence Livermore National Laboratory
Couture	Aaron	Los Alamos National Laboratory
Crandall	David H	DOE, Office of the Under Secretary for Science
Dean	David	DOE, Office of the Under Secretary for Science
Dehmer	Patricia	Office of Science, U.S. Department of Energy
Drake	R Paul	University of Michigan
Duffy	Thomas	Princeton University
Falcone	Roger	Lawrence Berkeley National Lab
Finn	Tom	NNSA
Finnegan	Sean	DOE-Fusion Energy Sciences
Fletcher	Kurtis	SUNY Geneseo
Frauendorf	Stefan	University Notre Dame
Frenje	Johan	MIT
Glenzer	Siegfried	NIF/ ICF & HED
Glownia	James	Office of Science - US DOE
Goldstein	William	LLNL
Goncharov	Alexander	Carnegie Institution of Washington
Gregori	Gianluca	Oxford University
Gupta	Yogendra	Washington State University
Hamza	Alex	LLNL
Harris	Kathryn	NNSA
Hayes	Anna	Los Alamos National Laboratory
Hegelich	B. Manuel	Los Alamos National Laboratory
Hemley	Russell	Carnegie Institution
Herrmann	Hans	Los Alamos National Laboratory

Jeanloz	Raymond	University of California, Berkeley
Joshi	Chandrashekhar	University of California
Kao	Chi-Chang	SLAC
Keane	Christopher	NIF/LLNL
Kerch	Helen	US DOE
Kilkenny	Joe	General Atomics
Kindel	Joseph	Contractor to NNSA
Knudson	Marcus	Sandia National Labs
Koenig	Michel	Ecole Polytechnique
Kreisler	Michael	SAIC Contractor to NNSA
Krushelnick	Karl	University of Michigan
Kung	Harriet	DOE, Office of Science, Basic Energy Sciences
Lacerda	Alex	LANL-LANSCE
Lamb	Don	University of Chicago
Lebedev	Sergey	Imperial College
Ledingham	Ken	University of Strathclyde
Lee	Hae Ja	SLAC
Levedahl	William	NNSA/DOE
Loubeyre	Paul	Commissariat a` l'Energie Atomique (CEA)
Mancini	Roberto	Physics Department, University of Nevada, Reno
McNabb	Dennis	LLNL
Milchberg	Howard	University of Maryland
Montgomery	David	Los Alamos National Laboratory
Mori	Warren	UCLA
Moses	Edward	Lawrence Livermore National Laboratory
Murnane	Margaret	University of Colorado
Natowitz	Joseph	Terxas A&M University
Norreys	Peter	STFC Rutherford Appleton Laboratory
Oberg	Karin	Harvard-Smithsonian Center for Astrophysics
Patel	Pravesh	Lawrence Livermore National Laboratory
Petrasso	Richard	MIT
Plewa	Tomasz	Florida State University
Remington	Bruce	Lawrence Livermore National Laboratory
Sakawa	Youichi	ILE. Osaka Univ.
Salama	Farid	NASA Ames Research Center
Sarrao	John	Los Alamos National Laboratory
Satsangi	Ann	DOE - Office of Science, Fusion Energy Science
Schneider	Ralph	DOE/NNSA
Schroeder	W. Udo	University of Rochester

Silva	Luis	Instituto Superior Técnico
Soures	John	University of Rochester, LLE
Stewart	Sarah	Harvard University
Symons	James	Lawrence Berkeley National Laboratory
Thiyagarajan	Thiyaga	DOE- BES
Takabe	Hideaki	Osaka University
Tochitsky	Sergei	UCLA
Tsung	Frank	University of California
Wark	Justin	University of Oxford
Wiescher	Michael	University of Notre Dame
Wootton	Alan	Vector Resources
Young	Linda	Argonne National Laboratory