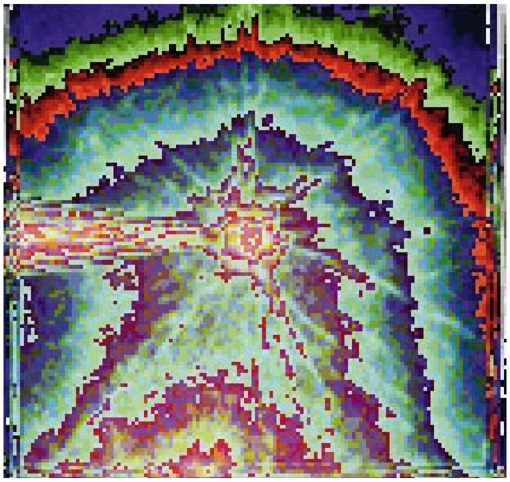
Science on the NIF



The National Ignition Facility will allow scientists to explore a previously inaccessible region of physical phenomena that could validate their current theories and experimental observations and provide a foundation for new knowledge of the physical world.

LAST March, at the behest of the Department of Energy, a group of scientists from around the world convened at the University of California, Berkeley, to discuss potential scientific applications of the National Ignition Facility (NIF). The NIF is a 192-beam, neodymium glass laser that the Department of Energy will use to obtain information on high-energy-density matter, which is important for the generation of energy through inertial confinement fusion. This information will also be used to maintain the skills and information base necessary to manage the nation's nuclear stockpile, and most importantly from a scientific perspective, to pursue basic and applied research.

The objective of the gathering in Berkeley was to identify those areas of research in which the NIF and other high-energy lasers could be used to advance knowledge in the physical sciences and to define a tentative program of high-energy laser experiments. The scientists determined that the NIF as well as other high-energy lasers have effective application in areas relating to astrophysics, hydrodynamics, material properties, plasma physics, and radiation physics. Their determination was based on the wide range of experiments already being performed on high-energy lasers, the diverse interests of the scientific community, and the extraordinary range of physical conditions that would be achievable with the NIF—densities from one millionth the density of air to ten times the density of the solar core and temperatures that would be relevant to anything from a terrestrial lightning bolt (approximately 10^4 K) to the core of a carbon-burning star (10^9 K).

In short, this versatile and powerful research tool would enable scientists in these fields to explore previously inaccessible regions of the physical parameter space that could validate current theories and experimental observations and provide a foundation for new knowledge. Following are the areas where the NIF is expected to make notable contributions to science and applied science.

Astrophysics

To obtain information about stars and other astronomical bodies, the astrophysicist produces a sample plasma in the laboratory and studies its physical properties. For example, to determine a star's structure throughout the various stages of its lifetime—that is, its mass, heat, luminosity, and pulsational instabilities—the astrophysicist may require information on the radiative opacity of a plasma that mimics the outer stellar envelope and/or information on the equations of state (how density and temperature relate to the pressure or internal energy) of a plasma that resemble the dwarf star interior. Furthermore, to get a better idea of a star's structure during various stages of evolution, the astrophysicist may be interested in producing a stellar-like plasma to investigate its nuclear reaction rates. The key to success in all of these experiments is the ability to synthesize the very hot plasmas that characterize the stellar environment during stages of stellar evolution. The astrophysical community is interested in developing this potential with high-energy lasers, especially with the NIF.

Equation of State

Under many circumstances, the equation of state of a stellar interior is simple: most of the gas is hydrogen and other light elements that have lost a good portion of their electrons. Unfortunately, the equation of state of the star's interior is not as simple when the star is in its later stages of evolution. Density is quite high, and the material becomes strongly coupled; that is, the ions interact strongly and no longer behave as free particles. This behavior is often accompanied by electron degeneracy. This leads to the tendency of the electrons to fill up certain energy states in a way that forces some of the electrons to be very energetic, thereby affecting the pressure and internal energy.

The theory of stellar evolution is affected by uncertainties in the equation of state in a few areas. For example, in white dwarfs—the "nuclear ashes," or compressed cores—of stars that have shed their hydrogen-containing outer layers and gone through most of their evolution, the pressure from degenerate electrons supports the material against gravity. Near the surface of the material, however, degenerate electrons lose their dominance. The ions then take over, setting the specific heat and establishing the rate at which the white dwarf will cool, a process that takes many millions of years.

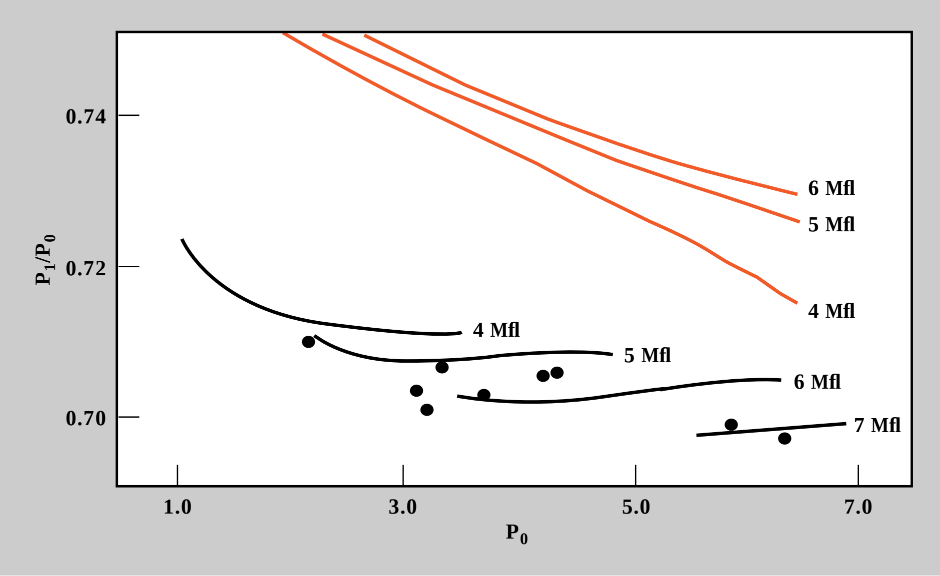


Figure 1. The effects of opacity on pulsations of Cepheid stars. The stellar mass (Mfl) is predicted from the ratio of the first harmonic, P_1, to the fundamental, P_0. The black lines are the results based on the new opacity calculations; the red lines are the results based on the old opacity calculations; the dots are the observed ratios. The new calculations, which predict a much wider range of surface temperature for the hydrogen-burning phase of stellar evolution, put observation and theory in agreement. Experiments on the NIF will allow us to verify these effects and confirm our theoretical predictions.

Radiative Opacity

The radiative opacity of the material in stellar interiors plays a key role in determining how stars evolve: what the maximum mass of a stable star is, how hot and how luminous the star is while it burns its hydrogen fuel, what pulsational instabilities may occur. Previous to recent experiments, astrophysicists were using a set of opacity calculations that predicted a very narrow range of surface temperatures for the hydrogen-burning phase of stellar evolution for all stars—in other words, all stars were very hot at this time despite their differences in mass. These calculations also tied pulsation instability to stellar luminosity and mass, which resulted in the wrong pulsation periods. The solution then was to correct the opacities used in the calculations.

In the last few years, a group of physicists at LLNL has been able to reduce the discrepancy by using a new set of opacity calculations. Although these are definitely closer to observation (Figure 1) than the previous calculations, they still embody many approximations. Thus, to verify opacity at the relevant conditions, astrophysicists will need to conduct direct experiments. A high-energy facility like the NIF will allow them to do this.

Thermonuclear Reaction Rates

Although astrophysicists have been studying nuclear reactions for decades, their experiments have rarely achieved the energies at which such reactions occur in stellar environments. With the NIF, they will be able to conduct experiments that achieve such energies.

Figure 2 shows the temperature and density regimes attainable with the NIF and compares them to the conditions of a star as it progresses through each phase of evolutionary nuclear burning. The first regime, which extends up to about 14 keV, shows the temperatures and densities that may be reached in a laser-heated hohlraum or an imploding capsule without nuclear ignition and includes a star's hydrogen- and helium-burning phases. The second regime, which is between 9 and 60 keV, shows the conditions that might exist in a deuterium–tritium capsule after ignition and includes the temperatures and densities achieved up to a star's carbon-burning phase.

The nuclear cross sections depend on energy (temperature), and we are currently limited by conventional accelerator methods' inability to probe the relevant energy regimes of interest (see Figure 2). The NIF will allow us to measure the nuclear reaction rates at precisely the energies relevant to stellar interiors.

In a thermalized NIF capsule, where a temperature of 8 keV could be attained, the number of radioactive ^{13}N nuclei, which would have a half-life of approximately 10 minutes, could be counted after the event, or scintillators could be positioned around the target to detect their pulse of 2-MeV gamma rays during the event. Because the events would be produced all at once in this type of experiment, the usual low signal-to-noise ratio would be avoided, making it easy to distinguish the reactions from ambient room background noise.

NIF experiments may further our understanding of nuclear reactions that explore the proton–proton chain of hydrogen-burning reactions in solar-type stars and also the carbon-nitrogen-oxygen cycle. As examples, three reactions of interest in astrophysics include the ^{12}C(p,γ)^{13}N reaction, the ^{3}He(^{3}He,2p)^{4}He reaction, and the ^{3}He(^{4}He,γ)^{7}Be reaction. The first plays an important role in every star's carbon-nitrogen-oxygen cycle; the latter two form part of the proton–proton chain of hydrogen-burning reactions in solar-like stars.

Hydrodynamics

Hydrodynamics is the study of fluid motion and the fluid's interaction with its boundaries. The NIF will allow us to further our understanding of the hydrodynamics of inertial confinement fusion and shock wave phenomena in the galaxy.

Because the NIF will be capable of depositing a large quantity of energy in a large amount of material over a long time and at high densities, it will be able to generate hydrodynamic flow conditions that are much more extreme than those generated by wind tunnels, shock tubes, or even

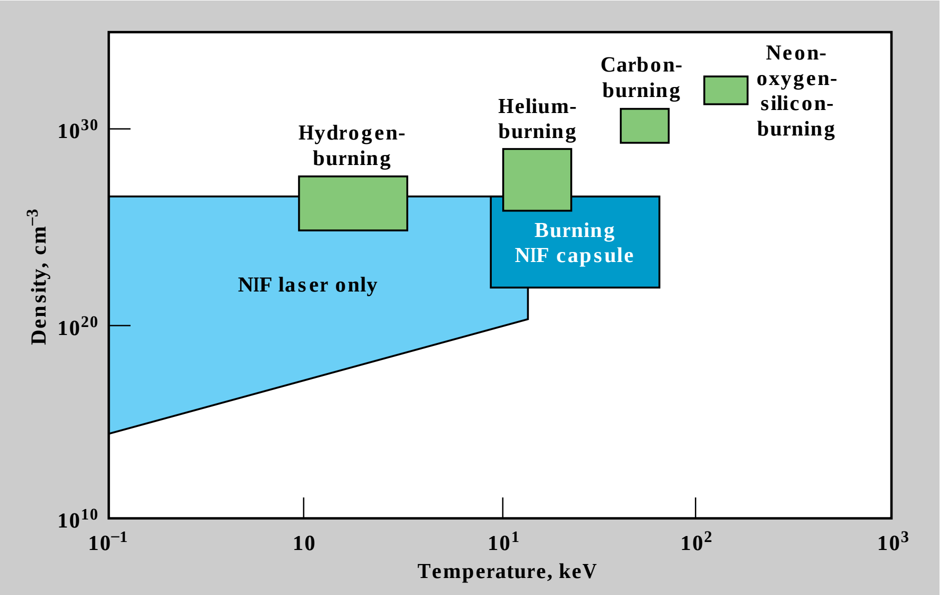


Figure 2. Temperature and density regimes attainable on the NIF overlap with the conditions of a star as it progresses through evolutionary nuclear burning. The first regime, which overlaps with a star's hydrogen- and helium-burning phases, could be reached in a laser-heated hohlraum or an imploding capsule without nuclear ignition. The second regime, which overlaps with the conditions achieved up to a star's carbon-burning phase, might exist in a deuterium–tritium capsule after ignition. Experiments conducted in these regimes could greatly enhance our knowledge of stellar evolution.

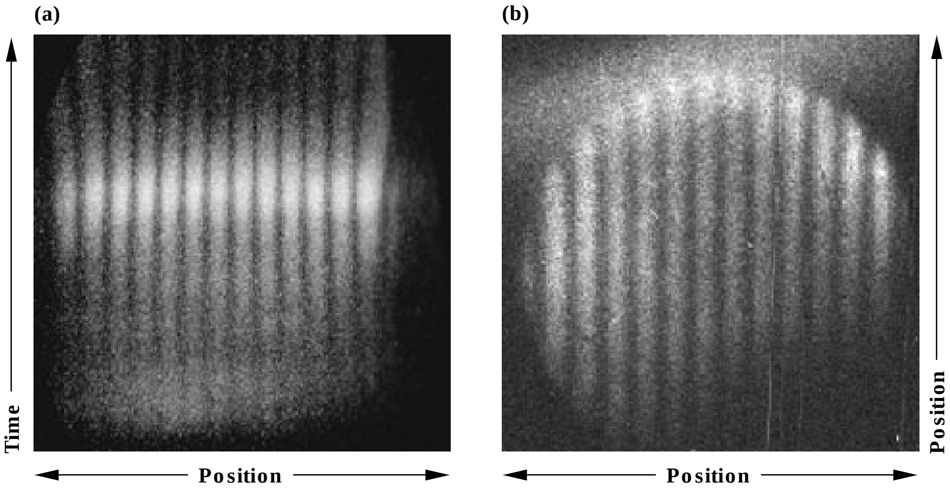
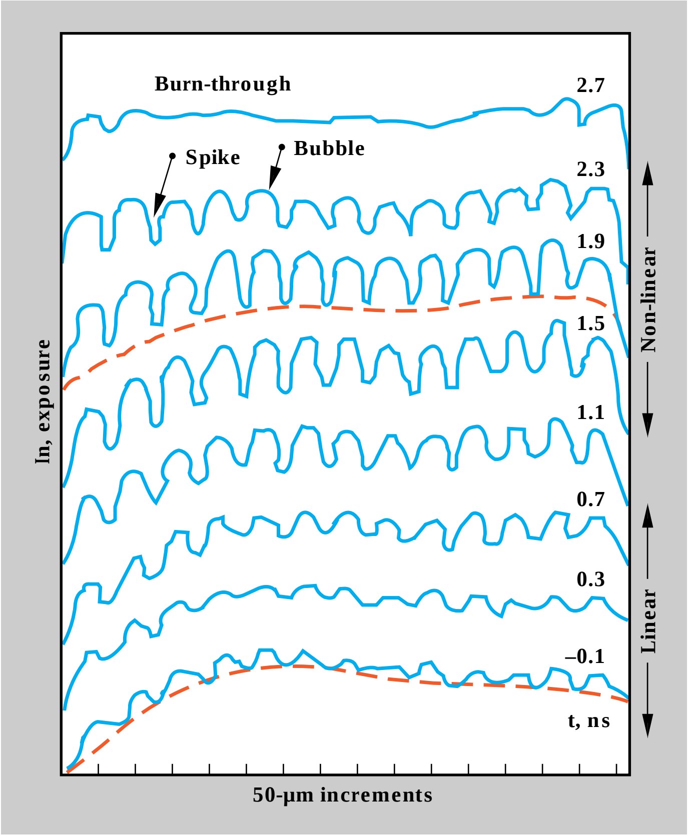


Figure 3. One- and two-dimensional views of the backlight absorbed by a foil with initial perturbation. The one-dimensional view (a) shows that the end of the bright spot occurs when the backlight ceases to radiate effectively. The face-on, two-dimensional view (b) shows little if any distortion of the foil.

Figure 4. Traces for an accelerated foil with an imposed perturbation. The curves are offset vertically to allow simple comparison. The dashed lines indicate the backlight intensity, which varies across the foil as a function of time.



high-energy lasers such as Nova. Thus, scientists will be able to investigate a number of flow problems under previously unattainable conditions. NIF experiments designed to study these problems—for example, the growth of perturbations at a fluid interface (unstable flow) and shock–shock boundary interactions (stable flow)—will lead to new understandings in fluid dynamics.

Imposed Perturbations

To study the growth of an imposed perturbation under continuous acceleration, we shock planar foils of fluorosilicone by x-ray ablation. The foil trajectory is recorded by a radiographic streak camera so that we can check the bulk movement of the sample. The image's contrast in optical depth is then measured as a function of time. From this measurement, we deduce the evolution of the imposed perturbation.

Figure 3 shows two images of a foil from a perturbation experiment conducted on the Nova laser. The image on the left shows that foil has become increasingly bright; this is the result of thinning caused by the "bubble and spike" shape characteristic of the nonlinear regime. The image on the right, taken approximately 2.6 μs after the start of the drive for a duration of 100 ps, shows no transverse distortion of the foil.

We obtain quantitative data by taking intensity traces at different times transverse to the grooved structure, as shown in Figure 4. Note that the curves, which represent different times in the growth of the perturbation, are offset for ease of comparison. At early times, the growth is small and still sinusoidal, indicating that the instability is in the linear regime. Late in time, the growth is larger and distinctly nonsinusoidal, exhibiting the characteristic bubble-and-spike shape. The rapid flattening of the modulations in the top two curves results from the burn-through that occurs when the bubbles break out of the back side of the foil. At this point, the spikes are still being ablated away; however, they can no longer be replenished by matter flowing down from the bubbles.

These experiments extend from the single-mode example described here to multiple-mode experiments and to buried interfaces with imposed mode structures. The limiting case of a random set of perturbations at a buried interface requires a somewhat different technique.

Impact Cratering

Many phenomena in impact cratering occur on temporal and spatial scales that are very large when compared to those of the impacting object; as a result, we can model the impact as a point source of high energy and momentum density. This modeling is usually done by depositing focused laser energy in small spheres of high-*Z* (high-atomic-number) material or by generating prodigious shocks and post-shock pressures with flyer foils.

A study of concentrated impacts on surfaces shows that scaling laws apply to craters formed by impact and surface energy deposition. A proof-of-principle experiment designed to explore the effects of impact cratering on simulated soil (Figure 5) indicates that further research in this area would be of great interest. The ability of the laser to deposit large amounts of energy in a spot volume without residual gases—the by-product of the same experiment performed with high explosive—indicates its utility as a simulation source. On the NIF, the amount of energy deposited and the *in situ* diagnostic potential would make investigation of hydrodynamic response possible in real time.

Material Properties

For the last several decades, scientists have been studying the physical properties of materials—e.g., their equations of state, opacity, and radiative transport—by conducting experiments with gas guns, high explosives, and high-pressure mechanical devices. Although these experiments have provided a wealth of precise data on a wide range of materials, they are limited because they do not provide information on material behavior at the extreme pressures and temperatures of scientific interest, i.e., pressures from 1 to 100 terapascals and temperatures up to a few hundred electron volts. Although a few laser-driven and shock-wave experiments have been carried out in this range of interest, the resulting data are quite imprecise and do not validate any of the theoretical models of material behavior.

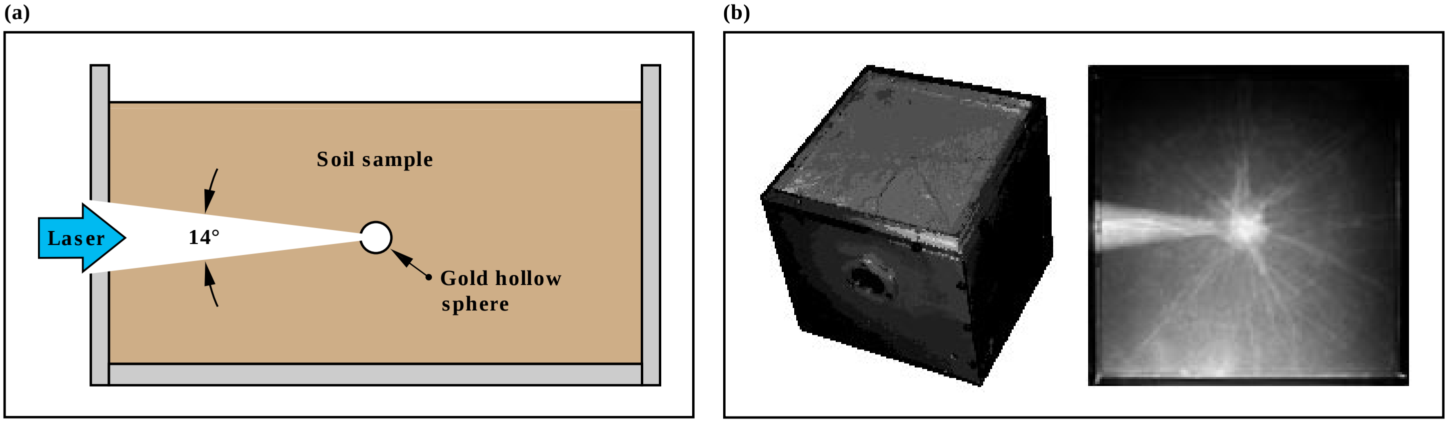


Figure 5. To explore the hydrodynamic response of a simulated soil to impact cratering, we deposited 4 kJ of laser energy into the 1.5-mm radius cavity of a 16 x 16 x 16-cm aluminum-plate cube filled with grout (a). The energy density provided by 4 kJ of laser energy in 1 ns was enough to vaporize a hollow gold target at the bottom of the 6-cm deep cavity and the surrounding grout. Less than 200 J of laser radiation escaped the target, as indicated by the top surface of the cube (b). Although this surface is crazed and slightly bowed, the cavity and the entry cone are clearly visible. There is also a profusion of radial cracks and a faint but definite indication of tangential (spherical) cracks. This diagnostic is an example of what we can learn from scaled experiments.

With the NIF, scientists will be able to investigate material behavior in this range and obtain the primary data needed to test their theoretical models. The experimental methods used to obtain these data include colliding foil experiments (for equation-of-state data) and high-resolution x-ray measurements (for radiative opacity data).

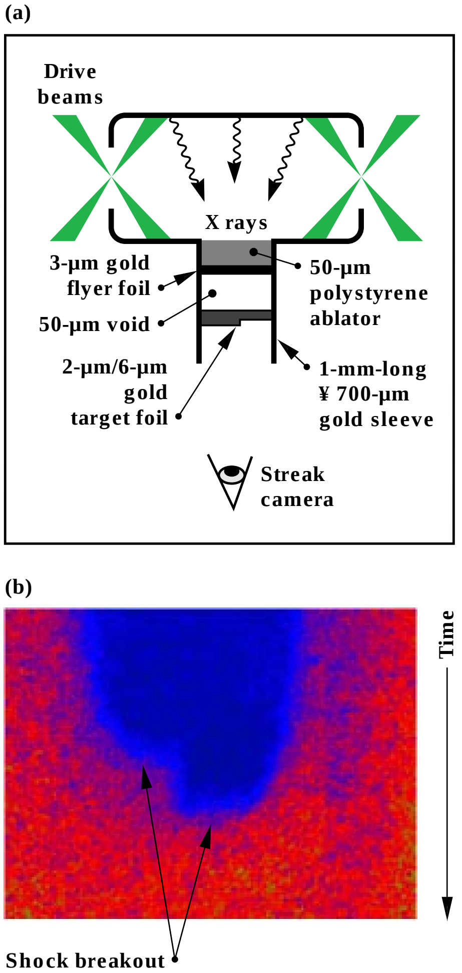


Figure 6. (a) Schematic of a radiation-driven shock experiment. The x rays escape from a hole in the cylindrical gold hohlraum and ablate a 50-µm layer of polystyrene with a 3-µm gold flyer foil. The flyer foil accelerates through a 50-µm void, collides with a two-step gold target foil, and launches a compression wave in the target foil. (b) A typical streak camera image of a shock breakout showing the time interval between the two sides of the step.

Indirectly Driven Colliding Foil Experiments

To reach a regime of very high pressure without sacrificing laser spot size and one-dimensionality, we employ a variation of the well-known flyer-plate technique. In this technique, a flyer—in this case a foil—stores kinetic energy from the driver during an acceleration and rapidly delivers it as thermal energy when it collides with another foil. The flyer foil also acts as a preheat shield so that the target remains on a lower adiabat, that is, for a given pressure the temperature is kept lower than it would be if exposed to the driver.

In this type of experiment (Figure 6), the laser beams are focused into a millimeter-scale cylindrical gold hohlraum; the radiation that escapes from a hole in the hohlraum becomes the x-ray drive. The hohlraum x rays ablate a 50-μm layer of polystyrene with a 3-mm-thick gold flyer foil. This foil then accelerates through a void and, near the end of the laser pulse, collides with a stationary, two-step (two-thickness) gold target foil. The shock on the rear side of the target foil is then imaged with an optical streak camera.

Figure 6b is a typical streak camera image of shock breakout on a two-step target foil. The time interval between the two breakout times (one for each thickness) measures the shock speed in the target. An interval of 57 ps between breakout on the two steps corresponds to an average shock velocity of 70 km/s. According to our equation-of-state tables, this shock speed corresponds to a density of 90 g/cm^3 and a pressure of 0.74 Gbar in the gold target, which is *by far* the highest inferred pressure obtained in a laboratory.

In this experiment, any spatial imbalance in the drive or any unpredicted edge effects (for example, those from interactions between the flyer foil and sleeve containing the target assembly) could cause the flyer foil to tilt or curve and drive a nonplanar shock into the target. However, any nonplanarity would be readily observed because of the relatively large diameter of the foils; furthermore, any edge-induced nonuniformities would be minimized because the step in the target is at the center of the foil. (See pp. 28–29 for a discussion of this experiment relative to weapons physics equation-of-state experiments.)

If the target foil is preheated by high-energy x rays from the hohlraum before the flyer foil hits it, the measurement is compromised. To test this possibility, we altered the x-ray drive in one experiment so that the overall intensity would be identical to that in other experiments but the intensity of high-energy x rays (those ≥2.5 keV) would be reduced by more than a factor of five. The result indicated that the measurement was not affected by preheat.

X-Ray Opacity Measurements

To understand the plasma state and radiative transport, we need to obtain high-quality measurements of the radiative opacity of materials. To do this, we must simultaneously measure the x-ray transmission, temperature, and density of a material sample in a single experiment. These measurements have been done successfully on Nova using point-projection spectroscopy (see Figure 7); we believe that this technique will be even more successful in similar experiments on NIF because we will be able to access larger ranges of material densities and temperatures.

When we use point-projection spectroscopy on Nova, we use eight laser beams to heat the sample. Then, a point source of x rays is produced by tightly focusing one of the remaining laser beams onto a small backlight target of high-*Z* material. X rays from the backlight pass through the sample onto an x-ray diffraction crystal and are then recorded on x-ray film. Other x rays from the same point bypass the sample but are still diffracted from the crystal onto the film record. The ratio of attenuated to unattenuated x rays provides the x-ray transmission spectrum of the sample. Proper collimation allows a highly quantitative analysis of the spectrum. Background from film chemicals, sample emission, and crystal x-ray fluorescence can all be separately determined from the x-ray film record.

The sample itself must be uniform in temperature and density. Uniformity of temperature is achieved by heating the sample in a hohlraum that does not allow laser light to reflect or impinge on it directly; thus, the sample is heated only by x rays. The hohlraum, by providing x-ray drive that volumetrically heats the sample that is tamped, also maintains the relatively high density of the sample and ensures that it is in local thermodynamic equilibrium.

The sample is tamped by plastic so that as it expands, its density remains constant. The thickness of the tamper is determined by calculations, and the density of the sample is determined by imaging. Usually, a second point-projection spectrometer images the expansion of the sample. The first point-projection spectrometer is used to measure the sample's absorption. The relative intensities of the transitions from the different ion species give the ion balance in the sample, which, when coupled to the density measurement, gives the temperature of the sample.

The two point-projection measurements allow density to be measured to an accuracy of ±10% and the temperature to an accuracy of about 5%. With these accuracies it is possible to make a quantitative comparison between the experimental results and the theoretical calculations of the opacity.

In one experiment on Nova, we measured the opacity of niobium in an aluminum–niobium sample. The sample contained 14% aluminum by weight for the temperature measurement. Figure 8 shows the transmission of the aluminum and the transmission of the niobium. The dotted lines overlaying the experimental data are the calculations. In general, there is excellent agreement. This experiment is a milestone. It shows that we can obtain opacity measurements accurate enough to serve as an *in situ* temperature diagnostic for the sample. The accuracy of the sample's temperature, measured to be 48 eV (±2 eV), represents a very important advance in measuring temperatures of high-energy-density matter. (See pp. 27–28 for a discussion of this experiment in relation to weapons physics opacity experiments.)

Plasma Physics

In the broadest sense, plasma physics is the scientific investigation of the predominant state of matter in our universe, plasma. The study of plasma physics has been stimulated over the past four decades by its close

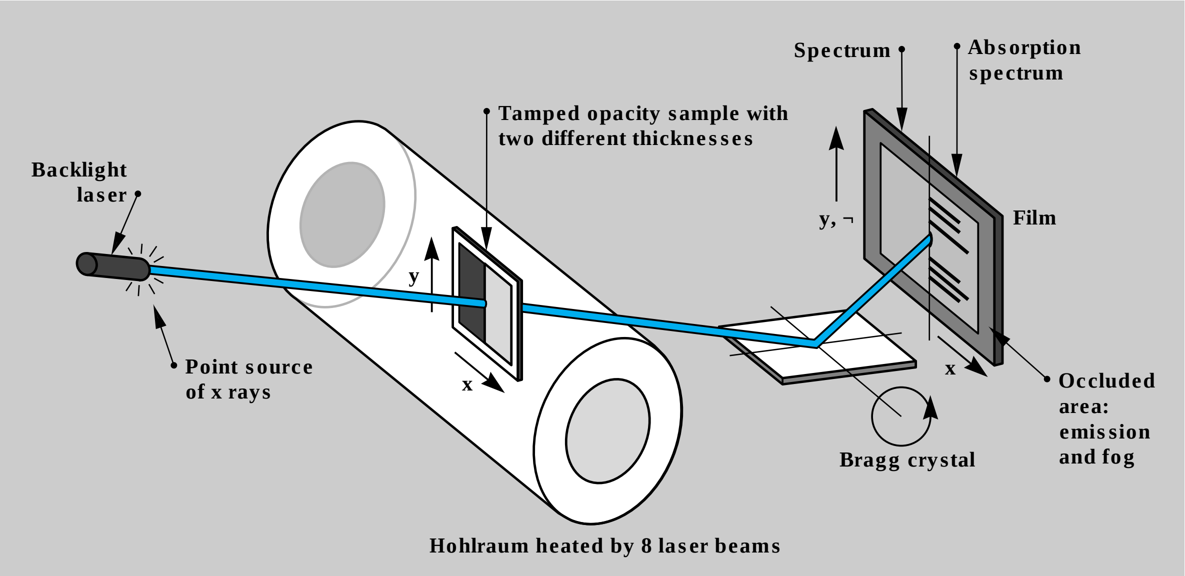


Figure 7. Schematic of point-projection spectroscopy for opacity measurements. The laser-produced backlight x rays pass through the target and are imaged. A Bragg crystal disperses the spectrum so that a spatially and spectrally resolved image is obtained. Temporal resolution is provided by backlight duration.

connection with the goal of creating fusion as an energy source and with the exploration of various astrophysical plasmas.

The advanced experimental capabilities of the NIF will allow us to produce and characterize large, hot, uniform plasmas. With large uniform plasmas, we will be able to measure electron and ion temperature, charge state, electron density, and flow velocity. In short, we will be able to perform a wide range of *quantitative* experiments on a medium that is a very good approximation of a real test bed for plasma physics. Many experiments will be extensions of the fusion energy experiments that have been performed on smaller, less powerful high-energy lasers. Many others, however, will go beyond the requirements of fusion energy to explore a range of basic topics in plasma physics, a few of which are discussed here.

Filamentation

When a small hot spot, or speckle, in the laser-intensity profile undergoes self-focusing, filamentation occurs: that is, electrons (and eventually ions) are expelled from the filament, causing laser light to focus more tightly. This process, in turn, creates an unstable feedback loop; the more tightly focused the laser light is, the higher its intensity and the lower its electron density. Eventually, this instability is saturated by diffraction effects, thermal absorption, or parametric instabilities.

The growth of filamentary structures can be determined by the width and length of speckles in the incident laser beam. Because long speckles are more likely to self-focus than short speckles, filamentation can be described by a growth rate along the length of a speckle, or $8f^2l$, where f is the f-number of the beam (i.e., beam focal length divided by effective maximum beam diameter) and l is the wavelength of the laser light. If the speckle lengths are smaller than the scale length of the plasma, the f-number and the wavelength of the incident beam can be very powerful levers for modifying filamentation. By using large uniform plasmas on the NIF, we will be able to produce sufficiently large filaments to study this process over a wide range of wavelengths and f-numbers. We will also be able to explore this process over a broad range of experimental parameters by varying the color and f-number of the filamentation beam and by varying the plasma conditions (e.g., temperature, density, and average ion charge).

The primary diagnostic for filamentation would be the stimulated Raman scattering signal, which is indicative of the low density in the filaments. That could be coupled with high spatial-resolution imaging, high-resolution optical probing, and a study of the angular distribution of scattered light.

Thomson scattering could be used for these investigations to make highly localized measurements of plasma temperature and density. It could also be used to measure the coherent motion of electrons involved in ion acoustic and electron plasma waves. This measurement would provide a temporally and spatially resolved measure of the coherent fluctuation amplitude in a specific direction, as determined by the detector angle, the scattering volume, and the scattering light source. Measurement of the background fluctuation levels would provide information about the initial level of the coherent fluctuations, their amplification, and their saturation. It also could provide useful information about the coupling between stimulated Raman and Brillouin scattering if it were done at the same location and at the same time as the

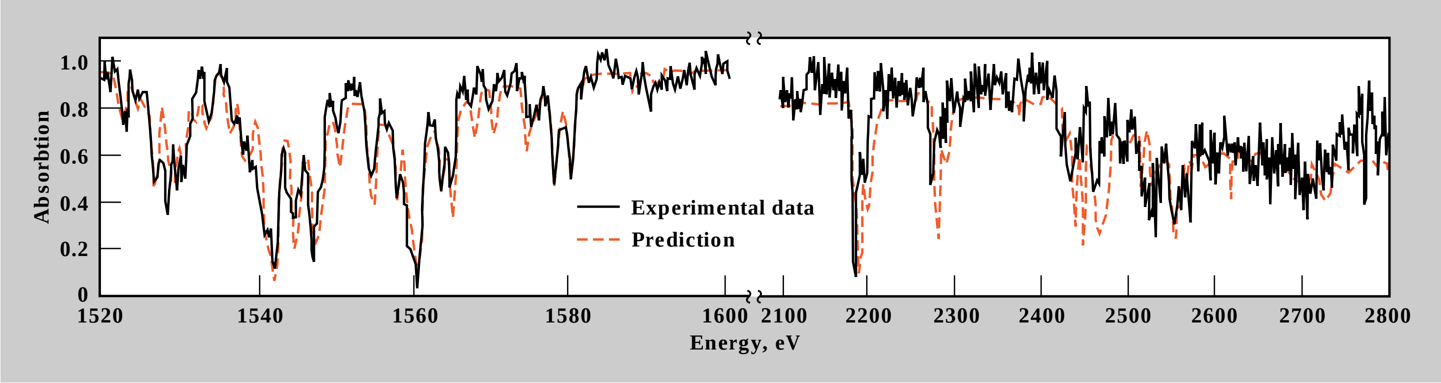


Figure 8. Absorption of an aluminum–niobium sample. The experimental data are in the solid black line and the opacity prediction is the dashed line. The spectrum of the aluminum-potassium alpha lines, which were verified to yield an accurate temperature, were measured on the same experiment as the niobium spectrum.

coherent motion measurements. Developing an x-ray Thomson scattering measurement to study coherent plasma motion in high density plasmas is another exciting possibility.

Formation of Large, Uniform Plasmas

Presently, we can produce relatively high-temperature (3000-eV), millimeter-scale plasmas using the diagnostic complement and experiments shown in Figure 9. These large, uniform plasmas are used to study phenomena as diverse as plasma–laser interactions and nuclear reaction rates. The experimental geometry should be directly scalable to the NIF, with nine-tenths of the laser being used to form the plasma and one-tenth being used to create interactions. The ability to produce these large uniform plasmas on the NIF will allow us to study fundamental aspects of our experiments, such as hohlraum environments and sidescatter, that have been virtually impossible to interpret quantitatively.

Short-Pulse, High-Power Experiments

There is widespread agreement that the NIF should include a beam line for short-pulse, high-power experiments. This capability is especially important for studying such basic topics as relativistic, ultra-high-intensity regimes of laser–matter interaction; high-gradient accelerator schemes; and fast ignition (Figure 10). It is also more amenable to detailed simulation and to systematic exploration of linear and nonlinear behavior of plasmas.

The high-gradient accelerator schemes employ plasmas that support much higher energy fields than those associated with conventional accelerator schemes. As a result, the device will be much more compact

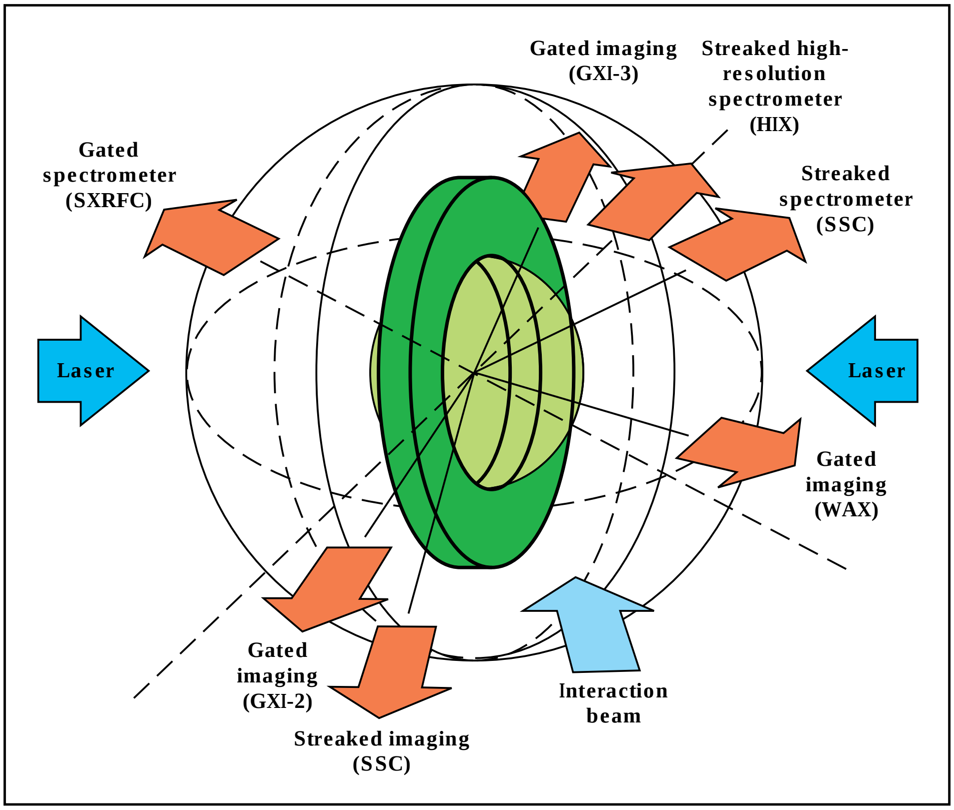


Figure 9. Schematic of the experiments and diagnostic complement (red arrows) used to form a large, hot, uniform plasma. A gas bag (light green) is filled through two tubes in the hoop (dark green). The pressure is stabilized by a pressure transducer that causes the fully ionized species to yield electron densities of approximately 10^{-1} cm^3. The roughly spherical plasma, which has a volume of 0.066 cm^3 and a radius of 2.5 mm, is heated to a temperature of about 3000 eV by heating lasers (blue arrows). A separate interaction beam (light blue arrow) drives the instabilities in a controlled way. This geometry should be directly scalable to the NIF.

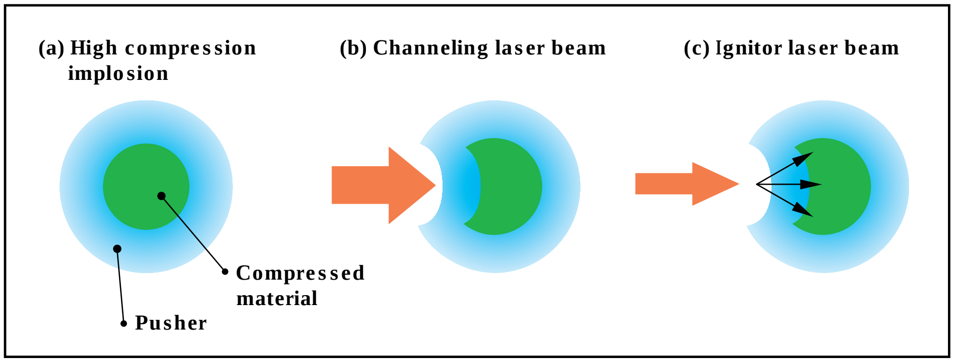


Figure 10. Fast ignition requires high compression, two laser systems, and system diagnoses. (a) In the first step of this process, a gas-filled sphere is imploded. The core of the compressed gas is at densities of 600 g/cm^3. (b) In the next step, a laser with a pulse duration of 100 ps and an intensity of 10^{18} W/cm^2 creates a channel by pushing the critical density surface toward the core. (c) Finally, the heater, or ignitor, beam is turned on. This beam interacts with the density gradient and generates hot electrons at MeV energies. These electrons penetrate into the core of the compressed gas and cause an instantaneous rise in the local temperature of the core.

and potentially cheaper. A number of novel schemes have been proposed and studied at laser powers not quite high enough to produce the desired electron velocity. If these schemes prove successful, applications to tunable sources of x rays are also envisioned.

Radiation Sources

The conversion of laser energy into short wavelength radiation is a major goal of many high-energy laser experiments. On the NIF, we will be able to convert laser energy to a wide variety of x-ray and particle sources needed to address several important questions in basic and applied physics. For example, we will be able to produce intense broadband thermal x rays from high-*Z* targets, coherent amplified x rays (x-ray lasers) from high-gain plasmas, intense neutron pulses from implosion plasmas, and intense pulses of hard x rays from fast electrons. Accurate energy spectra and absolute measurements of the conversion of laser energy into all types of radiation and particle fluxes will play an important role in benchmarking our basic understanding of laser–plasma interactions and atomic physics.

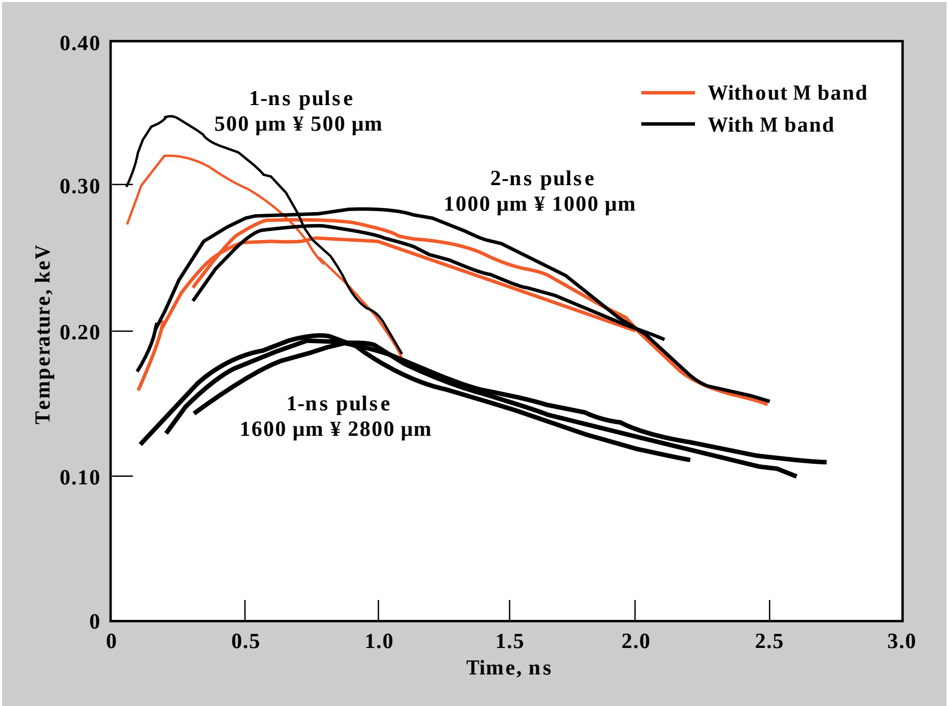


Figure 11. Equivalent radiation temperature vs time for three gold hohlraum experiments performed on Nova. The experiments used a total energy of 18 kJ. Laser entrance holes were in the sides of the 500- and 1000-µm-length hohlraums and through the ends of the 2800-µm-length hohlraum. The curves for each hohlraum show the reproducibility of the data. The black line indicates the equivalent radiation temperature with the M band; the red line indicates the equivalent radiation temperature without the M band. The contribution of the M band to the radiation temperature was greatest in the small hohlraums because of the closure of the holes; it was very small in the large hohlraums because they were large and because their viewing angle did not accommodate a view of the laser-irradiated spots.

Broadband x rays generated by NIF laser plasmas will be used to produce and characterize large, uniform plasmas relevant to inertial confinement fusion and astrophysics. The high temperatures and densities produced during implosion and subsequent ignition will be an excellent source of continuum x rays—those extending from the soft x-ray region to MeV with pulse durations of less than 100 ps.

Besides producing important coherent radiation sources (i.e., x-ray lasers), NIF will offer a critical test of our atomic modeling, allowing us to extrapolate existing neon-like and nickel-like collisional x-ray lasers to wavelengths of about 20 angstroms (Å = 10^{-10} m). At these wavelengths, we can use x-ray laser interferometry (the interference created by splitting and then recombining the x-ray laser beam) to measure electron densities in plasmas exceeding solid densities. Also, the short-pulse capability of the NIF may enable us to develop new x-ray lasers that emit radiation at wavelengths shorter than 10 Å; such bright, coherent sources would be very useful in characterizing solid matter for materials science and biophysics research.

The NIF will be able to generate more than 10^{18} neutrons in a single 100-ps pulse, making it very useful for producing uniform, high-density, low-temperature plasmas. It will be able to generate fast electrons with hundreds of kiloelectron volts in energy—which is a potential source of high-energy x rays for backlighting and probing plasmas.

These radiation sources are supplemented by the possibility of using radiation enclosures, or hohlraums (such as those shown in Figure 11), to generate radiation environments and x-ray drive fluxes. These sources will be able to produce far in excess of the approximately 200 eV produced by hohlraum sources available on current high-energy lasers. These sources will be of higher effective temperature and also will be able to provide uniform x-ray drive over far larger areas than is possible with today's sources. Thus, the advantages of using x-ray heating for the study of hot, dense matter will be greatly enhanced on the NIF.

Radiative Properties

The importance of radiative properties in high-energy-density plasma derives from three factors:

- First, the radiative property can be the best indicator of the level of scientific knowledge in a particular area. For example, when scientists want to develop new descriptions of atomic structure, they look at transition energies.
- Second, radiative properties serve as primary data for numerous other studies. For example, spectral line lists are inadequate for many of the charge states of heavier elements. Thus, scientists measure and categorize the energies of highly ionized species for a variety of uses.
- Third, radiative properties serve as noninterfering probes. For example, by looking at the emission or absorption spectrum of a plasma, scientists can obtain fundamental information about the plasma's ionization balance, rate processes, densities, temperatures, and fluctuation levels. The radiative properties are therefore a powerful diagnostic of the plasma state.

Experiments on high-energy lasers have done much to enhance our knowledge of the radiative properties of hot, dense matter; thus, we expect that experiments on the NIF, such as those employing interferometry and plasma spectroscopy, will advance that knowledge even further.

Interferometry Experiments

For years, optical probing of high-density or large plasmas has been difficult because of the high absorption of the probe, the effects of refraction, and the impossibility of going beyond critical densities. Recently, we did an experiment to see whether an optical measuring device, known as a Mach-Zehnder interferometer, and a standard 3-cm-long yttrium x-ray laser could be used to probe these plasmas more successfully.

In this experiment (shown schematically in Figure 12), the output from a standard 3-cm-long yttrium x-ray laser was collimated by a multilayer mirror and injected into the interferometer. An imaging optic from the interferometer then imaged a plane within the interferometer where a plasma was produced. Figure 13 shows the recorded interferogram of the plasma. The fringes, or contrast modulations, due to the plasma are clearly visible, indicating the feasibility of this technique. However, plasma blow-off, evident in the central region of the image, completely obscures the laser, indicating that the technique still has its limits. On the NIF we will be able to push the x-ray laser interferometer to shorter x-ray laser

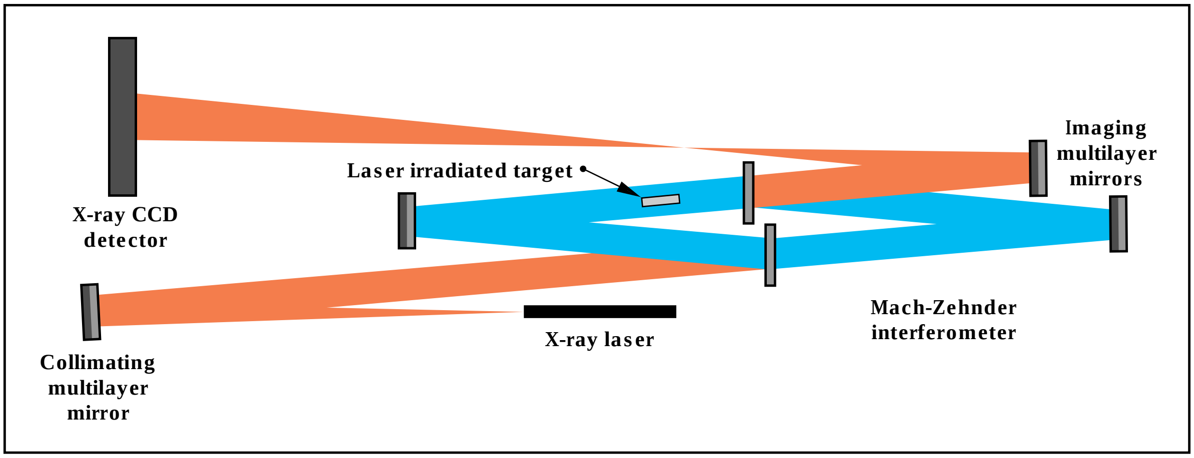


Figure 12. Schematic of the experimental setup for x-ray laser interferometry.

wavelengths, making it an even more important diagnostic tool in the study and characterization of large-scale plasmas.

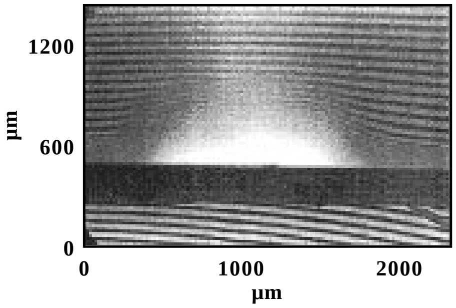
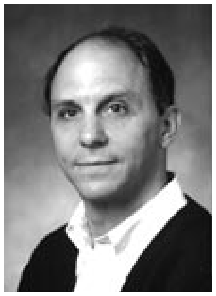


Figure 13. Interferogram of a high-density plasma produced by x-ray laser interferometry. The plasma is made by irradiating the surface of a mylar plastic sample (solid horizontal band) with an x-ray beam. The bright spot above the plastic sample is the self-emission of the plastic.

Summary

The extraordinary range of physical conditions that will be achievable on the NIF will advance knowledge in the physical sciences. It will give us the ability to synthesize and analyze the plasmas that characterize the stellar environment during its evolution. It will enable us to investigate a number of stable and unstable flow problems under conditions that cannot be obtained by conventional means, such as wind tunnels, shock tubes, or other high-energy lasers. It will give us the ability to investigate material behavior at pressures from 1 to 100 terapascals and temperatures up to a few hundred electron volts so that we can validate our theoretical understanding of material behavior at extreme conditions. We will be able to convert NIF laser energy to a wide variety of x-ray and particle sources needed to address important questions in basic and applied physics. Finally, the NIF will enable us to push the x-ray laser interferometer to shorter x-ray laser wavelengths, making it an even more important diagnostic tool in the study and characterization of large-scale plasmas. The NIF will allow us to explore a previously inaccessible region of physical phenomena that could validate our current theories and experimental observations and provide a foundation for new knowledge.

Key Words: astrophysics; high-pressure physics; hydrodynamics; National Ignition Facility—high-energy laser experiments; plasma physics; radiation sources; radiative properties.



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