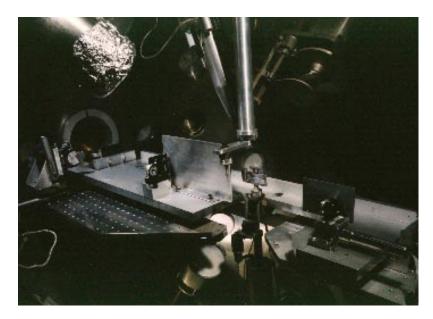# X-Ray Lasers and High-Density Plasma

X-ray lasers are ideal for studying high-density plasmas of the sort produced by the Nova laser. We have demonstrated single-micrometer resolution of plasma images and interferometric techniques for determining plasma density. Current work on developing shorter pulses of x-ray laser light will improve resolution in two dimensions.

OVER the course of only a few decades, lasers have become ubiquitous. In the future, x-ray lasers are likely to become widespread because of their growing range of uses. Among other promising developments, x-ray lasers are being applied in areas ranging from biological imaging to materials science. One of our most recent and sophisticated uses of the x-ray laser is as a probe for imaging and understanding high-density plasmas.

Optical probes have been historically important in studying and characterizing laser-produced plasmas. However, researchers have had to overcome many obstacles in their attempts to analyze large, high-density plasmas of the sort that can be created at LLNL by the Nova laser. The difficulties arise from several problems, including high absorption of the optical probe light, the adverse effects of refraction, and the impossibility of probing beyond critical densities in plasma. (Critical density, which is determined solely by the wavelength of the probe, is the electron density beyond which light of a given wavelength will not penetrate.)

Advances in high-energy, more reliable x-ray lasers together with improvements in mirror technology have made it possible to develop diagnostic techniques that are now suitable for evaluating the plasmas of interest. This article reviews the status of laboratory x-ray lasers and their clear advantages in plasma diagnostics. It describes our three principal techniques: high-resolution imaging of the fine structure in plasma, moiré deflectometry used to measure density gradients in plasma, and interferometry for directly measuring electron density. Our recent work in the area of interferometry is made possible as a result of new beam splitter technology developed at LLNL. Finally, we discuss future applications for this important tool, including the characterization of plasmas that will be created by the proposed National Ignition Facility (NIF).[1]

Photograph shows setup for generating an x-ray laser using one beam of the Nova laser.

About Plasmas

Researchers need detailed knowledge of the distribution of electron density in a laser-produced plasma for a wide range of endeavors. This type of information is essential for research in inertial confinement fusion, for laser–plasma interaction physics, and for interpreting high-temperature, high-density laboratory astrophysics experiments.

In laser-induced fusion, for example, a tiny capsule containing deuterium–tritium fuel (two heavy forms of hydrogen) is struck from all directions by radiant energy called the "drive." In one arrangement known as direct drive, many powerful laser beams are focused so they impinge on the capsule. The rapid, rocketlike expansion of the capsule shell drives the inner portions of the capsule inward, compressing and heating the fuel. At a density of more than 200 g/cm^3 (more than a thousand times the density of solid hydrogen) and a temperature of about 100 million K (kelvin) (comparable to temperatures deep in the sun), a fuel plasma forms, and nuclear fusion reactions occur. In the next several decades, fusion energy could become a clean and limitless alternative to our current reliance on fossil fuels.

On Earth, plasma is a short-lived, highly or completely ionized gas that can be produced using several different types of targets. When high-intensity laser light irradiates a solid target, such as a metal foil, the extent of the plasma is determined by the laser spot size; therefore, plasmas can range from hundreds of micrometers to several millimeters in diameter. The plasma is also relatively long in the direction parallel to the drive laser, so an irradiated foil can span orders of magnitude in density and temperature at a given time.

With each new laser system, we need increasingly sophisticated diagnostic instruments to "see" what is happening: as a function of the laser beam parameters (such as intensity and size), in targets of various types, and in the plasma. The central challenge in diagnosing such experiments is the ability to accommodate the spatial and time scales involved. The phenomena we are interested in occupy spatial scales from a single micrometer (about one-hundredth the diameter of a human hair) to a few millimeters, and time scales from several picoseconds (the time it takes light to move about a millimeter) to several nanoseconds. The plasma density can range from about 10^{20} to 10^{26} cm^{-3},* where solid density is about 10^{23} cm^{-3}. The electron densities we are interested in approach 10^{22} cm^{-3}.

We can obtain electron density information in many different ways. Examples include x-ray spectroscopy, absorption and scattering of incident laser light, and ultraviolet interferometry. However, each of these techniques has limitations, including the range of densities and scale sizes that can be measured. To overcome some of the limitations, we have developed several techniques based on a soft x-ray laser beam. Whereas the details of our techniques differ, they all have one central feature in common: they involve creating one plasma with one beam of Nova as a source of coherent x rays to image or diagnose a second plasma produced when a target is irradiated by another Nova beam.

What Is an X-Ray Laser?

The human eye sees only a small portion of the electromagnetic spectrum, namely, wavelengths extending from about 700 nm for red light to about 400 nm for violet light (a nanometer is one billionth of a meter). At shorter wavelengths beyond violet light is the ultraviolet region that is invisible to the unaided eye and associated with potentially skin-damaging rays of the sun. X rays are a form of penetrating electromagnetic radiation with even shorter wavelengths ranging from about 10^{-6} to 10^2 nm. The soft x rays various researchers are using as a probe lie just beyond the ultraviolet portion of the spectrum and have wavelengths of a few to tens of nanometers.

X rays can be generated by accelerating electrons to high velocities and then stopping them suddenly by collision with a solid body. This technique produces short-wavelength x rays that can be dominated by radiation from atomic inner-shell transitions. Electron bombardment is the technique used for generating medical x rays.

In recent years, researchers have developed many different schemes for producing a laser of x rays. The most successful of the schemes has been collisionally pumped x-ray lasers, which are produced in plasmas containing ions in a highly charged state. Within the ions, electrons move between the ground state and various higher energy levels so that the conditions are achieved for producing x rays. The box on p. 11 explains in more detail the principles behind lasers and collisional pumping schemes for generating a soft-x-ray laser.

In practical terms, collisionally pumped x-ray lasers are highly useful because they can operate over a wide range of pump conditions and with a variety of targets. Moreover, the

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*This is the conventional mathematical expression of electron density in a given volume. In this instance, it records how many electrons are contained in 1 cubic centimeter.

range of wavelengths over which collisionally pumped soft-x-ray lasers operate (about 3.5 to 40 nm) make them good candidates for many different applications.

For our work in plasma diagnosis, we selected the neonlike yttrium x-ray laser. The name itself says a good deal about how the device functions. The atomic number of yttrium is 39, so it normally contains 39 protons and an

equal number of electrons. In a neonlike yttrium laser, yttrium is stripped of 29 of its 39 electrons, leaving 10 electrons, like neon.

In our laser, the x rays are produced by using high-intensity optical laser light to irradiate a cold lasant material, as shown in Figure 1. Whereas the lasant material in various types of lasers can be a solid, liquid, or gas, the material we irradiate is

either a 3-cm-long plastic foil coated with a thin layer of yttrium or a solid slab of yttrium. We irradiate the yttrium with one of the ten beams of the Nova laser. When the intense optical laser light interacts with the lasant material, a very hot (approximately 10^7 K) cylindrical plasma is produced. X-ray laser amplification takes place along this plasma column.

What We Mean by a Collisionally Pumped X-Ray Laser

To produce a laser, the lasing material (lasant) must be put in the proper state; then the individual atoms (or ions) of the lasant must be properly prepared and then stimulated into emitting a photon at the laser wavelength. In each lasing atom, preparation is accomplished by adding energy to the atom so that an electron (usually the outermost electron in the atom) is excited to the upper lasing level, which is generally a metastable, or relatively long-lived, state. This is called pumping.

The excited atom can be induced to make a transition to the lower lasing level if the atom interacts with a photon possessing an energy equal to the energy difference between the two lasing levels. In the process of making the transition, the de-exciting atom emits a photon with this same energy. The emitted photons end up being in phase with each other; i.e., they are coherent. The emitted photon can induce the emission of additional photons (of energy and phase) in other already-pumped atoms. Additionally, each can be pumped again if the atom can be returned to its initial state, so the lower lasing level is usually very short-lived. This exponential increase in the number of photons in a given direction (called gain) gives rise to a large amount of coherent directed energy; this is a laser. In general, the more lasant atoms and the longer the laser, the brighter the resulting laser beam.

Most commercially available lasers use gases or lasing atoms suspended in a solid (such as glass) or a liquid. The pumping mechanism for these lasers is a bright light source (such as a flashlamp) that emits photons of the right wavelength to excite the lasing atoms to the upper lasing level. This is called photopumping. It is not a viable method of making an x-ray laser, however, because a very bright (and unavailable) source of x rays would be required to pump the atoms. Moreover, excitation produced in neutral atoms by x rays involve inner shell electrons (electrons interior of the outermost electron). In this situation, it is difficult to find a state to serve as an upper lasing level because the atom is very unstable.

The trick is to ionize the atoms first, removing many of the outer electrons so that excitation of the ions occurs in the remaining outer shell. These transitions can be at x-ray wavelengths. In our collisionally pumped x-ray laser, the ionization is accomplished by heating the lasant very quickly to high temperatures using one beam of the Nova laser focused to form a line, creating a long (a few centimeters), thin (a hundredth of a centimeter) plasma. This heating puts the lasant in the proper state to be pumped (for yttrium, 29 of the 39 electrons are removed). Pumping the ions is not performed by an outside x-ray source; it is done by the unbound electrons. The energetic electrons collide with the ions, thus creating a collisionally pumped x-ray laser. Lasing can then occur along the line of plasma. Finding the combination of material, ionization state, temperature, electron density, and lasing levels that will produce an x-ray is challenging.

Notice in Figure 1 that the three-dimensional plasma we create is relatively long (3 cm) but not very wide (approximately 120 μm) or high (approximately 500 μm). It is only in the long direction—along the line of the plasma—that x-ray photons interact with enough other excited atoms to produce more photons, resulting in amplification. The result is that our x-ray laser emerges from both ends of the plasma line, but not in other directions. The x-ray laser is coherent because a stimulated photon is similar to (has the same phase as) the photon that stimulates it.

X-ray lasers have several features that make them ideal for studying dense plasmas. First, the short wavelength of such lasers provides decreased refraction and greater penetration, compared to other longer-wavelength optical probes. As shown in Figure 2, the operating wavelength of our neonlike yttrium laser is dominated by a single line, or monochromatic spike, at 15.5 nm. We have produced multilayer mirrors for use in our experiments that are highly reflective at this wavelength.

A second advantage has to do with brightness. In imaging systems, brightness is one of the most important factors, and yttrium x-ray lasers are unequaled in this regard.[2] The high brightness of x-ray lasers makes them particularly well suited for imaging bright sources, such a laser-produced plasmas.

A third advantage arises from the fact that our x-ray probe is, indeed, a laser. This means that we can exploit the coherence properties of the x-ray laser, in particular, as a density diagnostic.

A potential limitation of collisionally pumped x-ray laser systems has to do with their output pulse lengths. When the pulse is relatively long, a few hundred picoseconds, considerable motion can take place in the plasmas we want to investigate. Such motion can cause blurring in an image. We have been developing ways to generate the short pulses (with durations of less than 50 ps) needed for extending diagnostic techniques. Our recent work on decreasing the pulse duration is described toward the end of this article.
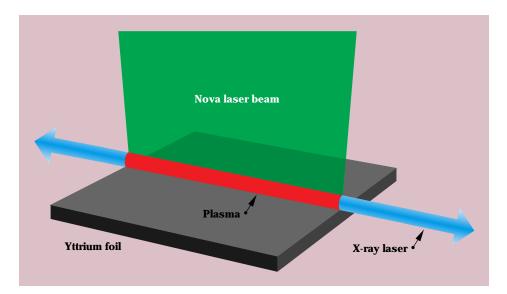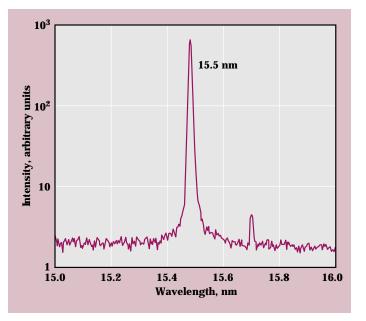

Figure 1. X rays are produced when a beam of high-intensity laser light from Nova bombards a plastic foil coated with a thin layer of yttrium. In our setup, the lasing medium we create is a very hot (approximately 10^7 K), uniform, and cylindrical plasma that is relatively long (3 cm) but only about 120 μm wide and 500 μm high. The lasing photons interact with enough other excited atoms only in the long direction (that is, along the 3-cm plasma line) to produce more photons, resulting in amplification. X-ray laser light emerges from both ends of this plasma line, but not in other directions.

Figure 2. This curve shows that the output of our yttrium x-ray laser is dominated by a single line, or monochromatic spike, at a wavelength of 15.5 nm. Such monochromatic light from a neonlike yttrium laser makes it well suited for studies of laser-produced plasmas.

Direct Imaging of Plasmas

Two fundamental issues in high-resolution imaging are the wavelength of the probe and refraction in the medium being imaged. In general, shorter-wavelength probes allow us to see an object better, with ideal optical systems achieving resolutions comparable to the wavelength of the probe. At present with our imaging system, we are imaging structures as small as 1 μm, but we can do better in the future.

As shown in Figure 3, refraction is a change in the direction of light that occurs when light passes through a density gradient, that is, through material in which the index of refraction changes. Refraction can be a substantial problem in imaging because the amount of refraction, or bending of light, increases directly with the magnitude of the density gradient and the length along the gradient. Conversely, the amount of refraction decreases with increasing critical density, which is solely determined by the wavelength of the light. The rule to remember is that shorter-wavelength light generally penetrates much farther into a plasma and is less affected by gradients.

Currently, we are using the neonlike yttrium x-ray laser to image high-density, large plasmas of interest to the laser-fusion and astrophysics communities. In the past, probing high-density or large plasmas was difficult. With the yttrium laser, a broader range of electron densities and plasma lengths is accessible to us, as shown in Figure 4. By using short-wavelength (15.5-nm) light, we can reduce the adverse effects of refraction and probe plasma densities up to 10^{23} cm^{-3}. Beyond this density, imaging is limited primarily by absorption.

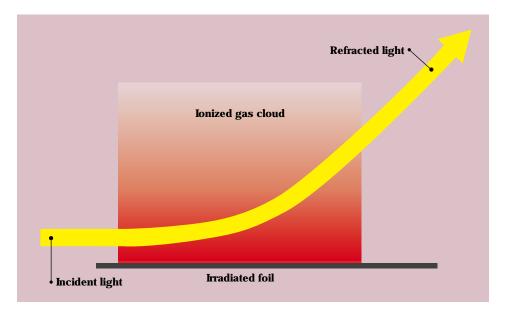Figure 5 shows our setup for high-resolution imaging experiments. To

Figure 3. When light passes through material in which the index of refraction changes, the light changes direction. As shown here, the amount of refraction, or bending of light, increases directly with the magnitude of the density gradient and the length along the gradient. In our work, the density gradient is a "cloud" of highly ionized gas, that is, a plasma produced when we irradiate a target. In general, shorter-wavelength light penetrates much farther into such a plasma and is less refracted by gradients.
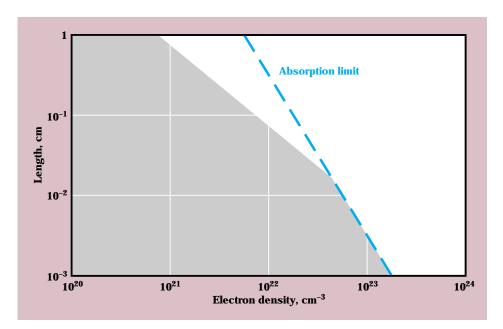

Figure 4. The shaded area shows the broad range of electron densities and plasma lengths that are accessible to us by using the yttrium x-ray laser. With its short-wavelength (15.5-nm) light, we can probe plasma densities up to 10^{23} cm^{-3}. Beyond this density, imaging is primarily limited by absorption. (At lower densities, the number of fringe shifts that can be resolved via interferometric techniques becomes the constraint.)

use an x-ray laser fully as a plasma diagnostic, we must include optical elements, such as mirrors. Notice that the setup in Figure 5 uses a sequence of two multilayer mirrors. The x-ray beam is first collected with a spherical multilayer mirror that collimates the beam so that it does not converge or diverge appreciably. This collimated beam backlights the laser-produced plasma formed when a target, such as a foil, is irradiated by another optical laser beam from Nova (the second beam is shown at the top of Figure 5). An image of the plasma is focused b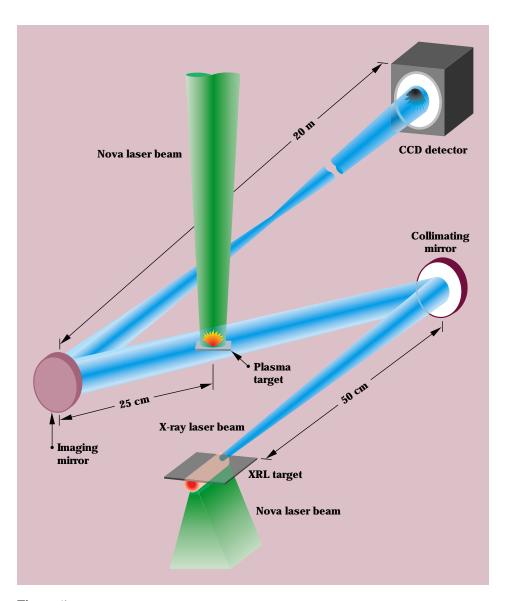y a second spherical multilayer mirror onto a charge-coupled device (CCD) detector that has high sensitivity to x rays and high dynamic range.

One potentially serious problem in our type of imaging system is that multilayer mirrors can be damaged by side-scattered laser light, especially when distances are short (less than 25 cm from mirror to plasma) and the laser light is intense. We have solved the problem by locating highly reflective mirrors 50 cm away from the plasma and by using only a small part of each mirror, shielding the remainder of the mirror. Multilayer mirrors are essentially crystals with layer spacings that are matched to the wavelengths being diagnosed. Our multilayer mirrors consist of 15 layer pairs of molybdenum and silicon, and they have a measured reflectivity at 15.5 nm of about 60% at normal incidence. High reflectivity is essential because the mirrors must be efficient in a complex optical system.

At our highest magnification ($30\times$) the spatial resolution of our imaging system is better than 1 μm. The resolution is limited by the CCD detector and by spherical aberrations caused by the mirrors.

Figure 6 shows an image of a 10-μm-thick polyethylene (CH) foil overcoated with 3 μm of aluminum and irradiated with a 1-ns pulse of intense green light (10^{14} W/cm^2) from the Nova laser. The foil was illuminated on the polyethylene side, where the CH serves as an ablator, similar to the function of a fusion capsule. We backlit this foil with a 150-ps pulse from the yttrium x-ray laser. Figure 6 is what we call a side-on image of the foil and plasma where the top of the picture corresponds with the foil's exploding rear surface. In this view, the Nova laser pulse comes from the bottom of the picture, and the x-ray pulse comes from behind the plane of the object to serve as a backlighter.

Figure 5. Experimental setup for directly imaging plasma. We use two beams of Nova, one to create the x-ray laser and another to produce a plasma. The yttrium x-ray laser beam (formed at the bottom) backlights the target. This beam is first collected and collimated by the multilayer mirror on the right. As the sample target is irradiated by another beam of the Nova laser (center), the backlit plasma image is formed by a second multilayer mirror (left) and is focused onto the backside of a highly sensitive charge-coupled device (CCD) detector (top right).

This image of an "accelerated" foil shows density perturbations on the foil's rear surface. At first, we hypothesized that the fine 5- to 6-μm structures visible in the side-on image might be small plasma filaments, which are sometimes seen in other kinds of experiments. Our imaging system, with its approximately 1-μm spatial resolution (along the x axis in Figure 6) was clearly able to resolve the structures, but an important question remained: exactly what would account for such perturbations? Repeated shots gave similar results. It seemed possible that the structure could arise from nonuniformities of the target mass or from techniques used to smooth the Nova laser beam.

More recently, we have concluded that the foil itself is breaking up as a result of the Nova beam imprinting its near-field beam intensity pattern on the foil. This finding could have important implications for inertial fusion target development for direct-drive experiments. Shots performed with smoother Nova beams show reduced filamentation. We will soon begin to take face-on images of exploding foils (where the foil's front surface is essentially driven toward the detector) to get another perspective on what is happening.

Notice that in Figure 6, the spatial resolution along the flight path of the foil (that is, along the vertical axis) is limited by the duration of the x-ray laser pulse. For a pulse about 200 ps in duration, which is typical in our work, we obtain a longitudinal resolution ranging from a few to 20 μm. Obviously, it would be desirable to improve the resolution along the flight path. This desire is just one of the reasons why developing a shorter-pulse x-ray laser is important.

We have also used our imaging system to study x-ray-heated foils. In this work, we use one Nova beam to illuminate a thin gold foil from which high-energy x rays heat an aluminum target foil placed 1 mm away. The smooth expansion of the aluminum we have observed agrees well with earlier computer simulations.

One drawback of direct plasma imaging is that we need an accurate estimate of opacity to determine the electron densities of plasmas. At the wavelengths of soft-x-ray lasers and with the metal targets we are using, such estimates can be difficult to make. Thus, we have developed two alternative techniques. Moiré deflectometry allows us to measure electron density gradients, and interferometry allows us to measure electron density itself directly.

Moiré Deflectometry

Moiré deflectometry is a relatively recent technique that has been widely used to measure many different physical phenomena. Deflectometry can be applied to characterize optical components, to study the dynamics of fluid flow, and to measure variations in plasma density.

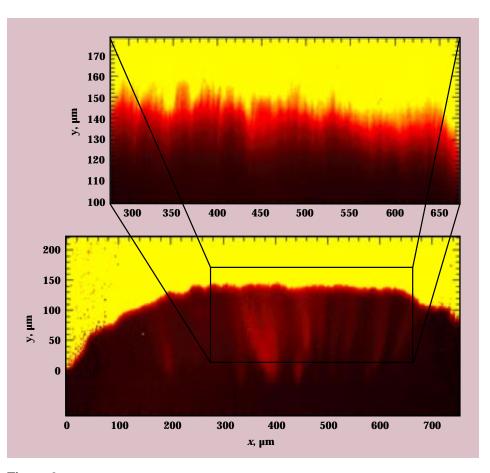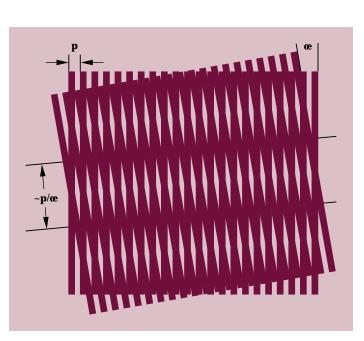Deflectometry measures the refraction of a collimated beam of light passing through a medium or

Figure 6. X-ray laser image of an exploding 10-μm foil overcoated with 3 μm of aluminum and irradiated with a 10^{14}-W/cm^2 beam of the Nova laser. The picture is a side-on view of the central region of the foil plasma, which is being driven upward. The foil was originally located at zero on the vertical scale. The resolution of the image is about 1 μm along the x axis. The plasma structure shows both large- and small-scale electron density perturbations, which may arise from breakup of the foil.

subject of interest. In our case, the collimated probe beam is a set of intense x rays that are nearly parallel. As in our direct-imaging work, we use the yttrium x-ray laser beam to probe millimeter-scale, laser-produced plasmas.[3] Previous work using visible and ultraviolet probe beams has been limited by excessive refraction. Our soft-x-ray laser provides the desired short-wavelength probe beam to avoid the problem.

When a probe beam passes through a pair of evenly spaced stripes (gratings) that are offset and rotated slightly with respect to one another, a moiré pattern is created. The moiré pattern, as shown in Figure 7, is a set of dark regions, or fringes, corresponding to the stripe intersections and lighter regions that are the open areas in between the stripes. In everyday experience, we see moiré patterns if we look through a double-screen door or window. Normally, we don't see all the details of such patterns; instead, we observe a smooth set of fringes or lines. Such is the case in our work.

If we look through a pair of gratings at an angle, the fringes are shifted from the original position they had in a perpendicular view. In moiré deflectometry, we can exploit the fringe shifts, and the connection between the angle of refraction and electron density, to obtain a measure of the electron density gradient along a plasma. To do so, we simply placed a pair of offset gratings just before the CCD detector in the experimental setup (Figure 5). We also added a combination of flat mirrors and a filter to the setup so that the detector would see a narrow range of radiation centered at 15.5 nm. We control the sensitivity of the deflectometer by varying the distance separating the gratings.

First, we created a deflectogram by using the x-ray beam, a CH target, and a pair of gratings without any plasma present. In this control experiment, the second beam of Nova was not used, so no target plasma was created to deflect the fringes. Figure 8a shows the control image, which consists of a uniform moiré pattern except where the beam was blocked by the side of the CH target.

Next, we obtained a deflectogram of a CH plasma. As in the control experiment, we used a 5-mm-square, 50-μm-thick CH foil, but this time, we irradiated the foil with the Nova

Figure 7. A moiré pattern, consisting of a set of dark bands or fringes, is produced when two one-dimensional gratings are overlaid and rotated slightly with respect to one another. By locating a pair of offset gratings like these just before the CCD detector in our experimental setup, we can measure the deflection of the fringes to obtain an electron density gradient along a plasma.
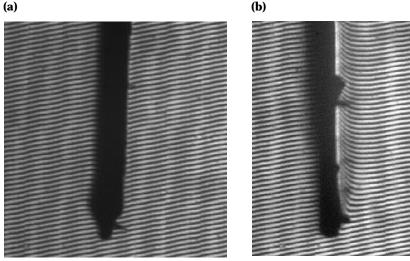

Figure 8. Two deflectograms of a polyethylene (CH) target viewed from the side. (a) A control image with no plasma present shows the expected unperturbed moiré pattern. (b) A deflectogram of a laser-irradiated CH foil target illuminated from the right side. This image shows distinct fringe shifts close to the target surface. We can use the deflections to infer the electron density gradient near the surface. The dark features associated with the target surface are probably caused by ripples in the CH material.

laser. The pulse duration of the x-ray laser was about 200 ps, which is short enough to avoid significant blurring. In this experiment, the x-ray beam passed through the plasma about 1 ns after the start of irradiation. To maximize fringe shifts and demonstrate our ability to probe relatively large plasmas, we used a large, 3-mm-diameter Nova laser spot on the CH target.

Figure 8b is a deflectogram of a CH plasma. In areas that are far from the surface of the foil, which is once again viewed from the side, this image shows the expected unperturbed moiré pattern. Closer to the surface, fringe shifts (or displacements) by as much as about four fringe spacings are visible. Immediately adjacent to the surface, the fringes disappear because contrast is lost to very strong density gradients. (We can reduce this limitation by increasing the magnification and reducing the separation between rulings.) Subsequent analysis of the deflectogram—which assumes we know the boundary density far from the target surface—allows us to infer a density of slightly greater that 4×10^{21} cm^{-3} near the foil surface.

It is noteworthy that this type of deflectometry can be done with probes that are much weaker than our intense yttrium x-ray laser. In fact, the intensity could be reduced by a factor of 25, and the image quality would still be acceptable. By making other modifications, such as reducing the thickness of filters used in our setup, we could optimize the system even further. This ability means that it should be possible to produce a deflectogram with low-energy x-ray laser systems, such as those that use selenium or germanium.

The primary disadvantage of deflectometry is that it gives us a measurement of the plasma density gradient, not the plasma density. The desired density measurement can be made by interferometry.

Interferometry

Our most recent technique is, in some respects, also our most useful tool in terms of its potential applications. Because an observed fringe shift is directly proportional to the electron density in a plasma being probed by interferometry, this tool can provide a direct measurement of density in two dimensions.

The technique of interferometry adds a reference beam to the system. The interference of the reference beam and the probe beam supplies information directly on the index of refraction of the target. Such an approach requires the use of beam splitters that are effective at x-ray laser wavelengths. Recently, LLNL researchers have developed and fabricated such beam splitters with reflectivity in the range of about 25% and transmission of about 20%. The beam splitters are similar to our multilayer mirrors and consist of eight layer pairs of molybdenum and silicon on a 100-nm-thick silicon nitride support. Our current beam splitters have a 1-cm-square aperture, and we are working on 2-cm-square apertures.

Figure 9 shows the experimental setup for soft-x-ray interferometry. In the terminology of optics, the arrangement includes a Mach-Zehnder interferometer. In essence, we add four multilayer mirrors to the setup we used for direct plasma imaging. Two of the mirrors are semitransparent (the beam splitters) and two are completely reflecting. Whereas the probe beam passes through the plasma, the reference beam does not. When the two beams recombine after the probe passes through the plasma, they interfere. The interference shows up as fringes on the detector. By measuring the number of fringe shifts and using the known values of the x-ray wavelength and the plasma path

length, we can calculate the electron density from a simple equation.

In a control experiment, we obtained an interferogram without using the second beam of Nova to produce a target plasma. The results showed excellent fringe contrast and proved the viability of the technique.

Figure 10 is an interferogram we obtained after irradiating a 10-mm-thick coating of CH on a polished silicon substrate. The CH coating, viewed from the side in this image, was irradiated from the top of the picture with the Nova laser. For this experiment, the laser spot size was about 700 μm in diameter, and the intensity of the beam was 2.7×10^{13} W/cm^2. By counting the fringe shifts that are clearly visible above the CH surface in the center of the spot, we find that the maximum electron density is 3×10^{21} cm^{-3}. This value and the overall density profile of the plasma are in good agreement with computer simulations.
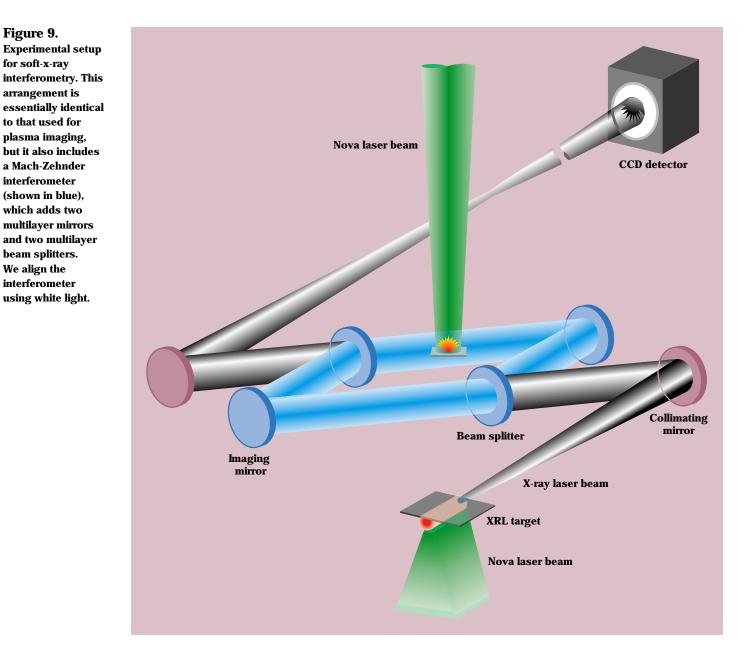
Current Work and Future Applications

Ultimately, the spatial resolution of a plasma image in two dimensions is limited by the duration of the x-ray laser pulse. Therefore, to obtain better images and improved measurements of plasma density, we need to improve the x-ray laser itself.

In work that is in progress to reduce the pulse duration, we have begun to irradiate thin yttrium foils with multiple optical laser pulses. The first Nova pulse, which has less energy than those that follow, heats the thin foil target to produce a plasma. The subsequent pulses ionize the preformed plasma to produce conditions suitable for generating shorter-duration x-ray pulses.

When using multiple pulses in this way, we need to overcome the anticipated problem of limited gain

(or brightness). One way to shorten the x-ray laser pulse and to maintain brightness at the same time is to use a so-called traveling wave. In this approach, the incident Nova wave front is tilted by inserting a grating so that the pulse, in effect, is swept along the 3-cm foil target. The technique matches the optical pump (the Nova pulse) to the propagation of the x-ray pulse along the plasma. Our early efforts have yielded an x-ray laser pulse duration of 45 ps.[4] To our knowledge, this is the shortest collisionally pumped x-ray laser to date. In the future, we expect to achieve pulse durations of less than 20 ps.

In the future, our x-ray laser can be applied as a probe to study the very dense plasmas that will be created at the proposed National Ignition Facility (NIF). The NIF would allow us to extend collisionally pumped neonlike and nickel-like x-ray laser systems to shorter wavelengths and high output energies, which would make the x-ray laser an even more important diagnostic tool. For example, we estimate that we will be able to

Figure 9.
Experimental setup for soft-x-ray interferometry. This arrangement is essentially identical to that used for plasma imaging, but it also includes a Mach-Zehnder interferometer (shown in blue), which adds two multilayer mirrors and two multilayer beam splitters. We align the interferometer using white light.

achieve wavelengths of about 2 nm and peak intensities of 1×10^{17} W/cm^2.

The short-pulse capabilities of NIF will also allow us to investigate a variety of new x-ray laser schemes, including recombination x-ray lasers. In recombination lasers, an atom is first stripped of several electrons, and then some of those electrons recombine with the ion into the upper lasing level. Recombination systems have long been viewed as an alternative to collisionally pumped systems, offering the potential for higher conversion efficiencies. To date, however, such systems have proven inefficient, in part because it is difficult to produce long, uniform plasmas suitable for x-ray propagation. A facility the size of NIF would allow recombination x-ray systems to be tested adequately.

Finally, x-ray lasers are well suited for a variety of other applications ranging from biological imaging to nonlinear optics. In the area of biological imaging, for example, x-ray microscopy offers a way to study wet, thick specimens with a demonstrated resolution that is about five times better than that of conventional optical microscopes. Electron microscopes are limited to thin samples (the limit is about 0.4 μm in thickness), and they cause radiation damage to and decomposition of the specimens being studied. In contrast, x-ray lasers have the potential to produce high-contrast, high-resolution images of whole cells or other structures that are 2 to 10 μm thick before significant damage occurs to the specimen.

Key Words: interferometry; moiré deflectometry; National Ignition Facility (NIF); plasma imaging; x-ray laser—plasma diagnostics.
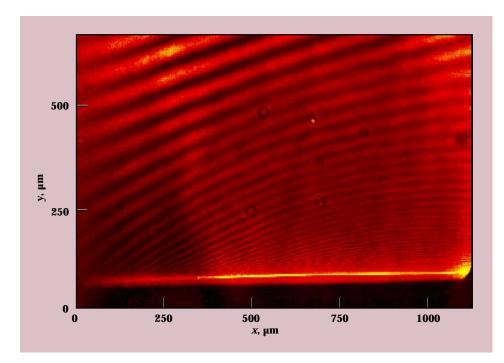

Figure 10. Interferogram of a laser-heated CH foil shown in a horizontal orientation and viewed from the side. The Nova drive laser, which produced the target plasma, is incident from the top of the picture. The fringe shifts are clearly visible just above the foil surface. One fringe shift corresponds to an electron density of 2×10^{20} cm^{-3}. By counting the shifts, we have determined that the maximum electron density near the foil surface is 3×10^{21} cm^{-3}.

Notes and References

1. For further reading on the proposed National Ignition Facility, see the December 1994 issue of *Energy and Technology Review*, UCRL-52000-94-12.
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