The diagnostic instruments and techniques used in LLNL's Inertial Confinement Fusion Program have met the central challenge of laser-driven fusion experiments: they can accommodate small spatial and temporal scales and a large detector dynamic range.

The Inertial Confinement Fusion (ICF) Program at LLNL addresses the critical physics and technology issues involved in demonstrating and exploiting fusion ignition and burn to achieve significant gain for both defense and civil applications. The spectrum of defense applications ranges from the current basic weapons-physics studies to vulnerability and effects studies that will use the neutron, x-ray, and gamma-ray output from a future ICF facility. The ultimate goal of civil applications is the achievement of a process for efficiently converting the energy from thermonuclear reactions into electrical power. Fusion-driven power plants would be an alternative to plants driven by exhaustible, and polluting, fossil fuels. Although we are many years away from developing ICF for commercial production, the essential requirements for achieving ignition and significant fusion yield are well understood.

A tiny (~1-mm radius) spherical capsule containing deuterium-tritium (DT) fuel is simultaneously and uniformly struck from all directions by a radiant energy called the "drive." The source of the drive can vary, depending on the approach. In direct drive, multiple laser beams are directly incident on the capsule. In indirect drive, the beams of lasers or charged particles (ions) generate secondary thermal x rays in a high-Z (atomic number) enclosure (hohlraum). The x rays, in turn, impinge on the capsule. In either case, the drive energy vaporizes, or ablates, the outer region of the capsule shell (the ablator), which expands in a rocketlike blowoff. This rapid expansion of the ablator drives the inner portion of the capsule (the pusher) inward, compressing and heating the DT fuel contained inside. By the end of this...
implosion, the fuel core reaches a density of more than 200 g/cm$^3$ and a temperature of 100 million degrees Celsius. At this density and temperature, nuclear fusion reactions occur, the primary reaction being

$$D + T \rightarrow \alpha + n + \text{energy.}$$

At high density, the alpha particle deposits its energy in the fuel, creating what is called self-heating. No more energy is required to sustain thermonuclear burn for the duration of the implosion. The thermonuclear burn wave spreads rapidly through the compressed fuel, producing an amount of fusion energy that can be many times the drive input energy—a condition called net gain. If numerous capsules were imploded in sequence, each producing substantial net gain, large amounts of energy could be extracted to use for producing electrical power.

The complex requirements for achieving ICF reduce to three basic processes: energy transfer from the drive to kinetic energy of the pusher, compression and heating of the fuel, and thermonuclear burn of the fuel. We currently believe that this can be accomplished by delivering 1 to 2 MJ of laser energy at a 350-nm wavelength in a complex, temporally varying 15-ns pulse.

The Nova laser, our current ICF experimental facility, is the latest in a succession of increasingly powerful lasers constructed and used in our research. With Nova, we have made major progress in experimentally demonstrating the requirements for ignition targets. We have extensively characterized the physics of laser-plasma interactions and how they scale, and we have demonstrated that high-quality, controllable implosions can be achieved. The objective of the Laboratory’s ICF Program is to achieve implosions that drive DT fuel to the temperature and density required to initiate thermonuclear ignition and burn. We hope to build the Nova Upgrade to reach this goal.

### The Diagnostic Challenge

Using an immense laser to drive the implosion of a tiny DT-filled capsule is only part of ICF research. To be able to “see” and understand what happens during driver-beam-target interaction and during the implosion requires highly specialized diagnostics: we need to measure, in as much detail as possible, the conditions that drive the capsule and the conditions before and during the implosion. For example, the spectrum of x rays emitted from the laser-produced plasma in a hohlraum is an indicator of the temperature, which, in turn, is a measure of the amount of energy driving the capsule. X rays are also used for high-resolution spatial imaging of the capsule during implosion, enabling us to look directly at the shape of the hot region of the imploded capsule. The shape and symmetry of the compressed fuel during implosion is critical to capsule performance. For example, if x-ray imaging shows an irregular or nonspherical shape, then the fuel has not been compressed uniformly, and the implosion will fall short of the conditions required for ignition.

Current implosion experiments on the Nova laser are designed to explore regimes of moderate radial convergence (the ratio of the initial fuel radius to the radius at peak compression) at relatively low fuel temperatures. Hence, the x-ray emission is modest, and time-dependent x-ray diagnostics must have high sensitivity. The irony is that, as we become more successful at compressing the pusher and fuel toward the high densities required for ignition, fewer and fewer x rays emitted by the fuel will be able to get out through the increasingly dense pusher. Improved implosion performance therefore requires an accompanying improvement in diagnostic techniques and instruments. Measurements with the highly penetrating neutrons emitted from the hot, compressed DD or DT fuel will become increasingly important as capsule performance improves.

Fortunately, for all practical considerations in ICF, neutrons that are produced by the burning DT fuel will escape regardless of the fuel's density. Accurate quantitative information on high-performance Nova Upgrade capsule experiments will therefore rely heavily on measurements of these burn-signature particles. Neutron diagnostics are currently used to measure implosion yield, implosion time (“bang time”), fuel ion temperature, density, and burn duration. Neutron imaging of the hot fuel region has also been demonstrated, but the spatial resolution is currently not as good as it is with x-ray techniques.

Experiments in the intermediate fuel density regime (20 g/cm$^3$ to perhaps 50 g/cm$^3$) will be useful for developing and cross verifying our neutron techniques with x-ray measurements in preparation for using neutrons as the main diagnostics of high-density ignition regime capsules.

The central challenge in diagnosing ICF experiments is the ability to accommodate the characteristically small spatial and temporal scales of these experiments. Phenomena of interest occupy spatial scales from a single micron to a few millimeters and time scales from several picoseconds to several nanoseconds. The plasma density regimes of interest range from $\sim 10^{20}$ cm$^{-3}$ in the...
Inertial Confinement Fusion Diagnostics

low-density corona (the vaporized outer shell that has expanded outward and decoupled from the capsule), to \( 10^{26} \text{ cm}^{-3} \) in the highly compressed fuel core. We therefore require diagnostic instruments and techniques capable of resolutions on micron and picosecond scales to make measurements that are applicable to the different regions of interest. In ICF, photon energies of interest range from 1 eV—the output of a neodymium:glass laser—up to \( 100 \text{ keV} \) —the energy of some suprathermal (high-energy) x rays that can be produced in laser-plasma interactions.

Neutron diagnostics must be able to measure neutron energies ranging from 2.5 MeV for the primary DD neutrons in D_2-loaded capsules to 17 MeV for the secondary neutrons, and up to 30 MeV for the tertiary neutrons. The bang time (that is, implosion time) and ion temperature diagnostics need subnanosecond time resolution, and the neutron burnwidth detector needs faster time response yet. Perhaps the most daunting requirement for the neutron detectors is the need for a large dynamic range of signal strength that can cover signals from both high-yield capsules (2 to 3 \( \times 10^{13} \) DT neutrons) and lower-yield experiments (\( 10^5 \) to \( 10^6 \) DT neutrons).

Evolution of ICF Diagnostics

In 1961, shortly after the first laser was demonstrated, Laboratory scientists drew on earlier work to describe how a laser could compress and heat small droplets of thermonuclear fuel to conditions that would produce efficient burn and net energy gain. However, early laser designers discovered the difficulties of obtaining high energy in subnanosecond pulses. Beams tended to focus into narrow, extremely intense filaments that could damage optical components and interfere with the focus of the beam at the target. Nevertheless, by the early 1970s, laser development and progress in computer calculations of laser-driven implosions had advanced to the point of requiring a significant experimental program to demonstrate the concept. Since then we have pursued ambitious programs to develop laser drivers, to explore target physics, to design and fabricate targets, and to develop diagnostics.

The diagnostic techniques used in the Laboratory’s ICF Program have evolved with our technological progress in lasers and target design. The history of diagnostics development in ICF can be roughly characterized by four periods.

In the early to middle 1970s, we built the first of our modern series of lasers (Janus in 1974 and Argus in 1976) and needed diagnostics to measure the characteristics of short, subnanosecond laser pulses. The experiments centered on understanding laser performance and the physics of laser-target interaction, and the diagnostics were developed accordingly. During this period, we began to develop and use ultrafast streak cameras.

In the second period, from the late 1970s to the early 1980s, we focused more on the physics of laser-plasma interactions and on acquiring basic measurements of the average fuel conditions in implored capsules. Driving implosions to high densities required maximizing the conversion of laser input energy to the inwardly directed kinetic energy of the pusher. Our first implosions yielded performance far below what was expected. Experiments and theory showed that these results were caused by poor laser-plasma coupling.

In the third period, from the middle to late 1980s, we continued to develop our optical and x-ray diagnostics. Using the Shiva, Novette, and Nova lasers, we applied these diagnostics to research on fundamental laser-plasma interaction physics and to measurements of capsule implosion dynamics, uniformity, and stability; we also applied them to more detailed measurements of compressed fuel conditions at increasing density. We performed extensive laser-target interaction experiments to measure the effect of different beam wavelengths and different beam conditions on the target.

One major outcome of this work was the discovery that the fundamental 1-\text{\mu m} wavelength of neodymium-doped glass (Nd:glass) lasers was a powerful source of stimulated Raman scattering (SRS) in a plasma. A large fraction of the laser energy was not being deposited as thermal energy in the ablator (for conversion to the kinetic energy of the pusher) and was instead being scattered away. In addition, the damping mechanism of SRS led to the production of high-energy electrons, which in turn preheated the fuel. On Shiva, for example, it was found that up to 50% of the incident laser light was converted to hot electrons. Achieving a high density during an implosion requires that the fuel remain relatively cool during compression; any preheating is a source of pressure in the fuel that resists compression. The combination of copious SRS and the accompanying preheat led to very poor implosion performance. We determined that using a shorter wavelength greatly reduces the amount of SRS and preheating. For today’s target experiments, the fundamental 1.05-\text{\mu m} wavelength from the Nd:glass laser is frequency tripled to 0.35 \text{\mu m} by passing the fully amplified laser signal through two KDP (potassium dihydrogen phosphate) crystals.
Today, at the beginning of the fourth period, we are emphasizing the higher-precision laser diagnostics that contemporary experiments demand for accurately measuring the power and energy balance of the Nova laser beams; the pointing and focusing of the beams have also been improved. We are also concentrating on a more precise understanding of the laser's interaction with long-scale-length plasmas, the implosion symmetry and stability, the conditions in the compressed fuel, and a fundamental understanding of hydrodynamic instabilities.

To achieve a high radial convergence of 30 to 40 (which is required for high gain) requires very uniform ablation over the surface of the capsule. In the direct-drive approach, this means using many ultra-uniform laser beams so that each region of the capsule receives overlapping beams for improved uniformity. On Nova, however, we achieve a uniform implosion by using indirect drive, i.e., by converting the laser light to x rays in a hohlraum.

Nova's ten beams typically deliver about 25 to 35 kJ of 0.35-μm laser light into a high-Z hohlraum. The hohlraum is designed so that the x rays produced create a uniform illumination of the capsule. The hohlraum is large, and the density of the plasma that fills it changes little over large distances. Unfortunately, such low-gradient, or long-scale-length, plasmas are an ideal environment for generating parametric instabilities—most notably SRS, stimulated Brillouin scattering (SBS), and filamentation. Thus, to use hohlraums for indirect drive, we will need to study the interaction between lasers and long-scale-length plasmas to measure the strength of the SRS and SBS.

We want to make more detailed measurements of the final fuel conditions achieved in implosions. These measurements will make heavy use of neutron diagnostics and temporally resolved x-ray imaging and spectroscopy. In addition, we are studying the effect of hydrodynamic instabilities (e.g., the Rayleigh-Taylor instability) on implosions and the resulting "mix" of pusher material in the fuel.

**Current Nova Diagnostics**

Nova is a ten-beam Nd:glass laser system designed for conducting ICF research. It has been in use since 1985.³⁴ It can produce up to 120 kJ of 1.05-μm laser light in 2- to 3-ns pulses. The light is frequency converted to the second or third harmonic (either 0.53 μm or 0.35 μm) with KDP crystals located just outside the target chamber. In most experiments, 20 to 30 kJ of 0.35-μm light is directed in 1- to 3-ns pulses onto a target at the center of the 4.6-m-diameter, ten-beam target chamber, as shown in Figure 1.

Figure 1b shows the chamber interior with a few of the "permanent" diagnostics.

Nova can easily produce a wide variety of temporally profiled pulses (that is, shaped pulses). At least 44 distinct pulse shapes are currently available for routine use. We use this...
feature to study the effects of pulse shape on capsule implosions so that we can design the optimum shape for our purposes. Figure 2a shows a continuously shaped pulse, at 0.35 μm, with a contrast (the ratio of peak to foot intensity) of 125:1; Figure 2b shows a series of discrete, rapid-fire pulses called a “comb” shot. Virtually any variation between these two extreme pulse shapes is possible, with the simplest being a 1-ns square pulse.

In keeping with these capabilities, we make regular use on Nova of over 65 diagnostics for detailed observations of implosion physics. Table 1 briefly describes some specific ultrafast camera-based diagnostic systems. Table 2 summarizes the types of measurements that provide data on the implosion and core conditions for ICF capsules. A substantial number of our detectors are among the most sophisticated diagnostic tools currently available. Because of space limitations, we discuss only four: x-ray framing cameras, streaked x-ray spectrometers, a Wölter grazing-incidence x-ray microscope, and a high-resolution neutron spectrometer called the large neutron scintillator array.

X-Ray Framing Cameras
For many years, we have relied heavily on ultrafast optical streak cameras, which produce one-dimensional images for a broad variety of diagnostic systems requiring high temporal resolution (a few picoseconds). A streak camera sacrifices one dimension of spatial imaging but replaces it with continuity in time. We are increasing our use of ultrafast x-ray framing cameras, which became available only recently. These cameras produce a sequence of two-dimensional images at an ultrahigh framing rate (more than $10^{10}$ frames per second and approximately 50 ps of exposure per frame). These devices are highly sensitive (they can detect weak input signals and still maintain high spatial resolution), and they are adaptable to a range of spectral sensitivities. An x-ray framing camera is basically an

![Figure 2. Laser pulses producible on Nova: (a) a temporally shaped, continuous pulse, and (b) a series of discrete, rapid-fire pulses called a “comb” shot.](image)

<table>
<thead>
<tr>
<th>Table 1. Examples of time-resolved ICF diagnostic systems based on ultrafast camera technologies.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X-ray transmission grating spectrometer</strong></td>
</tr>
<tr>
<td><strong>X-ray crystal spectrometer</strong></td>
</tr>
<tr>
<td><strong>High-resolution x-ray imaging</strong></td>
</tr>
<tr>
<td><strong>Optical pyrometer</strong></td>
</tr>
<tr>
<td><strong>Optical spectrometer</strong></td>
</tr>
<tr>
<td><strong>Optical streak camera</strong></td>
</tr>
<tr>
<td><strong>Broadband x-ray spectrometer</strong></td>
</tr>
</tbody>
</table>
x-ray pinhole camera in which the x-ray image is converted to electrons and amplified with a microchannel plate (MCP). Applying a high-voltage pulse to the MCP effectively "gates" or turns it on.

To date, we have used gated x-ray cameras with a spatial resolution of \( \sim 5 \text{ \(\mu\)m} \) (determined by the 5-\(\mu\)m pinhole size) and a time resolution of \( \sim 80 \text{ ps} \) to observe the effects of a shaped pulse on capsule compression. Figure 3 shows the results of two implosion experiments that were identical except for the shape of the laser pulses used as the drive. In (a), the drive was a simple 1-ns square (unshaped) pulse; the image of the x rays emitted by a mid-Z gas that was doped into the \( \text{D}_2 \) fuel shows the compressed core region. (A low-Z gas such as deuterium emits few x rays; thus, to image the shape of the fuel, we dope it with a trace amount of a higher Z material such as argon.) In (b), the shaped pulse produced a considerably smaller compressed core than did the simple pulse. These results confirm the modeling predictions that the shaped pulse will improve capsule performance. Images like those in the figure provide data that are vital for evaluating and normalizing target-design calculations.

A recent variation on the x-ray framing camera just described is the multiframe, continuous serpentine-strip x-ray camera. This camera also employs an electrically gated MCP as the shutter. As Figure 4 shows, the gold electrode on the surface of the MCP serves as the photocathode as well and is arranged in a serpentine strip. A fast, high-voltage pulse is launched and traverses the strip, generating the gain and effectively gating the region of the MCP located directly underneath the position of the pulse on the strip. If an x-ray image from one of the pinholes is
incident on the photocathode strip at the instant the high-voltage pulse passes by, the image is amplified by the MCP and recorded onto film at the back side of the phosphor. Once the 80-ps-wide high-voltage pulse passes beyond a given region of the MCP, that region no longer has gain and is no longer gated (it is "turned off"). Twelve images from the successive pinholes are transmitted and amplified in a rapid series as the voltage pulse traverses the serpentine strip. The camera has demonstrated a spatial resolution of \( \sim 5 \mu \text{m} \) and a frame time of \( \sim 80 \) ps. (The performance numbers of both the serpentine strip and the previously described framing camera are identical because both use the same pinholes, which determine spatial resolution, and both use the same width of high-voltage pulse, which determines time resolution.) Figure 5 shows multiple x-ray images of a direct-drive capsule implosion obtained with the serpentine-strip camera.

These two types of x-ray cameras are complementary to one another in application. The high-voltage pulse of the serpentine-strip camera traverses the entire strip in only \( 700 \) ps, making this sophisticated instrument ideal for short-duration experiments. If the experiment lasts longer—and most of ours do—we cannot yet query the entire experiment in one shot.

For this reason, we use four separate, individually gated strips, each corresponding to one pinhole, on a single MCP. The time delay for each of the four pinhole-strip pairs is set independently to span any duration of experiment. The latest designs are a hybrid of these two types of camera—namely, four individually timed photocathode strips, each of which supports multiple-pinhole images. Also, recent demonstrations of faster high-voltage pulses on thinner microchannel plates have yielded 33-ps exposure times.7

Streaked X-Ray Spectrometers

A very recent application of x-ray streak cameras has been to couple them with spectrometers for time-resolved spectroscopy of the fuel conditions during implosions. We now have a suite of low- and high-resolution crystal spectrometers coupled to variable-speed x-ray streak cameras that mount into retractable manipulators for placement near the Nova target chamber center. As mentioned above, to diagnose implosions, we typically dope the D₂ fuel with a trace amount of a higher-Z material such as argon. A streaked crystal spectrometer allows the K-shell emission of the argon dopant in the fuel to be temporally and spectrally resolved. By comparing the relative population that is derived from the intensity of emission lines of slightly different energy, such as the \( \text{Ar} \text{He-}\beta \) and \( \text{Ly-}\beta \) lines, we can deduce the fuel electron temperature.

Figure 6 shows a recent example of using line ratios to infer a fuel electron temperature, \( T_e \), during an implosion.8 The data and simulations show that as \( T_e \) increases, the higher-energy \( \text{Ly-}\beta \) line starts to dominate the lower-energy \( \text{He-}\beta \) line. At low \( T_e \), just the reverse is observed. We can also compare the width of the spectral lines with theoretical calculations of expected Stark
broadening to infer a density for the fuel. Figure 7 shows such a line-width measurement from an implosion with (a) an unshaped laser pulse (1-ns square) and (b) a shaped laser pulse (3:1 contrast). The broader line profile in Figure 7b can be interpreted as resulting from the higher density produced by the shaped drive; it corroborates the interpretation of the spatial images shown in Figure 3.

Grazing-Incidence X-Ray Microscope

A very powerful technique for diagnosing experiments is to record an x-ray backlit image. Figure 8 shows this technique, and the diagnostic to be described, within the context of a specific experiment. The experiment is designed to measure the growth of perturbations at the ablation front of a foil accelerated by x-ray ablation. The growth of these perturbations results from the Rayleigh-Taylor (RT) instability, and is an important concern in ICF for several reasons (see the box on pp. 16 and 17). Our goal is to design capsules in which the implosion is complete before the growth of instabilities can ruin it. To achieve the proper design, we need to know how rapidly the RT instability grows under different conditions.

To diagnose the perturbations growing on the ablation front of the accelerated foil, we provide a source of backlighting x rays by heating a separate disk target with one or two Nova laser beams. The intensity of backlighting x rays transmitted through the foil is spatially modulated by variations in the optical depth of the foil that result from the perturbations. The difference between the optical depth of the thick and thin regions of the foil will change as the modulations grow because of the fluid instability. Thus, the ratio of the maximum-to-

minimum spatially modulated x-ray intensity changes with time.

The transmitted x rays are imaged by a 22x-magnification Wölfle grazing-incidence x-ray microscope (the "22X") onto the slit of an ultrafast x-ray streak camera, or they are recorded as a two-dimensional image either directly onto x-ray film or with a gated single-frame camera. Figure 9a shows a schematic of the 22X on the Nova

![Figure 6. Spectrally and temporally resolved spectra of the fuel at peak emission (top row) and the corresponding simulations (bottom row) for (a) high, (b) medium, and (c) low 1-ns drive. The average fuel electron temperature \( T_e \) is indicated at the top of each figure.](image)

![Figure 7. High-resolution, spectrally and temporally resolved lines from the fuel at peak emission. The width of the line can be interpreted as a measure of Stark broadening and hence is a measure of fuel density. The laser pulse shapes used in the implosions were (a) 1-ns square and (b) 3:1 contrast-shaped pulse.](image)
ten-beam chamber. Figure 9b shows the Wolter x-ray optic itself, a combination of confocal hyperboloidal and ellipsoidal surfaces of revolution that act as 1-deg grazing incidence surfaces. This diagnostic yields high-brightness, minimal distortion images for 1- to 3-keV x rays with a spatial resolution of 5 to 10 μm, depending on whether the image is recorded onto x-ray film or with a streak camera. Figure 10a shows a streaked image from the experiment shown in Figure 8. The image is spatially resolved in one dimension and streaked (temporally resolved) in the other dimension. The streaked image gets brighter with time (reading from bottom to top as the arrow indicates) because the initial perturbations get bigger and generate thinner regions in the foil, which transmit more of the backlighter x rays. The dark upper boundary indicates extinction of the backlighter source. The right-hand, two-dimensional image was taken by a gated single-frame camera at 2.6 ns with a 100-ps gate. The grazing-incidence microscope is the best-suited

Rayleigh-Taylor Instability and ICF

We are all familiar with the Rayleigh-Taylor instability. Consider, for example, what happens if a layer of water is carefully laid on top of a lower-density liquid, such as alcohol, in a container. The heavier water will find its way through the lighter alcohol to the bottom of the container if the container is disturbed. The mechanism that initiates this fluid interchange is the Rayleigh-Taylor (RT) instability: fingers of the heavier fluid start poking into the lighter fluid, and bubbles of the lighter fluid rise through the heavier fluid until eventually the interchange is complete.

Now consider the process of ablatively accelerating the pusher of a capsule during an implosion, and imagine observing this from the accelerating reference frame of the ablation front. From this vantage point, the heavy pusher fluid appears to be sitting on top of the hot, expanding low-density-ablated (vaporized) fluid. (Here the pusher is called a fluid because shock waves during compression have passed through the solid material, heating it enough to break the chemical bonds that held it rigidly as a solid. Indeed, the compressed pusher fluid has a much higher density than did the original solid material!) During the acceleration phase of the implosion, the RT instability results in bubbles of low-density-ablated fluid that rise through the high-density pusher. In extreme cases, these bubbles can puncture the pusher. Similarly, during the pusher deceleration phase, as the fuel is being compressed to peak density, the inner wall of the pusher is RT unstable, and pusher puncture can occur once again. Also, spikes of pusher material can penetrate into the fuel, causing fuel contamination by mixing.

The process of ablatively driving an implosion is inherently RT unstable. Why is this of such great concern for ICF? From the classical theory of ideal fluids, we find that while the perturbations are very small (compared to their wavelength—see the first figure), the equations governing the growth are in the linear regime, which leads to a substantial simplification. Within this simplification, growth is exponential with time and can be written as

\[
\eta = \eta_0 e^{\sqrt{k g} t} = \eta_0 e^{\sqrt{2\pi g/\lambda} t}
\]

where \(\eta\) is the perturbation amplitude, \(\eta_0\) is the initial amplitude, \(k = 2\pi/\lambda\) is the wave number, and \(\lambda\) is the perturbation wavelength. If we consider only the wavelength that is the most detrimental (\(\lambda_{\text{worst}} = \pi \Delta R\)) in its ability to puncture the thin pusher shell (of

![Diagram](image-url)
diagnostic for this type of experiment because it has the highest magnification, collects a bright signal, and gives high spatial resolution.

**Large Neutron Scintillator Array**

In high-density ICF implosions, the nuclear reaction products, particularly the neutrons from DT or DD reactions, are important diagnostic probes. They are produced at the time of thermonuclear burn and are therefore useful for determining fuel conditions at peak density and temperature. By measuring when the neutron burst occurs relative to the leading edge of the laser pulse (bang time), we get an integral measure of how rapidly the implosion occurred. This is an important design parameter. For example, if the bang time occurs before peak drive (perhaps because the capsule and pulse shape are mismatched), then a considerable amount of drive energy is wasted. The shape of the neutron signal is another important quantity from which we can deduce either burn width (that is, the duration over which thermonuclear reactions occur)

thickness $\Delta R$, and we assume that the pusher acceleration lasts for about half the radius, then Eq. 1 can be rewritten as

$$\eta = \eta_0 e^{(2R/\Delta R)^{1/2}}. \quad (2)$$

This approximate form, based on the classical theory of ideal fluids, is what arouses concern about RT instability among ICF researchers. Simple considerations of efficiency dictate that $R/\Delta R \geq 50$; that is, high-aspect ratio capsules are desired to minimize the energy of the drive. Even very smooth surfaces have a roughness of $\sim 10\text{ nm} = 0.01\text{ \mu m}$. So from Eq. 2 we have $\eta \approx (0.01\text{ \mu m})e^{(2 \times 50)^{1/2}} = 220\text{ \mu m}$, which is on the order of the initial radius before turning on the laser. Clearly, if the classical theory for ideal fluids prevailed, ICF would be impossible. Fortunately, this theoretical oversimplification proves not to be valid.

It has long been known that there are a number of effects in ablatively driven RT growth that lead to growth rates substantially reduced from those expected in the above classical considerations. Clearly, careful experimental work is called for to establish precisely what the RT growth is for ablatively driven accelerations of interest in ICF; hence, the experiment shown in Figure 8.

The results of these experiments with indirectly driven foils lead to the conclusions summarized in the second figure. The jagged curve corresponds to the measured contrast of x-ray transmission through a sample with initial amplitude of 0.15 $\mu m$. The heavy solid curve represents the growth expected on the basis of classical analytic theory. Also shown is the point of transition from linear to nonlinear regime. The observed perturbation growth is only about half of that estimated from classical theory. We attribute this reduction primarily to two factors. First, between the low-density and high-density fluids there is a gradient rather than a perfectly sharp boundary. Second, the process of ablation is effectively “burning off” the perturbation as it is trying to grow. The smooth “theory” curve in the figure shows the results of a full two-dimensional computer simulation, which includes the stabilizing effects just mentioned as well as compression and radiation transport.

These results are fundamentally important because they show that, under conditions relevant to ICF, fluid instability growth is reduced from the large classical values to acceptable levels. The computer models incorporating the mechanisms responsible for this reduced growth can accurately match the experimental observations and hence can reliably predict the effects of the RT instability on implosions.
Inertial Confinement Fusion Diagnostics

Figure 8. Schematic of the arrangement for an indirectly driven, planar-fluid instability experiment on Nova.

![Diagram of indirectly driven, planar-fluid instability experiment on Nova](image)

Figure 9. (a) Schematic of the Wölfert x-ray grazing-incidence microscope setup in the Nova facility. The object (laser target) is at far left; several alignment and diagnostic devices are at the far right. (b) Cutout closeup of the Wölfert optic. The x rays to be imaged first reflect (at a 1-deg angle of incidence) off the hyperboloidal surface and form a virtual image at the focal point of the ellipsoidal surface. A second 1-deg reflection off the ellipsoidal surface then forms a real image at the film plane. With an object and image distance of $d_o = 30$ cm and $d_i = 660$ cm, the magnification is $M = d_i/d_o = 22$.

or fuel ion temperature, depending on the detector location.5

Perhaps the most exciting new development in neutron diagnostics makes use of two- and three-step processes (the so-called higher-order processes) leading to secondary and tertiary neutrons to deduce fuel density.11 In a D2-filled capsule, two primary DD nuclear reactions can occur with equal probability, namely,

$$D + D \rightarrow ^3\text{He} + n,$$

and

$$D + D \rightarrow T + p.$$  

The first DD nuclear reaction yields the primary 2.45-MeV DD neutron; the second yields a 2.45-MeV proton plus a 1-MeV triton. If the D2 fuel has been compressed to sufficient density, there is a possibility that the 1-MeV triton will fuse with a deuteron before escaping the fuel region and cause the reaction $D + T \rightarrow \alpha + n'$, where the secondary neutron ($n'$) from this two-step process has an energy of 12 to 17 MeV. This secondary neutron is moving substantially faster than the primary neutron. By measuring the neutron time-of-flight (TOF) with a standard TOF detector, we can determine the ratio of the secondary-to-primary neutron signal strength. From this ratio, we can deduce the fuel areal density. The situation becomes much more complex, however, if the fuel is dense enough to slow the triton significantly before it finds a deuteron with which to fuse. To deduce fuel density in such a situation, we must measure the actual shape of the secondary neutron energy spectrum. To supply the much higher resolution required, the large neutron scintillator array (LaNSA) was built and installed in a pit directly under the Nova target chamber (see Figure 11).
LaNSA consists of 960 scintillator-photomultiplier tube detectors and associated electronics (see Figure 12). Each detector can record the arrival time, relative to the laser pulse, of single or multiple neutrons. A neutron energy spectrum is obtained by summing the data from all the detectors. The data in Figure 13 show the resolution and sensitivity of LaNSA. The primary DD neutrons saturate the detector, but the yield and the spectrum of the

Figure 10. Wolter x-ray microscope data obtained from the experiment depicted in Figure 8. (a) The change in x-ray transmission with time resulting from the growth of the perturbations on an accelerated rippled foil. (b) A two-dimensional x-ray "snapshot" at 2.6 ns after the start of the drive.

Figure 11. Schematic of the ten-beam target chamber area of the Nova laser facility showing the location of the large neutron scintillator array (LaNSA) in a pit directly under the target chamber.

Figure 12. A module of the large neutron scintillator array (LaNSA) with 16 scintillator-photomultiplier tube detectors. There are 60 such modules in the array. A sealed vessel filled with a scintillator fluid sits atop each detector. Neutrons from the implosion enter the vessel and generate light (scintillation) that the photomultiplier tubes measure.
secondary DT neutrons are easily resolved in their earlier time of arrival. As just mentioned, the secondary neutron energy spectrum is important because it gives information about the degree of triton slowing, which, in turn, is related to the fuel density. Figure 14 compares the spectrum from two different targets; triton slowing in the fuel is small in one and large in the other. The effect on the secondary neutron spectrum is clear, and the data can be used to extend the range of validity of the secondary neutron technique as a fuel-density diagnostic and also perhaps as a mix diagnostic.

In future experiments, when we start doing high-density implosions with DT-filled capsules, we will be using third-order (three-step) processes as a density diagnostic, namely:

\[ D + T \rightarrow \alpha + n, \]
\[ n + D \rightarrow n' + D' \text{ or } n + T \rightarrow n' + T', \]
\[ D' + T \rightarrow \alpha' + n'' \text{ or } D + T' \rightarrow \alpha' + n''. \]

In this three-step process, the energy of the tertiary neutron \((n'')\) can extend all the way to 30 MeV, though with very low probability.

**Summary**

We have made steady and substantial progress in the development and application of diagnostic instruments and techniques for the Laboratory’s ICF Program. Many types of measurements not considered possible just a few years ago are today routinely accomplished on Nova and at other facilities around the world. Thanks to the rapid pace of development and innovation in ICF diagnostics, the measurements have reached a very high level of sophistication. Although the contribution of the Nova laser will remain indispensable, there is a major objective for ICF concept that cannot be addressed with Nova or any existing laser: triggering ignition in the fuel of an implosion capsule and demonstrating the principle of propagating burn to produce gain. The proposed Nova Upgrade will deliver 1 to 2 MJ of energy on target, and detailed computer simulations indicate that this energy is well over the threshold for capsule ignition. Investigations with the Nova laser will continue at their current intense pace. The Nova Upgrade will allow us to turn our attention to ignition physics with the same level of precision and sophistication that we have demonstrated on Nova.

**Key Words:** inertial confinement fusion (ICF); large neutron scintillator array (LaNSA); lasers—Argus, Janus, Nova, Nova Upgrade, Novette, Shiva; neutron diagnostics—streak cameras—single frame, multiframe; x-ray diagnostics—framing cameras, streaked x-ray spectrometers, Wolter grazing-incidence x-ray microscope.
Notes and References

For further information contact
Lamar W. Coleman (510) 423-0705 or
Bruce A. Remington (510) 423-2712.