PROGRESS TOWARD IGNITION AND BURN PROPAGATION IN INERTIAL CONFINEMENT FUSION

To achieve efficient inertial confinement fusion one must produce a small hot spot within the imploding target from which thermonuclear burn can ignite.

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For the past four decades, scientists throughout the world have pursued the dream of controlled thermonuclear fusion. The attraction of this goal is the enormous energy that is potentially available in fusion fuels and the view of fusion as a safe, clean energy source. The fusion reaction with the highest cross section uses the deuterium and tritium isotopes of hydrogen, and D–T would be the fuel of choice for the first generation of fusion reactors. (See the article by J. Geoffrey Cordey, Robert J. Goldston and Ronald R. Parker, January, page 22.)

Development of an economically viable fusion reactor would literally give us the energy equivalent of oceans of oil. Because seawater contains about 40 g of deuterium and 0.1 g of lithium per tonne, every barrel of seawater contains the energy equivalent of almost 30 barrels of oil in deuterium fuel and about one-fifth of a barrel of oil in D–T fuel (where tritium is obtained from neutron reactions on lithium). A volume of seawater equal to the top meter of the Earth's oceans would yield enough fuel to supply D–T fusion reactors for thousands of years of electricity production at today's rate of usage.

The two primary approaches to developing fusion are magnetic confinement fusion, reviewed in the January issue of PHYSICS TODAY, and inertial confinement fusion,[1] reviewed in this article and the article by William J. Hogan, Roger Bangerter and Gerald L. Kulcinski on page 42. Significant elements of the work presented here were carried out under classified Department of Energy programs and have been only recently declassified. In its review of ICF[2] carried out in 1990, the National Academy of Sciences found the DOE classification guidelines for ICF to be excessive and recommended that DOE review them and schedule further declassification of target physics. DOE is continuing to review its classification policy.

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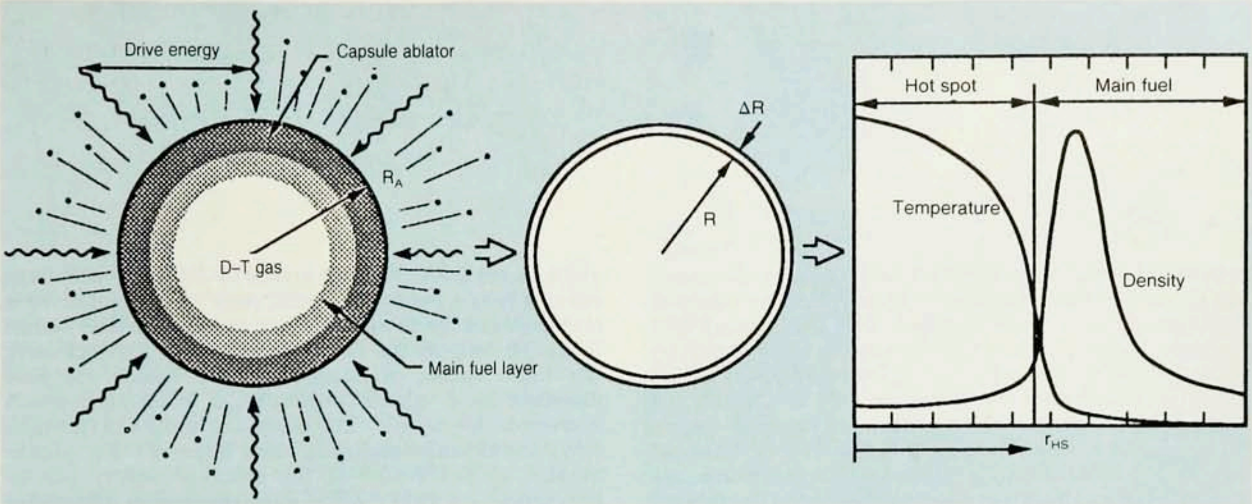
For D–T fuel, both the magnetic and inertial approaches require a fuel temperature in excess of 100 million K and a fuel particle density n and confinement time τ such that $n\tau = 10^{14}$–10^{15} sec/cm^3. Magnetic confinement fusion operates in a regime with $\tau \simeq 1$ sec and $n \simeq 10^{14}$ cm^{-3}. For magnetic confinement fusion, the density is limited by the maximum magnetic field that can be generated, which is determined by the strength of the material of the confinement vessels. Inertial confinement fusion relies on the inertia of an imploding target to provide confinement.[1] Confinement times are less than 10^{-10} sec, and particle densities in the fuel are typically greater than 10^{25} cm^{-3}.

Implosion and burn of ICF targets

High-gain ICF targets have features similar to those shown in figure 1. These capsules consist of a spherical shell filled with low-density ($\lesssim 1.0$ mg/cm^3) equimolar deuterium–tritium gas. The shell is composed of an ablator and an inner region of D–T, which forms the main fuel. Energy from a driver is rapidly delivered to the ablator, which heats up and expands. As the ablator expands outward, the rest of the shell is forced inward to conserve momentum. The capsule behaves as a spherical, ablation-driven rocket.

The fusion fuel is imploded with a typical efficiency of 5–15%. That is, 5–15% of the total absorbed energy goes into the fuel. In its final configuration, the fuel is nearly isobaric at pressures up to about 200 gigabars but consists of two effectively distinct regions: a central hot spot, containing about 2–5% of the fuel, and a dense main fuel region (the "cold fuel pusher"). Fusion begins in the central hot spot, and a thermonuclear burn front propagates rapidly outward into the main fuel, producing high gain.

The efficient arrangement of the fuel in this configu-



Proposed ICF capsules are imploded by ablation of an outer shell. Ignition occurs in a central hot spot, and fusion burn propagates out through the main mass of D–T fuel. **Figure 1**

ration places stringent requirements on the details of the driver coupling, including the time history of the irradiance and the hydrodynamics of the implosion.[3] Several features of the implosion process are important. One is the in-flight aspect ratio $R/\Delta R$, where R is the shell radius and ΔR its thickness, both taken during the implosion. The shell thickness ΔR is less than the initial thickness because the shell is compressed as it implodes. Hydrodynamic instabilities[4] similar to the classical Rayleigh–Taylor fluid instability impose limits on $R/\Delta R$, which result in a minimum required pressure or absorbed driver irradiance. For in-flight aspect ratios of 25–35, the peak values of pressure and irradiance during a pulse must reach about 100 megabars and 10^{15} W/cm^2, respectively. The required pressure depends on the required implosion velocity, which is determined by the capsule size. Minimum velocities are in the range of $3\text{–}4\times10^7$ cm/sec.

Another important parameter is the convergence ratio, defined as the initial outer radius of the ablator R_A divided by the final compressed radius of the hot spot r_{HS}. Typical values are 30–40. To maintain a near-spherical implosion, implosion velocities must be uniform to about 1%. Control of the implosion symmetry and minimization of mixing of the fuel by Rayleigh–Taylor-induced instabilities are crucial to the successful formation of the central hot spot. Mixing and departures from spherical symmetry can prevent the conditions required for ignition during the final stages of the capsule implosion.

The fusion yield E_F from an ICF capsule is given by $E_F = \epsilon_f \phi M$, where ϵ_f is the specific energy of fusion (energy per unit mass), ϕ is the burn efficiency, and M is the imploded fuel mass. For D–T fusion at a burn temperature between 20 and 40 keV, the burn efficiency is approximately

$$\phi = \frac{\rho r}{\rho r + 6\ \text{g/cm}^2} \tag{1}$$

where ρ and r are the compressed fuel density and radius, respectively. Because the inertial confinement time is proportional to r, the fuel areal density ρr is equivalent to the density–confinement time product $n\tau$ that is used to describe progress in magnetic confinement fusion. We can use the burn efficiency given by equation 1 to compare the requirements of magnetic confinement fusion with those of ICF.

Ignition occurs when the energy deposited by products of the thermonuclear burn during one confinement time equals the energy required to heat the plasma to thermonuclear burn temperatures. The specific energy (in J/g) required to heat a D–T plasma with equal electron and ion temperatures T (in keV) is

$$E_{\text{heat}} = 0.1152\times10^9 T = 2.3\times10^9\ \text{J/g at 20 keV} \tag{2}$$

In general only the charged-particle reaction products are available to heat the fuel because most of the neutrons escape the plasma. For D–T fusion

$$\text{D} + \text{T} \rightarrow \text{n(14.06 MeV)} + \alpha\text{(3.52 MeV)} \tag{3}$$

and $\epsilon_f = 3.54\times10^{11}$ J/g. If we assume that all of the alphas are deposited, then the energy per gram deposited in the fuel is

$$E_\alpha = \frac{\epsilon_f}{5}\phi = \frac{6.68\times10^{10}\rho r}{\rho r + 6\ \text{g/cm}^2}\ \text{J/g} \tag{4}$$

Equating E_{heat} and E_α from equations 2 and 4 shows that at 20 keV, ignition occurs for $\rho r > 0.21$ g/cm^2 ($n\tau > 1.7\times10^{14}$ sec/cm^3), corresponding to a burn efficiency of about 3.4%. Ignition is an adequate achievement for a magnetic fusion plasma if the energy required to maintain confinement is much less than the energy needed to heat the plasma. However, ignition alone is insufficient for ICF power production, which must overcome a factor of 10–20 due to implosion efficiency and a factor of 3–20 due to driver efficiency.

One of these factors of 10 can be recovered by increasing the burn efficiency. Compression of the D–T fuel mass makes it feasible, in the laboratory, to achieve the $\rho r = 3$ g/cm^2 necessary for $\phi = 1/3$. For a sphere, $M = (4\pi/3)(\rho r)^3/\rho^2$. Hence the mass (and driver energy at fixed coupling efficiency) required for a given ρr scales as $1/\rho^2$. For example, at a density of 400 g/cm^3 (plasma density of 10^{26} cm^{-3}), a spherical shell with a thickness of $r/2$ and radius r would have $\rho r = 3$ g/cm^2 with a mass of 5 mg. This mass would be imploded in about 10 nsec, would burn in about 10^{-10} sec and would have a yield of about 6×10^8 J. This yield is readily contained, and at 5–6 pulses per second such targets could drive a 1-gigawatt electric reactor for power production.

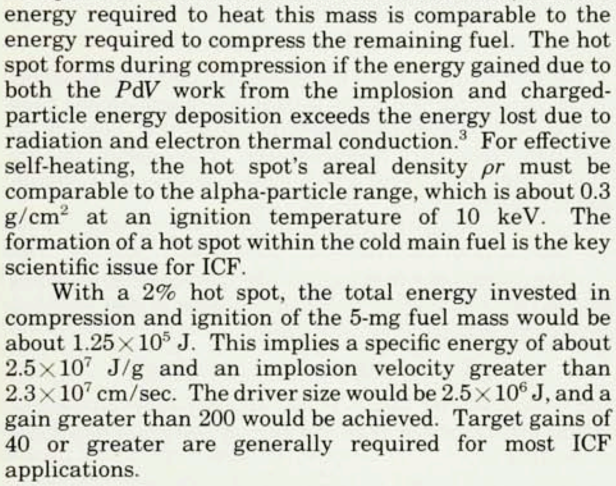
The fuel compression is energetically efficient if the D–T remains nearly Fermi degenerate.[1] Only 6.5×10^4 J is required to compress 5 mg of fuel to 400 g/cm^3 in this case, but the fuel remains too cold to burn during the inertial confinement time. Thus high gain also requires hot-spot ignition. To heat the entire 5 mg mass to 5 keV would require 3.0×10^6 J, and with an implosion efficiency of 5% the driver would need to deliver 6×10^7 J. This is near the upper limit of what could be considered for a laboratory driver, yet for a burn efficiency of ⅓ the target gain would only be 10. (Target gain is defined as the thermonuclear yield divided by the driver energy delivered to the target.)

However, if the target can be ignited from a central hot spot that contains about 2% of the total mass, then the energy required to heat this mass is comparable to the energy required to compress the remaining fuel. The hot spot forms during compression if the energy gained due to both the PdV work from the implosion and charged-particle energy deposition exceeds the energy lost due to radiation and electron thermal conduction.[3] For effective self-heating, the hot spot's areal density ρr must be comparable to the alpha-particle range, which is about 0.3 g/cm^2 at an ignition temperature of 10 keV. The formation of a hot spot within the cold main fuel is the key scientific issue for ICF.

With a 2% hot spot, the total energy invested in compression and ignition of the 5-mg fuel mass would be about 1.25×10^5 J. This implies a specific energy of about 2.5×10^7 J/g and an implosion velocity greater than 2.3×10^7 cm/sec. The driver size would be 2.5×10^6 J, and a gain greater than 200 would be achieved. Target gains of 40 or greater are generally required for most ICF applications.

Direct and indirect drive

ICF implosions fall into two classes, known as direct drive and indirect drive. (See the article by John H. Nuckolls in PHYSICS TODAY, September 1982, page 24.) Direct drive is characterized by laser beams or charged-particle beams being incident on the fusion capsule. For indirect drive the laser beams or charged-particle beams are first absorbed in a high-Z enclosure, a hohlraum, which surrounds the capsule. The hohlraum emits x rays, which drive the capsule implosion. (See figure 2.) For planar targets, up to 70–80% of the absorbed energy can be converted to x rays. While such conversion efficiencies have been demonstrated with lasers, the efficient generation of x rays with ion beams requires minimum irradiances of 10^{14}–10^{15} W/cm^2 for typical ion energies, which range from 30 MeV to 10 GeV, depending on ion mass. The primary challenge for ion beams has been and continues to be achieving the required focused intensity. (The article by Hogan, Bangerter and Kulcinski discusses the status of programs to develop the heavy-ion and light-ion drivers.



Hohlraums for indirect-drive ICF use lasers in **a** and heavy-ion beams in **b**. The capsules are imploded by x rays produced by the hohlraums. **Figure 2**

Direct drive is more efficient in transporting driver energy to the fusion capsule but is sensitive to the spatial quality of the illuminating radiation. Indirect drive has the advantage of being less sensitive to the details of the irradiating beams. In addition, implosions using x-ray-driven ablation are more stable hydrodynamically. Indirect drive, however, generates a large volume of plasma through which the laser must propagate and thus may be more susceptible to laser-driven parametric instabilities.

Over the last ten years, significant progress has been made toward demonstrating the requirements for ignition and high gain with both indirectly and directly driven ICF targets.

The ICF program has used data from both laboratory experiments and underground nuclear explosion experiments at the Nevada Test Site. The latter program, called Halite/Centurion and conducted jointly by Lawrence Livermore and Los Alamos National Laboratories, demonstrated excellent performance, putting to rest fundamental questions about the basic feasibility of achieving high gain. The Halite/Centurion program performed experiments at higher energies than those available in the laboratory. The NAS review of the ICF program concluded that the Halite/Centurion experiments had met their objectives and that further uncertainties in achieving ignition could best be studied in laboratory experiments.[2] Because of this recommendation, DOE has scheduled no more experiments in the Halite/Centurion program. The details of these experiments remain classified.

Nova

Most indirect-drive laser experiments in the US have been done on Livermore's 10-beam Nd:glass Nova laser, whose experimental area is shown[5] in figure 3. Nova's potassium–dihydrogen–phosphate crystal arrays can efficiently convert the 1054-nm fundamental laser wavelength to either its 2nd or 3rd harmonic.[6] Most hohlraum experiments are conducted at the 3rd harmonic (351 nm) to control laser–plasma interaction instabilities.[7] Nova can deliver up to 40 kJ of 351-nm light in a 1-nsec pulse onto a target. This energy can be delivered with a wide variety of pulse durations and shapes. Since its completion in 1985, Nova has been the largest laser facility dedicated to ICF research. Experiments on radiation-heated cavities have also been reported at facilities in Japan, Germany, England and China.[8]

Because of the progress achieved in the past decade, the 1990 NAS review[2] and the review by DOE's Fusion Policy Advisory Committee[9] recommended that the nation's ICF program focus on the physics of ignition with indirect-drive targets. Subject to the successful completion of a series of experiments to be carried out on the Nova laser at Livermore, these reviews advocated construction of a 1- to 2-MJ glass laser whose purpose would be to demonstrate ignition and modest-gain ICF targets within about a decade. To create this national ignition facility, Livermore proposed upgrading Nova, and NAS and FPAC endorsed the proposal as the most timely and cost-effective path to this goal. We will say more about the Nova Upgrade later.

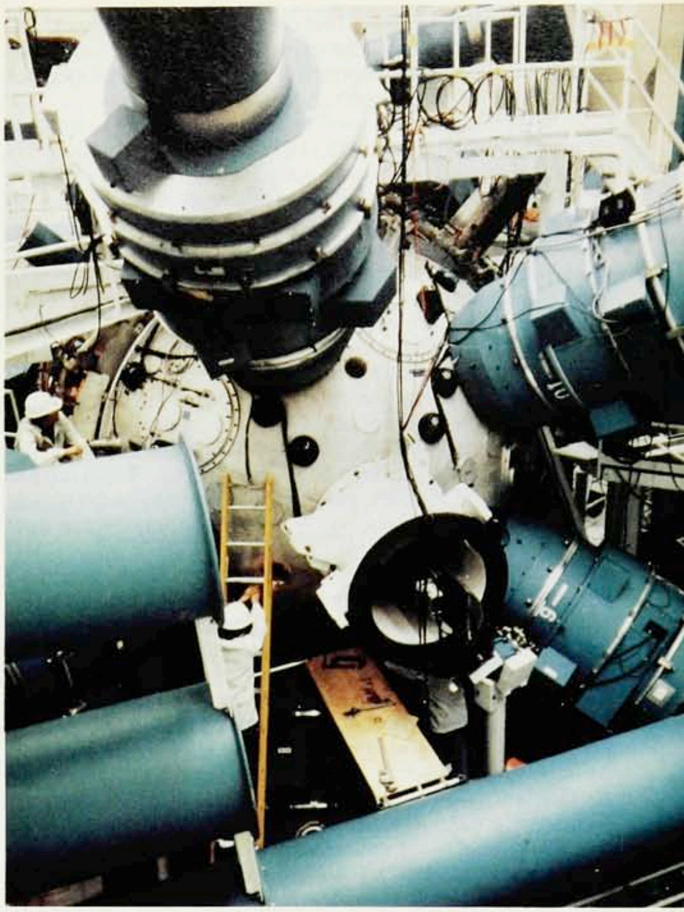
The series of experiments that NAS recommended as a prerequisite to upgrading Nova constitute what is called the Nova technical contract.[2] They will explore laser–plasma interaction physics and hydrodynamics. The former experiments address hohlraum energetics, the control of implosion symmetry and the scaling of a variety of plasma collective effects. The latter experiments address hydrodynamic instability and the effects of x-ray drive asymmetry on capsule performance. The Nova technical contract experiments, which are being jointly carried out by Livermore and Los Alamos, emphasize the further development and confirmation of numerical simulations of the experiments.

Nova experiments have demonstrated the hohlraum radiation temperatures, ablation pressures and coupling efficiencies required for ignition and gain on the proposed Nova Upgrade. These parameters have been achieved with acceptable levels of the parametric instabilities that can occur in the underdense plasma within the hohlraum. (The plasma is underdense if the electron density n_e is less than the critical density $n_c = 10^{21}\lambda^{-2}(\mu\text{m})\,\text{cm}^{-3}$ at which the refractive index goes to zero and the laser doesn't propagate.)

To achieve the radiation drive and symmetry required for indirect-drive ICF, energy losses due to processes such as stimulated Raman scattering and stimulated Brillouin scattering[7] must be kept below 5–10%. Both of these processes can redirect energy in the hohlraum and reduce the absorption efficiency. In addition, high-energy electrons generated from Landau damping of the plasma wave in stimulated Raman scattering can preheat the fuel and reduce its compressibility. The use of 351-nm light has kept these instabilities to a low level (below 5%) on Nova experiments to date.[10] Investigation of the scaling and control of these instabilities for Nova-Upgrade-scale plasmas continues to be a primary objective of experiments on Nova.

Symmetry and hydrodynamic instability

As discussed above, to efficiently compress D–T to several hundred g/cm^3, the compression must be near Fermi



Nova target chamber. When in operation, ten laser beams deliver up to a total of 40 kJ of light in a 1-nsec pulse onto a target within this 16-foot-diameter aluminum sphere. **Figure 3**

degenerate. To ensure this, the entropy generated in the main fuel must be limited to that which would be generated by a 1-Mbar shock passing through solid density D–T. Because the peak pressures in the implosion must be about 100 Mbar, the pressure in the shell must be increased from an initial shock of 1 Mbar to 100 Mbar in such a way that little additional entropy is generated.[3] Various types of irradiating pulse shapes can accomplish this objective.

One very effective method developed on Nova for measuring the time-varying ablation pressure maps the space–time trajectory of the ablation-driven shock wave. The shock velocity V_s, from which the ablation pressure can be determined ($P \propto V_s^2$), is measured by the time of arrival of the shock through a material of varying but known thickness. The arrival of the shock is detected by the near-ultraviolet emission from the shock-heated material. The curvature of the shock trajectory in space–time indicates the time variation of the ablation pressure. Sophisticated numerical simulations accurately predict the results of such experiments and related x-ray and capsule measurements.

Demonstration of drive symmetry control in laser-driven hohlraums is a primary objective of the Nova technical contract.[2] Time-integrated fluxes uniform to a few percent have been seen in hohlraum experiments in which the compressed fuel region of an x-ray-driven implosion is imaged. The capsule convergence amplifies the flux uniformity, allowing flux nonuniformities smaller than 2% to be measured.

A typical capsule used in these experiments consists of a plastic shell filled with D–D fuel and a small quantity of argon trace gas, which enhances the x-ray emission from the fuel volume.[11] The fuel is imaged using a two-dimensional x-ray framing camera with a "shutter opening" of 80 psec. Diagnostic advances such as framing cameras have contributed to the rapid progress in ICF. Shown in figure 4 is a series of four images of the self emission taken as a capsule was driven by a 1-nsec laser pulse. No image is seen at the earliest time (the fuel is not hot enough to radiate); the later images show the evolution of the fuel shape during stagnation, when the inward-moving shell is decelerated by the hot spot. With the appropriate choice of geometry or pointing, it is possible to achieve time-integrated fluxes uniform to a few percent. Experiments that use more complex pulse shapes and that also obtain information about time variations in symmetry are now underway.

During an ICF capsule implosion there are two occurrences of a hydrodynamic instability similar to the classical Rayleigh–Taylor fluid instability.[4] The first occurs during the ablation process that drives the capsule implosion: The hot, ablated material acts like a low-density fluid, while the unablated dense shell acts like a heavy fluid. The second occurrence takes place during stagnation when the inward-moving shell is decelerated by the lower-density, high-temperature hot spot. The Rayleigh–Taylor instability can cause the cold main fuel to mix with the hot spot, preventing ignition.

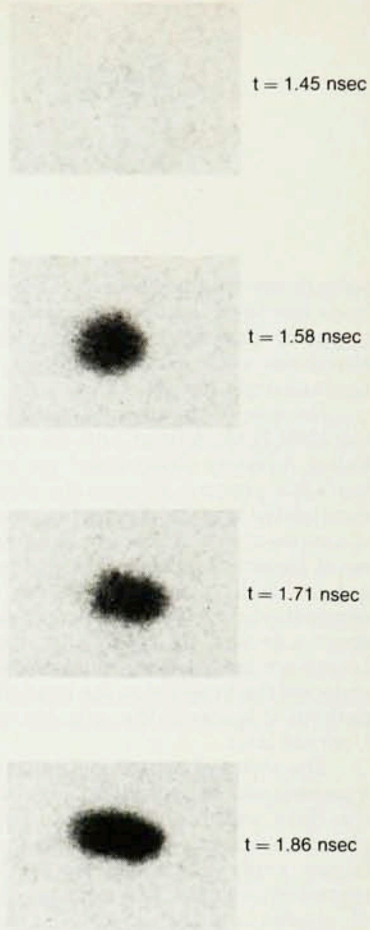
The initial source of noise for this instability can be either imperfections in the capsule surface or surface roughness induced by spatial variations in the driving pulse. For targets having a roughness of 500–1000 Å, about 6–7 e-folds of Rayleigh–Taylor growth can be tolerated.[3] The minimum capsule size required to achieve ignition and burn propagation depends on the implosion velocity that can be achieved. This velocity is primarily determined by the peak pressure that can be generated and by the in-flight aspect ratio, which determines the degree of hydrodynamic instability of the implosion process. We will consider this in more detail below.

For both direct-drive[12] and indirect-drive[13] implosions, recent experiments have shown that the growth rate γ of the Rayleigh–Taylor instability during ablation is well modeled by[14,15]

$$\gamma = \left(\frac{ka}{1+kL}\right)^{1/2} - \alpha k V_{\text{abl}} \qquad (5)$$

where k is the modal wavenumber, a is the acceleration, L is the density gradient scale length in the ablation front, and α is a constant between 1 and 3. The velocity V_{abl} with which the ablation front moves through the shell is given by $V_{\text{abl}} = \dot{m}/\rho$, where ρ is the shell density, and $\dot{m}$ is the rate of mass ablation per unit area.

Figure 5a shows how the experiments are carried out for x-ray-driven implosions.[13] A sample with a sinusoidal areal density perturbation is placed adjacent to an opening in a hohlraum. A time- and space-resolving x-ray microscope coupled to a streak camera views an x-ray backlighter source through the sample. As the perturbations grow, material moves from the thin to the thick regions, causing the x-ray contrast between the thick and thin regions to increase with time. Representative data are shown in figure 5b. In this example, the sample was driven until the perturbation had evolved into the nonlinear bubble and spike phase. This nonlinearity is exhibited by the presence of perturbations up to the fourth harmonic. Agreement between the experiment and simulation is excellent, as shown in figure 5c. Experiments have been done with a variety of wavelengths, amplitudes and materials. Depending on the experimental conditions, growth rates have been observed ranging from near the classical value of $\sqrt{ka}$ to complete stabilization.



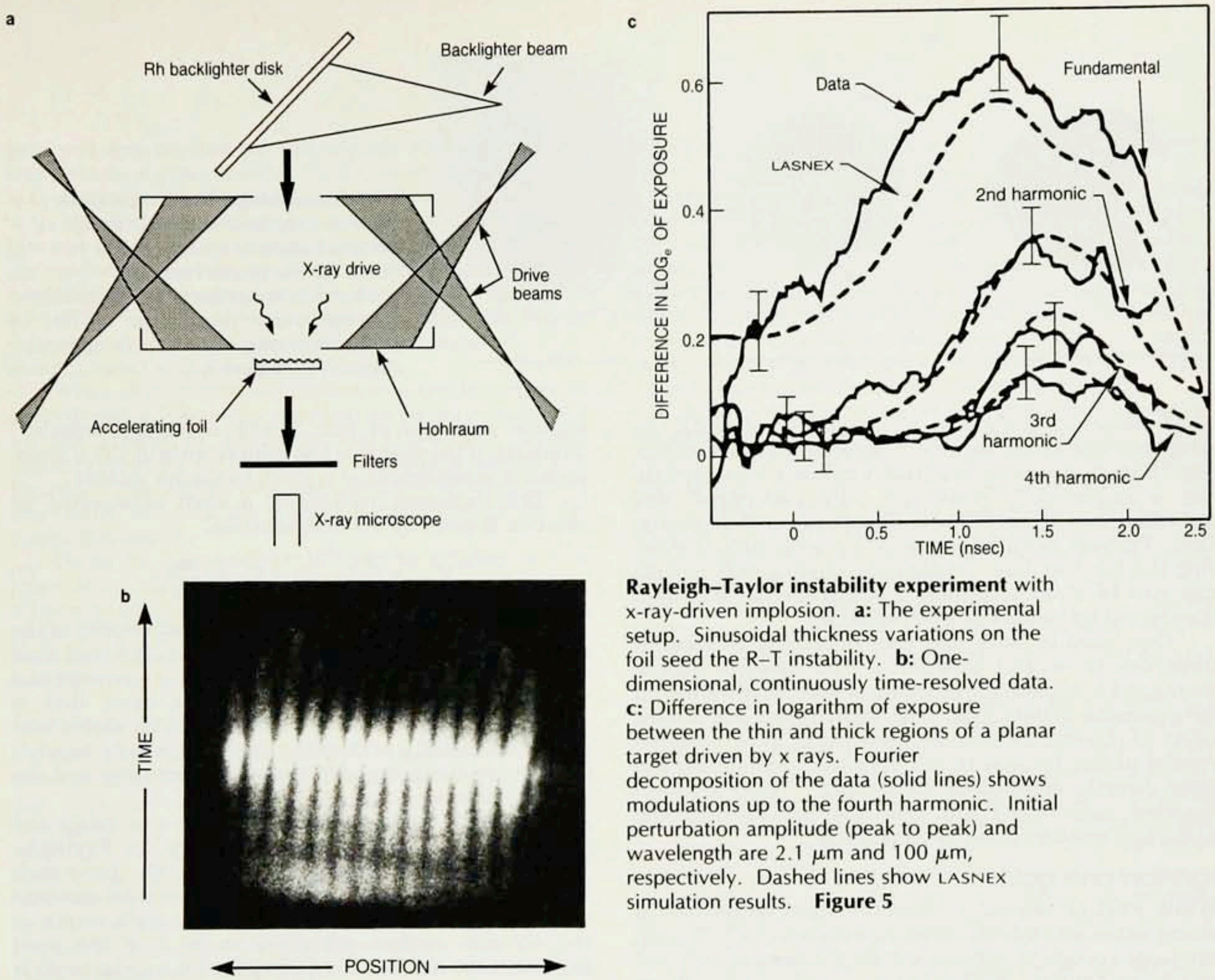
X-ray self emission from the compressed fuel region of a target compressed by x rays driven by a 1-ns laser pulse. Such experiments measure time-integrated drive uniformity. **Figure 4**

Present implosion experiments on Nova are accurately modeled when the effects of fuel mixing and drive asymmetry are properly accounted for. The table on page 38 compares measurements from a representative Nova implosion experiment with predictions from sophisticated numerical simulations.

Direct-drive experiments

While the experiments discussed above illustrate the progress in indirect-drive ICF, substantial progress in direct-drive ICF has also occurred. The two principal facilities for direct-drive implosion experiments are the Omega laser at the University of Rochester's Laboratory for Laser Energetics and Gekko XII at Osaka University. A number of smaller facilities in Germany, Russia, England, Italy, China and India are also used for direct-drive ICF research. Omega is a 24-beam Nd:glass laser facility capable of delivering 2–3 kJ of 351-nm light on target. Since 1986,[16] experiments on Omega using targets with a layer of solid D–T fuel surrounded by glass ablators have achieved average fuel densities[17] of 20–40 g/cm^3.

Gekko XII, an approximately 10-kJ, 526-nm Nd:glass laser, is the principal facility outside the US for conducting direct-drive implosion experiments. Experiments on Gekko using D–T-doped plastic shells with no gas fill have achieved densities[18] in the imploded plastic of about



Rayleigh–Taylor instability experiment with x-ray-driven implosion. **a:** The experimental setup. Sinusoidal thickness variations on the foil seed the R–T instability. **b:** One-dimensional, continuously time-resolved data. **c:** Difference in logarithm of exposure between the thin and thick regions of a planar target driven by x rays. Fourier decomposition of the data (solid lines) shows modulations up to the fourth harmonic. Initial perturbation amplitude (peak to peak) and wavelength are 2.1 μm and 100 μm, respectively. Dashed lines show LASNEX simulation results. **Figure 5**

600 g/cm^3. High-density implosion experiments on both Gekko and Omega observed neutron yields significantly lower than predicted for an ideal spherical implosion. This has been attributed to the effects of hydrodynamic instability seeded by irradiation nonuniformities and defects in the targets' fabrication.

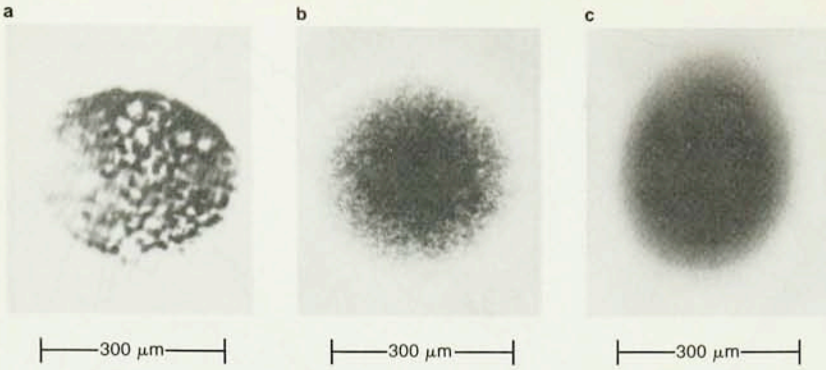
Nonuniformities in laser irradiance can destroy the symmetry of an implosion and create large seeds for the Rayleigh–Taylor instability. They can also drive laser–plasma instabilities in the underdense plasma corona. The most notable technological advance in direct-drive ICF has been the development of techniques to smooth the spatial profile of the irradiating laser beam.[19–21]

Essentially all approaches to beam smoothing entail a trade-off between reduced coherence of the laser beam and improved uniformity. A typical laser beam can be focused to a much smaller spot than is required for ICF experiments. Phase errors across the beam diameter result in large, uncontrolled intensity variations in the target plane. However, a laser beam can be divided into a large number of overlapping beamlets whose diffraction-limited spot size is matched to the target. This overlap eliminates large-scale spatial nonuniformity in the beam at the expense of small-scale interference (speckle) between the beamlets.

One approach to beam smoothing introduces an optical element called a random phase plate at the output of the laser chain.[19] A random phase plate has a large number of elements, each of which has a phase shift of 0 or π relative to adjacent elements. The pattern of phase shifts is distributed in a quasi-random fashion over the surface of the phase plate.

If in addition to a phase plate, temporal incoherence (bandwidth) can be introduced between the beamlets, then the small-scale interference pattern moves around rapidly, resulting in a time-asymptotic pattern of uniform intensity.[20,21] The Rochester Laboratory for Laser Energetics has introduced an example of this technique called smoothing by spectral dispersion.[20] The technique is well suited to harmonically up-converted solid-state lasers. In conjunction with a phase plate, smoothing by spectral dispersion uses a combination of gratings and an electro-optic modulator to impress a spatially varying frequency over the laser aperture. By using this method and by overlapping several beams, the small-scale intensity structure on target can be smoothed in less than about 50 psec on Rochester's Omega. Figure 6 shows target-plane images for a beam from the Omega laser, demonstrating the improvement in the time-averaged irradiance using such beam-smoothing technology. Most calculations indicate that 60–100 beamlets are required to adequately smooth the beam over the range of spatial scales important for high-convergence implosions.

Every major direct-drive ICF facility now employs beam smoothing. Many laboratories have used uniform beams to conduct successful experiments addressing



Beam smoothing. The images show the time-integrated irradiance profile in the target plane of a nominal 351-nm beam. **a:** The profile from the unadorned Omega laser. **b:** The profile from the random phase plate. **c:** The profile employing smoothing by spectral dispersion. **Figure 6**

laser–plasma coupling and hydrodynamic stability. In many circumstances, parametric processes such as stimulated Raman scattering are greatly reduced when smoothing is employed.[10] While not fully understood, this reduction is most likely due to a suppression of filamentation. Perhaps more importantly, by accurately controlling the incident laser irradiance, coupling experiments can now be more accurately modeled and an improved theoretical framework can be developed.

One beam of Nova also uses smoothing by spectral dispersion to conduct direct-drive hydrodynamic experiments and to explore the influence of coherence control on laser–plasma instabilities. The experiments are a joint effort of Livermore and Rochester and have achieved results similar to those shown in figure 5, except that the laser directly illuminates the sample.[12] They are well modeled numerically and can also be fit with the dispersion relation given by equation 5.

Ignition and gain

While existing laboratory facilities have established a strong experimental and modeling data base for ICF, none are large enough to implode a sufficient mass of D–T fuel to achieve ignition. Sophisticated numerical simulations that accurately describe laboratory and Halite/Centurion experiments have specified the driver and target requirements for a laboratory demonstration of ignition.

Numerical calculations predict that to ignite a hot spot and propagate burn into a compressed main fuel region of D–T, the minimum driver energy required is

$$E_{\text{driver}} = \frac{E_0}{\eta_h \eta_c} V_{\text{imp}}^{-5} \beta^4 \tag{6}$$

where V_{imp} is the implosion velocity, E_0 is a scale factor, η_h is the hydrodynamic efficiency of an implosion, η_c is the efficiency with which the driver energy is coupled to the capsule, and β is the ratio of the fuel pressure at a given density to the Fermi degenerate pressure. As the implosion velocity increases for a given β, the cold fuel pusher can generate a higher pressure and achieve ignition values of ρr and T with a smaller capsule.[11] Similarly, if the pusher is less compressible ($\beta > 1$), a lower pressure is achievable at a given implosion velocity.

The implosion velocity of a shell accelerated by ablation is given by a rocket equation,

$$V_{\text{imp}} = \frac{P}{\dot{m}} \ln \frac{m_0}{m} = V_{\text{ex}} \ln \frac{m_0}{m} \tag{7}$$

where P is the pressure, V_{ex} is the exhaust velocity of the ablated mass, and m_0 and m are the initial and final shell masses, respectively. For $V_{\text{ex}} < V_{\text{imp}}$ (as is characteristic of x-ray-driven implosions) and for a shell that is accelerated through half its radius, it can be shown that $V_{\text{imp}} \sim 2(R/\Delta R)V_{\text{abl}}$. Thus the threshold energy depends strongly on the acceptable capsule aspect ratio and the ablation velocity.

Furthermore, using equation 5 we can relate the amplification of surface perturbations by the Rayleigh–Taylor instability to the capsule aspect ratio. For a shell accelerated through half the shell radius with constant acceleration and with a density-gradient scale length at the ablation surface optimized to be half the shell thickness, the number of e-foldings γt for a given mode is

$$\gamma t \simeq \left(\frac{l}{1 + \frac{l}{2}\left(\frac{\Delta R}{R}\right)} \right)^{1/2} - al\left(\frac{\Delta R}{R}\right) \tag{8}$$

where $l = kR$ is the spherical harmonic mode number. For a given l, the amplification depends only on the shell aspect ratio. The maximum aspect ratio that will allow sufficient stability depends in turn on the capsule surface finish and the spectral distribution of perturbations.[22]

Numerical simulations using present experimental and theoretical information can predict capsule performance at incident driver energies larger than those currently achieved in the laboratory. Figure 7 shows gain curves computed by such methods. The two indirect-drive curves correspond to different implosion velocities[11] and were calculated under the assumption of a fixed hohlraum coupling efficiency of laser energy to a capsule. At any given velocity, capsules driven by a driver that is below a certain energy, given by equation 6, will fail to ignite because the hot spot will not achieve sufficient ρr and temperature. The shaded bands correspond to the uncertainty in the capsule surface quality. The left-hand edge of each band corresponds to the gain for perfectly uniform implosions. The right-hand edge of each band corresponds to the gain for targets with surface finishes of 500–1000 Å (as used in present experiments).

As the driver energy increases, the minimum implosion velocity required to ignite a capsule decreases. If we exceed the minimum velocity for any driver size, the capsule will still ignite, but performance will suffer. The

Comparison of observed and simulated results from a Nova implosion experiment

	Observed	Simulated
Neutron yield	$(1.6 \pm 0.2) \times 10^8$	3.4×10^8
Fuel areal density (mg/cm²)	11.8 ± 0.6	11.3
Fuel ρ (g/cm³)	14.4 ± 3	13.8
Ion temperature (keV)	1.1 ± 0.2	1.2

gain will drop because we will implode less mass and get less yield for a given energy. Hence the optimum strategy is to operate at the minimum implosion velocity consistent with the desired yield or driver size. This optimum is given by the dotted line through the two curves in figure 7. As mentioned earlier, on Nova we have demonstrated hohlraum drive temperatures consistent with a velocity of 4×10^7 cm/sec. As shown in figure 7, with this higher implosion velocity, ignition and burn propagation can be demonstrated with a 1- to 2-MJ laser.

When the capsules are limited to a similar degree of hydrodynamic instability, detailed numerical calculations by the groups at Rochester and Livermore predict comparable gains for direct-drive implosions as shown in figure 7. The higher coupling efficiency of direct drive essentially balances the greater sensitivity to hydrodynamic instability.

Gains for indirect-drive ICF can be a factor of 2 or more above those of figure 7 if the hohlraum coupling efficiency can be improved, and direct-drive gains can be a factor of 2 or more higher if the hydrodynamic instability constraints are relaxed by improving target-fabrication techniques and irradiation uniformity.

The next generation

Advances in laser science and technology since the construction of Nova now make it possible for the 1- to 2-MJ solid-state lasers required for ignition and burn propagation to be housed within the existing Nova building.[23] This proposal, the Nova Upgrade, would use modern electro-optic technology and pulsed-power, compact segmented amplifiers, and multipass laser architecture. Improvements in optical manufacturing will enable optical fluences more than 2–4 times those now used on Nova, substantially reducing the total laser aperture (and thus cost) required for ignition performance. Figure 8 shows a schematic of the Nova Upgrade.

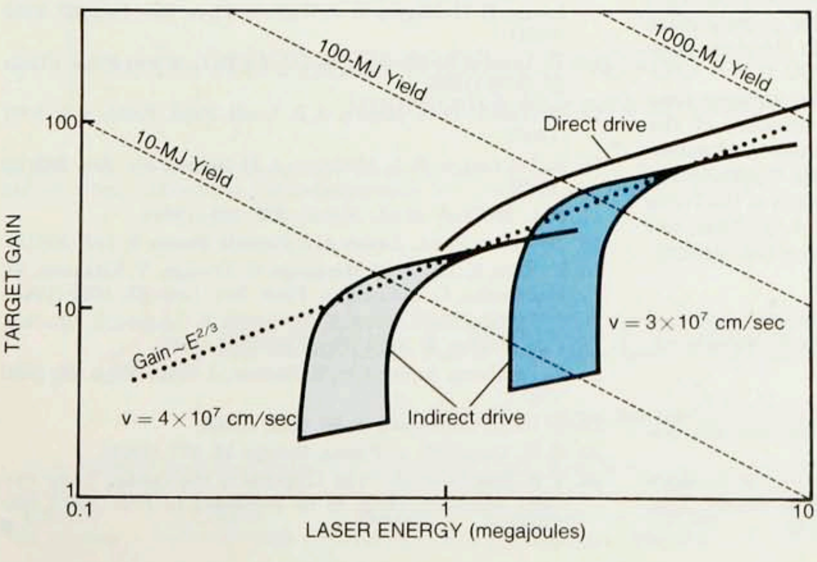
Livermore estimates the construction cost of the Nova Upgrade to be about \$400 million, assuming expected advances in manufacturing technology, the use of the Nova building and facilities, and a project startup in fiscal year 1995. A detailed conceptual engineering design, which has not yet been completed, will be required before more accurate cost estimates can be obtained.

Depending on the aperture size of each segment of the beam (30 to 35 cm), the Nova Upgrade will consist of 192 to 288 beamlets, each of which can independently irradiate the target. The full laser would be capable of delivering 1–2 MJ of energy and 400–700 TW of power, depending on the laser pulse length. The National Academy of Sciences report recommended demonstration of a single beamlet, with the goal of extracting 5 kJ of 351-nm light in a 3-nsec pulse.[2] This milestone should be reached in 1994.

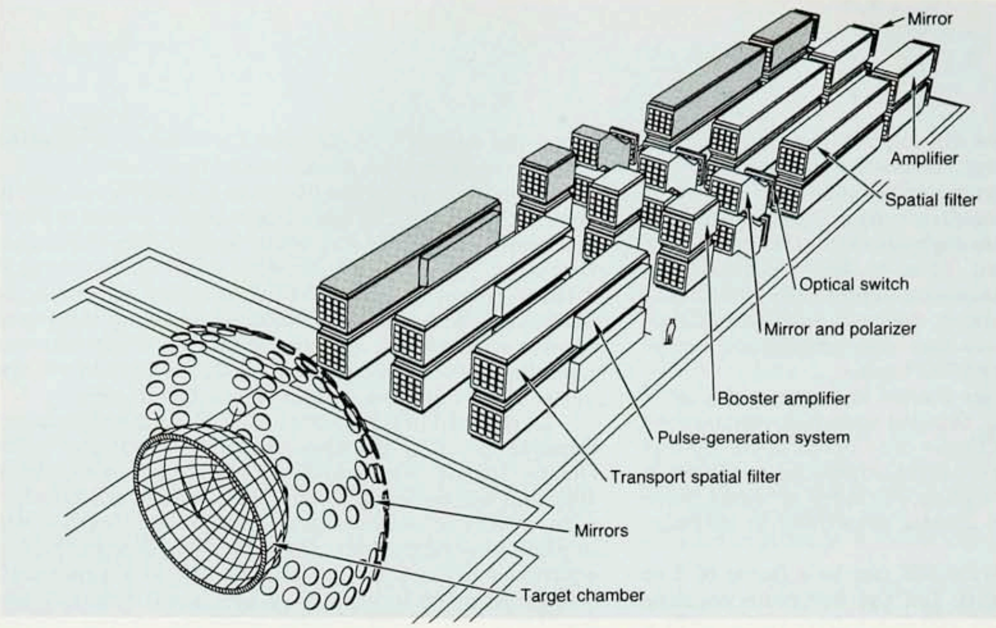
In the field of direct-drive ICF, Rochester has begun construction of a 60-beam upgrade of Omega.[24] The Omega Upgrade is scheduled for completion by the end of 1994 and will be able to deliver 30 kJ of 351-nm light in a wide variety of pulse shapes. The Omega Upgrade will implode direct-drive capsules that are hydrodynamically equivalent to capsules that would ignite at a larger scale (the direct-drive equivalent of the Nova technical contract). If the target-physics program of the Omega Upgrade is successful, an additional target area could be added to the Nova Upgrade to explore ignition and gain for direct-drive ICF.

The Nova and Omega systems and their upgrades use solid-state lasers. The Naval Research Laboratory in collaboration with Los Alamos is constructing a KrF laser called Nike. This laser is designed to deliver 2–4 kJ of energy at a wavelength of 267 nm. Nike, which is designed for planar hydrodynamic and laser-coupling experiments, is intended as a testbed for a beam-smoothing technique developed by NRL called echelon-free induced spatial incoherence.[2,21] Nike will also demonstrate the technology for high-precision kilojoule-class KrF lasers for ICF experiments.

Ion-beam drivers also are being developed for indirect-drive ICF. Sandia National Laboratories has developed a succession of light-ion (H, Li) drivers. The primary challenge for ion beams has been and continues to be achieving the brightness required for focused irradiances of 10^{14}–10^{15} W/cm^2. Completed in 1985, the Particle Beam Fusion Accelerator II at Sandia can at present deliver about 100 kJ of Li ions at 10^{12} W/cm^2.



Predicted target gain as a function of laser energy for direct- and indirect-drive inertial fusion. The indirect-drive curves are for a fixed coupling efficiency and are parametrized by the capsule implosion velocity. Bands indicate how performance depends on implosion uniformity. Similar hydrodynamic stability criteria are applied to all three curves. **Figure 7**



The Nova upgrade at Lawrence Livermore has been proposed as the national ignition facility, at which ignition and modest-gain ICF targets would be demonstrated. One half of the laser and target chamber is shown. **Figure 8**

Sandia is currently conducting preliminary hohlraum experiments on PBFA II.

Of the current ICF drivers, the reviews by the National Academy of Sciences and the DOE's Fusion Policy Advisory Committee concluded that heavy-ion drivers have the greatest potential for inertial fusion power plants because of their potential efficiency, durability and rep rate. The US program in heavy-ion drivers concentrates on induction accelerators and has been carried out primarily at Lawrence Berkeley Laboratory. Complementary programs in Europe and Japan are developing rf accelerators. All the programs emphasize driver development and are at least a decade away from being able to conduct ICF target experiments. The article by Hogan, Bangerter and Kulcinski discusses these two heavy-ion driver approaches.

The demonstration of ignition and burn propagation in the laboratory would complete the basic target-physics objectives of the ICF program and would set the stage for development of the applications of ICF. Although DOE has not yet endorsed construction of a national ignition facility for ICF, it has begun implementing the NAS recommendations, including the Nova technical contract and the beamlet demonstration, which are prerequisites for construction of an advanced megajoule Nd:glass laser ignition facility.

The next few years promise to be a very exciting time for ICF research. With the continued success of the technical program on Nova, the construction and subsequent experimental program at the Omega Upgrade and other facilities, and the proposed construction of the Nova Upgrade, it should be possible to achieve ignition and fusion burn propagation soon after the turn of the century.

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References

1. J. H. Nuckolls, L. Wood, A. Thiessen, G. B. Zimmerman, Nature **239**, 139 (1972).
2. Natl Acad. Sci., "Review of the Department of Energy's Inertial Confinement Fusion Program," final Report, Natl Acad. P., Washington, D.C. (September 1990).
3. J. D. Lindl, in *International School of Plasma Physics Piero Caldirola: Inertial Confinement Fusion*, A. Caruso, E. Sindoni, eds., Società Italiana di Fisica, Bologna (1988), p. 617.
4. S. Chandrasekhar, *Hydrodynamic and Hydromagnetic Stability*, Oxford U. P., Glasgow (1961), p. 428.
5. E. M. Campbell, Rev. Sci. Instrum. **57**, 2101 (1986).
6. R. S. Craxton, Opt. Commun. **34**, 474 (1980).
7. W. L. Kruer, *Physics of Laser Plasma Interactions*, Addison–Wesley, Redwood City, Calif. (1988).
8. R. Sigel *et al.*, Phys. Rev. Lett. **65**, 587 (1990), and references within.
9. Fusion Policy Advisory Committee Final Report, DOE/S-0081, Department of Energy, Washington D.C. (September 1990).
10. E. M. Campbell, "The Physics of Megajoule, Large-Scale and Ultrafast Short-Scale Laser Plasmas," to be published in Phys. Fluids B.
11. J. D. Lindl, in *Fusion to Light Surfing*, T. Katsouleas, ed., Addison–Wesley, Redwood City, Calif. (1991), p. 177.
12. G. Glendinning, "Laser-Driven Planar Rayleigh–Taylor Instability Experiments," pub. UCRL-LR-105821-92-1, Lawrence Livermore Natl Lab., Livermore, Calif. (1991).
13. B. A. Remington, S. W. Haan, S. G. Glendinning, J. D. Kilkenny, D. H. Munro, R. J. Wallace, Phys. Rev. Lett. **67**, 3259 (1991).
14. H. Takabe, K. Mimo, L. Montierth, R. L. Morse, Phys. Fluids **28**, 3676 (1985).
15. M. Tabak, D. H. Munro, J. D. Lindl, Phys. Fluids B **2**, 1007 (1990).
16. R. S. Craxton, R. L. McCrory, J. M. Soures, Sci. Am. **255**, 68 (1986).
17. R. L. McCrory *et al.*, Nature **335**, 225 (1988).
18. H. Azechi *et al.*, Lasers and Particle Beams **9**, 193 (1991).
19. Y. Kato, K. Mima, N. Miyanaga, S. Arinaga, Y. Kitagawa, M. Nakatsuka, C. Yamanaka, Phys. Rev. Lett. **53**, 1057 (1984).
20. S. Skupsky, R. W. Short, T. Kessler, R. S. Craxton, S. Letzring, J. M. Soures, J. Appl. Phys. **66**, 3456 (1989).
21. R. Lemburg, A. Schmitt, S. Bodner, J. Appl. Phys. **62**, 2680 (1987).
22. S. Haan, Phys. Rev. A **39**, 5812 (1989).
23. E. M. Campbell, J. Fusion Energy **10**, 277 (1991).
24. T. R. Boehly *et al.*, "The Upgrade to the Omega Laser System," (January 1992), to be published in *Proc. SPIE OE/LASE.* ■