

that would trigger symmetry breaking. One day, when he was watching a crystal form, he noticed it fall to the bottom of the flask. On a whim, he stirred the solution. To his astonishment, the stirring caused all subsequent crystals to adopt the same chirality as the original crystal. He and his colleagues Rebecca Kaufman and Nolini Singh submitted a paper to *Science*. One of the referees promptly repeated the experiment and obtained the same result. The paper appeared in 1990.³

Secondary nucleation

Kondepudi explained his results in terms of primary and secondary nucleation. In primary nucleation, crystals emerge from solution at a rate proportional to $\exp[-A(T)/\ln^2(c/c_0)]$. Here, $A(T)$ is a function that depends on the temperature T , c is the concentration, and c_0 is the saturation concentration. Left-handed and right-handed crystals have the same chance of forming.

In secondary nucleation, solute crystallizes on the surface of an existing crystal. Newly added material assumes the chirality of the surface.

In the 1990 paper, Kondepudi sketched out the sequence of events. First, a single crystal forms via primary nucleation. In doing so, the crystal reduces the concentration of solute and, with it, the likelihood of further primary nucleation. Stirring the solution increases the likelihood of secondary nucleation, both by bringing more solute into contact with the crystal and by breaking off newly crystallized material to form additional nucleation sites. If no further primary nucleation occurs, all the crystals share the first crystal's chirality.

Secondary nucleation is well known to chemical engineers, who've developed phenomenological rate equations for it. But a physical theory in terms of quantities such as temperature or Boltzmann's constant is lacking. After Kondepudi's paper ap-



peared, various workers, including Kondepudi himself, tried to quantify how stirring promotes secondary nucleation. Does contact with the stirrer matter? Does convection—that is, stirring without a stirrer—produce the same results?

Last year, Julian Cartwright of the Spanish Research Council realized that stirring, contact with the bar, convection, and so on were all doing the same thing on the microscale: breaking off the tiny whiskers that sprout from crystals when they form. In a paper published last year, Cartwright and his collaborators demonstrated the idea in a mix of theory, computation, and experiment.⁴

Viedma has added a new twist. In Kondepudi's and Cartwright's experiments, the starting point is a solution devoid of chiral entities. Viedma started instead with a supersaturated solution that contains a fifty-fifty mix of chiral crystals. Like Kondepudi, he stirred the solution, but in the presence of glass marbles (see figure 2). Crushed between the marbles, any crystals that have just formed are broken down. Meanwhile, others form and the cycle repeats—but not

Figure 2. A metal bar, controlled electromagnetically, forces crystals between glass beads and breaks them up. At the same time, new crystals form. Eventually chiral purity results. (Courtesy of C. Viedma.)

in a chiral steady state.

Viedma found that if he left his samples grinding away for several hours, one chiral form would steadily predominate. The dominant form was random, but the result was the same: complete chiral purity.

To understand the results, one needs to add another ingredient: Ostwald ripening. In 1896, Wilhelm Ostwald observed that big crystals grow at the expense of little crystals thanks to the big crystals' greater thermodynamic stability. In Viedma's experiment, one would expect left-handed and right-handed crystals to grow and dissolve at the same rate. But if there's a slight, chance preponderance of one chiral form, then Ostwald ripening, amplified by secondary nucleation, will shift the chiral balance.

Viedma's experiment, though it converts an achiral mixture into a homochiral one, is still a far chemical cry from chiral amino acids or the origin of life. But five years after Kondepudi's 1990 experiment, Kenso Soai of the Tokyo University of Science in Japan demonstrated that he could guide the homochiral formation of an organic molecule by recruiting the help of sodium chlorate crystals.⁵ Inorganic chiral crystals, Soai points out, were around when life began.

Charles Day

References

1. C. Viedma, *Phys. Rev. Lett.* **94**, 065504 (2005).
2. F. C. Frank, *Biochim. Biophys. Acta* **11**, 459 (1953).
3. D. K. Kondepudi, R. J. Kaufman, N. Singh, *Science* **250**, 975 (1990).
4. J. H. E. Cartwright et al., *Phys. Rev. Lett.* **93**, 035502 (2004).
5. K. Soai, T. Shibata, H. Morioka, K. Choji, *Nature* **378**, 767 (1995).

First Experiment at National Ignition Facility Focuses on Hydrodynamics of Plasma Jets

Supersonic jets generated by shock waves are common, on vastly different scales, to high-energy astrophysics, inertial-confinement-fusion targets, and nuclear weapons.

As big as a football stadium, the National Ignition Facility (NIF), under construction at Lawrence Livermore National Laboratory, is scheduled for completion in 2009. The \$3.5 billion undertaking will serve an im-

pressive variety of users. When focused on a millimeter-size capsule filled with tritium and deuterium, NIF's 192 laser beams will be able to heat and squeeze it with a 2-megajoule, nanosecond pulse of light (see

the cover of this issue). As the facility's name implies, such a pulse is thought to be powerful enough to ignite a thermonuclear burn in the hydrogen-isotope mix.

The NIF project is administered by the Department of Energy's National Nuclear Security Administration, which oversees the stockpile stewardship program for ensuring the reliability of the nation's nuclear arsenal

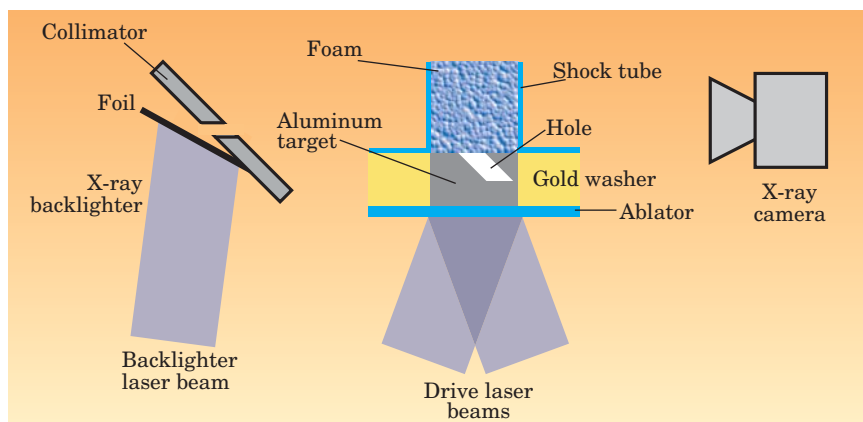


Figure 1. The first physics experiment at the National Ignition Facility uses a 6-kJ nanosecond pulse from two laser beams to ablate the backing on a 0.8-mm-diameter aluminum disk, generating a shock wave that launches a supersonic jet of Al plasma when the wave encounters a cylindrical hole—skewed from the disk's symmetry axis in some shots, as shown here. Propagating into aerogel foam, the evolving jet is backlit by x rays from a foil heated by a third laser beam, and is imaged at several delay times by a pinhole camera. (Adapted from ref. 1.)

in the absence of actual weapons testing. “But to get something as big as NIF through Congress and DOE,” says Livermore deputy associate director Bruce Warner, “a lot of people have to want it to happen” (see *PHYSICS TODAY*, January 2001, page 21). And indeed, stockpile stewardship and other weapons-related programs represent only about half the community of prospective NIF users. The facility’s anticipated ability to trigger thermonuclear ignition is of particular interest to those hoping to develop inertial confinement fusion (ICF) as an energy source.

NIF’s first physics experiment

An experiment reported in the 11 March issue of *Physical Review Letters* highlights yet another, more purely academic role for NIF.¹ The experiment, carried out last fall with the first four operational laser beams, is the first published physics result from the still-unfinished facility. The paper falls under the broad rubric of high-energy-density physics, a rapidly growing field of considerable interest to astrophysicists and materials scientists as well as designers of ICF schemes and weapons.

The experimental group, led by Livermore’s Harry Robey, used the first “quad” of NIF laser beams to create miniature supersonic plasma jets. The hydrodynamic behavior of these submillimeter jets is relevant to the astrophysical mechanisms that create and propagate the enormous jets that appear in stellar and galactic phenomena. A common mechanism at work in the launching of supersonic jets, large and small, is the interac-

tion of a shock wave with a spatial density perturbation in the medium through which the shock is propagating. It produces high-Mach-number jets at layer boundaries inside supernovae and at joints in ICF capsules—two examples whose linear scales differ by 16 orders of magnitude.

The hydrodynamic equations that govern the evolution of jets and the mixing of layers are the same to the extent that the relevant scale-invariant parameters—for example, Reynolds number, Mach number, and Prandtl number—that characterize the relative importance of viscosity, inertia, turbulence, heat transport, and magnetism, are the same. Although magnetic fields are thought to play an important role in driving astrophysical jets, they were not involved in the NIF experiment.

In the experiment, two of the quad’s four laser beams directed a 6-kJ nanosecond pulse of near-UV light at the ablative backing of an aluminum disk 0.8 mm in diameter (see figure 1). The ablation sent a 40-megabar shock front through the 0.25-mm-thick disk. Halfway through the disk, the front encountered a cylindrical hole that was axial in some of the experiment’s laser shots and skewed (as in figure 1) in others. The front’s encounter with the hole launched a 30-km/s jet of Al plasma into carbon aerogel behind the disk. In the foam, the evolving jet was backlit by x-rays from a metal foil illuminated by the quad’s third laser beam and imaged at several delay times by a pinhole x-ray camera (see figure 2).

NIF’s ultimate ability to generate megajoule pulses, exquisitely

Metals & Materials from

www.goodfellow.com

**Faster
Better
Cheaper**

Find what you
need quickly

48,000 items
plus detailed
technical data

5% discount on
online orders

Goodfellow

Metals • Alloys • Composites • Polymers
1-800-821-2870
Fax 1-800-283-2020
info@goodfellow.com
©2001 Goodfellow Corporation

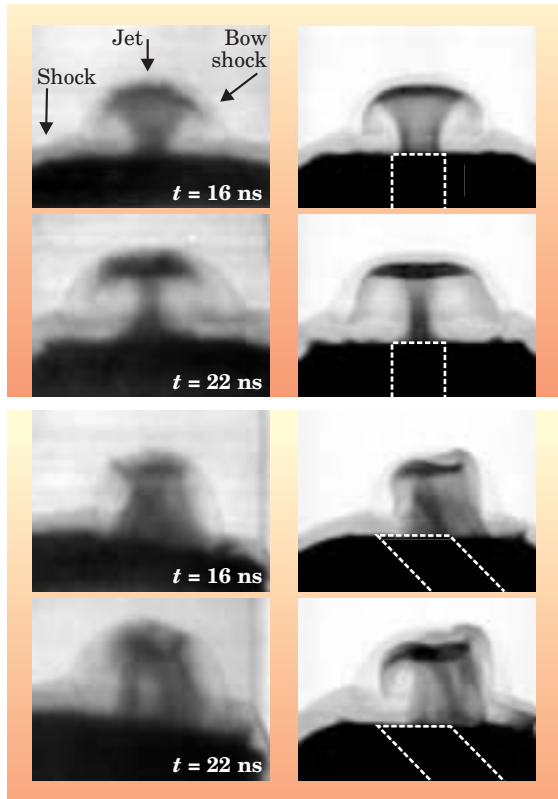


Figure 2. Backlit x-ray images (left) and computer simulations (right) of the supersonic jets of aluminum plasma propagating through aerogel foam in the NIF experiment. The Al plasma absorbs x rays more strongly than the foam. Each dashed outline indicates the 0.16-mm-diameter cylindrical hole in the Al disk whose interaction with a laser-generated shock wave launched the jet. Shown in the bottom rows is an experimental shot with a skewed hole that makes the situation truly three-dimensional. The jets are imaged 16 and 22 ns after the laser pulse that initiated the shock wave. The shock front, which leads the jet as a bow wave, is also seen as a pedestal around the jet's base in the foam just above the Al disk. (Adapted from ref. 1.)

tailorable for pulse durations as long as 30 ns, is far beyond the capacity of any laser facility now in operation. But the 6-kJ shots of the first published experiment are comparable to what's already been done in similar jet hydrodynamics experiments at the University of Rochester's Omega facility,² NIF's Nova predecessor at Livermore, at other laser complexes worldwide, and in Z-pinch machines at Sandia National Laboratories and Imperial College London.³

Hydrodynamics in 3D

A new feature of the NIF experiment is the skewed hole that breaks cylindrical symmetry and thus requires a truly three-dimensional simulation code to predict the result. An important aspect of all the hydrodynamics experiments has been the validation of elaborate hydrodynamic computer codes to predict and explain supersonic jets and other instabilities. Validation of such hydrodynamic codes is essential for understanding high-energy astrophysical phenomena, designing ICF capsules, and maintaining the nation's nuclear arsenal (see the article by Douglass Post and Lawrence Votta in *PHYSICS TODAY*, January 2005, page 35).

More important, perhaps, than the modest 3D innovation of the new experiment and its reassuring code simulation is the message it sends to NIF's funders and potential users—that the

facility, even at this early stage, can produce useful scientific results.

Figure 2 compares the x-ray images of the jets, 16 and 22 ns after the ablation pulse, with the results from a 3D hydrodynamic simulation code called HYDRA, which a Livermore group led by Michael Marinak has been developing since 1994. Extensively used in ICF studies, HYDRA is a Lagrange–Euler hybrid. The Lagrangian treatment of hydrodynamics, in which the coordinates follow individual fluid elements, works best when the flow is reasonably smooth. With increasing turbulence, it becomes easier to take the more field-theoretic Eulerian approach, which describes the fluid in a coordinate system fixed in space.

For the skewed hole, the 3D simulation correctly predicts the offset of the jet's axis from the hole's downstream end. But the pictures alone don't tell the whole story. From detailed analysis of the x-ray images, Robey and company determined the time evolution of the jet's mass (6 μg of Al plasma after 22 ns in the skewed case) as well as its velocity and horizontal displacement with uncertainties of only about 10%. The measurements turned out to be in quite good agreement with the predictions of the 3D code.

The experimenters did, however, find departures from the simulations in small-scale flow patterns and mass

distribution within the jets. That's because the system's very high Reynolds number (about 10^7) implies significant turbulence on scales too small for the available computing power. The differences between measurement and simulation are more pronounced in the 3D skewed-hole shots, because the axial symmetry of the 2D configuration delays the onset of the full-blown vorticity field.

“Our results should contribute to understanding the complex hydrodynamics of supernovae and ICF capsules,” says Robey. The formation of supersonic jets in the collapsing cores of massive stars is thought to trigger highly nonspherical type II supernova explosions.⁴

Back to construction

The jet experiment was not the only accomplishment of NIF's first quad. Other experiments done last fall, involving laser–plasma interactions and the conversion of laser energy to isotropic x-ray heating by means of hohlraum cavities, will be published soon.

As construction accelerates, however, new experiments are unlikely in the near future. For fiscal year 2005, the NIF construction and experimental budgets suffered cuts that are not recovered in President Bush's proposed FY 2006 budget (see page 31 of this issue). “So we're busy rebaselining the construction schedule,” says Warner. “We're still evaluating whether physics experiments should resume before the facility is completed in 2009.”

Eighty percent of NIF's large-scale construction is already completed, and most of the optical glass required for the 192 10-kJ pulsed lasers is ready for installation. In the first experiments, the lasers were run well below their nominal limits. The neodymium dopant in the ultrahigh-quality phosphate glass provides the atomic lasing transitions. The lasers are pumped by flash lamps powered by a 400-MJ capacitor bank.

In operation, the lasers get so hot that they can be fired on target only a few times a day. That's just one of the problems a functioning ICF power plant would have to overcome.

Bertram Schwarzschild

References

1. B. E. Blue et al., *Phys. Rev. Lett.* **94**, 095005 (2005).
2. J. M. Foster et al., *Phys. Plasma* **9**, 2251 (2002).
3. S. V. Lebedev et al., *Astrophys. J.* **616**, 988 (2004).
4. A. M. Khokhlov et al., *Astrophys. J.* **524**, L107 (1999). ■