NIF Project Completed; Ultraviolet Energy Exceeds One Megajoule

Just before 2:00 A.M. on Feb. 26, National Ignition Facility (NIF) Control Room operators set in motion the countdown they have been using for months to fire NIF’s laser beams. The number of beams had been inching up every few days, as the installation of optics was completed on a growing number of beamlines.

Early that morning, they were finally ready to test all of them. It was the first time the entire system of 192 beams was to converge simultaneously in the 10-meter-diameter target chamber.

The countdown was routine, and the shot went off without a hitch, sending an average of 420 joules of ultraviolet laser energy racing through each beamline’s final optics to their ultimate destination.

“This is a major milestone for the greater NIF team, for the nation and the world,” said Ed Moses, Lawrence Livermore National Laboratory’s principal associate director for NIF & Photon Science. “We are well on our way to achieving what we set out to do – controlled, sustained nuclear fusion and energy gain for the first time ever in a laboratory setting.”

“NIF is well on its way to producing breakthroughs in science never imagined”

—Ed Moses

This photo montage of the target chamber of the National Ignition Facility combines three floors, spanning more than 50 feet from top to bottom.

Photo: Jacqueline McBride

January/February 2009
This Month in Photons & Fusion

NIF Project Completed; Ultraviolet Energy Exceeds One Megajoule — 1

AAAS Symposium Explores Origin and Evolution of Planets — 2

Studying Diamond at Extremely High Pressures — 3

Determining the Limits of Large-mode Optical Fibers — 3

A Programmable Spatial Shaper for NIF — 4

Photons & Fusion is a bimonthly review of science and technology at the National Ignition Facility & Photon Science Principal Directorate, Lawrence Livermore National Laboratory. For more information, submit a question.
A month before the landmark shot, NIF had met all of its project completion criteria except for official certification of project completion by the Department of Energy, which is due by March 31.

And only two weeks after the first 192-beam shot, on the morning of March 10, NIF became the first fusion laser in the world to break the megajoule barrier by delivering 1.1 million joules of ultraviolet energy to the target chamber center.

When all NIF lasers are fired at full energy, they will focus 1.8 megajoules of ultraviolet energy on the target in a shaped laser pulse lasting only a few nanoseconds, equivalent to 500 trillion watts of peak power – more than the peak electrical generating power of the entire United States.

This is considered more than enough energy to fuse the hydrogen isotopes of deuterium and tritium in the target into helium nuclei (alpha particles) and yield considerably more energy in the process than required to initiate the reaction.

“NIF is well on its way to producing breakthroughs in science never imagined,” Moses said. “Through our readiness testing we will see glimpses of what that future will bring.”

The facility will hold an official dedication ceremony May 29. Scientific experiments will start as soon as this spring, including high-energy-density studies in support of the National Nuclear Security Administration (NNSA) Stockpile Stewardship Program. The program ensures the safety and security of the nation’s nuclear weapons stockpile.

Later in the year, the National Ignition Campaign, a multi-institutional effort that will take NIF from a construction project to routine operations as a highly flexible, high-energy-density science facility, will begin conducting a series of shots to prepare for the first ignition experiments, planned for late 2010.

Along with its stockpile stewardship responsibilities, NIF also will be a key player in providing energy security for the United States. By demonstrating the ability to attain fusion ignition in the laboratory, NIF will lay the groundwork for future decisions about fusion’s long-term potential as a safe, virtually unlimited energy source. Fusion, the same energy source that powers the stars, produces no greenhouse gases and is environmentally more benign than fossil-fuel or nuclear-fission-based energy.

NIF also is an important tool for astrophysicists engaged in the study of how materials change when they are subjected to the tremendous gravitational pressures inside planets (see related articles below).

**AAAS Symposium Explores Origin and Evolution of Planets**

A symposium on the origin and evolution of planets, organized by LLNL’s Gilbert (Rip) Collins and NIF collaborator Raymond Jeanloz of the University of California, Berkeley, was a highlight of February’s annual meeting of the American Association for the Advancement of Science in Chicago.

The symposium ranged from descriptions of the formation of terrestrial planets to speculation about the presence of Earth-like planets in neighboring solar systems, based on the recent discovery of more than 300 extra-solar planets. Jeanloz and other speakers discussed new experimental techniques and results that could shed light on the formation and composition of gas giants like Jupiter and Saturn and “super-Earths” – extra-solar planets five to 20 times more massive than Earth.

In the symposium and a news conference, the panelists noted that facilities like NIF, which will be able to re-create the extreme pressures in the deep interiors of giant planets, will give experimenters unprecedented tools to study these environments, which challenge current theoretical understanding of condensed matter. Collins said one purpose of the symposium was to bring researchers in a variety of fields related to astronomy, materials science and planetary physics together to share their insights and steer emerging capabilities toward understanding the range of possible host planets for life.

For more information, see the New Scientist article, “Mega-laser to probe secrets of exoplanets” (http://www.newscientist.com/article/mg20126975.400-megalaser-to-probe-secrets-of-exoplanets.html).
Determining the Limits of Large-mode Optical Fibers

Researchers in the Photon Science & Applications Program have determined the limits to the energy that can be sustained by circularly symmetric optical fiber modes, a finding that could lead to new approaches to manufacturing robust and scalable fiber laser technology.

In a paper presented at the January SPIE Photonics West conference in San Jose, researchers Michael J. Messerly, Paul H. Pax, John E. Heebner, Arun K. Sridharan and Jay W. Dawson described several bounds to the scalability of large-mode optical fibers, including a mode-spacing-area product that ultimately determines the manufacturability of a fiber.

“There are two challenges here,” he says. “The first is that as we increase the size of the mode we want to excite, it necessarily becomes more similar to the modes we don’t want to excite, so fiber manufacturers must become more adept at controlling the refractive indices of glasses that comprise their fibers.”

Research by Messerly and his colleagues quantified the tradeoffs involved and concluded that currently achieved modes, which can sustain powers of about five kilowatts, require refractive index control on the order of $10^{-4}$, or roughly the index difference between air and vacuum. “This is impressive,” Messerly says. “To create a fiber that can sustain 50 kilowatts, though, would require a 10-times larger mode and necessarily a 10-times reduction in index tolerance, to $10^{-5}$. This is difficult to even measure.”

Studying Diamond at Extremely High Pressures

The cores of Jupiter, Saturn, and many extra-solar planets are believed to contain solid material at pressures greater than one trillion pascals (10 million times Earth’s atmospheric pressure). Diamond-anvil cells typically are used to investigate the behavior of solids at extreme pressures.

These cells, however, normally can withstand pressures of up to only 300 billion pascals (GPa) due to the mechanical strength limit of diamond. Shock compression can produce significantly higher pressures than static experiments, but shocks produce a significant temperature increase, so that above a few hundred GPa only properties of the fluid phase can typically be explored. Solid-state theories significantly above this range are untested.

In a paper published Feb. 18 in Physical Review Letters (DOI: 10.1103/PhysRevLett.102.075503), LLNL researchers describe a new ramp-wave compression technique (sometimes called quasi-isentropic compression) that allows them to study diamond at 800 GPa, more than five times higher than previously achieved ramp compression pressures and the highest-pressure solid equation-of-state data ever collected.

The diamond sample is ablated with X-ray lasers that are ramped up monotonically until a uniform compression wave is produced. This wave propagates faster than the thermal wave caused by the laser ablation, resulting in compression without heating and enabling the study of solids into the trillion-pascal regime.

The researchers were able to compress diamond to a peak pressure of 1,400 GPa. Diamond stress versus density data were reported to 800 GPa and suggest that the diamond phase of carbon is stable and remains strong up to at least this stress level. Applying these techniques with an optimized 30-nanosecond pulse shape on the higher-energy NIF laser system will potentially ramp-compress a broad range of solids to several trillion pascals.

Contributing to the paper were David K. Bradley, Jon H. Eggert, Raymond F. Smith, Shon T. Prisbrey, Damien G. Hicks, David G. Braun, Juergen Biener, Alex V. Hamza, Robert E. Rudd, and Gilbert Collins.
Messery said the second challenge is to devise a waveguide structure that allows large modes to be coiled without loss. Using a truck winding its way down from the peak of the San Francisco area’s Mt. Diablo as an analogy, Messery asked, “Is it possible to make a heavy, high-capacity truck – a large mode – that can race down the twists and turns of Mt. Diablo faster than a low-capacity bicycle – a small mode?

“We believe that if a careful apples-to-apples comparison is made – and we presented normalized parameters for making such comparisons – then the answer, for a circularly symmetric mode, is ‘no’ – the cornering speed is dictated, to a great extent, by the mass of the vehicle and is not appreciably affected by, say, the stickiness of the truck’s tires.

“Our conclusion is important,” he said, “since attempts continue to be made to design and fabricate large, circularly symmetric modes that can be packaged as tightly, or nearly so, as the modes of telecom-like optical fibers. We believe that the right approach is to make the fiber’s mode elliptical, rather than circular – to, in effect, reduce its center of mass on bending – the same solution you’d use with the truck on Mt. Diablo.” For more information, see “Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power,” in Optics Express, Vol. 16 Issue 17, pp.13240-13266 (2008) (doi:10.1364/OE.16.013240).

A Programmable Spatial Shaper for NIF

In the low-fluence, low-power region upstream in the NIF amplifier chain, it is possible to locate small obscurations that can protect defect sites on downstream optics subjected to much harsher conditions.

In the past year, static chrome masks, each containing a “blocker,” have been introduced into the preamplifier modules (PAMs) feeding some of the beamlines on NIF. This approach will continue to be used for the near term. A programmable means for introducing this type of blocker, however, would provide significant flexibility for NIF operations. Work is now under way to develop a programmable spatial shaper (PSS) that can dynamically create these blockers.

The PSS is based on an optically-addressable liquid crystal light valve. In this two-stage system, supplied bitmaps are first imprinted on an auxiliary incoherent address beam derived from a blue light emitting diode (LED) source. The address beam is then projected on a large, single-pixel liquid crystal light modulator containing a photoconductive layer. The photoconductive layer enables bright and dark regions of the address beam to control the transmission of the valve for the coherent beam at 1,053 nanometers.

Using this technique, PSS developers are able to realize arbitrarily defined masks with smooth shapes, high transmission (>90 percent) and low wavefront distortion (<0.5 waves). The image fidelity is evidenced by the high-resolution NIF beam logo shown above. Retrosits of the 48 NIF PAMs with this new upgrade package will begin this summer.

PSS developers are John Heebner, Mark Franks, Mike Borden, Kim Christensen, Steve Hunter, Ed Marley, Tracy Budge, Robert Bickel, Lynn Seppala, Nan Wong, Eddy Tse, Gordon Brunton, Marcus Monticelli, Justin Wolfe, James Embree, Peter Thelin, Dan Walmer, Sham Dixit, Mark Henesian, Clay Widmayer, Chris Haynam, and Dave Smauley.