Nuclear diagnostics help pave way to ignition on NIF inertial confinement fusion

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Target area operator Bill Board removes a neutron imager snout from a diagnostic instrument manipulator. The NIF neutron imaging system produces an image of the source distribution of the primary neutrons produced by fusion reactions and the lower energy neutrons that are downscattered in energy by the compressed fuel in an ICF capsule. Credit: Lawrence Livermore National Laboratory

At its peak, a NIF inertial confinement fusion (ICF) implosion lasts about 100 trillionths of a second. The imploded fuel is a hundred millionths of a meter in diameter and as much as eight times denser than lead. The center of the imploded capsule is a few times hotter than the core of the sun.

Developing a clear understanding of exactly what's happening in a NIF implosion under those extreme conditions is one of the biggest challenges researchers face as they work toward achieving fusion ignition on the world's largest and highest-energy laser system.

To help meet that challenge, Lawrence Livermore National Laboratory (LLNL) and its partner laboratories and universities have designed and built an extensive suite of more than a dozen nuclear diagnostics, with more on the way.

"What you'd like when diagnosing the implosion is to know everything about the imploding plasma," said LLNL physicist Dave Schlossberg.

"The nuclear diagnostic suite tries to tackle different parameters that you can measure independently," he said. "The neutron imaging system measures the spatial distribution of the implosion. Neutron time-of-flight diagnostics measure average energy and drift velocity. And gamma reaction history measures emission with respect to time. By assembling that information, we piece together a better picture of what's going on in the implosion."

"Some of the diagnostics 'cross-talk' with each other," added physicist Kelly Hahn. "Some provide different pieces (of information), some have similar pieces and we can bring them all together to assemble a more comprehensive picture. If you want to achieve ignition, nuclear diagnostics are crucial."

Clues to performance

Among the key factors that provide clues to implosion performance are the neutron yield, the ion (plasma) temperature and the downscatter ratio—the ratio between the number of high-energy neutrons and lower-energy neutrons that have been scattered through interactions with the hydrogen isotopes in the fuel, an indication of fuel density and distribution of the cold fuel surrounding the hot spot.

The magnetic recoil spectrometer (MRS) was developed by MIT and the University of Rochester's Laboratory for Laser Energetics to measure the neutron spectrum from an implosion by measuring proton (or deuteron) energy knocked out from a plastic foil held close to the implosion. MRS is a critical diagnostic for measuring the aerial density and yield of imploded targets, helping researchers quantify how well the shot is approaching ignition conditions. Credit: Lawrence Livermore National Laboratory

Also important are bang time—the time of peak neutron emission that characterizes the speed of the implosion—and burn width, the length of time the implosion is producing neutrons.

All these parameters, and others, are assessed by nuclear diagnostics.

"The nuclear diagnostics basically are the only diagnostics that are really measuring the fuel density and temperature," said Nuclear Diagnostics Group Leader Alastair Moore. "And they're completely critical to understanding how well we assembled the fuel and how close to ignition we are."

In NIF ICF experiments, up to 192 powerful laser beams heat a cylindrical X-ray "oven" called a hohlraum. The X-rays compress the hydrogen isotopes, deuterium and tritium (DT), partially frozen inside a tiny capsule suspended within the hohlraum. If the density and temperature are high enough and last long enough, the fuel will ignite and generate a self-sustaining thermonuclear reaction that spreads through the fuel and releases a large amount of energy, primarily in the form of high-energy neutrons.

The implosion process creates temperatures and pressures similar to those found inside stars, giant planets and nuclear detonations. NIF is a key component of the National Nuclear Security Administration's Stockpile Stewardship Program, and experiments on NIF advance scientific research into high energy density (HED) science including astrophysics, materials science and ICF.

Unknown unknowns

A particular value of NIF's nuclear diagnostics is their ability to help answer questions that researchers didn't even know they had—what scientists call "unknown unknowns."

Recently, for example, the array of four neutron time-of-flight detectors positioned around the target chamber revealed that the tiny hot spot at the center of the implosion was drifting at a speed of about 100 kilometers per second—an indication of implosion asymmetry, a major cause of degraded performance.

Engineer Jaben Root installs a real-time neutron activation detector assembly into a hole in the NIF target chamber. Neutron activation diagnostics measure the yield of unscattered neutrons from a NIF implosion. They are installed at 48 locations on the target chamber, including 27 locations where holes had to be drilled into the gunite (hard concrete) that surrounds the target chamber and provides the first layer of shielding from neutrons produced from the fusion reactions in target experiments. Credit: Lawrence Livermore National

"We originally had two spectrometers," said physicist Ed Hartouni, "and adding a third spectrometer gave us the capability to see motion and to measure the drift velocity of the hot spot, which was not expected at all. It actually took quite some time to be accepted, this interpretation of what these detectors were telling us.

"They revealed something that was going on in the implosion that we didn't anticipate, that nobody had expected," he said. "That the hot spot could move—it was quite surprising."

"We actually have a fifth spectrometer coming on line," noted Moore, "which will give us an even better ability to understand whether the hot spot is moving because we've driven it asymmetrically, or because the capsule is asymmetric, or the hohlraum is asymmetric. All these failure modes that can lead to poor implosion performance can be diagnosed directly by having multiple spectrometers looking at the same implosion."

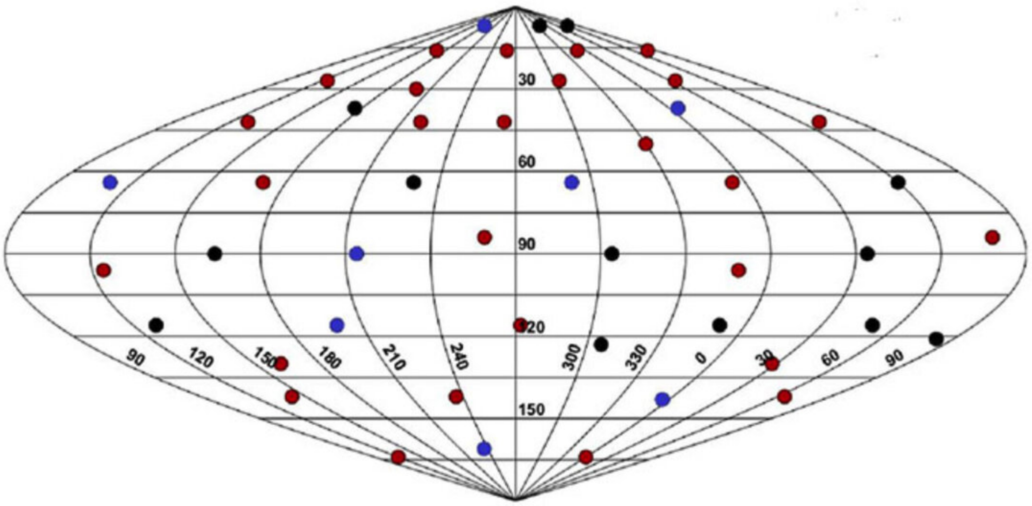
And that's not all. In a collaboration led by the Los Alamos National Laboratory (LANL) Neutron Imaging Team, researchers from LANL, LLNL and the Laboratory for Laser Energetics (LLE) at the University of Rochester recently added a third neutron imaging system, NIS3, designed to provide a 3-D image showing the size and shape of the burning DT plasma during the ignition stage of an implosion.

The hot-spot size and fuel asymmetry are determined from the image of the primary, or high-energy, neutrons, and the cold fuel areal density, known as rho-R, is inferred from the downscatter ratio. Areal density is an important factor in the final configuration of the fuel for obtaining ignition and fusion burn.

"As NIF moves toward higher performance, understanding the three-dimensional nature of these implosions becomes critical," said LLNL physicist David Fittinghoff. "With the two previous neutron imaging sight lines (on the equator and the north pole of the target chamber) we had to make an assumption about the symmetry of the implosion.

"Now with the new NIS3 we have three orthogonal lines of sight with which to reconstruct a volume of fusing plasma," he said. "An analogy might be the difference between seeing a painting of a man and actually walking around his sculpture."

Along with improving neutron imaging, NIS3 also provides a line of sight for imaging gamma rays produced by inelastic scattering of the fusion neutrons from carbon in the target capsule material remaining during an implosion. This could help researchers determine the amount and effect of the mixing of capsule material with the fusion fuel, a known source of performance degradation.



Distribution of RT-NADs detectors on the NIF target chamber. The red dots indicate locations where holes were drilled to insert the detectors. Credit: Lawrence Livermore National Laboratory

Yet another major diagnostics upgrade was completed in 2017 with the installation of an array of 48 real-time neutron activation detectors, or RT-NADs, at strategic locations around the target Chamber.

Earlier NADs, called flange NADs, worked when unscattered neutrons activated a sample of zirconium. The activated samples were removed from the chamber and the activation level was determined using nuclear counting techniques elsewhere on the site. Activation of the real-time NAD detectors is monitored in situ, providing better sampling of the angular distribution of the unscattered neutron yield with much more rapid turnaround and at a significantly lower operating cost.

The system provides near real-time time determination of the neutron fluence distribution. It operates over two to three orders of magnitude of neutron yield, providing overall yield estimates precise to 2 percent or better.

"Neutron yield varies around the chamber because you have different thicknesses of the fuel in the compressed core of the explosion," Moore explained. "RT-NADs is primarily a way for telling how the fuel is distributed around the hot spot when the capsule goes bang."

"It has twice the number of detectors and five times the sensitivity" of the flange NADs system, noted diagnostic physicist Richard Bionta, responsible scientist for the RT-NADs system. "In the old system, we only had one detector. Each of the 20 pucks were placed in the detector one at a time, so that took five days to go through. (The RT-NADs) are certainly a lot better than the way we used to do it."

"Richard spent more than two years developing the capability to manage that stream of data," added Moore. "You've got 48 detectors that are reading out every 10 minutes and producing terabytes of data. You try to analyze that and piece that picture back together again, of what happened with the shot."

Provided by Lawrence Livermore National Laboratory

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