TARGETING LASERS AS SOURCES

LAWRENCE Livermore National Laboratory has a rich history in laser research since the pursuit of inertial confinement fusion (ICF) began decades ago. In addition to Livermore's December 2022 ignition achievement at the National Ignition Facility (NIF), the Laboratory's laser science research has led to several significant technological advances, including designing and building ultraintense, high-average-power lasers. Recent developments using these short-pulse lasers involve efficiently generating beams of particles—electrons, protons, neutrons, x rays, and muons. The types of particles produced depend on the strength, shape, and pulse of the laser beam, the materials used in the laser target (a tiny capsule holding matter that is heated to more than 3 million degrees Celsius), and the interaction between the laser and those materials.

Laser-driven particle sources are opening frontiers in inertial fusion energy, high-energy-density (HED) science, material science, radiography, medical therapies, and non-destructive evaluation. The Laboratory is researching and testing methods to use lasers as particle sources in a more efficient manner and to better understand what parameters impact the stability and repeatability for different applications.

From left: Lawrence Livermore team members on the Intense and Compact Muon Sources for Science and Security (ICMuS2) project, Drew Willard, Brendan Reagan, and Issa Tamer, work on a Livermore-led project to advance muon-based imaging in a project funded by the Defense Advanced Research Projects Agency. Photo by Jason Laurea.

Within Livermore's National Ignition Facility and Photon Sciences (NIF&PS) program, Advanced Photon Technologies (APT) addresses the national security mission by providing fundamental laser and particle research, designing and building laser systems, and engineering system integration using x rays, neutrons, and muons.

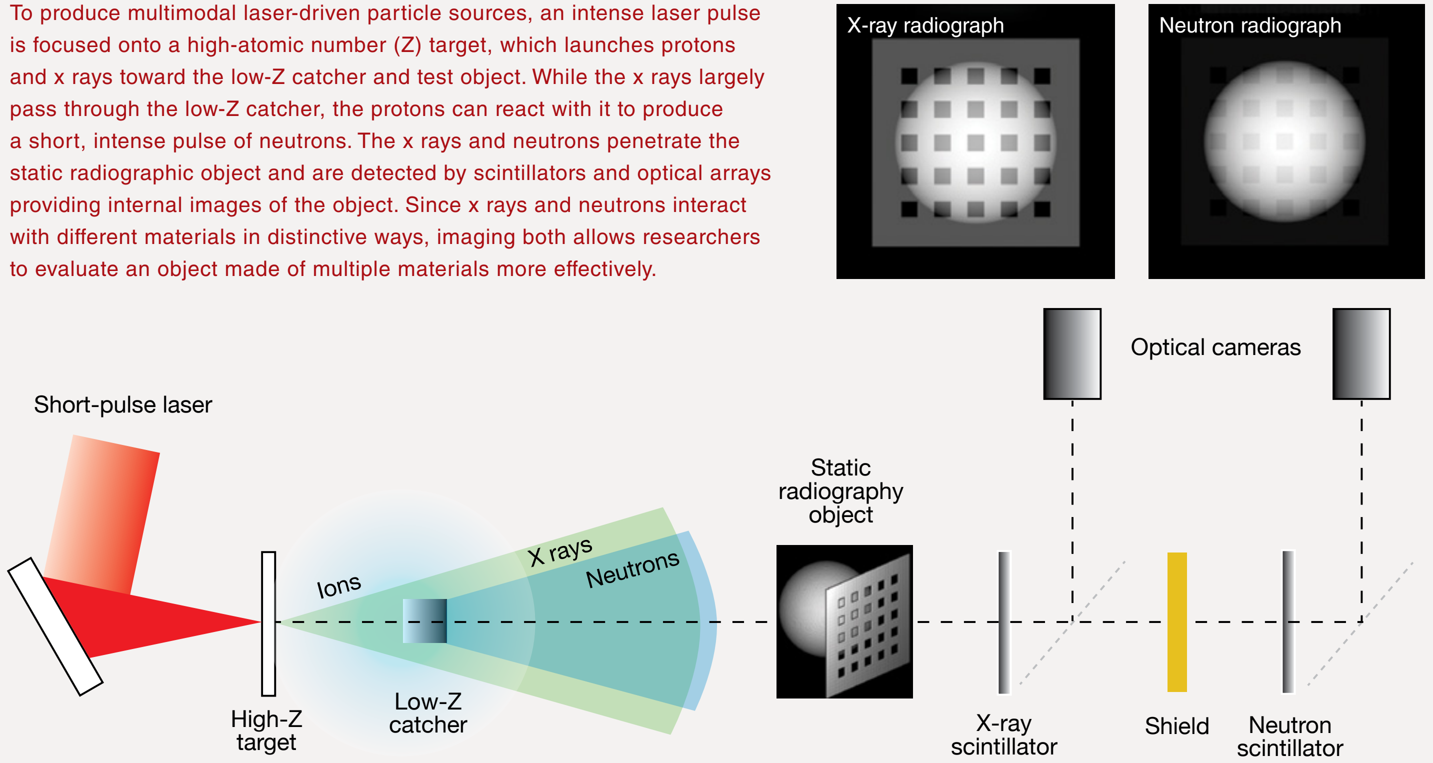
Livermore's expertise in relevant laser systems, capabilities for studying the physics of laser–matter interaction, and the mission for advancing laser research enable the Laboratory to lead the world in laser-driven particle sources. "Working on particle sources to support Livermore's mission is a very consequential role for us," says James McCarrick, program director for the HED and Photon Systems element in NIF&PS. "We have expertise to generate laser-driven particle sources and to then work in the application space, both for the National Nuclear Security Administration, other government entities such as the Defense Advanced Research Projects Agency [DARPA] under the Department of Defense, and the broader research community."

Radiography Applications

Laser-driven sources at Livermore support ICF research at NIF, the world's most energetic laser, which contains the Advanced Radiographic Capability (ARC), the world's most energetic short-pulse laser. ARC provides a diagnostic tool to see through the fast moving, small feature, and dense NIF target, evaluating the shape of the target as it compresses and examining material response to stresses at extreme conditions. ARC is a highly capable driver of high-energy, high-flux particle beams to probe or generate HED environments. The ARC laser beamlet interacts with a thin metal foil to generate fast electrons, which pass through the foil and create an electric field that accelerates protons from the residual layer to form a proton beam that can then be used to image material or electromagnetic fields. (See *S&TR*, September 2018, pp. 4–11.)

Livemore researchers are using ARC to develop laser-based x-ray and neutron sources for radiography, an imaging technique that uses x rays, gamma rays, or similar ionizing or non-ionizing radiation to view the internal form of an object. Radiography is used to conduct x-ray imaging of humans and to inspect flaws or cracks within materials that may not be visible to the naked eye. Among other uses at Livermore, radiography using laser-produced particles offers new opportunities for non-destructive evaluation of weapons components and the complex internal structures of 3D-printed materials.

Livermore researcher Jackson Williams is exploring multimodal radiography, a capability in which the laser source produces two particles at the same time to simultaneously obtain x-ray and neutron radiographs. Williams leads a Laboratory-Directed Research and Development (LDRD) project testing the feasibility of using large lasers as multimodal radiography drivers for images of dynamic objects as well as smaller, high-repetition rate lasers for static imaging, in which upwards of 1,000 laser shots can be fired in 1 minute. Using ARC and the Jupiter Laser Facility's Titan Laser, which delivers over 10^{18} watts per square centimeter, combined with a target for x-ray and ion generation and a low-atomic number (Z) converter for neutron generation, Williams and his team are testing how x-ray and neutron radiography can be optimized for a range of potential applications.



To produce multimodal laser-driven particle sources, an intense laser pulse is focused onto a high-atomic number (Z) target, which launches protons and x rays toward the low-Z catcher and test object. While the x rays largely pass through the low-Z catcher, the protons can react with it to produce a short, intense pulse of neutrons. The x rays and neutrons penetrate the static radiographic object and are detected by scintillators and optical arrays providing internal images of the object. Since x rays and neutrons interact with different materials in distinctive ways, imaging both allows researchers to evaluate an object made of multiple materials more effectively.

Laser-driven mega electronvolt (MeV) x rays and neutrons' distinctive properties, short pulse duration, flexible geometry, and favorable energy scaling make the multiparticle approach promising. The different particles have distinctive interactions with different materials, enabling Livermore researchers to simultaneously evaluate multiple portions of a component or part made of multiple materials, such as plastics, stainless steel, or other metals, rapidly and at high resolution.

The challenges that limit lasers as particle sources vary considerably based on the details of the desired application. Livermore researcher Matt Hill emphasizes that these limitations usually involve having to choose where to focus the greatest effort among laser control and performance, target design, target build, and diagnostics. "If we want a bright, hard x-ray source, for example, we might make our target very thick to efficiently convert the electrons into bremsstrahlung x rays, but this approach will result in very broad-band emission and will also create significant target debris that could cause problems elsewhere," says Hill.

High-energy "hard" x rays are more penetrating and useful for radiography of dense, high-Z objects than lower-energy "soft" x rays, which are useful for providing contrast in images of low-density objects. Bremsstrahlung x rays, or "braking radiation," are generated as a charged particle decelerates while passing through an object, in this case laser-accelerated electrons slowing down within the target. Thinner targets are better proton sources but with less material to stop the electrons, result in lower numbers of x rays. Smaller targets produce less debris, but the trade-off is that laser alignment, target fabrication, and delivery are more difficult and less repeatable. What might be feasibly demonstrated in an experimental setting does not guarantee that the laser-driven source would be attractive in industrial applications, and projects such as Williams' LDRD are crucial in finding where the best trade-offs are in such a complex, interdependent design space.

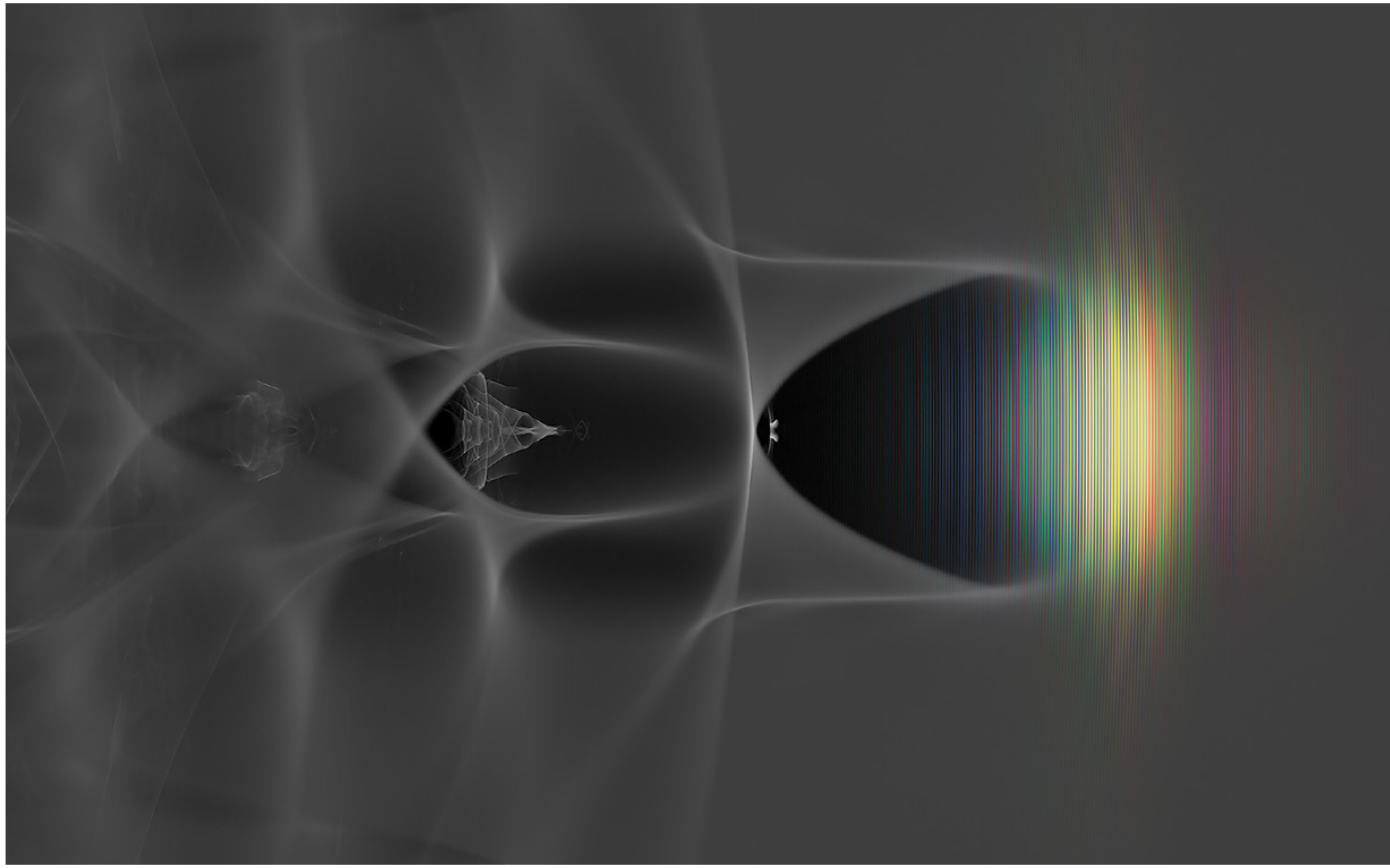
Hill and his team have worked to address these challenges using machine learning tools to tune the laser pulses through experiments conducted at the Extreme Light Infrastructure (ELI) Beamlines Facility in the Czech Republic. Firing more than 3,500 laser shots over a three-week period, Hill's team identified patterns in the protons, heavy ions, and plasma interactions coming out of the thin foil target to make future particle production processes more efficient and repeatable. As the laser fires every five seconds and generates significant amounts of data, deploying machine learning tools offers an efficient way to sort and analyze data and a useful means of highlighting important patterns. "By handing over control of just a few of the dials to our machine learning algorithm, we've found laser settings that reliably produce more protons, for example. Most importantly, we're seeing that the optimization routine is working," says Hill. Looking ahead, Hill expects this kind of optimization will be applied to many other laser-driven sources and will become more powerful as researchers identify the best set of controls to apply to the machine learning routines.

Advancing Muon Imaging

Muon imaging is another promising application of laser-driven particle sources. Livermore is leading an ambitious project with partners from universities, industry, and the national laboratory system, on the Intense and Compact Muon Sources for Science and Security (ICMuS2) project—part of DARPA's Muons for Science and Security program. The program aims to create a new, compact laser-driven particle source of deeply penetrating subatomic particles called muons, which are similar to electrons but about 200 times heavier. At high energy, muons can pass through dozens to hundreds of meters of water, solid rock, and soil. Muon imaging has already been used to see inside large, dense structures such as nuclear reactors and Egypt's Great Pyramid of Giza using naturally occurring muons generated from cosmic rays.

Producing muons requires a very high-energy, giga-electronvolt (GeV) particle source. The ICMuS2 initiative is employing laser–plasma acceleration (LPA) to initially create 10-GeV particles in the space of tens of centimeters, compared to hundreds of meters needed for state-of-the-art linear accelerators. The program's goal is to develop scalable and practical processes to produce conditions that can create muons exceeding 100 GeV through innovations in LPA, target design, and compact laser-driver technology.

The ICMuS2 project, running up to four years and split across two phases, aims to develop a technical design for a portable, laser-based muon emitter. The designers need to achieve orders of magnitude greater flux than is possible using naturally occurring muons for imaging. Brendan Reagan of the APT program is leading ICMuS2, a partnership involving world leaders in laser acceleration and experiments, high-power laser development, systems engineering, and high-energy physics. In addition to Livermore, the team includes: the ELI European Research Infrastructure Consortium at the ELI Beamlines Facility; Colorado State University (CSU); the University of Maryland; Lockheed Martin; XUV Lasers; and Lawrence Berkeley National Laboratory.



The image above simulates laser–plasma acceleration (LPA) used to create 10 gigaelectron-volt (GeV) particles in the space of tens of centimeters. An ultra-intense short laser pulse accelerates electrons (right), which are propagated through the laser plasma (left). The ICMuS2 project aims to use LPA to produce conditions that can create muons exceeding 100 GeV.

In October and November 2023, the ICMuS2 team completed a successful first experimental campaign on CSU's Advanced Laser for Extreme Photonics, a petawatt-class ultra-short-pulse, titanium-doped sapphire laser system. "Great progress was made on many fronts, including electron acceleration and laser wakefield acceleration electron-beam-driven muon generation," says Reagan. "The ICMuS2 project is off to a strong start, and initial results are very exciting."

The results from the first experimental campaign at CSU included the acceleration of electrons to 6–7 GeV in an all-optical setup at high repetition-rate and the demonstration of a long series of multi-GeV beams. The team employed these robust high-energy electron beams to make a preliminary measurement consistent with the production and detection of laser-produced muons and also generated electron–positron pairs. These results were confirmed in a second experimental campaign that concluded in April 2024.

Laser technology has been one of Livermore's distinctive strongpoints for more than 50 years, from developing the concept of ICF to NIF's milestone of fusion ignition. (See *S&TR,* April/May 2022, pp. 4–15.) The Laboratory is constantly forging ahead to new frontiers in laser research, and research in laser-drive particle sources offers many new opportunities for advancements in inertial fusion energy, HED science, radiography, and imaging.

—Jon Kawamoto

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