LLE and General Atomics: A Partnership for the Future

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General Atomics

The Three-Decade Relationship has been a High-Impact Influence on Inertial Fusion Research
For a collaboration that is often measured in microns, it is a bit ironic that the Laboratory for Laser Energetics (LLE) and General Atomics (GA) are more than 2500 miles apart. LLE was established in 1970 as a center for the investigation of the interaction between matter and intense laser radiation (Fig. 1). The development of a series of high-powered, neodymium-glass laser systems at LLE (DELTA, ZETA, and the 24-beam OMEGA) eventually led to the 60-beam OMEGA Laser System. The 60-beam OMEGA laser has been operational since 1995 and is one of the primary research tools for inertial confinement fusion (ICF) and high-energy-density (HED) physics research in the U.S.

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Figure 1
Exterior of the Laboratory for Laser Energetics at the University of Rochester.

OMEGA is maintained and operated by LLE for the Department of Energy's (DOE's) National Nuclear Security Administration (NNSA). OMEGA can focus up to 30,000 J of 351-nm laser energy onto a target that measures less than 1 mm diam in approximately one billionth of a second. In addition to the 60-beam OMEGA, the 4-beam OMEGA EP laser has also been a main research tool for the community since 2008.

OMEGA EP consists of four beamlines similar to those at the National Ignition Facility (NIF). Two of those beams can be compressed for short-pulse, petawatt-class operation. Both of these facilities allow scientists to explore physics conditions at extremely high pressures and temperatures—including fusion, the process that powers the Sun. Approximately 60% of all experiments conducted at the Omega Laser Facility are led by researchers from outside LLE.

Since 1991, nearly all of the LLE target capsules, which hold the material that is compressed by high-powered laser pulses, have been manufactured by GA in San Diego. Dr. Mike Campbell, the director of LLE, is frank about the close interdependence of LLE and GA. "LLE is the main facility for direct-drive fusion research, where the laser directly impinges on the fusion capsule. So, in addition to the laser and diagnostics that make up the facility, you need to have targets to shoot. All those capsules are made for us at General Atomics, and the progress that we can make in the fusion program is directly dependent on the characteristics of the targets that GA delivers."

"It's been a three-decade, high-impact relationship," said Mike Farrell, vice president of inertial fusion at GA. "Whether it's been engineered systems, targets, diagnostic instrumentation, or other activities in support of the science that researchers are conducting at LLE, GA's contributions to enabling the physics research performed at LLE have been a constant and significant enabling factor."

GA's involvement in fusion research reaches back to its founding in the 1950s. Although its global operations now extend into technologies as diverse as aerospace and biotech, fusion remains a core focus of its research and development activities (Fig. 2). For decades, GA has worked with DOE and its predecessor agency, the Atomic Energy Commission, on a wide variety of fusion energy initiatives. Many GA employees have worked at DOE laboratories and facilities like LLE—including Dr. Campbell, who headed up GA's target fabrication operations from 2000 to 2007.

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Figure 2
The General Atomics campus in San Diego (photo Ronalyn Conception/GA).

Target Development

The LLE–GA collaboration began in the early 1990s, when DOE awarded GA the contract to fabricate targets for the U.S. ICF program, which supports much of the research at LLE (Fig. 3). One of the first major projects to emerge from LLE's work with GA was an upgraded Cryogenic Target Handling System. Direct-drive fusion targets on OMEGA need to be filled with fusion fuel, which is a mixture of the hydrogen isotopes deuterium and tritium (DT). In order to increase the amount of fuel each target can hold and to start with the highest density, the DT fuel is frozen at cryogenic temperatures. These tiny capsules are then placed into the target chamber.

Dr. David Harding, group leader for target fabrication at LLE, joined the team during development of the new system in 1995. "On the old system, the researchers would fill the targets with a very small amount of tritium at room temperature so that the capsule wouldn't burst, and put it into the cryostat at 19 K to create a very rudimentary DT ice layer," he explained.

This was sufficient for early experiments in the late 1980s, but researchers wanted to shoot targets with significantly more fuel. The goal of the new system was to load very thick (up to ~100-μm) DT layers into very thin-walled (less than 5-μm) polymer capsules (Fig. 4). The experiments also required that the ice wall be uniformly thick with a smooth surface. As might be expected, creating targets with these attributes was a significant challenge.

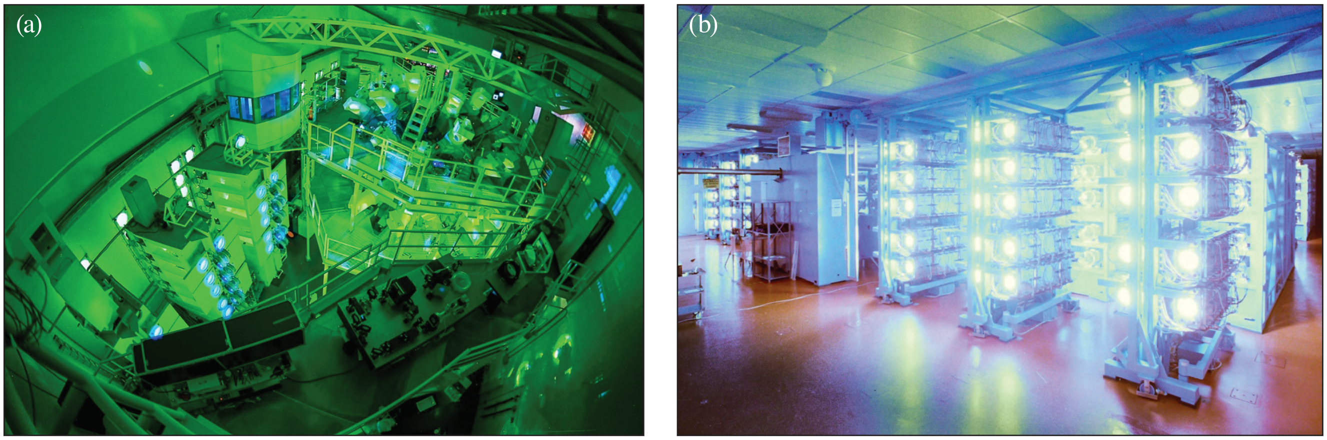

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Figure 3
The (a) Target Bay and (b) Laser Bay at LLE during a laser shot.

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Figure 4
One of the cryogenic targets used on OMEGA, fabricated by GA.

"The capsules are filled with fuel by diffusion, which is placing the capsules under more 1000 atm of pressure in a vessel filled with the fuel gas, so that it diffuses across the thin capsule walls," Dr. Harding said. "After you've pressurized the capsule, you have to freeze the fuel to keep it from bursting once the target is removed from the pressure vessel."

The challenge was doing this in a way that the capsules could be filled, frozen, placed into the target chamber, and shot before the ice thawed and the capsules burst. "The job was to design a cryostat with a pressure vessel inside it, so you could ramp the pressure up, cool the targets, and do it in a very controlled manner," Dr. Harding said.

On top of that, the targets still needed to get to the chamber where they could be shot by the lasers. The team designed a smaller, mobile cryostat that would take the target from the larger cryostat and place it into the target chamber. To maintain the cryogenic temperatures, the target would be covered by a copper shroud during transport.

That might sound simple, but the process needed to operate in an extremely precise manner. The target had to be placed within 5 μm of the center of the target chamber, and the cryogenic protective shroud had to be retracted very rapidly, less than 100 μs prior to the shot.

The challenging demands of this system led to some initial difficulties in development. GA and LLE began working together on the process in 1995, and GA designed all the major components with assistance from LLE. The parts were then shipped to Rochester and assembled, integrated, and tested by LLE staff. "It was a complete collaboration between LLE scientists and engineers and GA's personnel," Dr. Harding said. "It was a great success, especially given that it was completed in such a short time."

The first target using the new system was shot on 14 July 2000—just five years after the project began. The new system was a major improvement over the old one on the 24-beam OMEGA laser. It was able to process and shoot four targets per day in exactly the conditions the researchers needed (Fig. 5). "There were no compromises on the physics quality of the targets," Dr. Harding said.

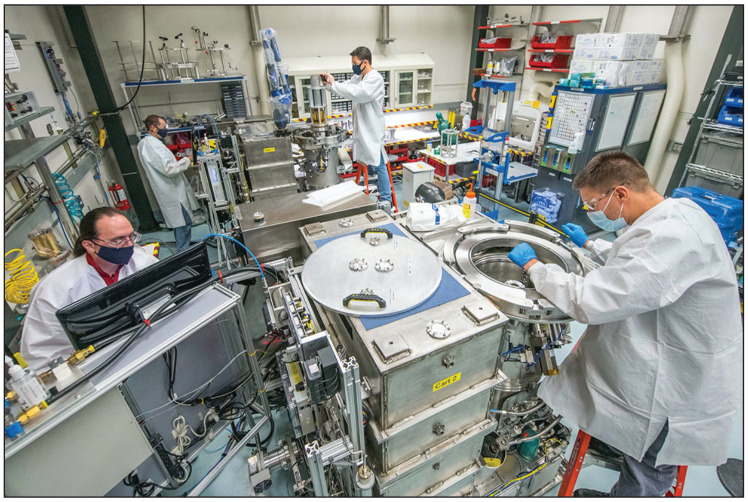

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Figure 5
Operators from LLE's Cryogenic and Tritium Facility are shown performing routine maintenance and performance checks on moving cryostat transport carts (MCTC's) in the Cart Maintenance Room. Steven Verbridge and Chad Fella (foreground) are preparing to raise the moving cryostat (MC) from MCTC#2 in order to perform service. Sean Adams and Michael Coffey (background) are employing a coordinate measuring machine on an (elevated) MC on MCTC#7 to verify proper alignment of the removable shroud. Operators are wearing disposable jackets and gloves given the trace tritium surface contamination on internal equipment.

The system was so successful that elements of the tritium-handling approach were used to inform the design of the cryogenic target system on the NIF at Lawrence Livermore National Laboratory (LLNL), which GA also developed. LLE shared its experiences with the new system with GA, which incorporated it into the work on the NIF. "Many of the features in our cryogenic system fed directly into the NIF system," Dr. Harding said.

Another innovation that flowed from the LLE–GA partnership related to the composition of the polymer target capsules. Researchers at LLNL first demonstrated a process for making the polymer shells known as glow-discharge polymerization (GDP). However, LLNL had little interest in pursuing the process at the time. LLE staff asked GA to improve and develop the technology for use on OMEGA. "We used the targets and told GA how they performed and what changes they needed to make," Dr. Harding said. "They used results from OMEGA implosions to further define the target specifications. That technology is now the baseline target fabrication methodology."

Working together, GA and LLE scientists have continued to refine methods for producing the polymer capsules and making them much smoother and free from defects. This is important because any defect or imperfection in the capsule serves as a "noise" source from which hydrodynamic instabilities can grow and adversely affect the quality of the implosion experiments. At LLE's request, GA developed a technique for producing polystyrene shells using a solvent-based microencapsulation method, resulting in capsules that are significantly smoother than GDP targets (Fig. 6). "GA was able to control the uniformity and thickness of the shells and make them many, many orders of magnitude smoother than the GDP targets," Dr. Harding said.

Diagnostics

Another key element of LLE's work are the diagnostic systems that record data from the laser shots. After all, the experiments are of little use unless scientists are able to analyze exactly what happened. Here too, LLE and GA have worked together

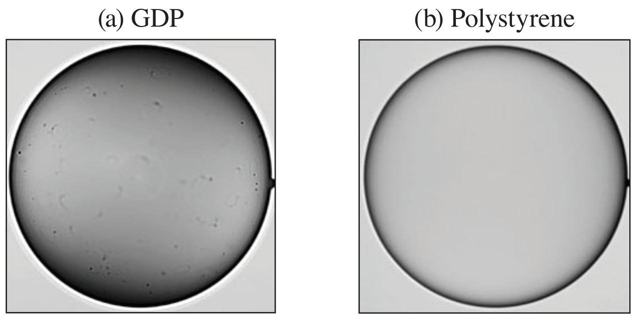

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Figure 6
The improvement in smoothness between (a) 1-mm-diam GDP shells and (b) polystyrene shells, both made by GA for experiments on OMEGA. The shell wall is 0.01 mm thick. The notable difference is the absence of features on the surface of the polystyrene shell, which is important for high-performing implosions.

to bring significant innovations to the field. “In these implosion experiments, we need to know the shape of the central hot-spot plasma formed in a laser-direct-drive implosion,” said Dr. Sean Regan, LLE’s Experimental Division Director. “To do that, we need some very specialized instrumentation.”

The ideal implosion is spherically symmetric. “We don’t get that,” Dr. Regan said, “because we don’t position the target accurately enough, or the laser is stronger on one side than the other, or some other factor. So, we need to understand the causal relationships between the implosion inputs and the outputs.”

Several years ago, through the National Diagnostics Working Group, LLE joined a productive collaboration between GA, LLNL, Sandia National Laboratories (SNL), and Kentech Instruments that involved the development of a single-line-of-sight (SLOS) camera that can capture multiple images with a shutter speed of about 25 ps (Fig. 7). GA has delivered two versions of the SLOS instrument so far. The SLOS-CBI (crystal backlighter imager) was delivered to LLNL in 2017 and is in use on the NIF. The SLOS-TRXI (time-resolved x-ray imager) was delivered to LLE and is now operating as part of OMEGA (Fig. 8).

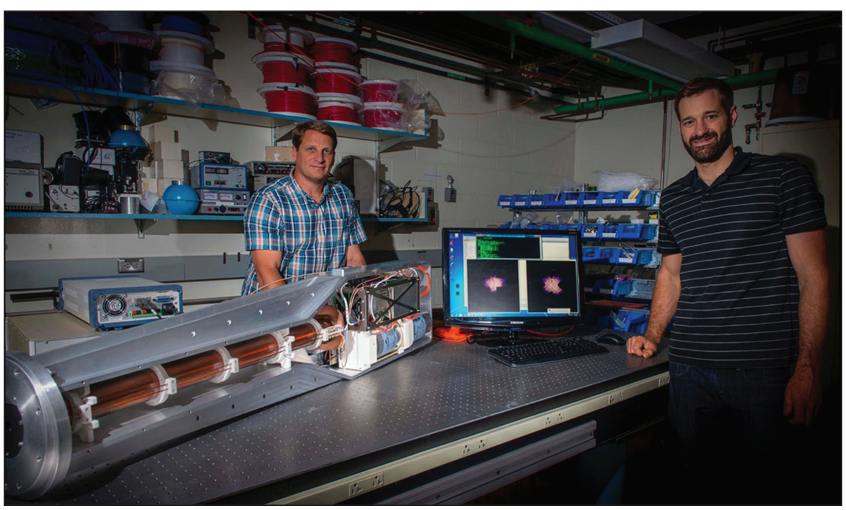

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Figure 7
Terry Hilsabeck and Kyle Engelhorn of General Atomics with the SLOS-TRXI instrument during assembly (photo: Eugene Kowaluk).

SLOS-TRXI is a primary diagnostic for the DT cryogenic implosion campaigns on OMEGA (Fig. 8). It images the hot-spot plasma emission with 25-ps temporal resolution and 10-μm spatial resolution using a pinhole camera and a time-dilation tube. To put that speed in perspective, 25 ps is the time it takes a beam of light to travel almost half of an inch. As impressive as this is, the researchers at the Omega Laser Facility are not satisfied with the status quo. “Because the hot spot is about 40 μm,” Dr. Regan said, “a 10-μm resolution doesn’t give you a very crisp image. We want to do better. We also want to diagnose the low-mode structure of the hot-spot plasma.”

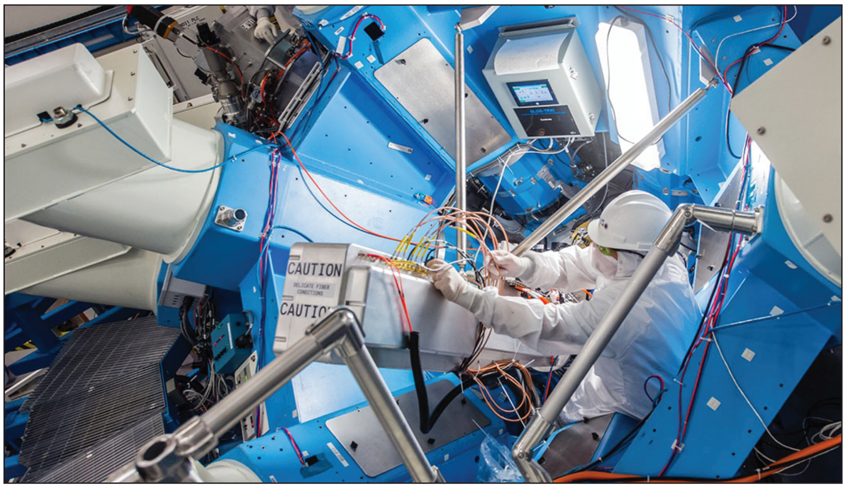

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Figure 8
The SLOS-TRIXI instrument being installed on OMEGA.

The team is currently designing what might be termed "SLOS-TRXI 2.0" that will add a third line of sight to the instrument, allowing for a full 3-D low-mode reconstruction of the hot-spot plasma. Under this same collaboration, a hot-spot x-ray imager with 20-ps temporal resolution and 5-μm spatial resolution is being developed for OMEGA. This imager will allow scientists to determine the overall shape of the hot spot and how it deviates from a perfectly spherical shape. This can also be compared to data from the other OMEGA diagnostics.

"Using nuclear spectroscopy measurements recorded along three quasi-orthogonal diagnostic lines of sight, we can infer the hot-spot flow velocity," Dr. Regan said. "If there's a significant flow in the hot spot caused by an asymmetric implosion, it will doppler-shift the DT fusion neutron spectrum, and you'll see the mean energy of the spectrum shifted up or down. Combining the hot-spot flow measurements with the SLOS-TRXI x-ray images of the hot spot allows us to model the structure of the hot spot. This will ultimately help us understand how the hot-spot formation is affected by multidimensional effects on the implosion."

The working group is drawing on lessons learned from SLOS-TRXI to develop the third line-of-sight instrument. LLE is responsible for project oversight and design and the x-ray pinhole camera, while GA is developing the drift tube. SNL, LLNL, Kentech, and Sydor Technologies are developing other elements. A conceptual design has been developed, and discussions about the construction have recently started. "It's a fantastic collaboration between LLE, GA, the national labs, and these other innovative and highly talented private firms," Dr. Regan said.

National Laser Users' Facility

Another key element of the collaboration has occurred through the DOE's National Laser Users' Facility (NLUF) program, which provides beam-time access at the Omega Laser Facility for scientists in both academia and private industry to conduct basic research and train graduate students. These experiments explore a wide range of HED science topic areas such as plasma physics, laboratory astrophysics, high-pressure materials, magnetized HED plasmas, nuclear science, and novel diagnostic development. NLUF is part of the Joint Program in High-Energy-Density Laboratory Plasmas, which is sponsored jointly by the NNSA Office of Research, Development, Test, and Evaluation and the DOE Office of Fusion Energy Sciences.

DOE funds the operation of NLUF, making it possible for researchers, including students, to conduct experiments without a direct facility charge. In addition, DOE provides research funds directly to these users for experiments. To broaden the science scope and grow the user community, NLUF will become a facility access program starting in 2022 with no restrictions on the source of the research funds users may have.

"The benefits of the NLUF Program are really tremendous," said Dr. Mingsheng Wei, an alumna of NLUF and GA who now serves as the NLUF Manager at LLE. "NLUF has compiled a strong record of excellence in HED and frontier science research and trained over 200 Ph.D. graduate students and postdoctoral researchers." More than 60 graduate students from 18 institutions (excluding UR) are currently conducting thesis research using OMEGA, primarily through the NLUF.

GA fabricates a wide variety of targets and components and performs metrology and target assembly to support over 350 shots at the Omega Laser Facility each year for NLUF users. "There are a lot of specialized targets and materials that we aren't able to make in our lab because we don't have the machinery or the expertise here," said Dr. Carolyn Kuranz, associate professor of nuclear engineering and radiological sciences at the University of Michigan. "We depend on GA for that. For example, there are hydrodynamic instability experiments that we wouldn't be able to do or characterize without those targets and materials. And we've been able to do some really cool and exciting work because of it."

After earning her Ph.D., Dr. Wei worked as a project scientist performing HED physics research at the University of California San Diego (UCSD) including NLUF-supported research on OMEGA. She joined GA in 2010, where she continued her research in HED physics, leading several NLUF projects with experiments on OMEGA and supporting target development, before moving to LLE in 2018. Kuranz also participated in the NLUF Program and now supervises graduate students doing their own research through it.

Professor Farhat Beg at UCSD has been involved in the NLUF for more than ten years. The UCSD campus is directly across the street from GA's main campus in the Torrey Pines neighborhood of San Diego. "NLUF makes it possible for us to do state-of-the-art science that we simply cannot do on any other facility," Prof. Beg said. "The program has given us an outstanding platform and opportunities for our students and post-docs to carry out top-quality work on OMEGA. GA has been instrumental in providing us with the complex targets we need to do this."

A 2016 article[1] in *Nature Physics* co-authored by Dr. Wei and Prof. Beg serves as one example of what the NLUF has helped achieve. A team of researchers from UCSD, GA, LLE, LLNL, and several other institutions (Fig. 9) conducted a series of experiments on OMEGA using copper-doped plastic shell targets from GA to demonstrate a significant improvement in energy coupling of high-intensity, laser-produced relativistic electrons in integrated cone-in-shell fast-ignition experiments. The lead graduate student on the project, Leonard C. Jarrott from UCSD, is now a staff scientist at LLNL.

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Figure 9
This NLUF-supported team of scientists from UCSD, GA, LLE, and LLNL demonstrated a significant improvement in energy coupling of high-intensity, laser-produced relativistic electrons in integrated cone-in-shell fast-ignition experiments on OMEGA. Front row (left to right): Chris McGuffey (UCSD), Chad Mileham (LLE), and Wolfgang Theobald (LLE); middle row: Farhat Beg (UCSD), Gennady Giksel (then at LLE, currently with University of Michigan), and Mingsheng Wei (then at General Atomics, currently with LLE); back row: Leonard Charlie Jarrott (then a graduate student at UCSD, currently a Staff Scientist at LLNL), Toshinori Yabuuchi (then at UCSD, currently at SACLA, Japan), Richard Stephens (then at GA, currently retired), and Hiroshi Sawada (then at UCSD, currently at University of Nevada, Reno). (Photo: Farhat Beg.)

Professor Beg praised the record of the NLUF in preparing students for careers in HED physics and particularly the work at DOE national labs. He noted that most of his graduate students have gone on to work at LLNL, LLE, and GA. One of his former post-doc researchers, Dr. Christine Krauland, did her doctoral work at LLE with NLUF funding while at the University of Michigan, and now works in GA's Inertial Fusion Division studying an alternative ICF scheme called "shock ignition," also under an award from NLUF (Fig. 10). "I have only good things to say about NLUF and LLE," Dr. Krauland said. "It's a critical talent pipeline for the ICF labs and the HED community as a whole."


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Figure 10
Dr. Christine Krauland (photo: Christine Krauland).

Dr. Johan Frenje, assistant head of the High Energy Density Physics Division at MIT's Plasma Science and Fusion Center, had similar praise for the NLUF program. "It's everything for us," he said of the opportunity to work on OMEGA through the collaboration with GA. Frenje has guided about 15 to 20 doctoral students through the program in the 20 years he's been at MIT. "Of those," he said, "80% to 90% have gone on to work at the national labs."

"GA's participation in the NLUF Program is absolutely essential," Dr. Frenje said. "There's no question that we can't do this otherwise. We rely on GA to help us push the boundaries of science. Our requirements for targets have gotten tougher and tougher, but GA has delivered."

"We are equal partners, and it is a very collaborative process," Prof. Beg said of GA. "They provide opportunities for us to do really challenging science. They work to make the targets we need and have devoted substantial R&D money to make these projects possible."

Dr. Wei found that her experience working at GA to design targets for experiments on OMEGA gave her additional perspective on what the program has accomplished: "Working on the target side, it was really rewarding being able to bridge the gap between the physics and design and the actual experiments."

Toward the Future

"We do 10 to 15 experiments a day," Dr. Campbell said, "and maybe 3 or 4 cryogenic experiments. I'd like to do a hundred a day. That means we have to learn how to fabricate targets much more rapidly, and higher quality, and that's a real challenge. To be more relevant to NNSA and others, we need more-complicated targets made from multiple layers—multi-shell rather than single shell. That's something that GA is working on."

"Target design offers the greatest level of flexibility of all of the experimental parameters available to academic and laboratory researchers and physicists," M. Farrell said. "Enabling today's experiments while advancing the state of the art in targets for future designs is a passion for the engineers and scientists at GA. Transitioning from a "single shot" to '"repetition-rated shot" capability is a grand challenge the GA and LLE collaboration is looking forward to taking on."

As much as the collaboration has accomplished, Dr. Campbell believes there is still much more to be done, given sufficient support. “I think the country does not devote enough R&D toward target fabrication,” he said, “and I would like to see that grow. We have these three active facilities: Omega, the NIF, and the Z Machine at Sandia. We need to not only supply the targets for the ongoing programs, but also supply the targets for the future. That’s critical to maintaining U.S. leadership in this field and ensuring we can reap the benefits of all this effort.”

1. L. C. Jarrott *et al*., Nat. Phys. **12**, 499 (2016).