SPOT-SHADOWING DAMAGE on Laser Optics

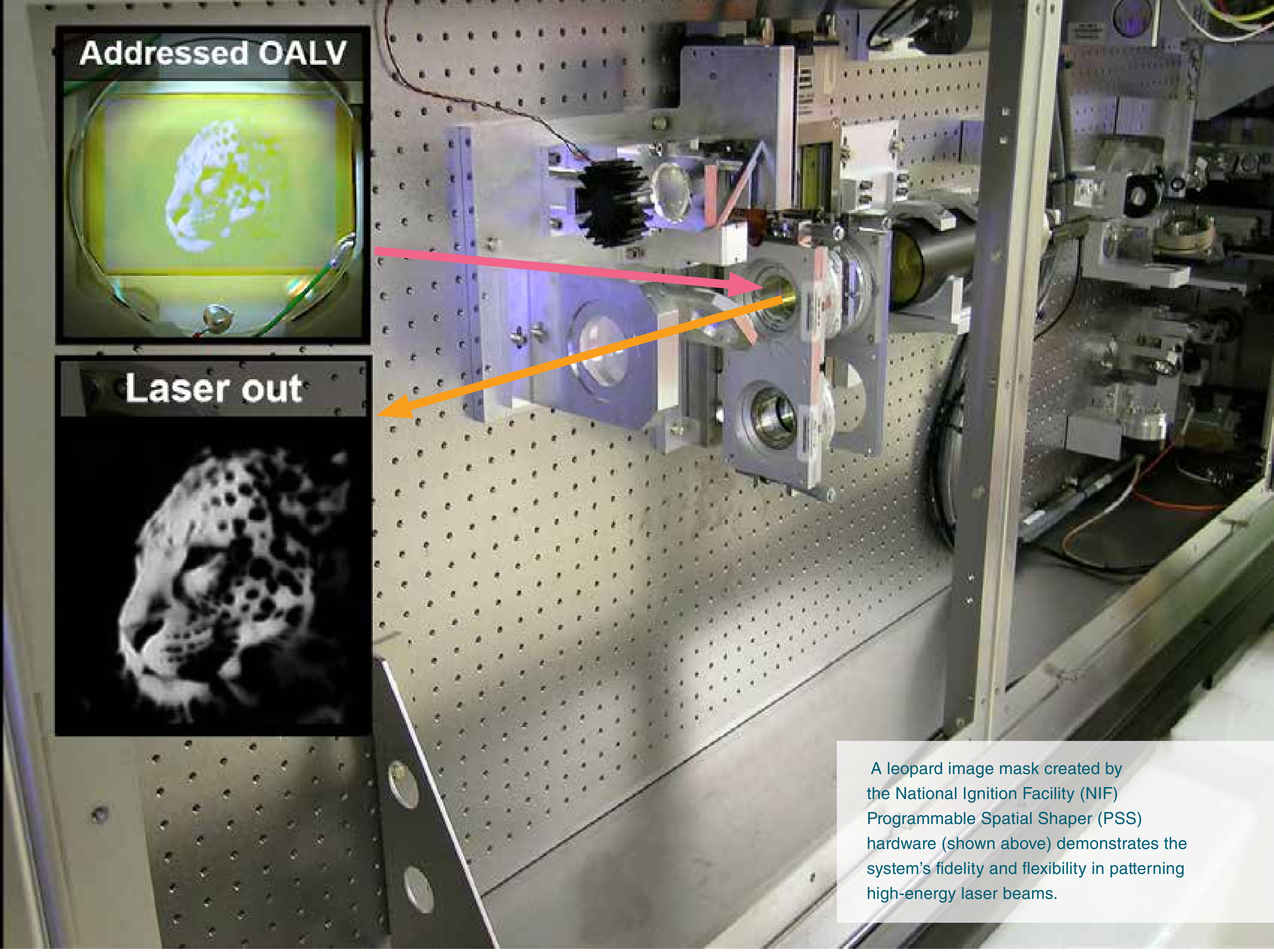
THE Laser Energy Optimization by Precision Adjustments to the Radiant Distribution (LEOPARD) technology was created from a need to protect and prolong the lifetime of optical components in high-energy lasers. Since its deployment in 2010, LEOPARD continues to support the world's most energetic pulsed laser system. LEOPARD has also spurred several technological advances, cementing itself as a mission-critical technology with valuable spin-off applications. Its components have proven relevant not only to high-energy lasers, but also to additive manufacturing, inspiring a startup company that is revolutionizing the 3D printing of large metal parts with lower carbon emissions.

Developed by a Livermore team in collaboration with Meadowlark Optics in Colorado, LEOPARD enhances the performance and operability of the National Ignition Facility (NIF). By casting shadows on a handful of flaws in the laser's large ultraviolet (UV) optics, LEOPARD helps maximize the number of shots fired at NIF and also reduces repair and refurbishment time and cost.

Protecting Laser Optics

NIF's final optics, while able to withstand high energy densities of UV light, see repeated laser exposure, making them susceptible to the growth of a small number of flaws across their over 1,000 square centimeter aperture. LEOPARD's optically addressable light valve (OALV) component, the hallmark of the system, allows for high-fidelity spatial patterning of the laser beams. Once the flaws are detected, LEOPARD deploys shadows or "spot blockers" over the flaws' specific locations to protect them until maintenance periods take place onsite, during which the optics are routinely repaired.

LEOPARD has enabled NIF to operate at a higher energy by mitigating lasers' propensity to develop undesirable local fluence (energy per unit area) spikes, also called "hot spots." Spikes, which can initiate more flaws in a laser's optics, limit most lasers' maximum safe output energy. However, if a laser has a more uniform fluence profile, it may operate at a higher average fluence because its spikes will stay below the damage



A leopard image mask created by the National Ignition Facility (NIF) Programmable Spatial Shaper (PSS) hardware (shown above) demonstrates the system's fidelity and flexibility in patterning high-energy laser beams.

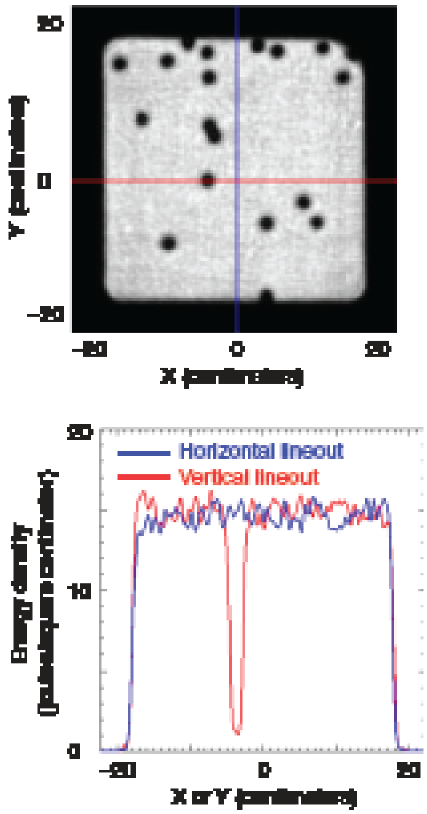
threshold. Thus, LEOPARD improves the spatial uniformity of NIF's beams by eliminating hot spots and allowing an increase in output energy. This additional capability was inspired by a previous system demonstration performed at the French Alternative Energies and Atomic Energy Commission (CEA) before Livermore developed LEOPARD.

LEOPARD was created by Livermore scientists in collaboration with Meadowlark Optics and CEA. Jean-Michel Di Nicola, co-program director for the NIF & Photon Science Laser Science and Systems Engineering organization, initially worked for CEA near Bordeaux, France, where studies on beam shaping for the French Laser Mégajoule, an inertial confinement fusion laser, served as an early demonstration for the idea. "At CEA, we had no concept of shadowing flaws with spot blockers, but we wanted to improve beam flatness to reduce damage initiation on the optics. At Livermore, we combined the two ideas and went far beyond the originally envisioned applications," says Di Nicola.

The team's ongoing efforts since 2008 to improve the OALV technology for NIF's strict beam quality demands resulted in LEOPARD winning a 2012 R&D 100 award. "The LEOPARD system's biggest impact over the last 14 years since we deployed on NIF has been in improving the operational availability of the NIF system and safely increasing the laser's energy," says John Heebner, lead scientist for the LEOPARD development team and group lead in the Materials Engineering Division. Due to the implementation of LEOPARD and other technologies, such as Laser SHIELD (Screening at High throughput to Identify Energetic Laser Distortion), NIF has achieved record-breaking yields culminating in the 2022 breakthrough of fusion ignition.

Hallmark Component

LEOPARD, also known as the Programmable Spatial Shaper (PSS), offers its unique protection by combining a conventional spatial light modulator with an OALV, which allows it to imprint arbitrary patterns from a digital bitmap image. Both components



Diagnostics from one of NIF's laser beams (top) during the February 10, 2024, ignition experiment show the laser beam (grey background) and fluence-blocking spots (black dots). Blue and red lines correspond to the lineout of laser fluence (bottom). Where the red vertical lineout crosses the section intentionally shadowed by the PSS unit, the fluence is reduced to nearly zero, and the beam profile is flattened.

rely on voltage-controlled liquid crystal (LC) molecules to rotate the laser beams' polarization state and control the beam's intensity. The conventional modulator is pixelated into a matrix of LC cells, while the OALV contains a single, large LC cell. This configuration allows the system to meet strict laser beam quality requirements with the OALV while maintaining the ability to address the beam spatially with images imprinted onto an auxiliary 470-nanometer blue beam by the spatial light modulator. The OALV includes a layer of photoconductive bismuth silicon oxide in series with its LC layer. This key feature enables blue light to open a conductive pathway for voltage to control the LC molecules. With a globally applied voltage and locally applied blue light, the LC molecules can open a patch of high transmission for the laser beam. Applying a programmed blue image pattern onto the OALV allows the laser beam to be transmitted in this same pattern.

The OALV's analog and unpixellated nature makes it effective in creating and shaping ultrasmooth patterns on laser beams. The OALV maintains over 90 percent transmission of the NIF laser and imprints minimal wavefront distortions. The component's transmissive capability enables the OALV to act as a drop-in upgrade module that can be assembled free from the laser and easily installed where needed.

An ongoing Laboratory Directed Research and Development (LDRD) project led by Lars Voss, group leader for high-power electronics research at Livermore, is underway to improve photoconductive materials, in turn improving LEOPARD's capabilities for spot blocking. Currently, LEOPARD is a quad-based device, which means that shadowing a flaw for one laser beam within a quad of NIF beams also shadows three others, decreasing transmission unnecessarily. The new-generation LEOPARD version will be beam-based, which enables flexibility in spot blocking each of NIF's 192 beams on an individual level, maintaining as much beam transmission as possible. The project will facilitate this outcome by bolstering the OALV using more robust materials with larger apertures, enabling more energy per shot, and minimizing growth of optic flaws. (See *S&TR,* December 2023, pp. 4–11.)

LEOPARD's Adaptations

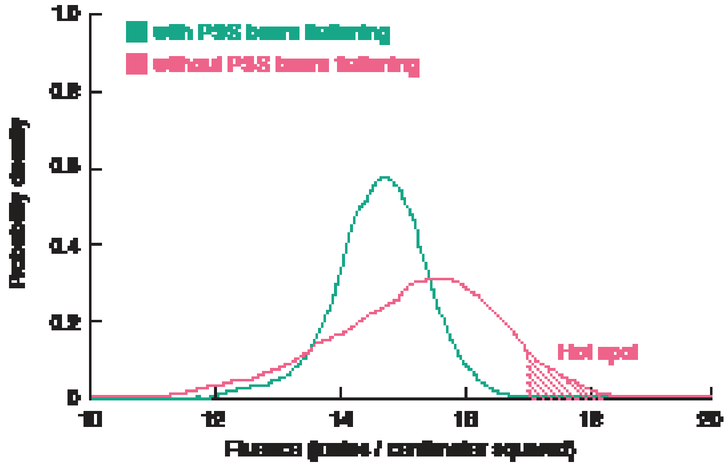
LEOPARD's OALV has been expanded to applications beyond high-energy lasers. In 2013, the technology played a part in an LDRD effort titled Diode-based Additive Manufacturing (DiAM) to Scale-up 3D Metal Printing. The traditional method for 3D printing large metal parts—laser-based powder-bed fusion (L-PBF) additive manufacturing—requires raster scanning with a laser across each horizontal layer of material. With L-PBF, a laser flashes onto part of a thin layer of metal powder, melting and welding that section down to the layer below it.

The speed at which the powdered metal melts depends upon the laser's power, and the resolution of the printed metal depends upon the laser spot's size. A larger spot covering more area per shot generates a lower-resolution product at a higher speed than a smaller laser spot covering less area. Using L-PBF, therefore, would require years to print large, high-resolution parts such as those used for aeronautics. Hence, a method was needed to manufacture metal parts in more reasonable timeframes while still maintaining quality.

Through the LDRD project at Livermore, Area

Using technology that originated through the development of LEOPARD, Seurat's Area Printing® technique enables printing of complex metal shapes and structures with unmatched speed and resolution.

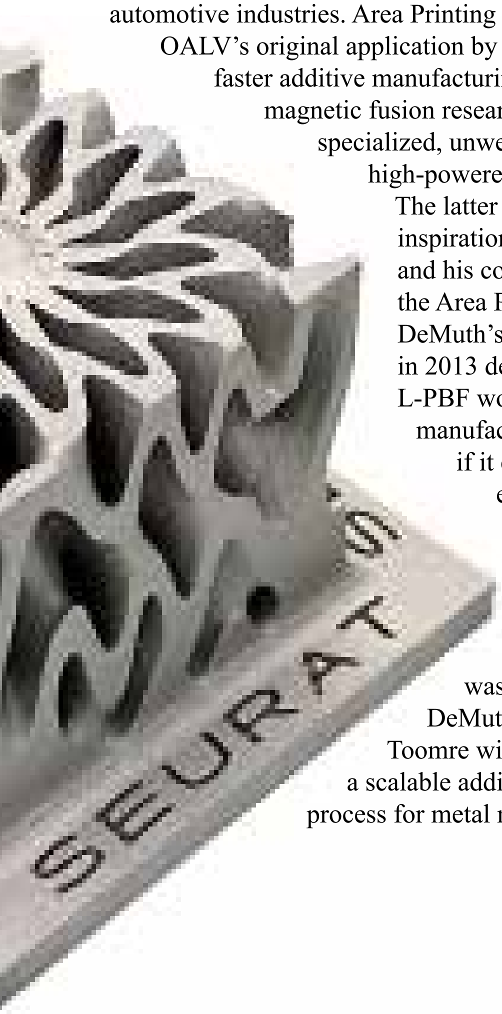
Printing®, an evolution of DiAM, was identified as a solution to overcome the inverse relationship between resolution and print speed. Area Printing, a distinctively novel form of L-PBF, flash-prints an entire area of metal powder at once, enabling faster, more responsive printing of large metal parts compared to traditional L-PBF processes. Area Printing incorporates an OALV like that of LEOPARD to shape high-power laser light in programmed, area-by-area images. In Area Printing, the laser passes through the OALV to pattern an image of each "slice" of the ultimate metal part onto a metal powder, instantly melting and printing entire layers at a time. Spot size no longer affects resolution, as the entire image is generated through the OALV. The OALV's utility in additive manufacturing was clear to Livermore scientist Ibo Matthews, who notes that the light valve was discussed for NIF around the same time that metal additive manufacturing was being more broadly applied in Laboratory programs.



LEOPARD's technology enables laser beam flattening, meaning there is a much narrow range of laser fluence or variation in energy. Probability distribution of fluence across the aperture of the NIF laser beam is shown here with (green) and without (red) beam flattening. A more uniform distribution indicates a flattened beam and more reliable energy transmission, whereas the less uniform distribution with the hotspot tail indicates higher fluence and more risk of damage to optical equipment.

Spin-off Startup

Area Printing's development offers potential for the additive manufacturing of large metal parts that today's 3D printers are incapable of printing within realistic timescales. The technology could, in turn, expand manufacturing possibilities for industries that make use of these large parts, such as the aerospace and automotive industries. Area Printing also supports the OALV's original application by making possible the faster additive manufacturing of chambers for magnetic fusion research, which require specialized, unweldable steel, for high-powered lasers such as NIF. The latter application was the inspiration for James DeMuth and his co-inventors in creating the Area Printing technology—DeMuth's experience at NIF in 2013 demonstrated that L-PBF would be the best way to manufacture fusion chambers if it could be made efficient enough. Area Printing achieved the necessary efficiency. Seurat Technologies, a startup company, was founded in 2015 by DeMuth and co-founder Erik Toomre with the goal of creating a scalable additive manufacturing process for metal manufacturing. The company secured the exclusive technology license for DiAM from Livermore in early 2016 and began commercializing it as Area Printing. In 2021, Seurat demonstrated the technology's ability to print stainless steel parts that exceeded industry standards. The company has garnered investment from key automotive, energy, and manufacturing companies due to Area Printing's improved capabilities over other additive and conventional manufacturing techniques.



Over the last 14 years, LEOPARD has supported high-energy lasers and unexpectedly revolutionized additive metal manufacturing by maturing OALV technology. Most importantly, LEOPARD has had a continuous impact on NIF, enabling the laser to operate cost-effectively and with minimal interruption. "I think the best testimony to LEOPARD is that the technology is used 24 hours a day, 7 days a week on NIF, and we don't hear about it," says Di Nicola. "We don't hear about a lot of downtime, breakdowns, or issues, which is a good sign. The system works well and does a tremendous job at protecting the NIF laser and increasing its output."

—Lilly Ackerman

For further information, contact John Heebner (925) 422-5474 (heebner1@llnl.gov).