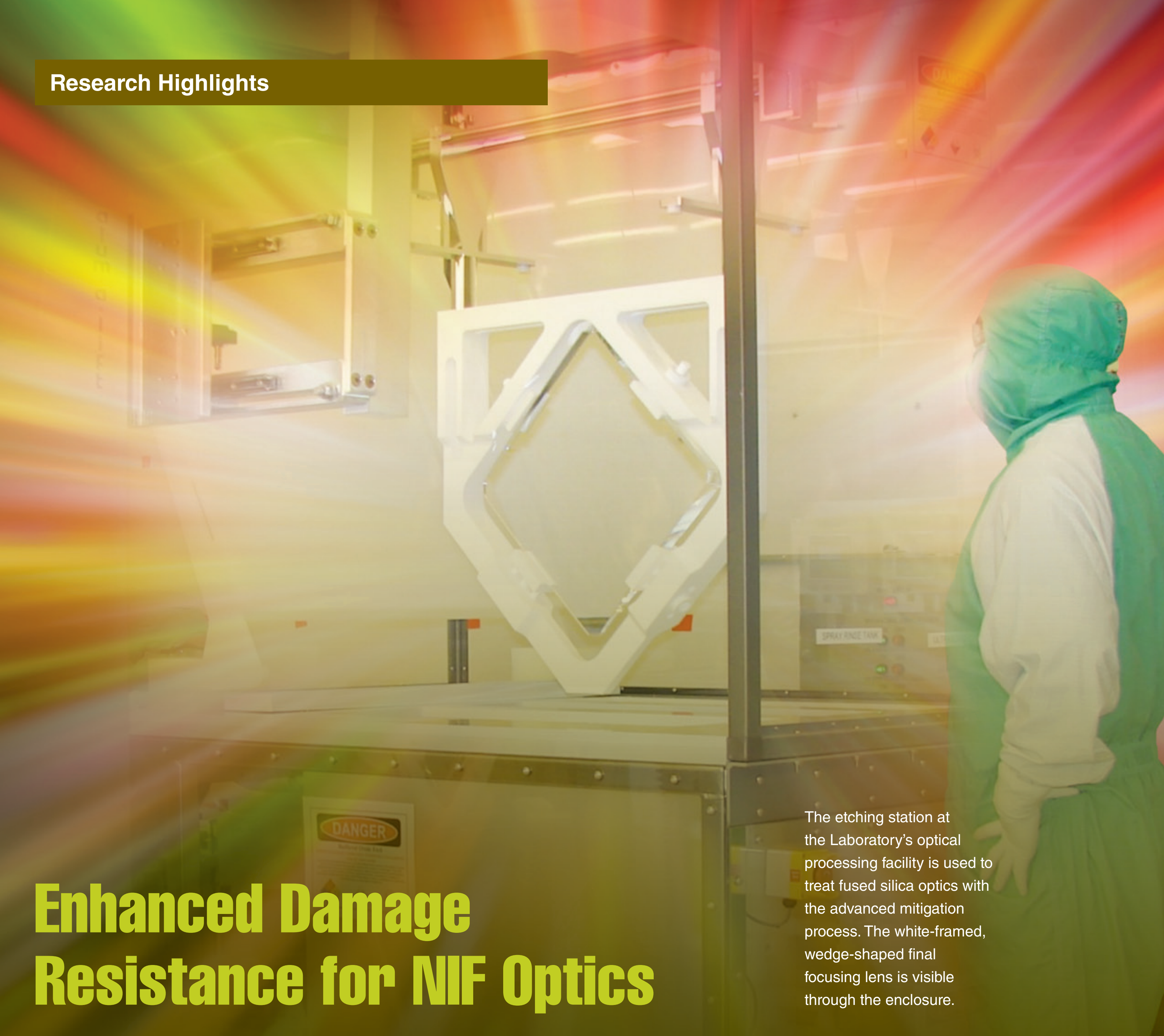


The etching station at the Laboratory's optical processing facility is used to treat fused silica optics with the advanced mitigation process. The white-framed, wedge-shaped final focusing lens is visible through the enclosure.

Enhanced Damage Resistance for NIF Optics

IN addition to being the world's largest and most energetic laser, the National Ignition Facility (NIF) is the largest optical instrument ever built. The giant laser has 7,500 large optics, ranging from 60 to 100 centimeters in diameter, and 30,000 smaller ones that guide, reflect, amplify, and focus 192 laser beams onto a fusion target about the size of a BB.

Many NIF optics are made of fused silica (noncrystalline silicon dioxide) because this material exhibits excellent optical properties. In particular, it transmits laser light over a wide spectral range. The manufacturing processes for fused silica optics can, however, produce microscopic defects, or damage precursors, on the glass surface, especially when optics are polished near the end of fabrication. When NIF construction began in 1997, even the best manufacturers produced high-quality optics with thousands of tiny defects. To lessen the potential for damage, Livermore researchers worked closely with their industrial partners to improve optics fabrication by developing more stringent finishing and quality assurance procedures.

That effort paid off: By 2007, improvements in surface finishing had reduced the number of defects in the final focusing lenses, which must withstand the highest fluences, from about 30,000 per lens to about 200. Livermore scientists also developed procedures to remove and mitigate the laser-induced damage on fused silica optics. These mitigation techniques are effective but time-consuming. In addition, lenses with a large number of defects must be treated more frequently, which can increase the cost for an experiment.

To further extend lens lifetimes, the NIF optics science and technology group conducted an exhaustive study to improve the damage resistance of fused silica surfaces. In a multiyear project funded by the Laboratory Directed Research and Development Program, the group first examined the nature of damage precursors that develop when the optics are polished and then worked to develop a cost-effective method that can prevent or significantly reduce the number of precursor sites.

Led by scientists Tayyab Suratwala and Jeff Bude of the Laboratory's Physical and Life Sciences Directorate, the researchers discovered an extremely thin defect layer on the surface of fine fractures that form on optic surfaces. This layer hosts damage precursors that limit a beam's fluence, or the energy passing it. A procedure developed by the Livermore team, called the advanced mitigation process (AMP), removes the problem layer. As a result, the process reduces expected damage sites in the final focusing lenses to less than 10 defects per optic over the course of 50 laser ignition shots.

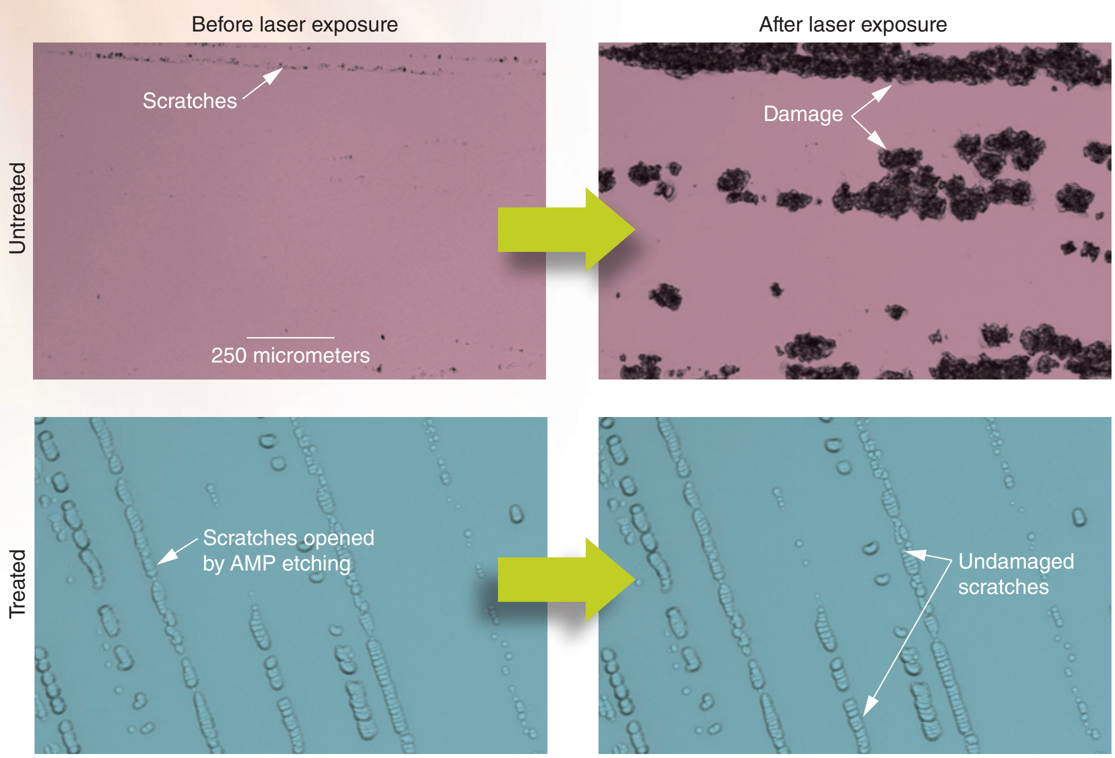
Bude attributed the success of this project to the wide range of talents on the AMP team. Phil Miller, William Steele, Nan Shen, Michael Feit, Ted Laurence, and Lana Wong worked with Bude and Suratwala to isolate the precursors and develop the process for laboratory testing. Laser physicists Mary Norton and Wren Carr performed large-area damage testing of the protocol, and chemical engineer Marcus Monticelli helped implement the production process for full-size lenses.

A Process to Remove Manufacturing Defects

Bude notes that throughout the history of laser research and development, important advances have been made in glass manufacturing and finishing, many of them developed by Livermore researchers working on the Laboratory's ever-larger lasers. Nevertheless, high-quality optics still contain minute scratches, fractures, deformations, or impurities. These defects, often measuring only about 100 nanometers in diameter, absorb laser energy and in less than a nanosecond, can cause an optic's surface temperature to reach up to 10,000 kelvins, hotter than the surface of the Sun.

Such extreme heat can trigger an explosive ejection of material, leaving a surface crater measuring tens of micrometers in diameter. If the initial sites remained small, they would not pose a serious problem. However, they tend to grow exponentially with each laser shot. Repeated exposure to the photon energy densities, or fluences, of a NIF-size laser can adversely affect a component's performance and limit its useful lifetime. Eventually, a damaged optic must be removed and either replaced or recycled.

In developing AMP, researchers concentrated on the fused silica lenses used in the 48 final optics assemblies that connect NIF's 192 beamlines to the target chamber. These assemblies convert the wavelength of laser light from 1,053 nanometers in the infrared portion of the electromagnetic spectrum (which scientists designate



Micrographs of fused silica samples illustrate how well Livermore's advanced mitigation process (AMP) works to reduce the number of damage precursors on optic surfaces. The top left image shows a scratched, untreated sample. The bottom left image shows a scratched sample treated with AMP. Both optics were exposed to three shots of three-omega (ultraviolet) light, each with a photon energy density of 12 joules per square centimeter and lasting for 3 nanoseconds. The untreated sample (top right) had extensive damage, while the treated sample (lower right) shows no damage.

as 1-omega light) to 355 nanometers in the ultraviolet portion (called 3-omega light). As a result, lenses in these assemblies must withstand the highest ultraviolet fluence generated by the laser—9 joules per square centimeter.

Each final optics assembly is composed of a disposable debris shield and vacuum window, a fused silica grating debris shield, crystals that convert light from infrared to ultraviolet, and the aspheric fused silica lenses that precisely focus the ultraviolet light onto the target. Because of the intense fluences generated in the final optics assemblies, microscopic defects near the surface of the final focusing lenses have the potential to absorb enough energy to initiate small points of damage. Although a damage site may initially be only about 20 micrometers in diameter, it can grow quickly with repeated exposure to energetic laser light. "Three-omega photons are much more energetic than 1-omega photons," says Bude, "so the damage risk for lenses in the final optics assemblies is much higher."

Defect Layer 200 Nanometers Thick

In probing the nature of defects and damage precursors, the team found that defect layers less than 200 nanometers thick form on the surface of fine scratches made during the polishing operation. "For our high-quality finished lenses, this defect layer is the dominant source of laser damage initiation at nominal NIF fluences," says Bude.

Research showed that chemical etching with hydrofluoric acid can mitigate all types of defects, including impurities and scratches. A buffered solution of hydrofluoric acid is widely used by industries for cleaning glass and processing silicon wafers. "Hydrofluoric acid is one of the few chemicals that can attack silica, which is chemically quite inert," says Bude. "We invested a lot of effort to make sure we knew how to work safely with this potent acid."

To mimic real defects caused by polishing, the team rubbed silica beads across the surface of small-scale fused silica samples. The purposely scratched samples were submerged in various concentrations of hydrofluoric acid solutions under different process conditions. Although the solutions readily opened the fractures and removed the defect layer associated with them, by-products from the etching process precipitated in the open fractures. As with the original precursor sites, the precipitates could absorb light and initiate damage, frustrating attempts to improve damage resistance. With further research, the team found that details of the etching process, including acid composition, amount of agitation, and optic cleanliness, affect the amount of precipitation and, hence, damage resistance to 3-omega light.

To optimize AMP, the Livermore researchers combined extensive experiments with mass-transport simulations. They identified the concentrations of hydrofluoric acid and ammonium fluoride that best mitigate precursor sites. They also determined the correct amount and intensity of high-frequency acoustic waves to apply for shaking by-products loose from the surface and help transport them away. In the final step, lenses are rinsed in a series of deionized water baths that remove any remaining etch by-products.

The team characterized the effectiveness of AMP by using high-fluence laser light and imaging the treated optics with time-resolved photoluminescence. The results showed that AMP could open fractures, remove the defect layer, and leave a surface free of absorbing precursors. When a fused silica optic is treated with AMP, the optic is much more resistant to damage, with measured improvements over 10 times greater than before the treatment. With the defect layer eliminated, the average threshold at which damage is initiated in a 30-micrometer-wide scratch increased from 7 to 41 joules of applied laser energy per square centimeter.

Applying AMP to 192 Lenses

Having demonstrated the technique's effectiveness, the team developed a production process for AMP and oversaw its application to all 192 final focusing lenses. The procedure, performed at NIF's optical processing facility, involves lowering the optic into a 30-gallon (0.12-cubic-meter) tank for 14 hours, followed by treatment with high-frequency sound waves and a final series of rinses. Technicians monitor the operation to ensure that etching steps are performed uniformly and do not alter an optic's exact shape, which is critical for precise focusing. With this approach, the facility can treat two optics per day.

Bude estimates that in 1997, a final focusing lens exposed to 50 NIF-scale shots would have had more than 30,000 damage precursors. By 2007, advancements made in manufacturing processes had reduced that number to about 250. Now, thanks to AMP, the estimated number of defects per final focusing lens is less than 10. With such dramatic improvements, NIF operators can achieve more shots with each fused silica optic before it must be refurbished, and they can increase the laser's fluence with less concern for increased damage to critical components.

The Livermore team is now applying AMP to the fused silica grating debris shield, another critical optic in the final optics assembly. The researchers are also evaluating approaches to further reduce the number of defects produced during manufacturing and investigating new etch processes with even higher damage resistance. Says Bude, "We still have much more to learn about the fundamental nature of optics damage and effective mitigation techniques."

—Arnie Heller

Key Words: advanced mitigation process (AMP), final optics assembly, focusing lens, fused silica optics, hydrofluoric acid, National Ignition Facility (NIF), 3-omega light.

For further information contact Jeff Bude (925) 424-2407 (bude2@llnl.gov).