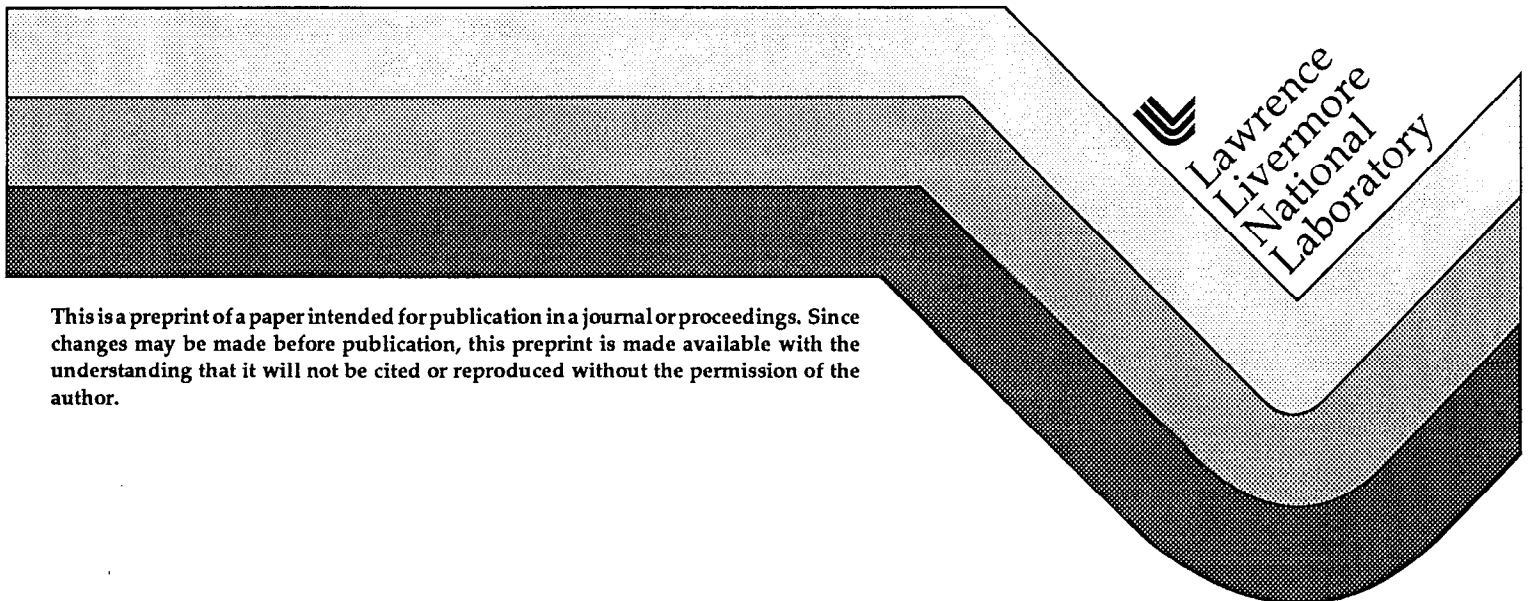


Laser Conditioning Methods of Hafnia Silica Multilayer Mirrors

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Laser conditioning methods of hafnia silica multilayer mirrors

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ABSTRACT

Large aperture multilayer hafnia silica high reflector coatings at 1064 nm, deposited by reactive electron-beam deposition, were prepared to examine different laser conditioning methods for manufacturing high fluence optics in the National Ignition Facility. Laser conditioning is a process where the damage threshold of the coating is increased or the damage that is created is minimized so that it does not grow upon further irradiation. Two laser conditioning methods were examined for coatings deposited from only oxide starting materials. Off-line laser conditioning consists of raster scanning a mirror past a 1 mm diameter Gaussian beam over the entire clear aperture; a process that takes approximately 24 hours per scan. On-line laser conditioning consisted of a large aperture 300 mm × 300 mm beam from the Beamlet laser that irradiated the entire full clear aperture of a series of mirrors; a process that was limited by a 2-4 hour shot rate. In both cases a six-step process was used with the mirror first irradiated at a low fluence, then successively higher fluences increased in equal increments up to the peak laser operating fluence. Mirrors that were only partially laser conditioned damaged catastrophically while fully conditioned mirrors survived fluences exceeding the safe operating Beamlet fluence. An alternative off-line laser conditioning method was examined for coatings deposited from hafnia or metallic hafnium sources. Single-step laser conditioning consists of off-line raster scanning an optic at the peak operating fluence, thus decreasing the laser conditioning cost by reducing the number of scans and required laser conditioning stations to process all the mirrors for the National Ignition Facility. Between pulses the optic is stepped approximately one fourth of the $1/e^2$ Gaussian beam diameter so each area of the coating is irradiated by different segments of the beam starting at a low fluence at the outer edge of the beam diameter and increasing to the peak fluence in the center of the beam. The one-step conditioning results appear positive, but the influence of the coating improvements due to the metallic hafnium process on laser conditioning is undefined.

Key words: laser conditioning, laser-induced damage, laser damage morphology, hafnia-silica multilayer coating

1. INTRODUCTION

Large aperture ($\sim 0.25 \text{ m}^2$) mirrors are required for steering 192 high fluence laser beams into the National Ignition Facility (NIF) target.¹ These mirrors must withstand fluences up to 22 J/cm^2 at a wavelength of 1053 nm (1ω) and 3 ns pulselength. In the current NIF design, the 1ω NIF fluence is limited by the damage threshold of the hafnia-silica multilayer transport mirrors and polarizer. Beamlet, a prototype single beam laser, was constructed to demonstrate performance of a single NIF beamline.² A mirror tower consisting of four 1ω transport mirrors was constructed on Beamlet as a test station to explore different laser conditioning methods for large aperture optics, and as a station to validate large aperture high fluence operation over multiple shots.

Laser conditioning is the process whereby the damage threshold of a coating is increased as a result of previous suboperating fluence exposure.³ The mechanisms for laser conditioning are not completely understood, although the relationship of laser conditioning and nodular ejection has been well documented.⁴⁻⁵ As a coating is deposited, seeds from source ejection or chamber contamination, are overcoated to form nodular defects as illustrated in Fig. 1.⁶⁻⁷ In a typical coating, the seed diameters vary as well as the depth of the seed. The geometry of the nodules lead to electric-field enhancements that are dependent on the seed diameter and depth.⁸ A thermomechanical model has been constructed to understand the variation in the nodular ejection fluence for nodules with seeds that have different diameters and depths as well as a theoretical understanding of

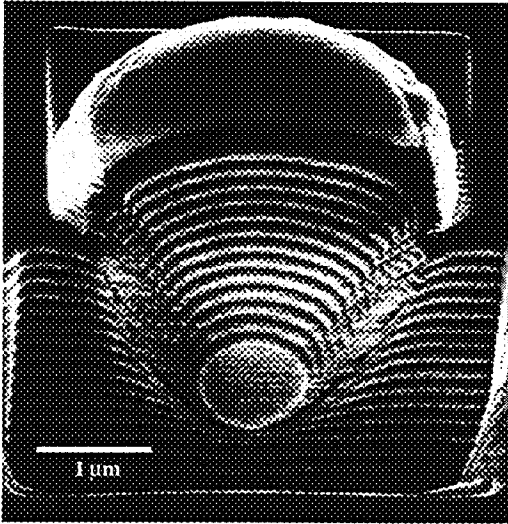


Fig. 1 Scanning electron micrograph of a nodular defect cross sectioned by a focused ion beam.

Approximately a year later a second set of eight mirrors, two each coated at four different vendors, were also deposited by reactive electron-beam deposition. Half of these mirrors are a simple quarterwave stack design at 1ω with a halfwave silica overcoat while the other half are proprietary nonquarterwave optimized designs to meet the NIF spectral requirements at 1, 2, and 3 ω with a halfwave silica overcoat. As a result of NIF coating development, some of the mirrors were deposited from hafnium and silica starting materials due to reduction in defects and plume instability from metallic hafnium deposition.¹⁵⁻¹⁶ The mirrors were coated for operation at 45 degrees incident angle irradiated at "S" polarization. Later requirements for realignment of the Beamlet laser dictated the need for repositioning the final two mirrors to compound angles. The maximum compound angle is less than 45.2° with no more than 13.7° in the "P" polarized plane. The substrates are B2359, a material of similar composition and material properties to BK7. After deposition, the mirrors were characterized on an interferometer for reflected wavefront distortion and a photometer for spectral performance. The mirrors were then manually cleaned and prepared for laser conditioning. After off-line laser conditioning, the mirrors were cleaned and mounted for installation on Beamlet as shown in Fig. 2.

The Beamlet laser was configured for a 30 cm square beam with a central 28 cm top hat spatial distribution of energy. Beamlet has routinely operated with 3 ns Gaussian pulse lengths at energies of 12 KJ at 1ω . Typically the peak-to-average of the spatial intensity distribution ranges from 1.3:1 to 1.5:1 at the mirror plane. This results in an average fluence of approximately 12 J/cm^2 and a peak of approximately 18 J/cm^2 .

The mirror tower is placed in the collimated large aperture beam between the exit lens of the transport spatial filter and an uncoated diagnostic beamsplitter as illustrated in Fig. 3a. The beamsplitter is placed after the mirror tower to image the mirror surfaces with a pilot laser, measure the 1ω near field spatial profile during a high fluence shot, and measure the beam wavefront. The disadvantage with the position of the beamsplitter is that if damage occurs, energy will be absorbed by the damage process and plasma formation. Therefore the measured fluence that exits the mirror tower

the ejection mechanism.⁹ When a nodular defect is irradiated above a critical fluence, the nodule is ejected. The critical fluence is loosely dependent on the seed diameter and depth.¹⁰⁻¹¹

Coatings that are laser conditioned have more benign nodular ejections than coatings that have not been conditioned. Benign nodular ejections leave smooth-edged pits that do not change with subsequent irradiation. Nonbenign nodular ejections, likely the result of irradiation at fluences greater than the critical ejection fluence, have rough edges and cracks that can lead to electric-field enhancement.¹² These damage morphologies are unstable and grow with subsequent irradiation therefore limiting the fluence that an optic can survive.¹³

2. EXPERIMENTAL PROCEDURE

In the first set of experiments eight mirrors, four each coated at two different vendors, with dimensions of 40 cm \times 57 cm were deposited by reactive electron-beam deposition from hafnia and silica starting materials. The mirrors are a simple quarterwave stack design at 1ω with a halfwave silica overcoat for high laser damage threshold.¹⁴

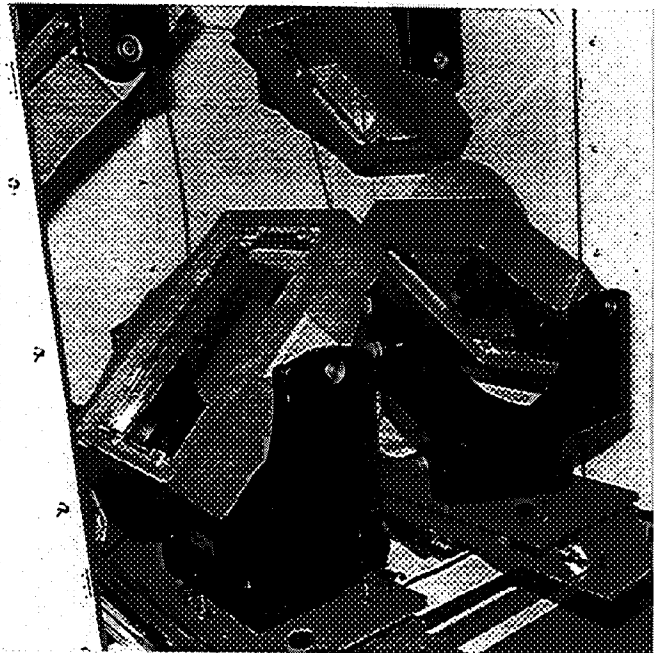


Fig. 2 Beamlet high fluence mirror tower.

will underestimate the fluence that enters the mirror tower. Because the beam wavefront quality is so crucial for optimum frequency conversion to 351 nm (3ω) in the full aperture KDP crystals, the beamsplitter is placed as close as possible to the KDP crystals for wavefront pre-correction by an upstream deformable mirror. The location of each mirror in the tower is illustrated in Fig. 3b.

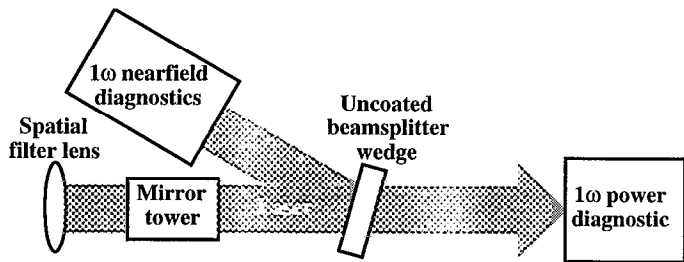


Fig. 3a Depiction of mirror tower placement in Beamlet relative to diagnostic systems.

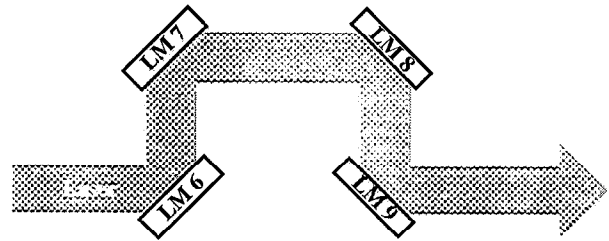


Fig. 3b Depiction of mirror locations within the Beamlet mirror tower.

2.1. CONDITIONING METHODS

For this study, three methods of laser conditioning are investigated. The first method, used to prepare optics for Beamlet startup, is the off-line six-step raster scan process illustrated in Figure 4a and described elsewhere.¹⁷ The optic is irradiated with six equal incrementally increasing fluences starting at one-half the unconditioned damage threshold and ending at the Beamlet operating fluence. The optic is conditioned in a laser processing lab where the optic is placed on a x-y translating stage and raster scanned past a stationary 1064 nm laser beam of approximately 1 mm diameter at $1/e^2$. The translation stage is on a rotary table to enable irradiation of the optic at its use angle and polarization. The laser operates at 10 Hz and the optic translates the distance equal to the diameter of the beam at 90 percent of the peak fluence (typically one-third the $1/e^2$ beam diameter). A HeNe scatter diagnostic on the laser conditioning station, is used to map the optics before and after conditioning for determination of laser damage. After operation on Beamlet, optics can also be scatter mapped for determination of laser damage.

Another conditioning method is the on-line laser conditioning process.¹⁸ Once again, a six-step process is used, but the full aperture (34 cm × 34 cm) Beamlet laser is used for the laser conditioning. The advantage of this approach for NIF optics production is the elimination of costly off-line laser conditioning stations since optics could be conditioned on their respective NIF beamline. The disadvantages being that the NIF transport mirrors are used for pointing and centering the beam into the target so it is possible to irradiate with a high fluence shot an area that has not been conditioned as illustrated in Fig. 5. Additionally mirrors that are replaced in a beamline would be unconditioned and the scheduled shot sequence maybe incompatible with on-line conditioning the mirrors. Finally, there is a significant advantage to being able to test the optic right after coating to verify coating process control given the significant delay between the start of NIF optics production and laser activation due to a one year difference in the time required for optical manufacturing and laser assembly.

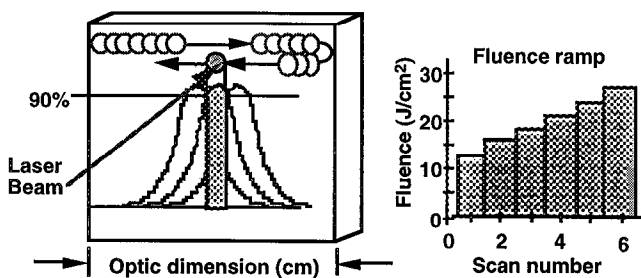


Fig. 4a Depiction of six-step laser conditioning process.

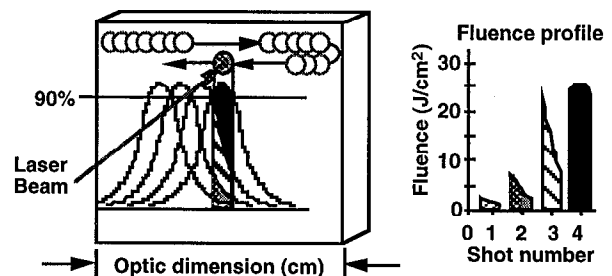


Fig. 4b Depiction of single-step laser conditioning process.

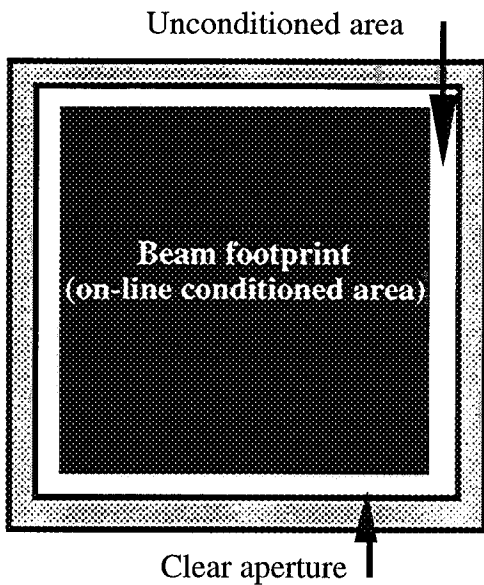


Fig. 5 An unconditioned area exists between the beam edge and clear aperture of an on-line conditioned optic.

The final conditioning method that has been investigated is off-line single-step laser conditioning. Since the conditioning laser has a Gaussian spatial profile, any position on the sample will be irradiated from low fluences up to NIF or Beamlet operating fluences as it scans across the laser beam as illustrated in Fig. 4b. This method reduces the number of required conditioning stations during NIF optics manufacturing and serves as a full aperture damage tester for rapid feedback to maintain coating process control.

3. RESULTS

Two experimental campaigns were conducted with the first set of mirrors to evaluate off-line and on-line laser conditioning. One mirror from each vendor was off-line conditioned to the NIF operating fluence of 22 J/cm^2 . During conditioning, laser damage smaller than $100 \mu\text{m}$ was observed on each mirror and massive damage occurred outside the Beamlet clear aperture on one mirror. Typically laser damage less than $100 \mu\text{m}$ in diameter does not grow with further irradiation or impact Beamlet laser propagation.^{13,19} A significant amount of plasma scalds were observed on one of the conditioned mirrors which did not impact the mirror performance. These mirrors were placed in the upper mirror positions, LM7 and LM8. An additional unconditional mirror from each vendor were placed in the lower mirror positions, LM6 and LM9. The lower mirrors were mounted on a rail system for ease of removal. In addition, the lower mirrors could be translated to an unconditioned area thus simulating an on-line conditioned NIF optic that is irradiated in an unconditioned area due to pointing and centering tolerances. The mirrors are enclosed in a cleaned sealed environment to minimize contamination of the coated surfaces.

The first campaign was terminated after four shots as illustrated in Fig. 6 due to low spatial frequency intensity modulations in excess of 2.5:1 resulting in fluences in excess of 15 J/cm^2 . This modulation led to massive laser damage on the two bottom partially on-line conditioned mirrors. Interestingly, the upper off-line conditioned mirrors were not damaged, thus validating that laser conditioning does increase the damage threshold of these mirrors. Comparison of the beam profile in Fig. 7a and scatter map in Fig. 7b, reveals a strong correlation between the high fluence areas and high scattering regions indicating laser damage. Fig. 7c is a photo of the largest damage site on the LM6 mirror which was exposed to the highest fluence. The damage morphology is delamination from the substrate indicating a weak adhesion between the multilayer and substrate. The remaining damage 2-4 sites were smaller catastrophic failures that would likely grow with further irradiation or plasma scalds, a damage morphology that does not impact beam propagation or change with further irradiation.^{13,19}

Despite precautionary measures to eliminate the unwanted beam modulation, a second campaign with new unconditioned mirrors placed in the lower mirror positions was terminated after seven shots due to a beam intensity modulation in excess of 3:1 as illustrated in Fig. 6. Both of the bottom on-line conditioned mirrors and one of the top off-line conditioned mirrors were massively damaged. Comparison of the beam profile in Fig. 8a and scatter map in Fig. 8b, again reveal a correlation between laser damaged and high fluence areas. The laser damage to the top off-line conditioned mirror was less severe than the two bottom mirrors.

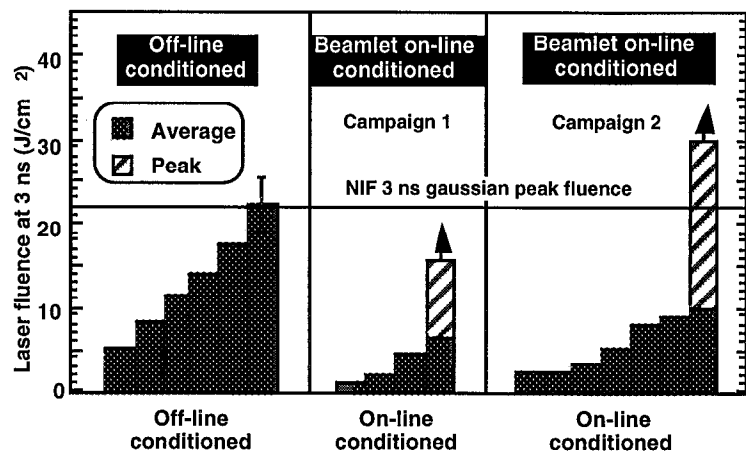


Fig. 6 Comparison of fluence ramps for off-line and on-line laser conditioning. Both campaigns were terminated due to severe modulation of the laser beam resulting in high peak fluences.

Fig. 8c illustrates a different damage morphology on the LM6 mirror that indicates better adhesion of the coating to the substrate, but massive failure most likely resulting from the interaction of a plasma with the coating. The different damage morphology may be the result of coating vendor process variances since a mirror from each vendor was placed in the LM 6 location for one of the two campaigns.

The high modulation observed during these experiments is a rare event not seen during normal Beamlet operations and was most likely the result partial pinhole closure by a plasma. Pinhole closure defocuses a portion of the beam resulting in an overlaying beam with the main beam creating long spatial length modulations similar to those observed during the two campaigns. Another indication of an overlaying defocused beam was an observable beam imprint on the mirror mount.

A final experiment is in progress on Beamlet to determine the feasibility of single-step off-line laser conditioning. Four mirrors from four vendors were successfully single-step off-line conditioned to 20 J/cm^2 average and 22 J/cm^2 peak. A significant amount of plasma scalding was present on the hafnia deposited mirror, but not on the remaining three hafnium deposited mirrors. The plasma scalding is most likely due variances in the coating deposition process other than the starting material composition since other vendor's hafnia deposited mirrors had significantly less plasma scalding. Two additional mirrors, one each from two different vendors, had a small number of damage sites with approximately 1 mm diameter which

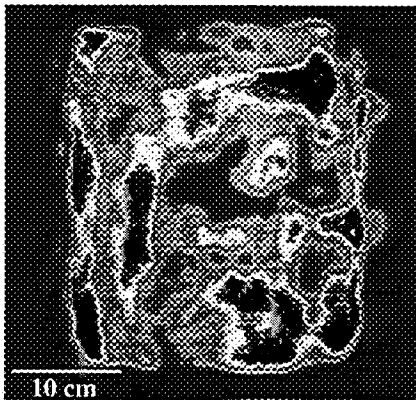


Fig. 7a Beam profile of campaign 1. Areas in black are $\geq 15 \text{ J/cm}^2$.

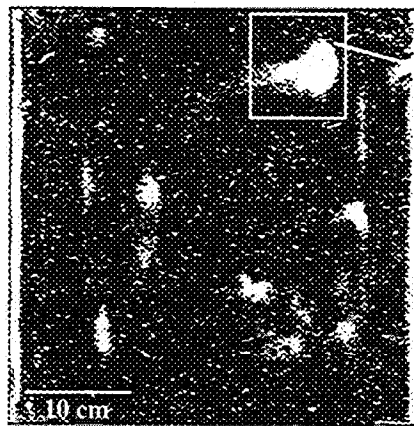


Fig. 7b Scatter map of optic after campaign 1. High scatter areas indicate laser damage.

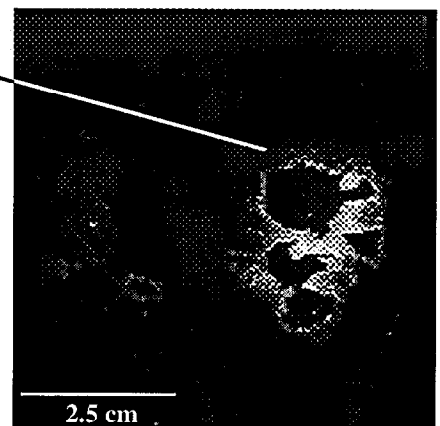


Fig. 7c Magnified view of damage site reveals coating delamination from the substrate.

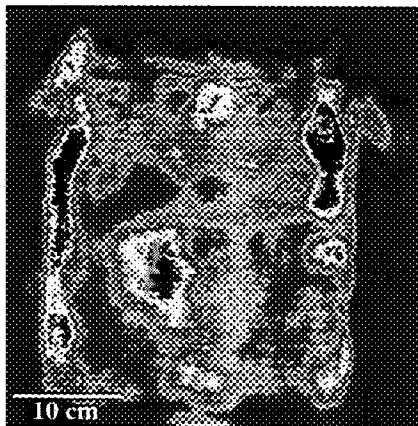


Fig. 8a Beam profile of campaign 2. Areas in black are $\geq 22 \text{ J/cm}^2$.

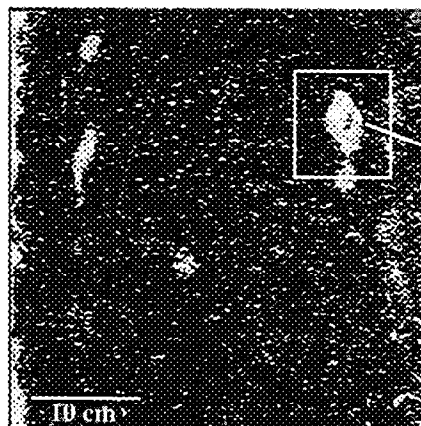


Fig. 8b Scatter map of optic after campaign 1. High scatter areas indicate laser damage.

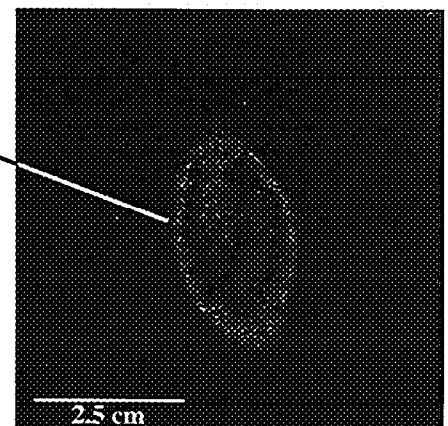


Fig. 8c Magnified view of damage site indicates plasma interaction with the coating.

is equivalent to the conditioning laser beam diameter. At this time it is unknown if laser damage is a result of the single-step laser conditioning process or the replacement of hafnia with hafnium in the coating process. After installation of the mirrors, a conservative 10 shot sequence starting at 1 KJ and ending at 8 KJ with a peak fluence of 11 J/cm² resulted in no visually observable damage to the mirrors. Further shots are scheduled in the spring of 1998 at peak fluences up to 18 J/cm².

4. ANALYSIS

In the first Beamlet campaign, survivability of the fully off-line conditioned mirrors placed between the damaged partially on-line conditioned bottom mirrors, demonstrates an increase in laser damage threshold as a result of proper laser conditioning. Unfortunately saturation of the beam profile camera and the placement of the uncoated 1 ω diagnostic beamsplitter make it impossible to determine the fluence at which only benign plasma scalds occurred and not catastrophic failure. It is known that damage did not occur below 15 J/cm² even on the partially conditioned mirrors. During the second Beamlet campaign, both top and bottom mirrors damaged indicating no significant difference in the on-line and off-line conditioning methods. Since the beam profile camera did not saturate in campaign 2, it is possible to determine a fluence boundary between plasma scalds and catastrophic failure of 30 J/cm² on successfully laser conditioned mirrors deposited from hafnia and silica. The influence of laser conditioning on hafnium deposited mirrors is less clearly understood since no large aperture tests similar to the first two Beamlet campaigns have occurred on unconditioned (or partially conditioned) hafnium deposited mirrors.

The one massive damage site that occurred during the 22 J/cm² scan outside of the clear aperture of one of the off-line conditioned mirrors demonstrates that the damage threshold of the large mirrors is limited by low density defects with damage thresholds below the peak NIF fluence. This observation is further justified in the two to four 1 mm diameter damage sites observed on two of the single-step laser conditioned mirrors. At this time we do not currently have a tool to nondestructively identify these fluence limiting defects to determine if they are conditionable. Current work on small samples with photothermal microscopy shows a correlation between defects with high photothermal signal and low damage threshold, but further work remains to develop a system capable of scanning NIF size optics.²⁰

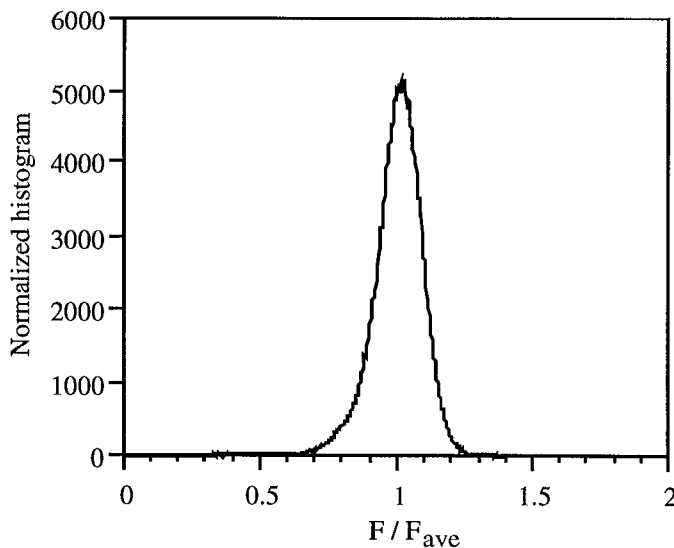


Fig. 8 Fluence statistics of a typical Beamlet shot.

There is a statistical nature to the fluence requirements of the NIF mirrors. The mirrors need to survive a limited number of shots dictated by a shot cycle of 3 shots per day over 6 days per week resulting in around 900 shots per year. NOVA mirrors have survived as long as 15 years without replacement providing a historical optic lifetime for a large aperture fusion laser. Only a small percentage of the NIF shots are expected to be at the peak NIF fluence since numerous high energy experiments can be successfully conducted at lower fluences. Finally, there is only a small segment of the beam that is at the peak fluence. A typical fluence histogram in Fig. 8 from the last Beamlet experiment illustrate the small area of the coating that is irradiated at the peak fluence. Therefore mirrors with fluence limiting defects have a probabilistic lifetime determined by the requirement for alignment of fluence limiting defects with the peak fluence locations of the beam during the most high energy NIF experiments.

5. SUMMARY

Three methods for laser conditioning coatings were explored including six-step on-line, six-step off-line, and one-step off-line laser conditioning. Each method has been successfully used on high reflector coatings to propagate the NIF peak fluence of 22 J/cm² at 1 ω with a 3 ns pulse length. The mirrors came from a total of four vendors and were deposited from two different compositions of hafnia (metal or oxide). The hafnia deposited mirrors clearly demonstrated a conditioning effect and have survived fluences up to 30 J/cm². The hafnium deposited mirrors have not yet been tested in a manner to determine if laser conditioning improves their damage threshold over large apertures.

6. ACKNOWLEDGMENTS

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