Damage to Fused-Silica, Spatial-Filter Lenses on the OMEGA Laser System

Vacuum surface damage to fused-silica, spatial-filter lenses is the most prevalent laser-damage problem occurring on the OMEGA laser system. Approximately one-half of the stage-C-input and output, D-input, E-input, and F-input spatial-filter lenses are currently damaged with millimeter-scale fracture sites. With the establishment of safe operational damage criteria, laser operation has not been impeded. These sol-gel-coated lenses see an average fluence of 2 to 4 J/cm^2 (peak fluence of 4 to 7 J/cm^2) at 1053 nm/1 ns. Sol-gel coatings on fused-silica glass have small-spot damage thresholds at least a factor of 2 higher than this peak operational fluence. It is now known that the vacuum surfaces of OMEGA's spatial-filter lenses are contaminated with vacuum pump oils and machine oils used in the manufacture of the spatial-filter tubes; however, development-phase damage tests were conducted on uncontaminated witness samples. Possible explanations for the damage include absorbing defects originating from ablated pinhole material, contamination nucleated at surface defects on the coating, or subsurface defects from the polishing process. The damage does not correlate with hot spots in the beam, and the possibility of damage from ghost reflections has been eliminated. Experiments have been initiated to investigate the long-term benefits of ion etching to remove subsurface damage and to replace sol-gel layers by dielectric oxide coatings, which do not degrade with oil contamination.

In this article, we discuss the implications of spatial-filter lens damage on OMEGA, damage morphologies, possible causes, and ongoing long-term experiments. The staging diagram depicted in Fig. 78.59 plots the peak design fluence (average fluence times 1.8 intensity modulation factor) at each stage of a single beamline on OMEGA; the bold lines indicate regions where spatial-filter lens damage is occurring.[1] These lenses are all fused-silica optics with a sol-gel-dipped, antireflection coating at 1053 nm. Several issues have been identified regarding these lenses. The first concern is the mechanical fracture of the lenses. As the damage continues to grow, a flaw-size criteria must be determined to prevent catastrophic lens failure (fracture into two pieces) and ensure safe laser operation. The damage morphology is important to understanding

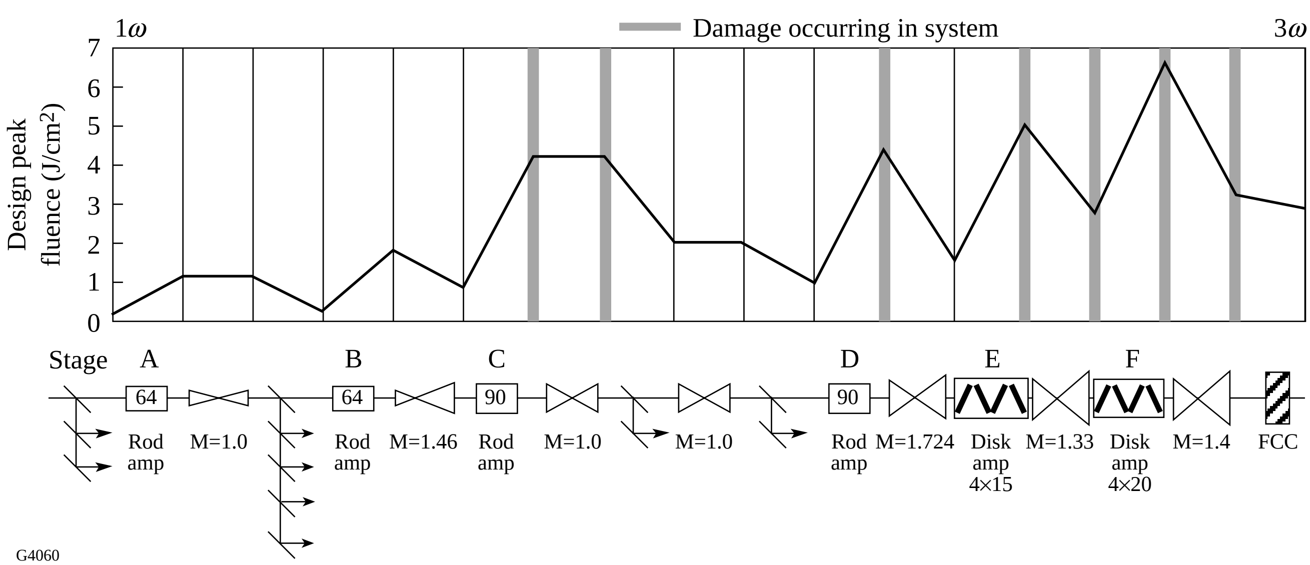

Figure 78.59
Peak design fluence plotted at each stage of the OMEGA laser. Operational laser damage is occurring at the high-fluence positions.

the initiator for large-scale fracture sites observed in Fig. 78.60 and discussed later in this article. A secondary and possibly related problem is the change in the sol-gel coating's reflectivity after exposure to the spatial-filter tube's vacuum environment. A few early experiments to investigate the damage cause are reviewed later.

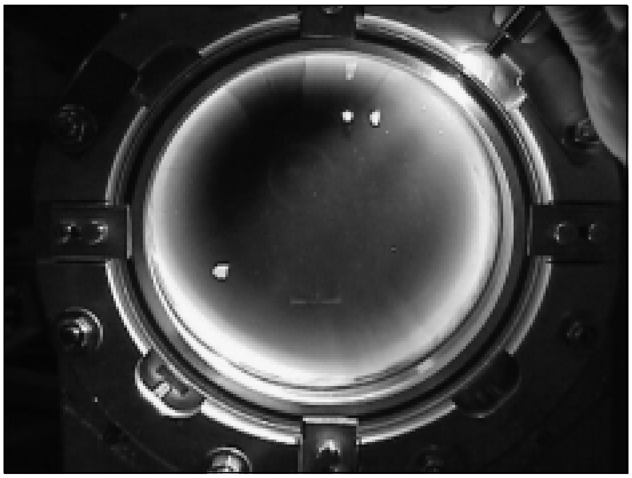

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Figure 78.60
An OMEGA stage-E-input, spatial-filter lens with multiple fracture sites. The largest site is approximately 10 mm.

Mechanical Fracture

The vacuum surface of an OMEGA spatial-filter lens is under tensile stress, and any damage to this vacuum surface can lead to catastrophic crack growth if a flaw reaches a size above the critical value a_c. The critical flaw depth a_c depends on the shape of the flaw with respect to the applied stresses and can be calculated with the following equation:[2]

$$a_c = \frac{\left(K_c\right)^2}{p(Ys)^2},$$

where K_c = fracture toughness of the glass, Y = geometrical factor of the flaw, and s = bending stress induced by atmospheric pressure p.

Actual defects on OMEGA spatial-filter lenses are shallow and elliptical in cross section, and these defects can be simulated with a half-penny–shaped defect ($Y = 1$), which has a surface diameter of twice the defect depth. This model assumes the defect to be located at the vacuum-side center of the lens where the tensile stresses are greatest; therefore, the critical-flaw-size calculations are a worst-case scenario. For an OMEGA stage-F-input lens, 25 mm thick, 283 mm in diameter, and subjected to a tensile stress of 615 psi, calculation for a half-penny defect on the vacuum side of a lens yields a critical flaw depth of 10 mm. A defect of this size will be easily detected before catastrophic failure occurs.

Lens fracture on Nova and Beamlet was modeled at Lawrence Livermore National Laboratory (LLNL), arriving at a "fail-safe" lens-design criterion with two key parameters: (1) a peak tensile stress of less than 500 psi and (2) the ratio of thickness to critical flaw size of less than six.[3] The definition of a fail-safe lens requires catastrophic fracture to proceed without implosion. An implosion refers to the action of a spatial-filter lens fracturing into many pieces and then being accelerated into the evacuated volume inside the spatial-filter housing due to atmospheric pressure.[4] Given these conditions, a properly mounted window under full vacuum load will break into two pieces only, provided the air leak through the fracture is rapid enough to reduce the load on the window before secondary crack growth ensues. The list of LLE spatial-filter lens specifications in Table 78.VII indicates that all OMEGA spatial-filter lenses meet the criteria for a fail-safe optic. Data for LLNL optics are provided in Table 78.VIII. Based on radial-fracture observations in these optics, one may expect no more than a single radial fracture in an OMEGA spatial-filter lens.

If the model is correct, fully vacuum-loaded OMEGA lenses should not implode into multiple fragments when defects reach their critical flaw size but should crack into two pieces and lock together as long as the mount restrains the radial motion of the fragments. While there have been several hundred observations of damage on the vacuum side of OMEGA spatial-filter lenses, there have been no incidents of an OMEGA spatial-filter lens fracturing into two or more pieces. For safety reasons, OMEGA optics are removed when defects reach one-half their critical flaw size.

Damage Morphology

Operational damage to 1ω, fused-silica, spatial-filter lenses occurs exclusively on the vacuum side of the lens, regardless of the beam propagation direction, and is dominated by two damage morphologies originating at or near the surface. The first morphology is that of a massive fracture greater than 100 μm on the surface, while the second is a surface crack linked to a planar, clam-shell flaw in the bulk. The photograph in Fig. 78.61 shows an example of the former. After initiation of this type, fractures grow in lateral size on subsequent laser shots until the defect reaches one-half the critical flaw size. At this time, the lens is replaced. Current OMEGA lenses have defects ranging in size from less than 0.5-mm to 10-mm diameter, and multiple damage sites on a len's vacuum surface are common. The damage depth tends to be less than one-third its surface diameter, and defects occur at apparently random radial locations. A clam-shell defect is depicted in a side view in Fig. 78.62 and in a head-on view in Fig. 78.63. The flaw's discoloration may signal that it is being filled by an absorbing material. On repeated irradiation, the clam-shell morphology is eventually obliterated and a crater develops, as in Fig. 78.61. While this clam-shell morphology is one initiator of millimeter-sized fractures, it remains inconclusive whether it is the only one. To further evaluate clam-shell damage, a sample was cleaved, as depicted in Fig. 78.64, and the exposed clam-shell cross section was analyzed by scanning electron microscopy (SEM). SEM/EDAX (energy dispersive x-ray analysis) element identification revealed the presence of carbon within the fracture while reporting its absence outside the fractured area. It is surmised that once a crack appears on the vacuum-side

Table 78.VII: Summary of peak tensile stresses and critical flaw size for OMEGA vacuum spatial-filter lenses.

Lens	Diameter (mm)	Peak stress (psi)	Peak stress (MPa)	Center thickness t (mm)	Flaw size a_c (mm)	t/a_c
C-in	149.4	656	4.52	12.5	8.8	1.4
D-in	149.4	683	4.71	12.5	8.1	1.5
E-in	213.5	538	3.71	20.0	13.0	1.5
F-in	283.4	615	4.24	25.0	10.0	2.5

Table 78.VIII: Summary of peak tensile stresses and critical flaw size for various vacuum optics in a LLNL study.[3]

Lens/Window	Peak stress (psi)	Peak stress (MPa)	Thickness t (mm)	Flaw size a_c (mm)	t/a_c	Number of radial fractures
Beamlet L3	1490	10.10	35.0	2.1	16.7	9–11
Nova SF-7	810	5.51	37.0	5.5	6.7	2–3
Nova 3ω focus	515	3.50	83.0	15.0	5.5	<1
15-cm SiO_2 plate	830	5.65	9.5	5.4	1.8	≤ 1

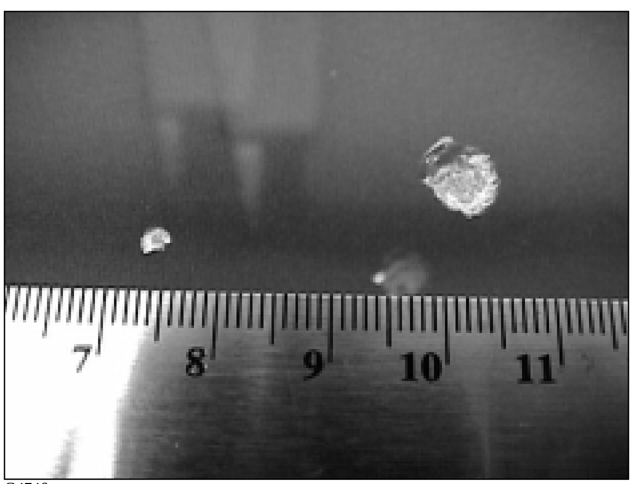

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Figure 78.61
Fractures on the vacuum side of an OMEGA lens. Scale units in centimeter.

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Figure 78.62
Clam-shell defect originating at the vacuum side (bulk view).

surface, oils from the machined surfaces of the spatial-filter tubes or oils from the mechanical pumping system seep into the crack over time. The combination of absorption by the trapped fluid and physical–chemical assistance in crack-front propagation during subsequent exposure is surmised to form the ring structure observed within the clam shell.

The cause of damage initiation to 1ω, fused-silica, spatial-filter lenses remains undetermined. Possible causes include (1) absorbing defects ablated from the tube wall or pinhole material, (2) oils or contamination nucleated at specific defects on the lens or coating, (3) oils absorbed into subsurface fractures expanded by tensile surface forces, and (4) isolated contamination remaining from coating application. Related work for the National Ignition Facility (NIF[5]) laser found (1) that the cause of 3ω damage was polishing-process defects within 500 μm of the surface and (2) that removal of these defects by etching improved the surface damage thresholds.[6] LLE-based ion-etching experiments to improve surface damage threshold are discussed later.

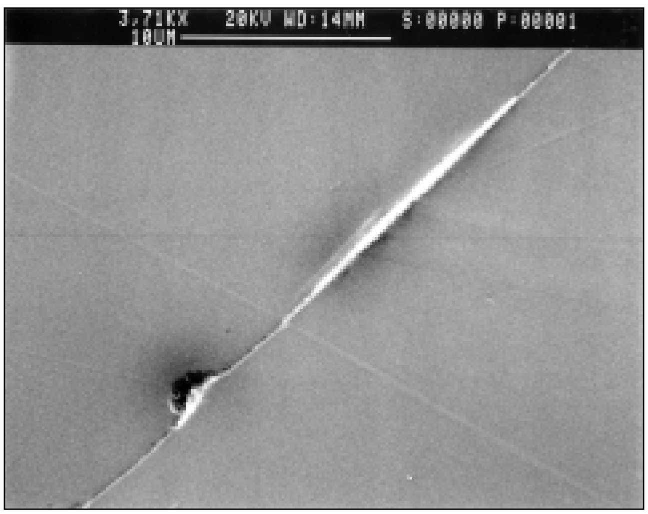

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Figure 78.63
SEM vacuum surface view of a clam-shell defect on an OMEGA lens (top view).

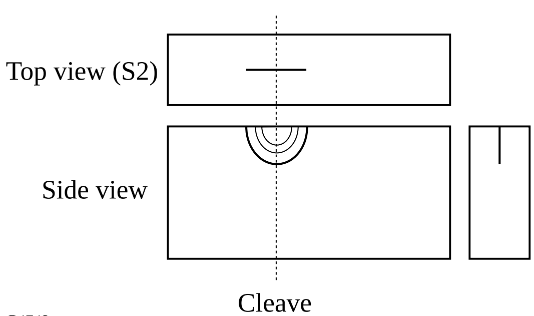

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Figure 78.64
Illustration of cleave sample orientation.

Sol-Gel Coating Degradation

OMEGA sol-gel coatings show a significant change in reflectivity when exposed to a vacuum contaminated with oil from mechanical pumps. A fiber-optic spectrometer is used to measure the lens reflectivity *in situ*. While the instrument provides only relative photometric measurements, the spectral-curve shapes provide essential information on coating performance. Spectra in Fig. 78.65 show an example for how spectral response among the two sol-gel-coated surfaces of a single lens is affected by exposure to oil. While the S1, nonvacuum-side reflectivity curve is expected for a 1ω antireflection coating, the spectral characteristics of the S2, vacuum-side data show an increase in reflectivity at 1ω from 0.1% to 3.4%, owing to refractive-index changes resulting from adsorbed organic material. Evaluation of the S2 sol-gel coating by gas chromatography/mass spectrometry detected the presence of vacuum-pump oil and other organic contamination. The effect of oil contamination on the film index on a fixed-thickness sol-gel coating is modeled in Fig. 78.66. As the film index varies from 1.23 to 1.44 (film thickness is constant), reflectivity minima disappear into a flat line similar to the experimental observation in Fig. 78.65. This coating problem is seen on all OMEGA sol-gel-coated spatial-filter lenses that are collectively pumped by a single mechanically pumped vacuum system. Coatings are found to fail at different rates, however, as a result of differing cleanliness conditions or

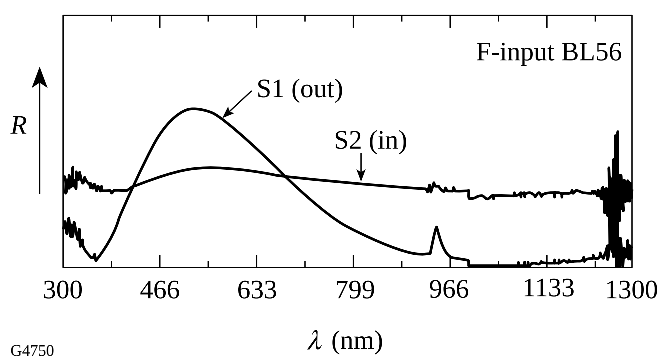

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Figure 78.65
Reflectance data measured on a sol-gel-coated spatial-filter lens. The S2 (in) surface is the vacuum interface; the S1 (out) surface resides in air.

vacuum pressure levels within the spatial-filter tubes. Loss of reflectivity on a mechanically pumped tube is suffered in about six weeks or more. Hard-oxide dielectric coatings pumped under similar vacuum conditions show no change in reflectivity after exposure for similar periods.

The prototype beamline laser (PBL) assembled years earlier was disassembled about the same time as this study. The sol-gel-coated lenses in those tubes showed no coating degradation due to contamination. The tubes were first pumped mechanically and were then switched to a titanium sublimation pump, which maintained a pressure of 1×10^{-5} mbar. No record exists to indicate what method was used to clean the tubes in this PBL. To gauge the effect of different pumping methods on OMEGA, a freshly sol-gel-coated lens was placed in a spatial-filter tube that was isolated from the OMEGA mechanical pumping system. The tube was then connected to a cleaner turbo-pumping system although the tube itself could not be decontaminated *in situ*. A properly run turbo pump will exhibit very little back streaming of high-molecular-weight oils such as those used by a mechanical pump. Surprisingly, the coating was contaminated after less than four days' exposure to this environment. It was surmised that the greater mean free path in the lower pressure allowed faster transport of the oil from the contaminated walls to the sol-gel coating. This rules out the relatively simple solution of redesigning the pumping system. Improvement of the oil-contaminated system could be effected only by removing the tubes, then cleaning and baking them, possibly in a vacuum along with all the associated plumbing. This would produce an unacceptable lapse in the OMEGA firing schedule.

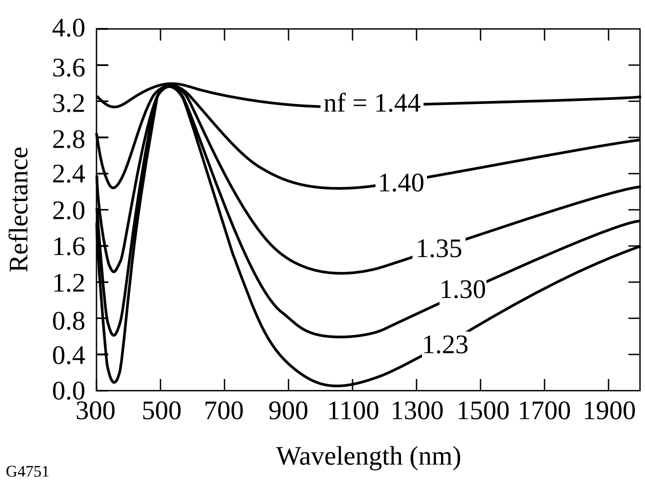

Figure 78.66
A model of reflectance change as the film index is varied for a constant film thickness. Film indices used are 1.44, 1.40, 1.35, 1.30, 1.23.

A causal link between sol-gel contamination and lens damage is suspected but has yet to be fully proven. Experiments to investigate this link and solve this damage problem are ongoing, and some results are reported in the next section. In addition, several solutions to this sol-gel-coating degradation problem are being examined to recover the light loss imposed by each "bad" surface: (1) replace sol-gel coatings with hard-oxide dielectric coatings (damage threshold is a key factor); (2) improve the spatial-filter pumping system and clean the spatial-filter tubes; and (3) add a "getter" material to adsorb the contamination before it reaches the coating.

Experiments

Several experiments were started to investigate the cause of damage to the vacuum surfaces of OMEGA spatial-filter lenses. One experiment resulted from a LLNL report that the damage threshold of fused silica at 3ω can be improved with etching. Etching appeared to remove polishing-process defects within a few hundred microns of the surface. Another experiment was proposed to examine the cleanliness conditions of the spatial-filter tubes and explore the probability that ablated pinhole debris produce damage-initiation sites.

1. Ion-Etching Tests

Since LLE developed an ion-etch capability for manufacturing distributed phase plates, it was logical to set up a process to ion etch the vacuum surface of spatial-filter lenses.[7] An experiment was designed to remove 3 μm of material from side 2 (vacuum side) of OMEGA stage-F-input, fused-silica, spatial-filter lenses, and then coat and install the optics on OMEGA to observe damage and coating failure. The following matrix was established with five lenses to be processed for each type:

(a) ion etch and sol-gel coat,
(b) ion etch and hard-oxide coat,
(c) ion etch and no coating, and
(d) no etch and no coating.

The hard-oxide coating is a hafnia/silica, e-beam-evaporated, antireflection coating.[8]

Once the optics are installed on OMEGA, observation over a long period of time (possibly one year) is required as damage onset times remain uncertain. The statistics of damage occurrence on these lenses in comparison to the damage statistics on OMEGA over the last three years will be reviewed. The experiment will evaluate the effect of subsurface defects on the laser-induced damage threshold (LIDT) and also the effect of ion etching in modifying subsurface topography. These tests may also provide a correlation between damage and type of coating.

Progress on this test has been hampered by the paucity of spare optics to complete the matrix. In August 1998, type-(a) optics were installed; as of March 1999, no damage has been observed on these surfaces, and only one of the five sol-gel coatings has enhanced vacuum-side (S2) reflectivity. Transmittance loss was incurred within six weeks of installation. Three of five type-(b) optics were installed—one in October 1998 and two in November 1998; to date no damage or coating degradation has been observed. The remaining tests will be completed in June 1999 and results reported in the future.

2. Spatial-Filter Witness Tests

To investigate the cleanliness conditions of spatial-filter tubes, ten 2-in.-diam, sol-gel-coated, fused-silica samples were installed in OMEGA's stage-E spatial-filter tubes for approximately two months. All samples were damage tested at 1053 nm with a 1-ns pulse before and after exposure to the spatial-filter tube environment. Three beamlines had one sample installed at the input lens location and one sample at the output lens location, and a fourth beamline had two samples installed at each location. The sample orientation within the spatial-filter tube is illustrated in Fig. 78.67. By mounting the samples in this manner, the top surface collects pinhole condensate, while the bottom surface remains shielded.

The results revealed that the spatial-filter tube's cleanliness condition inflicts a stiff penalty, regardless of pinhole debris. As seen in Table 78.IX, all samples showed a significant drop in damage threshold after a two-months' exposure to the spatial-filter tube environment, and the top and bottom surface threshold data are virtually indistinguishable. The reported thresholds are 1-on-1 damage tests with a 1-mm^2 beam size; approximately 12 sites per sample were tested. Further SEM analysis revealed no high-Z element presence on the post-exposure surfaces, indicative of an absence of spatial-filter pinhole emanations on the top witness surface. It is difficult to predict the trajectory of ablated material, and further tests with samples located at various orientations are required to identify the path of ablated pinhole material that may contribute to lens damage. There is evidence on some pinholes that the edges are melted and craters have formed. While further experiments are needed to confirm pinhole ablation as an initiator for vacuum surface damage sites, the data confirm that oil contamination does decrease the sol-gel-coating damage threshold.

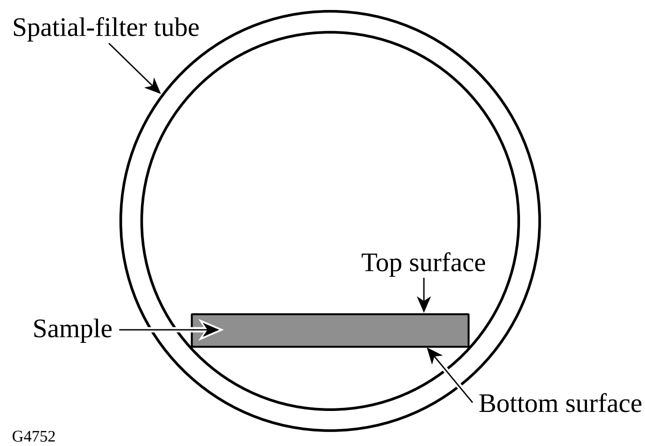

Figure 78.67
Witness sample orientation within a spatial-filter tube.

Table 78.IX: Witness sample damage threshold results before and after exposure to a spatial-filter tube environment.

Sample Orientation		Before-Exposure Damage Threshold* (J/cm^2)	After-Exposure Damage Threshold* (J/cm^2)
Top surface	average	20.7	11.9
	standard deviation	4.9	2.5
Bottom surface	average	22.1	11.3
	standard deviation	3.9	3.1

*1-on-1 damage tests at 1054 nm with a 1-ns pulse and 1-mm^2 beam size.

Conclusion

Approximately 50% of OMEGA's stage-C-input, C-output, D-input, E-input, and F-input fused-silica, spatial-filter lenses are damaged. LLE has implemented a plan to maintain the quality of OMEGA optics that includes frequent inspections and *in-situ* cleaning of optics by a skilled support group. Since damaged optics are closely monitored and the one-half critical flaw size is of the order of 10 mm in diameter, OMEGA lenses are not likely to catastrophically fail before replacement occurs. This allows for safe operation of the laser while the damage problem is being brought under control. Owing to the effectiveness of spatial filters in removing critical intensity modulations, propagating bulk or surface damage to components downstream of these damaged lenses has not been observed. Damage always occurs on the lens's vacuum surface regardless of the beam propagation direction, and an unusual clam-shell damage morphology has been observed. It is also known that the sol-gel coating on the vacuum surface fails due to organic contaminants, and this degradation is linked to a drop in the tested laser-damage threshold. A link between sol-gel contamination and lens damage is suspected but yet unproven. Experiments will continue to explore the role of subsurface fractures in the generation of the clam-shell morphology and to identify other absorbing defects on the vacuum surface, possibly originating from pinhole closures, which may be causing the damage.

ACKNOWLEDGMENT

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