Status of Optics on the OMEGA Laser after Eighteen Months of Operation

The OMEGA laser has sustained approximately 1000 target shots over its first 18 months of operation without significant damage to the optics. Both rod and disk amplifiers are used in the OMEGA laser chain; after each amplification stage at 1ω the beams are spatially filtered to remove high-spatial-frequency noise in the beam and to ensure correct image relaying. Optical damage thresholds dictated the minimum beam diameter in each stage and fixed the magnification between stages. The final 28-cm beam propagates through thin-film polarizers before reaching the frequency-conversion cells.[1–3] Frequency conversion to the third harmonic (351 nm) is carried out using the polarization-mismatch method developed at LLE.[4,5] A set of mirrors transports the 3ω beams through a final focus lens, and the last optic in the beam path serves as the vacuum barrier for the target chamber.

Fundamental to LLE's OMEGA operating philosophy is a maintenance plan to ensure (1) prevention of costly damage to system components and (2) reliable and efficient operation of the system.[6] One part of this preventative maintenance plan involves an estimated 3000 optics on the OMEGA laser system, not including laser glass, driver-line optics, and diagnostic components. The Optical Manufacturing Group is responsible for coordinating the inspection of these optics and tracking this information. On a periodic basis, the optical components are inspected for laser damage, coating degradation, and particulate contamination. During planned shutdown periods, extensive maintenance (cleaning, recoating) and replacement of optics occur. To date, the majority of optics on the OMEGA laser system have not been damaged, and there is no propagating bulk or surface damage to components downstream of damaged optics. While the current optics replacement rate is below the anticipated rate of 10% per year, this rate is expected to increase as the laser ages. In the sections that follow, a review of the types of optical component degradation is presented.

Laser-Damage Classification

In discussing laser damage, a distinction is made between operational and accidental system damage. An optic damaged when the laser operates within normal design limits is classified under operational damage; whereas, accidental damage occurs when the laser operates outside the design limits. This classification is useful because accidental damage can result in significant damage to an optic, but it is not an indication of continuing problems with that component. Tracking optics damaged due to routine laser operation results in statistical information about the longevity of a particular optic; this information is incorporated into decisions regarding an appropriate spare optic inventory. Observations of an optic's mean lifetime are necessary to determine an effective and economical spares program.

1. Operational Laser Damage

As the laser continues to operate, it is not surprising to observe operational damage in optics located at high-fluence positions of the laser. Figure 70.1 shows a staging diagram that plots the peak design fluence—average fluence times a 1.8 intensity modulation factor—at each stage of a single beamline on OMEGA.[7] The bold lines indicate areas where laser damage is occurring at present. Specific damage morphologies are presented on p. 52.

2. Accidental Laser Damage

While accidental laser damage occurs infrequently, it can result in significant optics damage. During the activation stage of OMEGA, six optics were damaged in a single shot when light back-propagated after striking the edge of an improperly positioned spatial filter pinhole assembly. The ring of damage is located at the edge of the beam diameter and was caused by the radial edge gain from the rod amplifiers. This beam imprint was observed on several mirrors and the liquid crystal component shown in Fig. 70.2.

Another instance of accidental damage was the development of a small damage site in one-third of the 3ω final focus lenses. A design analysis that locates the focus of unwanted surface reflections eliminated the possibility of a ghost reflection as the cause of this damage site.[8] The single, bulk damage site is less than 1 mm in diameter and is located at the optic's center near the exit surface. The damage has not propagated to

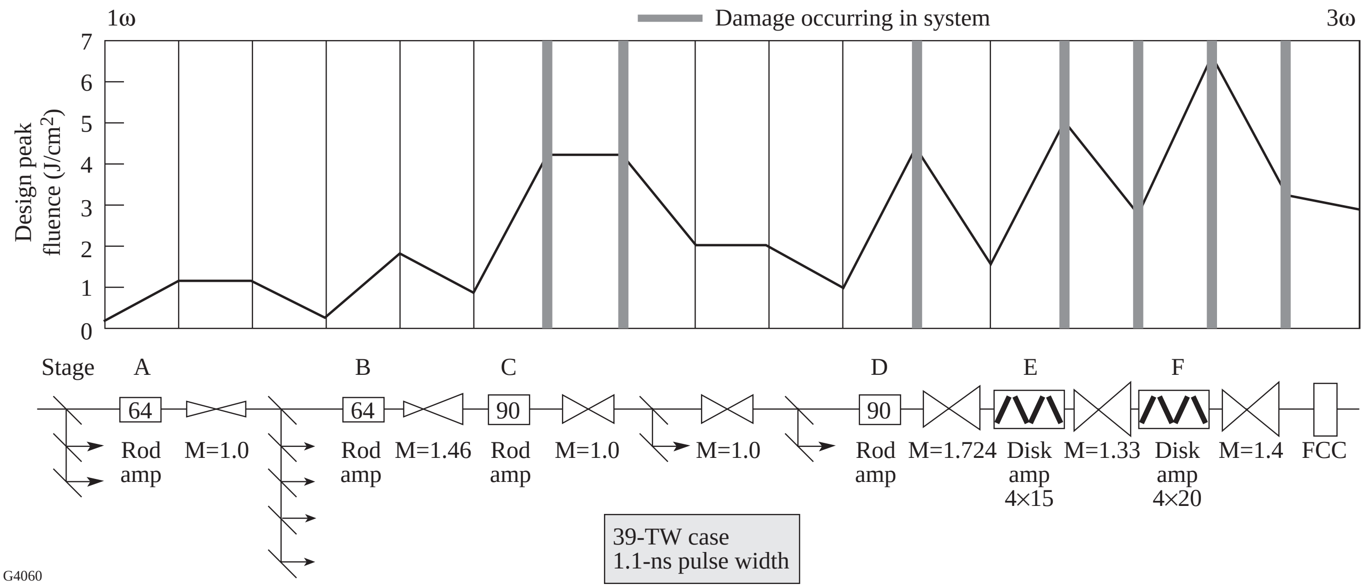

Figure 70.1
Peak design fluence plotted at each stage of the OMEGA laser. Operational laser damage is occurring at the high fluence positions.

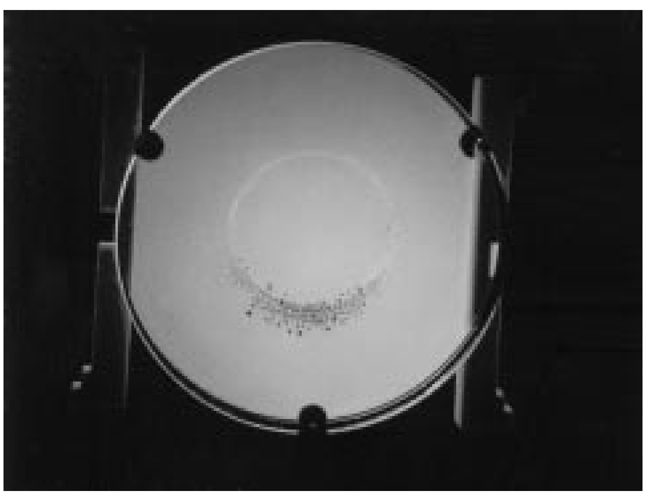

Figure 70.2
A malfunctioning spatial filter pinhole assembly caused the accidental damage to this liquid crystal polarizer component (135-mm diameter).

the blastshield optic located about 75 mm in front of the lens or to opposing beam port optics. Figure 70.3 shows a timeline of the discovery of damaged focus lenses. At the end of OMEGA activation, a large number of focus lenses were suspected to have damage, with only a slight increase since the initial observation. We believe this damage does not result from the normal operation of the laser because the plot of energy does not correlate with the number of damaged lenses reported. However, continued laser operation does contribute to the growth of the existing accidentally damaged site. During activation, a train of short pulses propagated down the system and were frequency converted to 2ω, instead of 3ω, which may have caused the damage. Since the sol-gel coating was designed for 3ω, a 2%–3% surface reflection occurs at 2ω. Analysis of multiple beam reflections inside the lens results in the formation of a 2ω caustic at the lens' center position 2 mm from the exit surface.[9]

Damage Morphologies

The damage observed on an optic can be classified as either stable or unstable. Given that the optical components will damage, it becomes important to distinguish between damage that is catastrophic to laser operation and damage that is tolerable. Stable damage does not affect the laser's performance and does not cause propagation of damage to other downstream optics. In addition, this type of damage does not appear to grow significantly on successive laser shots. Unstable damage does grow on subsequent laser shots and eventually prevents the safe operation of the laser. Unstable damage may result in catastrophic failure of a component; additionally, this type of damage could cause propagation of damage to other optics in a beamline. For these reasons, optics with unstable damage are monitored frequently for changes in damage size, and replacement occurs before the damage reaches a critical value.

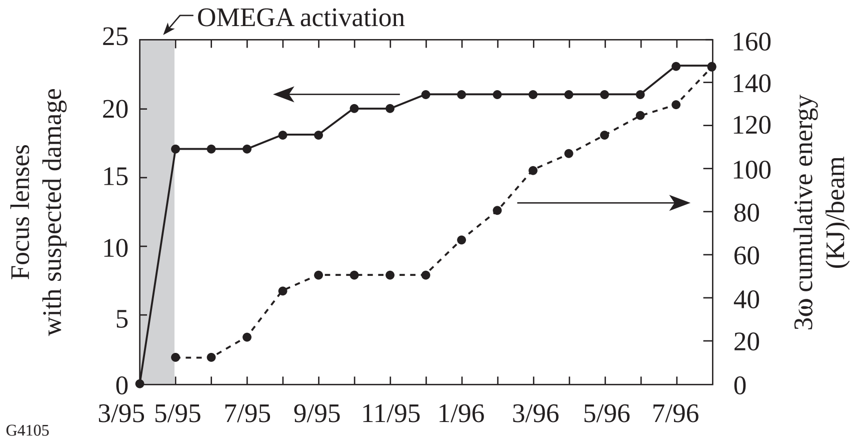

Figure 70.3
Observation timeline of OMEGA final focus lenses. The left axis plots the number of damaged focus lenses observed over the lifetime of the laser. The right axis plots the 3ω cumulative energy per beam over that same time frame.

1. Stable Damage

The occurrence of stable damage on OMEGA has been documented since activation of the laser system. Two forms of damage have been observed: (1) self-focusing damage in spatial filter lenses and (2) plasma scalds on transport mirrors.

Self-focusing damage is seen infrequently in OMEGA lenses. Currently, nine fused silica lenses have evidence of "angel-hair" tracking, which occurs in the bulk material. These tracks appear as a linear sequence of microscopic damage in the bulk of the optic aligned with the propagation axis. Table 70.I provides a list of the damaged components and the peak fluences they are subject to.

Figure 70.4 shows a photograph of self-focusing damage observed on an OMEGA lens. The large white spot is in the exit surface of the lens, and the typical diameter of this damage area is 1 mm. This large area contains a number of smaller, individual damage sites formed when the self-focusing tracks intercepted the output surface of the lens. These sites do not seem to grow on successive laser shots.

Plasma scalds are frequently seen on OMEGA's 3ω transport mirrors. As seen in Fig. 70.5, scalds appear as a

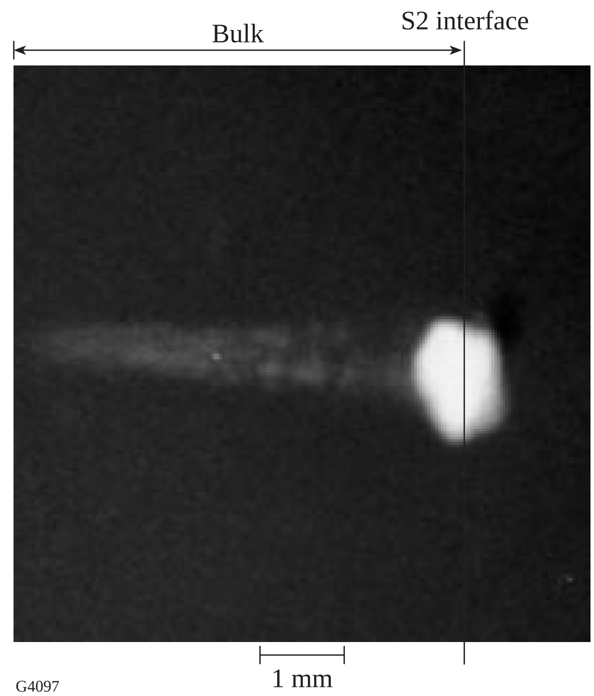

Figure 70.4
"Angel-hair" tracking damage observed in the bulk glass of an OMEGA stage-F input lens. The large bright area is the exit surface of the lens.

Table 70.I: Summary of the number of optics with self-focusing damage.

Component	Damaged Lenses/ Total Lenses	Design Peak Fluence (J/cm^2) with 1.1-ns pulse
Stage-E input spatial filter lens (1ω)	1/60	5.0
Stage-F input spatial filter lens (1ω)	5/60	6.6
Primary pickoff lens (3ω)	3/60	2.9

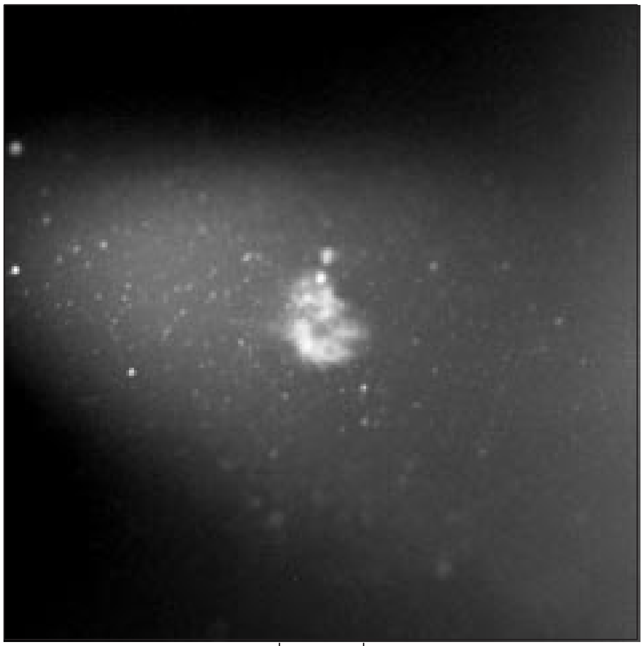

Figure 70.5
Plasma scalds are frequently seen on OMEGA's 3ω transport mirrors.

discoloration on the coated surface of the mirror. Scalds are initiated where particulates are on the mirror surface during a laser shot and are caused by an increase of temperature on the surface during plasma formation.[10] OMEGA transport mirrors are *not* contained in enclosed structures but are mounted in open, upward/downward-facing structures. This open architecture, which allows personnel access to target chamber equipment, results in an increased level of contamination on target bay optics as opposed to laser bay optics, which are vertically mounted with protecting covers on the structures. These plasma-scald defects do not grow in size on subsequent laser shots, but the number of scalds per surface may increase. At this time, no reflectance data is available to determine how plasma scalds affect performance of the mirror coating.

2. Unstable Damage

OMEGA optics that exhibit unstable damage include (1) tantala/silica-coated beam splitters, (2) BK-7 spatial filter lenses, and (3) fused-silica, input spatial filter lenses. Damage to these optics continues to grow on subsequent laser shots. The rate of growth and size of damage are dependent upon the type of damage observed.

All tantala/silica **beam splitters** located in OMEGA's C-split region (which is the region with the highest fluence of any multilayer coating) have significant damage after 18 months of laser operation. From Fig. 70.6, it is apparent that this damage was not accidental but operational laser damage. As the beam splitters continued to see an increase in 1ω cumulative energy, the observed number of damaged beam splitters increased. Microscopic evaluation of a beam splitter revealed coating-damage sites that were initially 50 to 100 μm in size and 7 μm deep. This depth indicates that the tantala/silica coating is damaged at the substrate interface. The size of these damage sites continues to grow on successive laser shots. Figure 70.7 shows a photograph of a beam splitter with the damage sites illuminated within the beam diameter.

During the OMEGA Upgrade, two types of beam splitters were produced using either the tantala/silica design or the hafnia(metal)/silica design. Hafnia(metal)/silica-coated beam splitters located in the same area as the tantala/silica beam splitters show no signs of coating damage, even though they have the same test damage threshold.[11] These test damage thresholds (reported in Fig. 70.8) were taken on a limited number of sites, and, as a result of this limited statistical process,

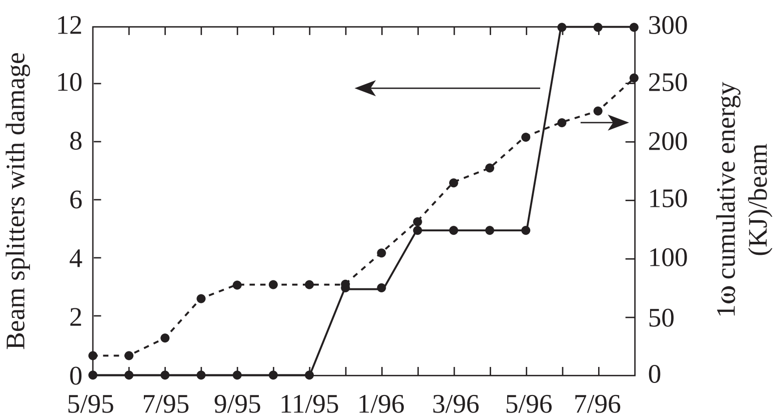

Figure 70.6
Observation timeline of OMEGA's stage-C beam splitters. The left axis plots the number of damaged beam splitters observed over the lifetime of the laser. The right axis plots the 1ω cumulative energy per beam over that same time frame.

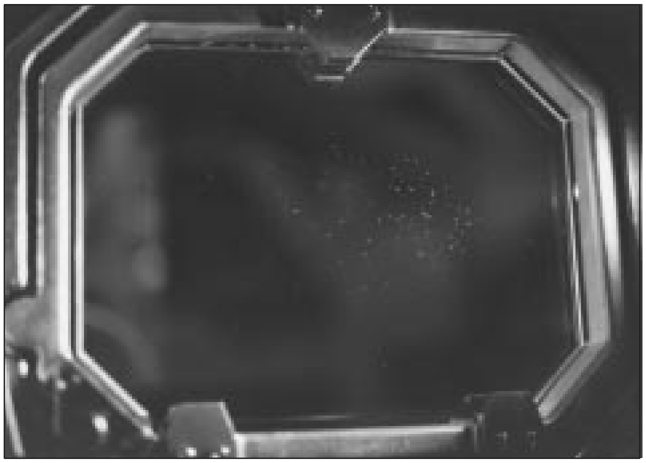

Figure 70.7
Coating damage observed on a 5.5-in. × 7.5-in. OMEGA stage-C, tantala/silica beam splitter. The highest fluence seen by a multilayer coating is in the C-split area.

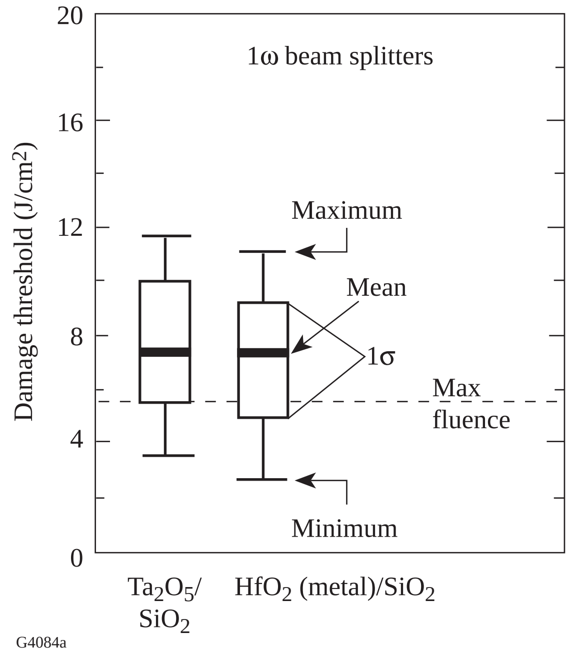

Figure 70.8
Damage thresholds for tantala/silica and hafnia(metal)/silica beam-splitter coatings measured at 1054 nm with a 1-ns pulse at *p*-polarization.

defect sites may have been missed. The results on OMEGA are equivalent to full-aperture testing, and this type of testing has revealed significant differences in damage thresholds between the two materials. The highest fluence seen by a multilayer coating is in the C-split area (which is 4.1 J/cm^2). Beam splitters in other areas see a lower fluence (typically ~1 J/cm^2), and neither design has demonstrated any sign of significant damage in these low fluence areas.

Isolated bulk damage sites have been seen in a number of OMEGA **BK-7 spatial filter lenses**. A summary of the location and number of damaged optics is provided in Table 70.II. The peak design fluence is the average fluence times a 1.8 intensity modulation factor.

Each lens has one to four damage sites, ranging in size from 50 to 800 μm, occurring at varying depths within the bulk glass. Photographs of damage sites from an OMEGA lens are shown in Fig. 70.9. Microscopic evaluation revealed damage sites with radial fractures forming a circular pattern perpendicular to the beam. This type of fracture pattern is characteristic of platinum-inclusion damage.[12] Previous data reported by LLNL showed that platinum inclusions in phosphate glass cause fractures when irradiated by laser pulses above a threshold value of 2.5 to 3.0 J/cm^2 with a 1-ns pulse.[13] These fractured sites do grow upon repeated irradiation, but this growth rate is slow with respect to a bimonthly inspection cycle. During inspection cycles, sizes are visually estimated by observation with a white-light source. Quantitative microscopic evaluation is difficult on *in-situ* optics inspection, so an accurate estimate of damage growth rate is not available. Currently, we have not observed any damage propagation from these lenses to other optics in the beam path.

Table 70.II: Summary of the number of optics with bulk damage sites.

Component	Damaged Lenses/ Total Lenses	Design Peak Fluence (J/cm^2) w/1.1-ns pulse
Stage-C relay lens (in/out)	8/60	2.3
Stage-E output lens	7/60	3.0
Stage-F output lens	34/60	3.6

Large-scale fractured damage sites have been observed in OMEGA's stage-C, -D, -E, and -F input **fused-silica spatial filter lenses**. These areas of the system see some of the highest 1ω fluences and exceed the 2.5 J/cm^2 criterion for the use of fused silica as opposed to BK7 glass (see Fig. 70.1 for the peak fluence in the OMEGA laser chain). The highest peak design 1ω fluence is at the F-input lenses with a fluence of 6.6 J/cm^2. The lowest 1ω fluence seen by these lenses is the C input, which has a fluence of 4.1 J/cm^2. Figure 70.10 shows a good correlation between the number of damaged lenses and the 1ω cumulative energy per beam plotted over the same time frame. As the 1ω cumulative energy per beam increases, the number of lenses with fractured damage sites also increases, indicating a form of operational damage.

The damage occurs on the exit vacuum side of the lens at random locations, and the sites grow in size on subsequent laser shots. The damage does not correlate to hot spots in the beam and is believed to be initiated at surface particulate sites. Some possible contamination sources are particulate blowoff from the pinhole and debris from fabrication of the spatial filter vacuum tubes. A fraction of the beam strikes the edge of the pinhole, causing material to vaporize and redeposit on the vacuum side of the input spatial filter lens. Investigation into the cause of this damage is ongoing. The fracture pattern from one of these damage sites is seen in Fig. 70.11.

The vacuum surface of an OMEGA spatial filter lens is under tensile stress, and any damage to this vacuum surface can

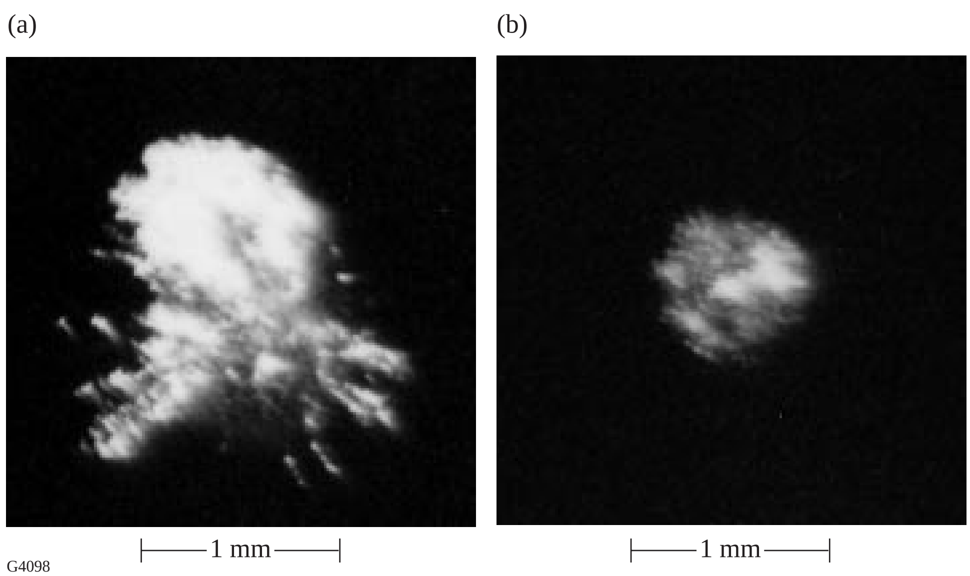

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Figure 70.9
Damage patterns observed on an OMEGA stage-F, BK-7, output spatial filter lens. Fracture patterns indicate platinum-inclusion damage.

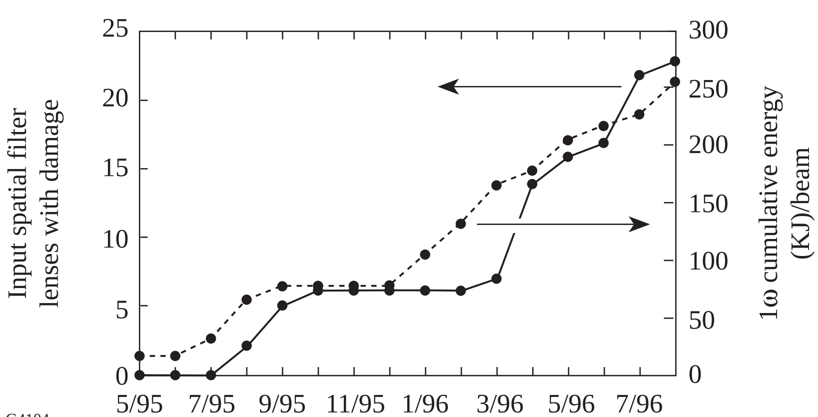

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Figure 70.10
Observation timeline of OMEGA fused-silica, input spatial filter lenses. The left axis plots the number of damaged spatial filter lenses observed over the lifetime of the laser. The right axis plots the 1ω cumulative energy per beam over that same time frame.

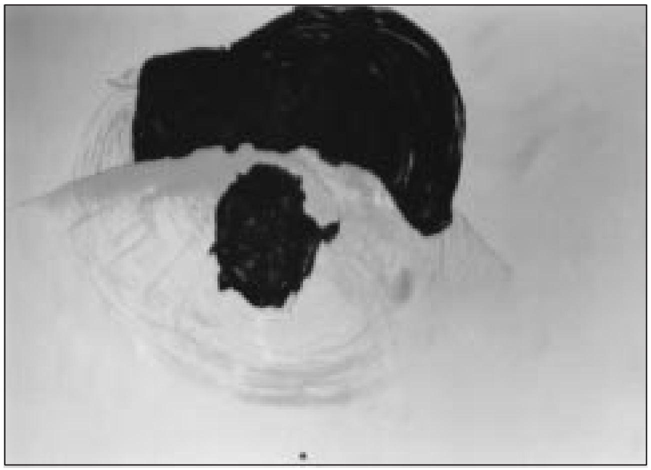

Figure 70.11
Fractured damage site observed on an OMEGA stage-C input, spatial filter lens.

lead to catastrophic crack growth if the flaw size reaches a 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 from[14]

$$a_c = \frac{(K_c)^2}{\pi(Y\sigma)^2},$$

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

Actual defects on OMEGA spatial filter lenses are shallow and elliptical, and these defects can be simulated with a half-penny–shaped defect ($Y = 1$) that has a surface diameter twice the defect depth. For an OMEGA stage-F input lens, 25 mm thick and 283 mm in diameter, a critical flaw depth of 8 mm is calculated for a half-penny defect on the vacuum side of a lens subjected to a tensile stress of 615 psi. A defect of this size will be easily detected before catastrophic failure occurs.

It is also important to understand how these lenses will fracture to avoid implosion of the lens when it is under a full vacuum load. Lens fracture on Nova and Beamlet was modeled at LLNL, where it was reported that the design of a "fail-safe" lens probably requires a stress $\sigma < 700$ psi.[15] A fail-safe lens would generate one large fracture and would not implode. The maximum bending stress for an OMEGA stage-F input lens is 615 psi and occurs at the center of the lens. If the model is correct, these lenses under full vacuum should not implode into several 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. Although damage on the vacuum side of OMEGA spatial filter lenses has been observed, there has been no incident where an OMEGA spatial filter lens has cracked into several pieces. For safety concerns, OMEGA optics will be removed when defects reach one-half their critical flaw size (i.e., when the depth is 4 mm). For convenience we measure the surface trace *in situ* and replace any lenses with a surface trace of 8 mm (which would imply a depth of 4 mm if the flaw is penny shaped). We have replaced two lenses that had surface traces of 8 mm. Later depth measurements showed only a depth of 2 mm, well within the criteria for failure.

Optical Property Changes

OMEGA's sol-gel coatings show a significant change in reflectivity when exposed to a vacuum. A guided wave spectrometer is used to measure the reflectivity of optics mounted on OMEGA. While the instrument is not photometrically accurate, the shape of the spectral curve does provide information on the performance of the coating. The spectral data in Fig. 70.12 was taken on a 1ω (1053-nm) sol-gel-coated spatial filter lens. While the S1, non-vacuum-side, reflectivity curve is as expected for a 1ω antireflection coating, the S2, vacuum-side data indicates that the porous sol-gel coating has adsorbed some organic material, which has affected its coating performance. Evaluation of the contaminated sol-gel coating by gas chromatography mass spectrometry detected the presence of

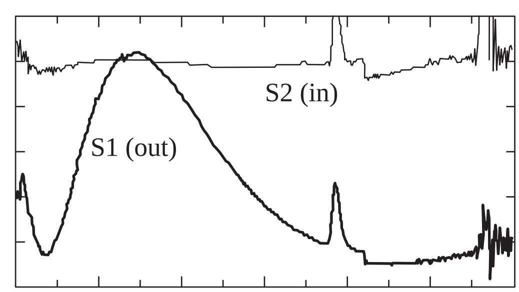

Figure 70.12
Reflectance data measured on a sol-gel-coated spatial filter lens. The S2 (in) surface is the vacuum interface. The S1 (out) surface is *not* exposed to a vacuum.

vacuum pump oil. This coating problem is seen on all OMEGA sol-gel-coated spatial filter lenses that are pumped by a mechanically pumped system. Hard-oxide dielectric coatings pumped under similar vacuum conditions and sol-gel coatings pumped by an ion sublimation pump show no change in reflectivity after exposure to a vacuum. Since OMEGA's optical layout was designed with the assumption of a 4% light loss per surface, damage is not expected from ghost reflections and no system damage has occurred as a result of this coating problem.[16] Two solutions to this sol-gel-coating problem are being investigated: (1) replace the sol-gel coatings with hard-oxide dielectric coatings and (2) improve the spatial filter pumping system. Sol-gel coatings were used on all fused silica spatial filter lenses since these lenses have the highest 1ω fluence on the system and sol-gel coatings have, in the past, shown considerably higher damage threshold than hard-oxide coatings. Recent improvements in the hard-oxide coating process have resulted in increased damage thresholds, which now make them viable replacements to the sol-gel type.

Target Chamber Optics

After 1000 target shots, no target chamber optics have been replaced because of damage. The inside target surface of the blastshield optics has degraded from the impact of target debris, and the damage is in the form of shallow pits ranging in size from 50 μm to 1 mm. Recently, self-focusing damage has been observed in several blastshields' optics, which serve as the vacuum barrier for the target chamber. Damage to the outside blastshield surface (non-vacuum side) is minimal and usually occurs as a result of mishandling during blastshield replacement. Degradation in the blastshields' sol-gel coating occurs with prolonged exposure (over 100 days) to the target chamber. This degradation leads to reduced transmission of laser energy to target center. The on-target imaging system (OTIS) diagnostic is used to measure the irradiation uniformity and can therefore be used as an *in-situ* measurement of the performance of the sol-gel coating. We use the OTIS measurement to recommend replacement of the optics with the lowest UV transmission. The baseline replacement rate of blastshield optics is 20 per month; optics are replaced during a regular maintenance day.

Conclusion

LLE has implemented a plan to maintain the quality of OMEGA optics. This preventative maintenance plan involves frequent inspections and *in-situ* cleaning of optics by a skilled support group as well as proper training of laser operations personnel to prevent optics handling damage. Damaged optics are placed on a critical optics list and are tracked frequently for damage growth. This critical optics list is used to report the current condition of OMEGA optics to the Laser Facility Manager.

This article has focused on specific optics that have started to damage after 18 months of OMEGA laser operation. Components that have *not* damaged include frequency-conversion crystals, polarizers, calorimeters, and liquid-crystal optics. In addition, there has been no propagating bulk or surface damage to components downstream of damaged optics.

ACKNOWLEDGMENT

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