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# Growth of Laser Initiated Damage in Fused Silica at 351 nm

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## ABSTRACT

The lifetime of optics in high-fluence UV laser applications is typically limited by the initiation of damage and its subsequent growth. We have measured the growth rate of laser-induced damage on fused silica surfaces in both air and vacuum. The data shows exponential growth in the lateral size of the damage site with shot number above a threshold fluence. The concurrent growth in depth follows a linear dependence with shot number. The size of the initial damage influences the threshold for growth; the morphology of the initial site depends strongly on the initiating fluence. We have found only a weak dependence on pulse length for growth rate. Most of the work has been on bare substrates but the presence of a sol-gel AR coating has no significant effect.

**Keywords:** Laser damage, UV laser damage, laser damage growth, UV fused silica.

## 1. INTRODUCTION

Advances in solid-state laser technology continue to increase demand for optics that can be operated at high fluence with little or no damage. The National Ignition Facility (NIF), currently under construction by the Department of Energy, is a mega-Joule class Nd:glass laser that will be used to irradiate ICF targets at a wavelength of 351 nm (3ω). The potential for damage in the high-fluence 3ω section of this laser is a possible limiter of component lifetimes and consequently a driver in the cost of its operation.

Work in the field of laser damage testing has traditionally centered on quantifying and understanding thresholds for damage initiation. Initiation of small isolated damage sites is in and of itself typically not a problem, unless the sites grow. This work is the first to focus on the growth of laser-initiated damage. The growth rate of laser-induced damage on fused silica surfaces has been measured at 351 nm under a variety of conditions. Measurements of growth rate have been made in vacuum and in air. The growth of sites initiated on bare and sol-gel AR coated surfaces has been measured. The influence of initial starting size on growth rate has been considered. The dependence of growth on laser pulse length has been measured. The significant finding in this work is that the growth rate of the lateral size with shot number shows exponential behavior whereas the concurrent growth in depth is linear with shot number.

## 2. EXPERIMENTAL DETAILS

Laser damage initiation is typically measured with small-beam laser systems having Gaussian beam profiles of diameters on the order of 1-mm. To make measurements of laser damage growth that are relevant to the large beam areas that will be employed on the NIF, it is necessary to use test beams with an area large relative to the maximum allowable damage size- typically on the order of a few mm. At LLNL there are two facilities that can provide a large-area, 351-nm beam suitable for damage growth measurements. The Optical Science Laser (OSL) is a Nd:glass 10-cm disk amplifier with an adjustable pulse width and shape. It has an output energy at 351 nm of 50 J at a repetition rate of approximately 2 shots per hour. This laser system was used to look at the pulse length dependence of the growth rate. The SLAB laser system[1] is a Nd: glass zig-zag slab amplifier with SBS phase conjugation. It produces a 351 nm beam of 10 J, with a 10 to 12 nsec FWHM Gaussian pulse at a repetition rate of 0.5-Hz. This repetition rate is limited by the data collection rate, as the SLAB laser itself has the capability of 6 Hz.

The layout for the experiments with the SLAB laser is shown in figure 1; a similar arrangement is used in the OSL. The 1.053-μm beam from the laser is image relayed onto the experiment table where it is reduced from 2.5 cm x 2.5 cm to 1.7 cm by 1.7 cm and relayed to the frequency converter: KD*P in a type I/type II tripler arrangement. The output pulse from the frequency converter is then passed through a vacuum relay with a magnification of two before reflecting from two dichroic mirrors where the unconverted green and red light is dumped and the UV is sent back through this same relay. The output of this relay is then passed through a second vacuum relay where the beam is spatially filtered to remove spatial frequencies above those resolvable with the diagnostic cameras before it is transported to the sample test chamber. The optical design of the system is such that the sample resides at an image plane of the frequency converter in an f/88 converging beam with the beam waist located ~40 mm downstream. The beam size on the sample is nominally 6 mm x 6 mm.

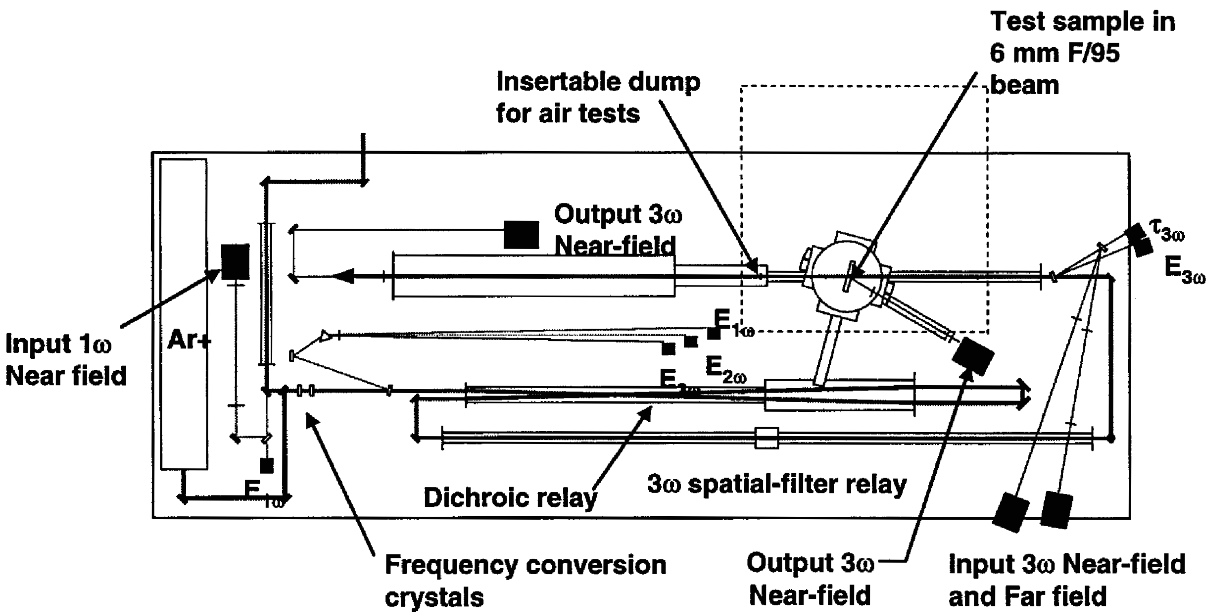


**Figure 1. Experimental layout for growth experiments.**

The test chamber is a precision-cleaned stainless steel vacuum vessel located under a class-100 clean hood, where samples up to 150 mm x 150 mm in size are handled during loading. For test series conducted in air at atmospheric pressure, a stainless steel beam dump is used to intercept the beam at a high angle of incidence in front of focus, thus preventing air-breakdown and coherent back-reflections from the focus that might otherwise damage the laser. Tests have shown no trace of steel contamination on the test sample after thousands of shots.

Diagnostics for the test beam on the part include measurement of the temporal pulse shape, energy, and input & output near-field fluence profiles. Diagnostics to measure the growth include a white-light illuminated, long- working distance microscope with CCD camera, and scientific grade CCD cameras viewing both the reflected and transmitted 351-nm light from the sample. The workhorse for the growth measurements is a 16-bit scientific-grade CCD camera that samples the input beam. It is calibrated both for energy and for magnification and is used to monitor the fluence on the sample. In practice, the output camera that views the beam transmitted through the sample is used to locate the initial damage, and the input camera is used to set the local fluence in a 1-mm patch surrounding the site. Registration between the two cameras is achieved by viewing a fiducial inserted at the common image plane near the frequency converter. The lateral growth of the damage site is measured either from the shadow in the transmitted beam profile or directly with the microscope.

The samples in the tests reported here were 2-inch diameter by 1-cm thick, Corning 7980 fused silica, super polished. Damage was initiated off-line at 351 nm with a 1.1 mm Gaussian beam at fluence levels of typically 45 J/cm$^2$ in an single shot with a 7.5 nsec FWHM Gaussian pulse. This high initiating fluence was chosen to generate reproducible damage sites in both size and morphology; even so there were some variations in the site morphology. Typical sites and a table summarizing the morphology we observed are given in figure 2 and Table 1 respectively. Table 1 catalogs the various morphologies based on the number of individual pits and the lateral size encompassing all the pits. Typical fluences for generating such morphologies are indicated in the table. Except for the sol-gel coating tests all surfaces were bare. All samples were oriented with the damage site on the exit face for the growth measurements.

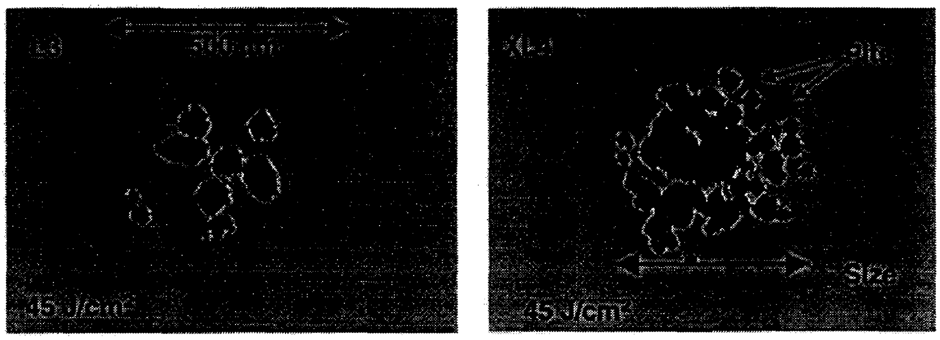

**Figure 2. Micrographs of typical initiation morphologies.**

| | | Number of pits | | | |
|---|---|---|---|---|---|
| | | >15 | 6 – 15 | 2 – 5 | 1 |
| **Lateral size** | | **4** | **3** | **2** | **1** |
| >300 μm | **XL** | 45 | 45 | | |
| 200 – 300 | **L** | 45 | 45 | 45 | |
| 100 – 200 | **M** | | 45, <35 | <35 | |
| 30 – 100 | **S** | | <35 | <35 | |
| <30 | **XS** | | | | <35 |

**Table 1. Table classifying the morphology of initial sites.**

## 3. RESULTS

The growth measurements consisted of irradiating a damage site at constant fluence and measuring the size of the site after each shot. The lateral size of the damage was calculated from the measured area by assuming a circular equivalent area. Typically the damaged area is roughly circular making this a reasonable approach. A typical plot showing the effective diameter plotted on the right hand axis vs. shot number and the average fluence in a 1-mm patch surrounding the initial damage plotted on the left hand axis is shown in figure 3. What was found on this site as well as on all other sites measured, regardless of the starting morphology, is exponential growth of the lateral diameter with shot number. The data was then fit to an exponential curve given by

$$L = L_0 e^{\alpha N} \tag{1}$$

where L is the size of the damage laterally, N is the shot number and $\alpha$ is the fluence-dependent growth coefficient. For some of the sites the depth of the damage was measured along with the lateral growth. The depth follows a linear dependence with shot number and typically the lateral size is 2 to 4 times as large as the vertical depth after the individual pits of the starting site coalesce into one site. The lateral growth is typified by cycles of crack growth on the perimeter followed by spallation of material.

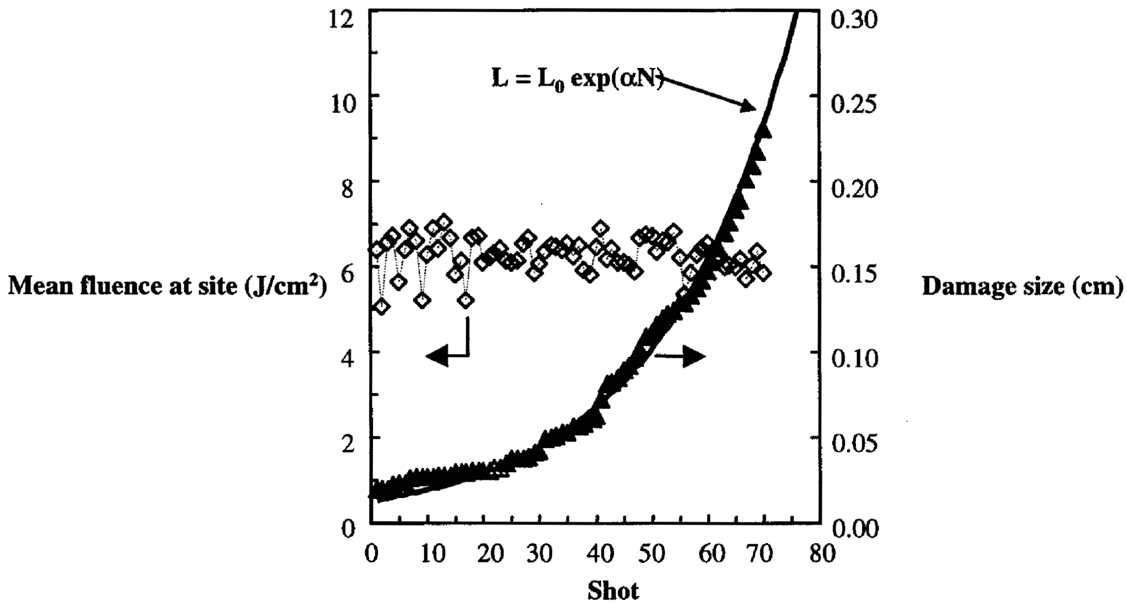


**Figure 3. Typical lateral growth behavior showing exponential growth with shot number.**

A plot of the fluence vs. growth coefficient for many sites of initial sizes in the L3 to XL4 range show a threshold behavior for growth as can be seen in figure 4. The linear fit to this data is shown along with the 3 sigma fits. The data predicts no growth for fluences less than approximately 5 J/cm$^2$. This data was obtained with laser pulse widths of 9 to 12 nsec. Pulse length scaling of the growth coefficients was addressed in a limited set of experiments scanning 1 nsec to 10 nsec. The growth coefficient was found to scale weakly with pulse length where the dependence was given as $\sim\tau^{0.1}$.

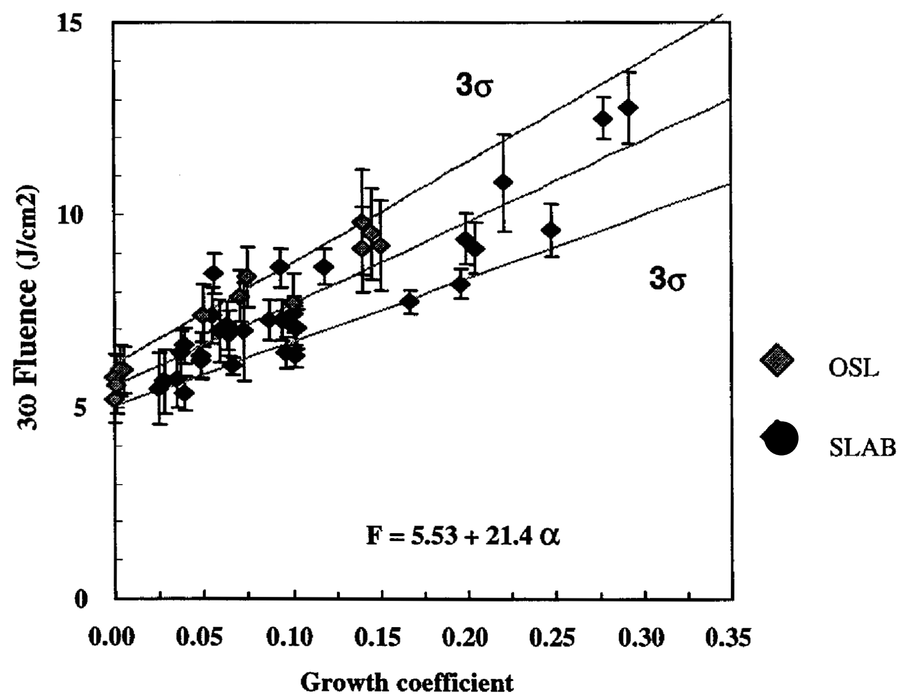


**Figure 4. Plot of fluence vs. growth coefficient showing threshold behavior.**

The threshold for growth was found to be dependent on the starting morphology; some sites of M & S designations did not grow at fluences as high as 7.5 J/cm$^2$. When the fluence was raised on these sites to 10 J/cm$^2$ they grew with growth coefficients that would be predicted from figure 4. Further study of sites initiated at lower fluences which produce smaller damage sites is underway.

Growth of sites has been measured with the sample in air as well as vacuum. Sol-gel AR coatings were applied and then damage initiated followed by measurement of the growth rate. The presence neither of air nor of sol-gel coatings effected the measured growth coefficients. The results obtained for all conditions studied can be seen in figure 5. This plot also includes the long pulse data taken on OSL.

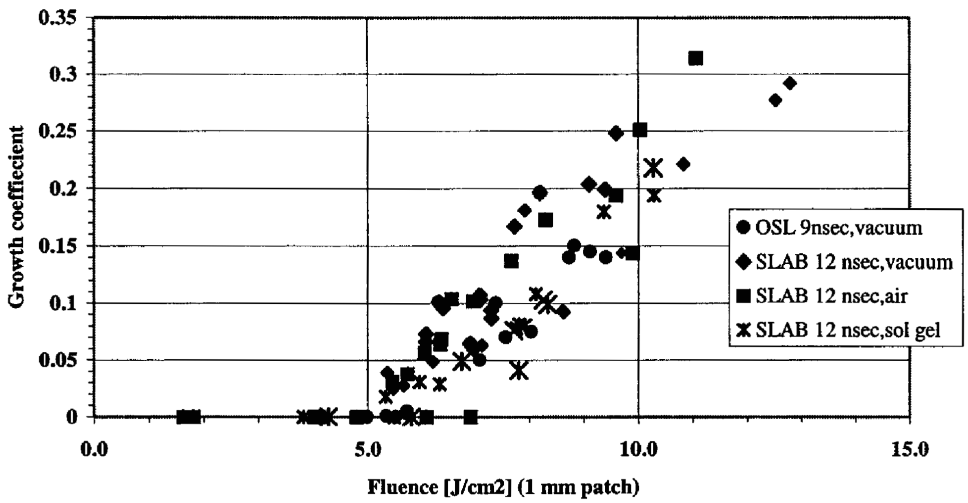


**Figure 5. Summary of growth data taken under a variety of conditions.**

## 4. DISCUSSION

Previous measurements with small-area beams typically used in drilling operations[2] showed linear growth in depth with shot number. The diameter of the hole for these drilling experiments was determined by the laser spot size and the depth grew linearly with the shot number. With the large beam areas used in the present experiments an exponential growth in lateral area with shot number has been measured in a variety of conditions. This exponential growth of rear surface damage will severely limit the useful lifetime of any UV fused silica optic used above the threshold for growth. For any large area laser beam only one site initiated on an output surface will grow to fill the entire beam area and render the optic useless. Since the elimination of all potential damage sites is unlikely to be achieved work on the mitigation of the growth measured in this work is currently underway.[3]

Of the parameters explored: starting morphology, vacuum vs. air, sol-gel coated vs bare and pulse length, only the starting size has been found to have a noticeable affect on growth. In this case, it is primarily that the threshold for growth is increased. The growth rate above threshold is independent of the initial morphology.

## ACKNOWLEDGEMENTS

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