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# Large Area Damage Testing of Optics

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## Abstract

The damage threshold specifications for the National Ignition Facility will include a mixture of standard small-area tests and new large-area tests. During our studies of laser damage and conditioning processes of various materials we have found that some damage morphologies are fairly small and this damage does not grow with further illumination. This type of damage might not be detrimental to the laser performance. We should therefore assume that some damage can be allowed on the optics, but decide on a maximum damage allowance of damage. A new specification of damage threshold termed "functional damage threshold" was derived. Further correlation of damage size and type to system performance must be determined in order to use this measurement, but it is clear that it will be a large factor in the optics performance specifications. Large-area tests have verified that small-area testing is not always sufficient when the optic in question has defect-initiated damage. This was evident for example on sputtered polarizer and mirror coatings where the defect density was low enough that the features could be missed by standard small-area testing. For some materials, the scale-length at which damage non-uniformities occur will effect the comparison of small-area and large-area tests. An example of this was the sub-aperture tests on KD*P crystals on the Beamlet test station. The tests verified the large-area damage threshold to be similar to that found when testing a small-area. Implying that for this KD*P material, the dominate damage mechanism is of sufficiently small scale-length that small-area testing is capable of determining the threshold. The Beamlet test station experiments also demonstrated the use of on-line laser conditioning to increase the crystals damage threshold.

## 1. Introduction

The Laser Damage Group at Lawrence Livermore National Laboratory (LLNL) has developed systems for damage testing up to meter-sized optical components for the future National Ignition Facility (NIF), an inertial confinement fusion project. The systems can be used to determine damage thresholds over large areas, or to conduct survivability testing at NIF fluences. Preliminary work on these damage test systems will help define the measurement and damage threshold specifications for the NIF.

For some optical materials, it has been found that damage may occur at fluences more that 50 % below the conventionally measured damage threshold. These conventional thresholds are determined by small-beam (1 mm ϕ) measurements on small witness samples (50 mm ϕ). Due to advances in fabrication technology, the number of damage causing defects have been reduced to the level that the defects may be missed when only a small area of a witness sample is tested. The area tested in a conventional test is typically only 0.01% of the area of a full-size NIF optic. This has led the group to construct several systems for testing apertures as large as that of the NIF optics. It has also led to the specification of a damage threshold measurement called the functional damage threshold (FDT). The measurement allows for some laser-induced damage to optics to be present as long as the performance of the laser is not effected. This specification addresses such issues as power losses, propagation of damage from optic to optic, and damage growth.

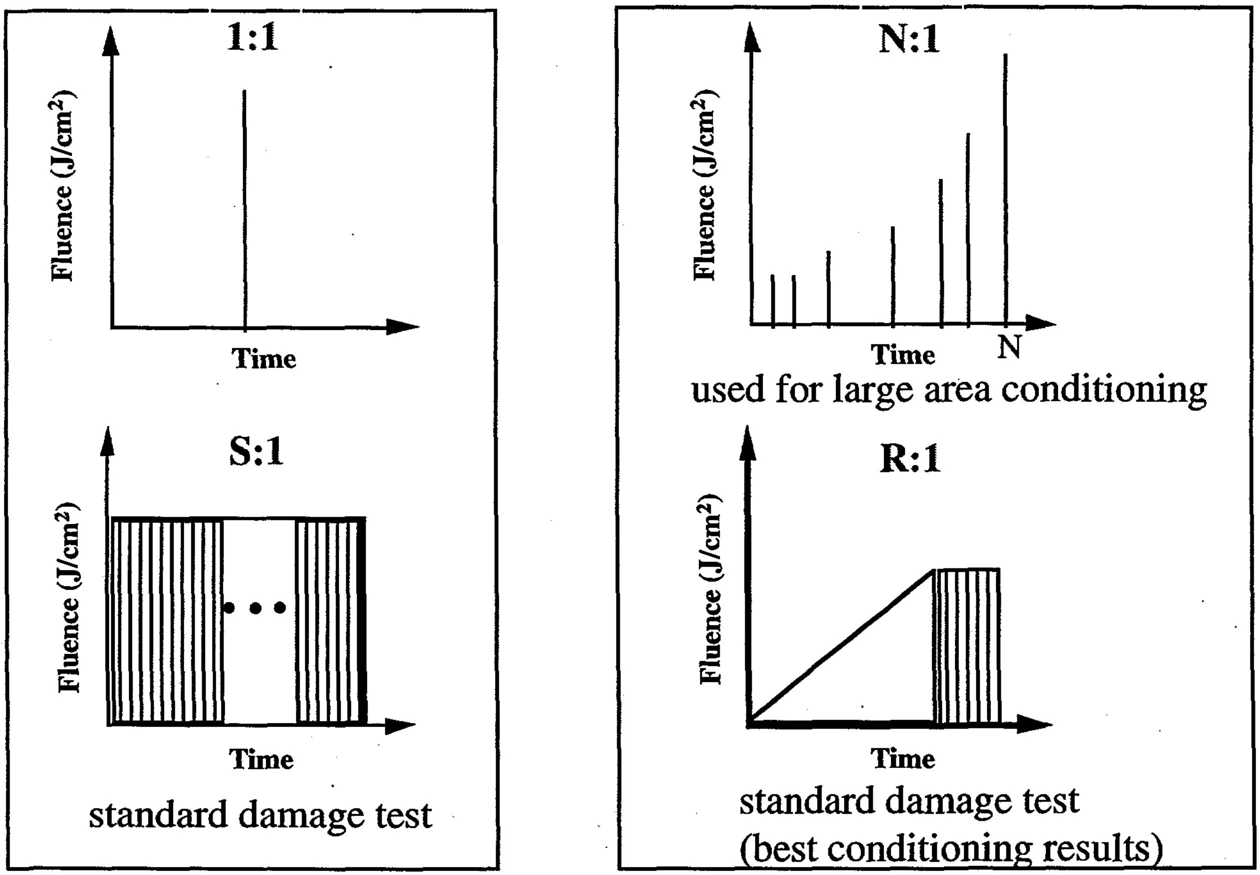
There are four systems available for large-area, high-fluence, testing. Two will be described here in detail. The first is PLATO (Probed Large Area Testing of Optics), which uses a commercial Nd:YAG laser to generate 1064 nm and 355 nm light. A beam diameter of 1.5-2 mm is generated on the sample, and a large XY translation stage moves the optic through the stationary beam in a raster style pattern. Optics with dimensions up to 1 meter and weighing as much as 400 pounds may be tested on this station. The second test system uses LLNL's Beamlet laser, a single beam prototype of the NIF, to damage test optics using a 10 cm by 10 cm or less beam at wavelengths of 1053 nm or 351 nm, or both. NIF fluences can be achieved in order to test damage threshold, survivability, on-line conditioning, and contamination effects.

## 2. Damage Threshold Determination

### 2.1 Standard Damage Threshold Testing

Damage testing at LLNL is performed using rep-rated (1-30 Hz) Nd:YAG lasers at 1064 nm and 355 nm with pulse lengths ranging from 3 to 11 ns. Nominal $1/e^2$ beam diameters are 1.0-1.5 mm. Fluences at the damage plane are measured by a commercial beam profiling system.(1,2)

There are four main types of irradiation sequences used to determine damage thresholds, 1:1, S:1, R:1, and N:1 (Fig. 1). A 1:1 test consists of one laser shot, at one test site. During a S:1 test, one site is irradiated with ~ 600 (60 s at 10 Hz) shots at the same fluence. A R:1 test consists of linearly increasing the fluence of a rep-rated beam over ~ 300 shots, resulting in very small incrementally increasing fluences, and maintaining the peak fluence for the subsequent ~ 300 shots, all on one site. A N:1 test consists of incrementing the fluence level at a site in steps, without a set time interval between each laser pulse. The R:1 and N:1 measurements represent conditioned damage thresholds, a process by which the fluence is increased in many (R:1) or a few (N:1) steps. This has shown to increase the damage threshold of some optical materials by a factor of 2 or 3(3,4). The best conditioning results for most multilayer coatings are found using the R:1 conditioning technique. However, the N:1 process is more practical for large areas from a time and cost perspective. Our standard damage thresholds are based on S:1 (unconditioned) and R:1 (conditioned) sequences, and damage is defined by any observable modification detected using optical microscopy with 100x magnification to detect changes > 5 μm. The relative magnitude of these threshold are shown schematically in Fig. 2.



a) b)

Fig. 1 Standard a) unconditioned and b) conditioned tests conducted at LLNL.

### 2.2 Large-Area Damage Testing

The materials tested often have defect-initiated damage which makes the measured result depend on the number of sites or size of the area that is tested. For example, laser interaction studies of nodular defects in e-beam deposited coatings show a dependence of the defects damage thresholds on their height.[5] It has also been reported that mapping of the damage threshold over large areas shows a damage dependence on defects in ultraviolet optical coatings [6]. Currently our standard S:1 damage test only samples about 0.01 % of a NIF optic area. Using the PLATO system we have found that large optics often incur damage at fluences below the measured damage threshold.

### 2.3 Functional Damage Threshold

For NIF, the damage measurement procedure will have to include standard and large-area tests. The current NIF design is based on a derating procedure to get from small-area testing to the NIF optic performance. As mentioned above, if larger areas are tested, the measured damage threshold in most cases will be lower than that in the small-area test, as shown in Fig. 2.

During our studies of laser damage and conditioning processes of various materials we have found that some damage morphologies are fairly small and this damage does not grow with further illumination. This type of damage might not be

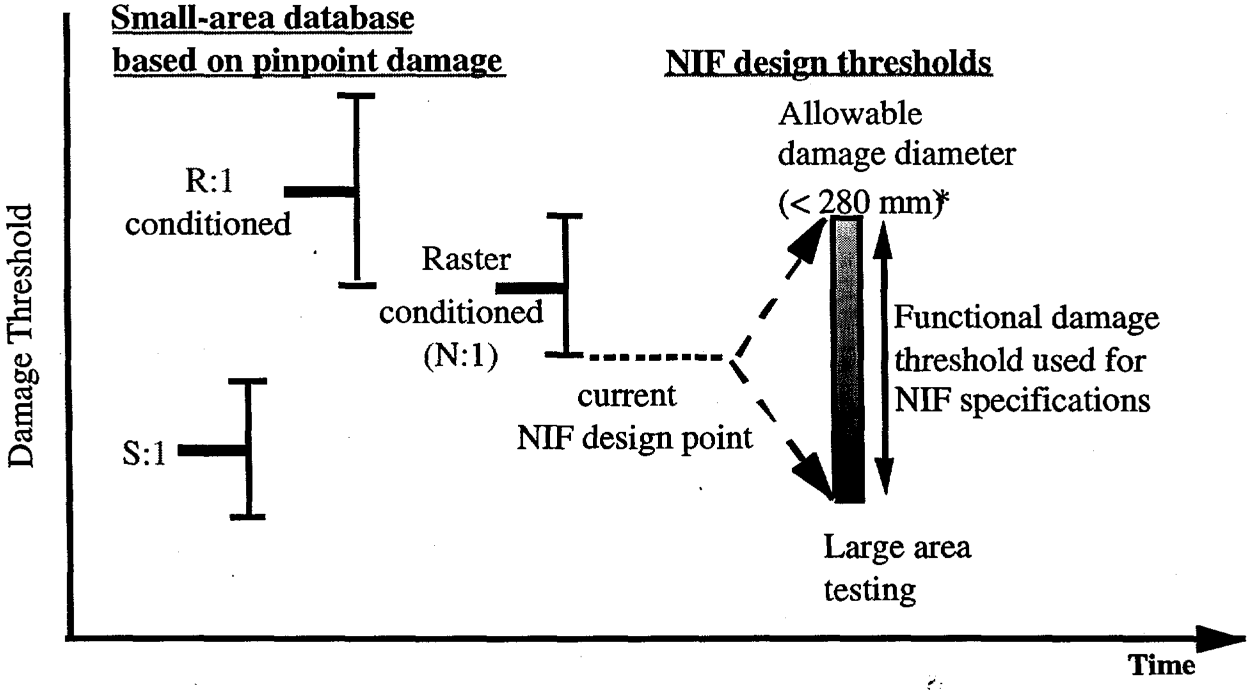


Fig. 2 The evolution of the functional damage threshold specification from the NIF begins with the small-area testing, then addresses large-area testing and the allowance of damage.

detrimental to the laser performance. We should therefore assume that some damage can be allowed on the optics, but decide on a maximum damage morphology limit. The fluence that will lead to this maximum allowable damage is called the functional damage threshold.

In order to address the high fluence requirements for NIF, a functional damage threshold will be determined. The FDT measurement allows for damage to be incurred on the optics, as long as; 1) the maximum damage size, quantity, and spacing is such that consequent beam modulation would not cause damage to propagate further down the optics chain, 2) the damage cannot grow to the maximum allowable size in the lifetime of the optic, 3) the damage cannot degrade the laser performance (wavefront shifts, losses due to scatter, reflection, and transmission) passed some set limit. The current specifications for functional damage threshold are:

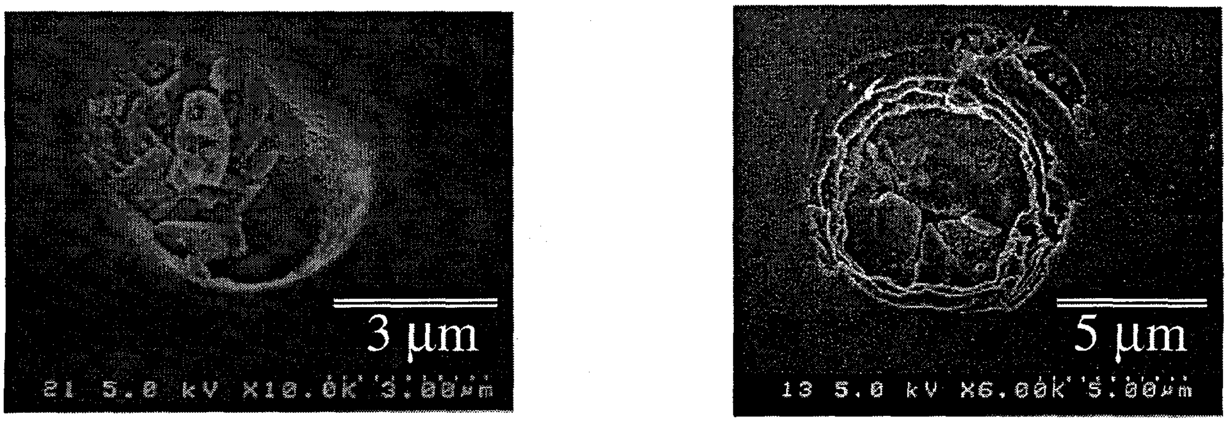
1) No single damage feature greater than 280 μm in diameter (7)
2) Maximum total obscuration due to damage at $10^{-4}$
3) No growth above these limits for > 1000 shots

The 280 μm size limit represents the proposed value at which damage would cause diffraction which can be re-imaged on optics further down the optic chain, causing damage.

Work has begun on investigating the FDT for optical coatings. In Fig. 3, scanning electron microscographs (SEM) of the 4 types of damage morphology seen at high fluences on 1064 nm optical coatings are shown. Pits are due to nodule defect ejection(8,9). Flat bottom pits are only a few layers deep, while delaminates correspond to the removal of the first layer of the coating. Scalds appear when slight modification of the surface of the coating occurs. They are usually associated with a pit. A different functional damage threshold fluence can ideally be determined for each morphology type.

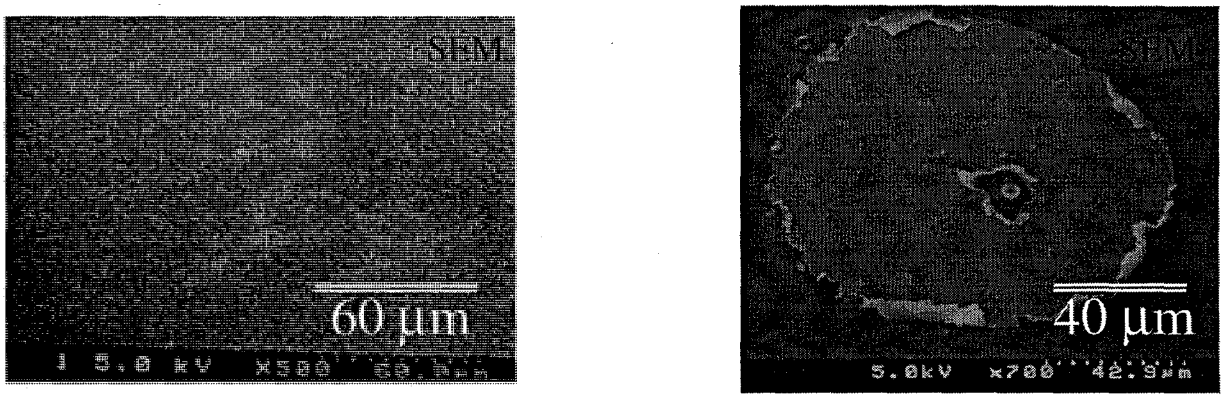
## 2.4 Functional Damage Threshold Measurement Results

An schematic summary of preliminary results from an FDT study of a polarizer (with S:1 damage threshold of 10 J/cm$^2$) is shown in Fig. 4. The size of damage as a function of number of shots for all four damage morphologies are plotted. The NIF maximum size requirement of 280 μm is represented by the thick horizontal line. The horizontal axis of the graph shows the number of shots, and each line on the plot is at a different fluence level. Fig 4a) is for pits, b) shows the flat bottom morphology, c) shows scalds, and d) represents delaminates. For pits no growth was observed up to 30 J/cm$^2$ at 3 ns, and the damage size was far below the maximum allowed. Flat bottoms met the size criteria, up to 30 J/cm$^2$, but above that growth of the damage occurred. Scald size increases with the fluence, but even at 40 J/cm$^2$ the



a) pit

b) flat bottom pit



c) scalds

d) delaminates

Fig. 3 SEM images of the four types of damage morphology found on our current optical coatings.

size limit was not exceeded. Delamination damage can quickly grow to catastrophic damage above 20 J/cm$^2$. Fig. 5 shows a study of the growth of a delaminate morphology on a polarizer coating over four subsequent laser shots at a fluence of 46 J/cm$^2$. The optic investigated would meet the NIF requirement of 19.3 J/cm$^2$ for a redline 3 ns gaussian pulse in s-polarization if a FDT is used. However, this allows for no safety factor and is not acceptable.

The same set of data was investigated on a 45° mirror coating which has a NIF redline fluence requirement of 20.3 J/cm$^2$. In this case, the worst morphology from above, (i.e. delaminates) was not observed. Fig. 6 shows the FDT plots for a) pits, b) flat bottoms, and c) scalds. This mirror exceeds the NIF requirement using the FDT standard for all morphologies with repeated shots.

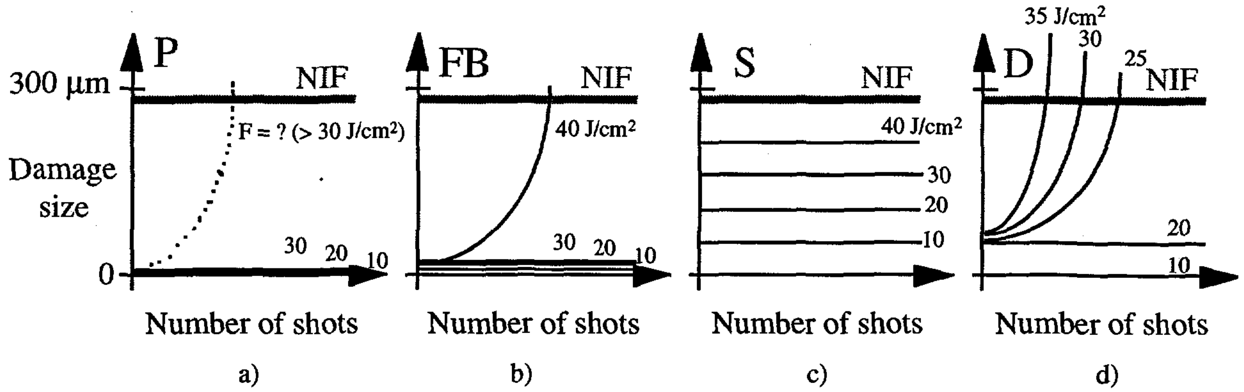


Fig. 4 FDT of a polarizer coating, for each of the damage morphologies a) pit, b) flat bottom pit, c) scald, d) delaminates.

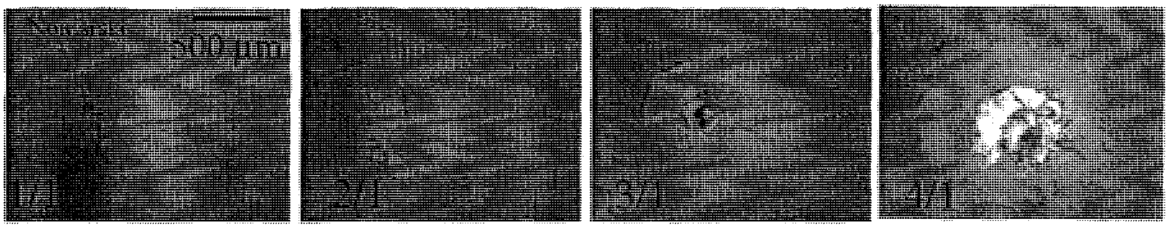


Fig. 5 Growth of delamination damage morphology in four laser pulses.

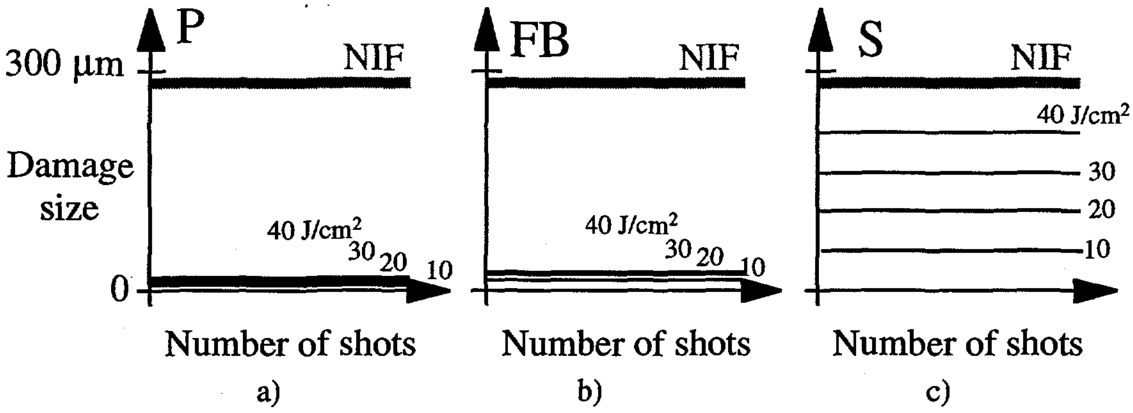


Fig. 6 FDT plots for 45° mirror morphologies a) pits, b) flat bottoms, and c) scalds.

### 3. Large-Area Damage Testing Facilities

The application of standard small-area, large-area, and functional damage threshold tests to the NIF has been presented, now we will discuss the facilities for conducting such tests. Table 1 summarizes the test systems currently at LLNL. Although all of the systems have capabilities which add to our understanding of the NIF damage threshold specification, only two of the large-area test systems will be discussed here; PLATO (probed large-area testing of optics), and the Beamlet large area test station.

Table 1 Damage test systems at LLNL include a number of different damage detection techniques and can test optics up to 1 meter in size.

| Facility name | Largest sample dimension | Damage detection technique |
|---|---|---|
| Chameleon | 5 cm | **Optical microscope** |
| Thor | 5 cm | **Atomic force microscope/** Optical microscope |
| Zeus | 5 cm | Optical microscope/ **bulk scatter detection system** |
| Plato | up to 1 meter | Optical microscope/**scattered light detection/plasma detection** |
| Beamlet | | |
| Large area test station | **20 cm** | Optical microscope/scattered light detection |
| High fluence mirror tower | **60 cm** | Optical microscope/scattered light detection |
| **Automated** damage test system | **20 cm** | Optical microscope/scattered light detection/plasma detection |

### 3.1 Probed Large Area Testing of Optics (PLATO)

The PLATO system is dedicated to large-area testing and laser-conditioning of meter-sized optics. The optic is translated through a stationary, 10-Hz rep-rated, 1064 nm or 355 nm beam, with 7-10 ns pulses. The translation system can be rotated so that the optic is illuminated at its use angle. The optic moves at a velocity such that the optic has translated one 90% intensity beam diameter between laser shots (~ 0.3-0.5 mm). Moving the optic in a raster pattern ensures that the entire surface is illuminated at the set fluence. A scatter measurement diagnostic allows on-the-fly evaluation of laser-induced damage during a scan(10), as well as mapping the inherent scatter in an optical component. This system has been used to laser-condition coated optics as large as 73 cm x 37 cm using the N:1 test sequence.(1) Such optics are now being used on the Beamlet laser system. The system has also verified damage thresholds of large coated and uncoated optics before installation on Beamlet. A layout of the system is shown in Fig. 7.

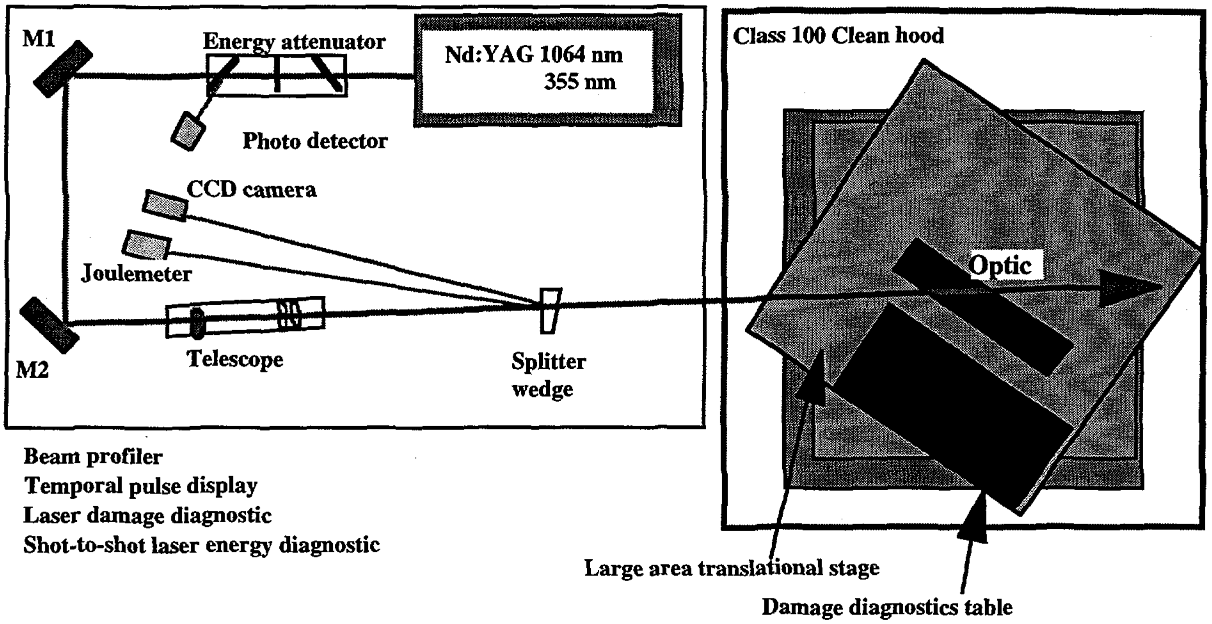


Fig. 7 PLATO system layout.

### 3.2 PLATO Large-Area Damage Test Results

An example of the use of a large-area test facility to verify the measurements conducted on small areas is illustrated in Fig. 8. The first set of data is from a test on a $HfO_2/SiO_2$ sputtered polarizer coating. The sputter process generally yields optics with very low defect densities. A small-area S:1 test showed a very high damage threshold greater than 45 $J/cm^2$ in the Chameleon facility. A S:1 test was also conducted in PLATO to show that with a small-area, this high threshold can again be determined, and that the two systems are in calibration with one another. Another test with a sputtered mirror showed a high S:1 threshold in the Chameleon facility (45.9 $J/cm^2$). Rastering in PLATO using large-area scanning showed, however, that the actual threshold was much lower. The fluence began at 11% of the measured threshold and increased by 5 $J/cm^2$ for each additional scan. Damage was detected at 10.1 $J/cm^2$. It was shown using the scatter measurement, that although very few defects can be found on these coatings, these defects have a very low damage threshold. Such defects are far enough apart that they can easily be missed doing small area tests. As a results, the measured damage threshold is overestimated.

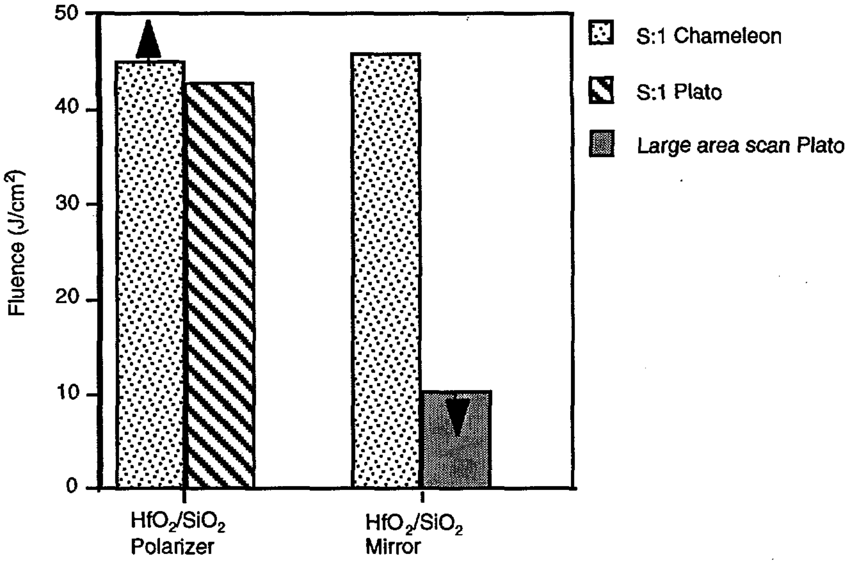


Fig. 8 Comparison of tests, both small-area S:1 and large-area scanned, on low-defect density, sputtered coatings, reveals that small-area testing can severely overestimate the damage threshold.

### 3.3 Beamlet Large-Area Test Station

Recently activated at LLNL is the Beamlet large-area test facility. This facility is used for several purposes: 1) correlate results in the damage testing lab to results on a large aperture laser, 2) compare on-line to off-line laser conditioning, 3) investigate damage uniformity, 4) conduct lifetime tests, and 5) verify large aperture performance of transparent optics at NIF fluences. The damage system is located at the output of the Beamlet laser chain. The Beamlet laser, frequency conversion crystals, primary focusing optics, and the primary focus are all to the left of the test station, as shown in Fig. 9. A pinhole can be used at the focus to block unwanted wavelengths and to reduce the modulation on the beam which reaches the sample. Several damage diagnostics are incorporated at the sample plane including white-light low-magnification viewing, and white-light or laser-illuminated high-magnification viewing. There is also a camera (not shown) which images the damage sample plane in order to capture the Beamlet beam profile for fluence determination.

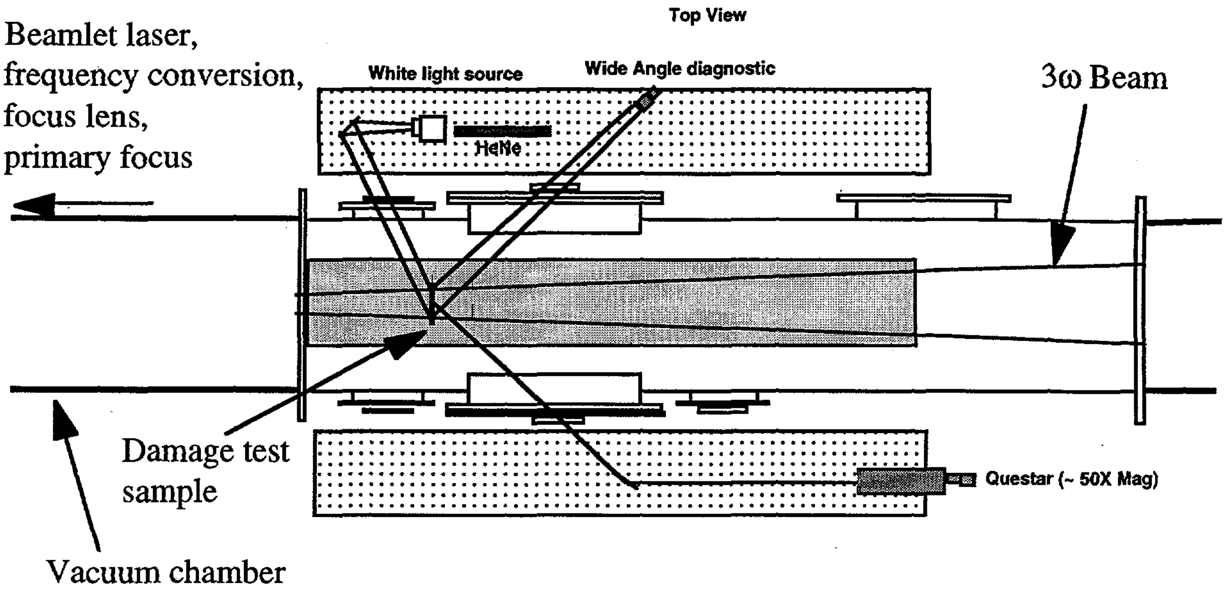
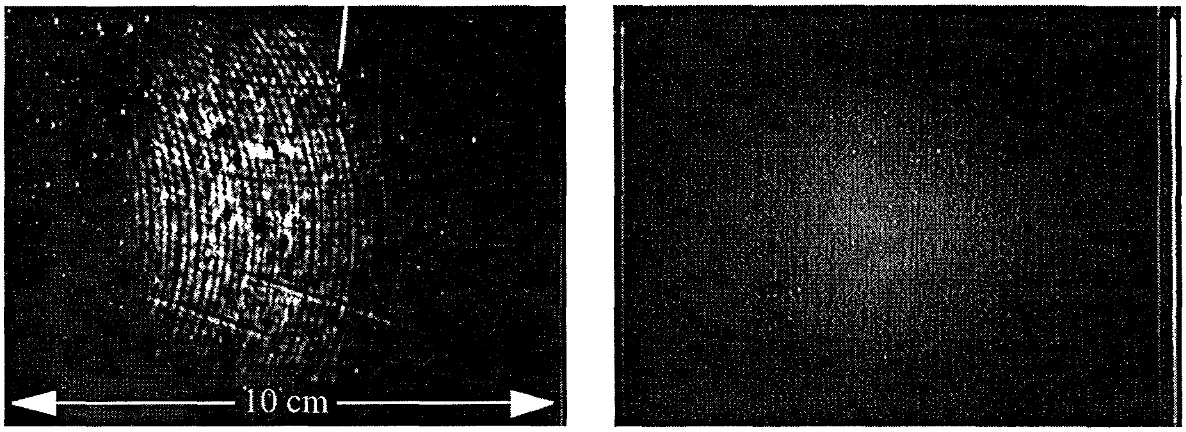


Fig. 9 Beamlet large-area test facility allows testing of optics at NIF fluences with a 10 cm x 10 cm beam, at 1053 nm, 527 nm, 351 nm, or all the three wavelengths simultaneously.

### 3.4 Beamlet Large-Area Test Results

The first test campaign was to investigate KD*P crystals using a 7 cm x 7 cm beam using only 351 nm light and 3-ns square pulses. It was verified that the damage threshold measured in the damage testing lab correlated with that on Beamlet. This implies that the initiation of damage is due to artifacts with small scale-lengths, in this particular set of crystals. It was also found that on-line conditioning was possible for the NIF crystals, and that only a few low fluence shots may be necessary. The conditioning result is shown in Fig. 10. The image on the left shows the damage on a crystal which was not conditioned before being illuminated at a 6.7 J/cm$^2$ average fluence. Catastrophic damage is evident. The high fluence modulation profile of the beam can be seen on the crystal. Correlation of the beam profile to the damage profile allows us to determine at which fluence damage initiated. The second image is of a crystal which was first illuminated at a low fluence, then at a average fluence of 6.5 J/cm$^2$ on a subsequent shot. No damage was detected, showing that on-line sub-threshold illumination, conditioned the optic.



LL6-15, single shot at 6.7 J/cm$^2$ average, unconditioned, catastrophic damage

LL1-15, conditioned with 2 shots up to a fluence of 6.5 J/cm$^2$ average no damage

Fig. 10 Test on KD*P crystals on the Beamlet large-area test system showed that a crystal which was laser conditioned on-line by illumination at sub-threshold fluences before high fluence shots, survived at fluences which caused catastrophic damage on unconditioned crystals.

## 4. Conclusions

- The damage threshold specifications for the NIF will include a mixture of small-area and large-area testing, as well as the use of a functional damage threshold.

- Further correlation of damage size and type to system performance will have to be determined in order to use the functional damage threshold measurement for NIF optics.

- Large-area tests have verified that small-area testing is not always sufficient when damage initiates at defects in the optic. Depending on the density of the defects, damage thresholds measured may not represent the overall performance of the optic. This was evident on the sputtered polarizer and mirror coatings where the density of defects was low enough that they could be missed by standard S:1 small-area testing.

- Tests on KD*P crystals on the Beamlet test station verified the large-area damage threshold to be similar to that found when testing small areas. This implies that the scale-length of damaging defects is such that small-area testing is currently sufficient for this particular KD*P. The Beamlet test station also demonstrated on-line laser conditioning to increase the crystals damage threshold.

## 5.0 Acknowledgments

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