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Automated Damage Test Facilities for Materials Development and Production Optic Quality Assurance at Lawrence Livermore National Laboratory

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ABSTRACT

The Laser Program at LLNL has developed automated facilities for damage testing optics up to 1 meter in diameter. The systems were developed to characterize the statistical distribution of localized damage performance across large-aperture National Ignition Facility optics. Full aperture testing is a key component of the quality assurance program for several of the optical components. The primary damage testing methods used are R:1 mapping and raster scanning. Automation of these test methods was required to meet the optics manufacturing schedule. The automated activities include control and diagnosis of the damage-test laser beam as well as detection and characterization of damage events.

Keywords: Automated damage testing, R:1 mapping, raster scan, damage diagnostics

1. INTRODUCTION

The National Ignition Facility (NIF) will contain several thousand meter-class optics as well as several tens-of-thousands of small optics (< 20 cm). The optical components include multilayer mirrors and polarizers, laser glass, fused silica, anti-reflection coatings and KDP/KD*P crystals. As part of the vendor selection and quality control activities, a laser damage specification has been identified for each component. Systems capable of verifying these specifications have been constructed at LLNL. Each group of facilities is designed to address one or several of these optic types. Some of the systems have been further developed as damage metrology tools and will be placed at optic manufacturers contracted by the National Ignition Facility. The metrology systems must maintain high throughput including 24 hour-a-day operations over the optic production period. The physical descriptions of the systems and their automated operation is presented here.

Damage diagnostics are fielded on each system depending on the specific needs of the measurement. For automated testing the diagnostics are based on a visible-wavelength laser scatter measurement. This scatter diagnostic can be used for the detection of both surface and bulk damage. For meter-sized optics, a Defect Mapping System (DMS) based on white light illumination allows detection of defects with sizes down to 5-μm over the full aperture of the optic.

2. DAMAGE TEST METHODS

Due to the localized nature of laser-induced damage on high quality optical components, test methods must be applied that can provide statistical data over large test areas. The two test methods that have been chosen at LLNL to achieve this are R:1 mapping and raster scanning. Both methods provide the statistical damage information needed for vendor qualification, process control, and damage performance prediction.

2.1 R:1 Mapping

The automated R:1 mapping method, which provides a damage threshold at each of typically 16 to 100 sites tested, was first described at this conference in 1995[1]. Its advantages were further documented in the following years[2-4]. The technique is most commonly applied most commonly where comparison of manufacturing processes or vendors is needed.

The R:1 threshold is determined by ramping the fluence in a continuous ramp at the lasers repetition rate. The ramp has a defined starting fluence and fluence increment step. During the ramp sequence, a scatter diagnostic is used to detect laser-induced changes in the surface or bulk of the material under test. Upon the detection in a change in scatter the laser is shuttered and the fluence at which damage occurred is logged. This process is shown graphically in Fig. 1. The sample is then translated a defined distance to the next site. This is repeated for a statistically significant number of sites, usually between 16 and 100, depending on the sample size and the purpose of the test.

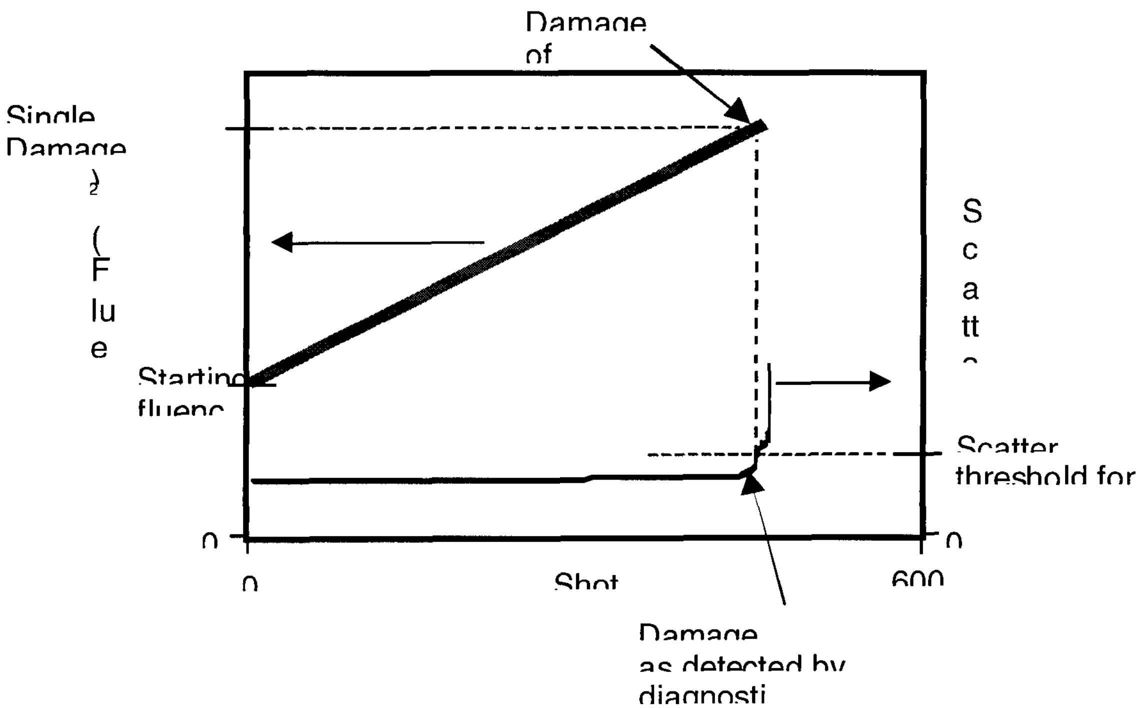

Fig. 1 R:1 testing method uses a fluence ramp and scatter-diagnostic damage detection for determination of a damage threshold at each site tested.

The results of the R:1 map are plotted as a cumulative probability curve as shown in Fig. 2. The highest measured damage threshold is the fluence at which there is a 100% probability of damage at any given site. In Fig. 2 Test A consisted of a 64 site test of a fused silica sample. Test B was a 16 site test conducted 6 weeks later on the same sample. On average there is only a 2% difference in the damage measurements. The repeatability of the R:1 mapping measurement allows the routine comparison of samples with variations as small as 5%. Test methods previously used at LLNL had an accuracy of only +/- 15%. As the number of sites tested in the R:1 map is increased the statistical reliability of the high and low ends of the curve are improved. To obtain more quantitative data at low fluences additional raster scan tests are applied.

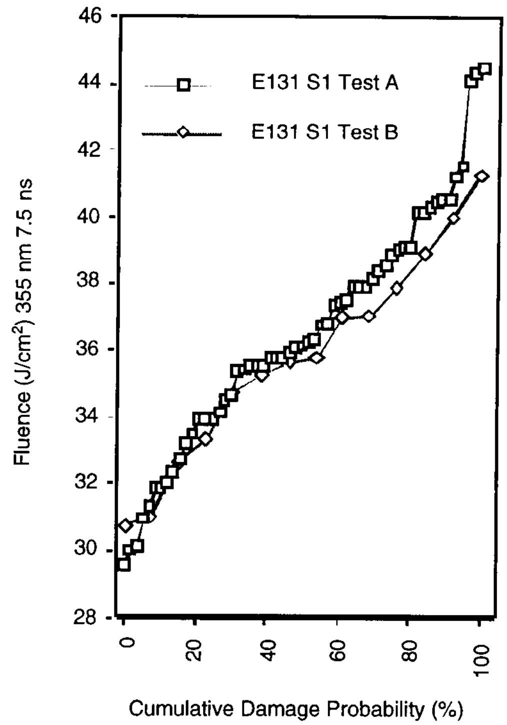

Fig. 2 Two damage probability curves measured on the same sample, using the R:1 mapping test. Test A examined 64 sites. Test B examined 16 sites and was performed six weeks after the first test. The agreement between the curves is good except at the high and low fluences where large numbers of sites must be tested to obtain good statistics.

2.2 Raster scan damage testing

The raster scan damage testing method allows large areas (several cm^2) to be sampled using a small beam (~ 1mm) in order clarify the low fluence tail of the probability distributions observed using R:1 mapping[5,6]. An understanding of low-probability, localized damage events is required for systems such as NIF which require high performance over large apertures.

The raster scan test is conducted by moving an optic through the stationary damage test beam such that the repetitive laser pulses overlap one another by a specified amount, as illustrated in Fig. 3. The scan area and the amount of beam overlap is varied based on the test requirements. The area scanned and the fluences used are also dependent on the application (further detailed in section 3). The damage density is determined by various diagnostics outlined in section 4.

By applying the raster scan technique, the probability of damage as a function of fluence (P_F) can be determined. This is done simply by dividing the number of detected damage sites (D_F) at a given scan fluence, by the number of laser pulses in the scan area (S_F) (equation 1). This probability is related to the optics characteristic damage concentration (c_F) value as shown by Feit et.al.[7] following equation 2. The concentration is corrected for the effective area tested (A_{eff}) so that tests done using different test areas and test beam profiles can be compared. An example of raster scan data for a fused silica surface is shown in Fig. 4 where the left axis is the optics measured P_F, and the right axis is the c_F calculated knowing A_{eff} and P_F.

$$P_F = D_F/S_F \qquad (1)$$

$$P_F = 1- \exp(-c_F A_{eff}) \qquad (2)$$

The use of a characteristic concentration and an effective area correction allows sub-aperture tests to be extrapolated to full aperture optics as demonstrated by Feit et al.

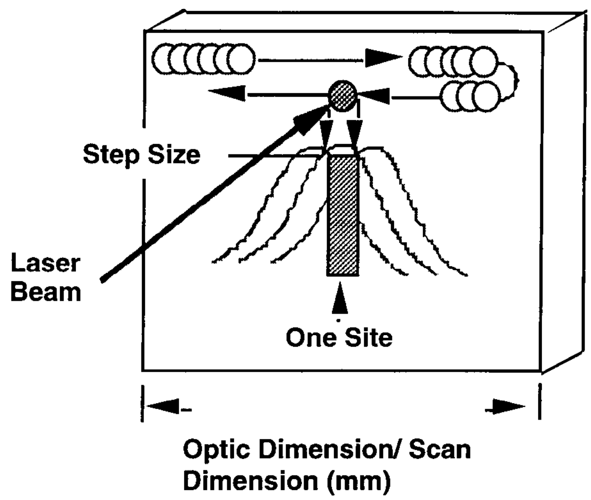

Fig. 3. For raster scan tests, the optic is translated through a mm scale laser such that the laser pulsedsverlap with each other by a user defined step size.

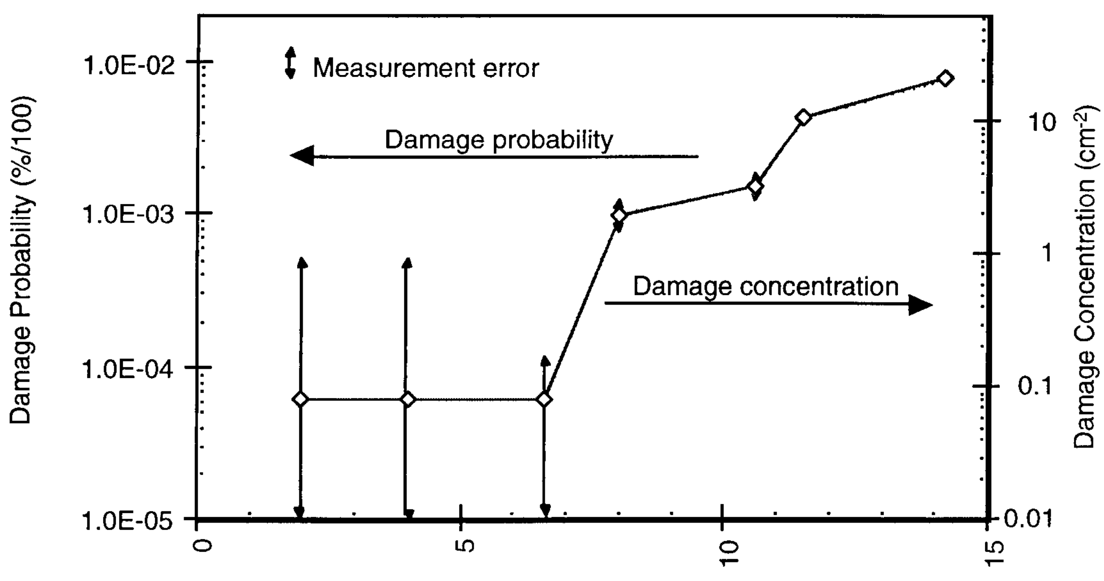

Fig. 4 Raster scan results obtained from seven scans at fluences 2 to 14 J/cm^2 each measured over a different ~ 20 cm^2 area of a fused silica optic.

3. AUTOMATION OF DAMAGE TEST FACILITIES AT LLNL

In order to meet the testing requirements for the broad spectrum of optical components on NIF, several damage testing systems have been developed at LLNL. All are capable of the R:1 mapping and raster scan tests. Sections 3.1 and 3.2 summarize the applications for the systems, whereas section 3.3 discusses the automation of the measurements. The development of these capabilities has allowed the deployment of several production-ready, turn-key damage test systems for NIF optics quality assurance.

3.1 Facilities for testing of optics up to 20 cm in dimension

There are three systems at LLNL for testing optical components up to 20 cm in size. They are summarized in Table 1 by capability and application. These systems are used extensively for manufacturing process evaluation, vendor comparisons, and material research.

Table 1 Small area test systems summary.

System Name	Test capabilities (λ, pulse repetition rate, pulselength)	Primary optic application
Automated Damage Tester (ADT)	355 nm, 10 Hz, 7.5 ns	Fused silica, Sol-gel AR coatings, contamination, 3ω mulitlayer coatings
Chameleon	1064 nm, 0.1-100 Hz, 3.0 ns	1ω substrates and coatings, contamination
Zeus	1064 nm, 10 Hz, 9.5 ns 355 nm, 10 Hz, 7.5 ns	1ω & 3ω KDP and KD*P crystals

3.2 Facilities for testing of meter-sized optics

There are three types of systems for testing optical components up to one meter in size. They are summarized in Table 2 by capability and application. The first system, Plato, was developed in 1992 for laser conditioning of 1ω coatings(5). It has since been upgraded to be able to test at 3ω as well, allowing it to test any NIF component. The second system, the Laser Glass Damage Tester (LGDT) (Fig. 5), is an upgraded version of a system developed for the construction of the NOVA laser at LLNL (8). The system is used to raster scan the entire aperture of laser amplifier slabs in order to locate and damage platinum inclusions in the glass. Two such systems will be located at vendor sites for the NIF. There will be four Large Area Conditioning (LAC) systems at the NIF 1ω coating vendors. These systems are used for laser conditioning of the coatings before they are installed into the NIF laser(6). The laser conditioning procedure includes high fluence scans, that will also verify that the components meet the NIF damage performance specifications. The 3ω Damage Tester, shown in Fig. 6, is used for raster scanning the 3ω optics to ensure that the optics meet the damage specifications before being installed on the NIF laser(9).

Table 2 Systems for testing of meter-sized optical components for NIF.

System Name	Test capabilities (λ, pulse repetition rate, pulselength)	Primary optic application
Plato 1 system at LLNL	1064 nm, 10 Hz, 9.5 ns 355 nm, 10 Hz, 7.5 ns	LAC and 3ω DT prototype, capable of testing all optics
Laser Glass Damage Tester (LGDT) 2 systems at vendor sites	1064 nm, 30 Hz, 9.5 ns	Laser glass
Large Area Conditioning (LAC) 4 systems will be located at vendor sites	1064 nm, 30 Hz, 9.5 ns	1 ω Coatings
3ω Damage Tester 1 system at LLNL	355 nm, 10 Hz, 7.5 ns	3ω Optics

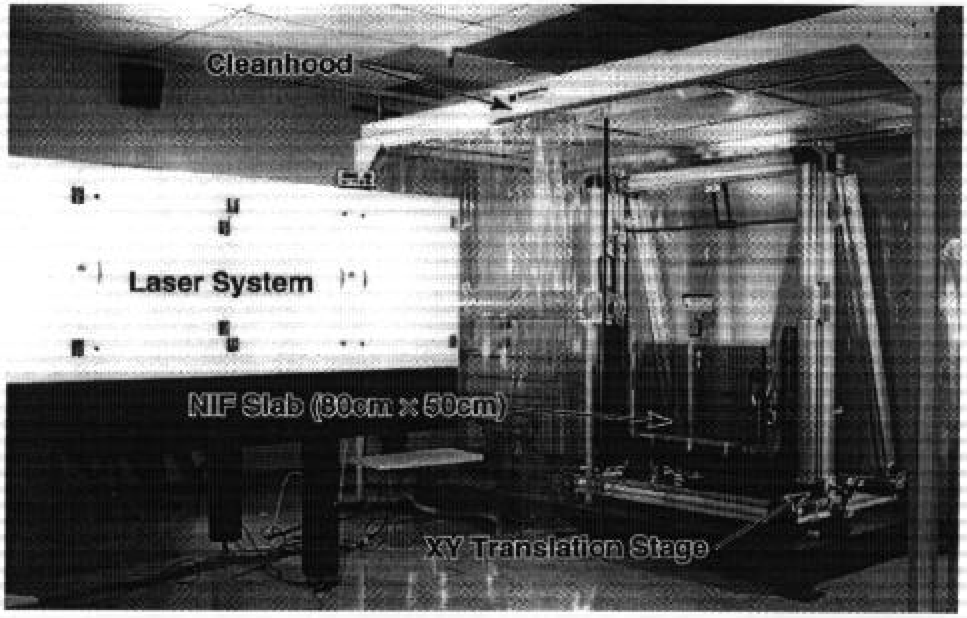

Fig. 5 Laser Glass Damage Tester (LGDT) at NIF vendor facility

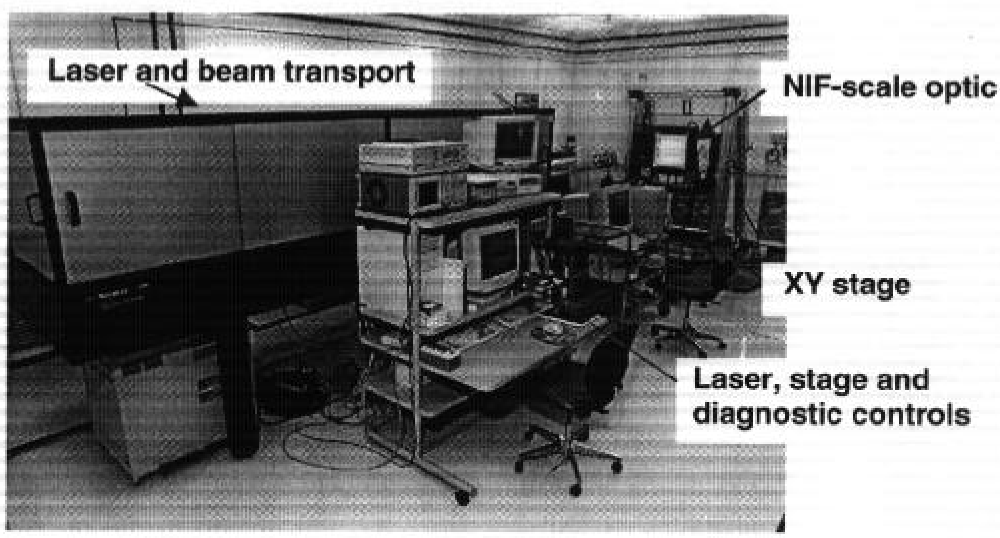

Fig.6 3ω DT system in place at LLNL

3.3 System construction and automation

The damage testing systems are all based on the generic layout shown in Fig. 7. The choice of laser source depends on the wavelength, pulselength, and rep-rate required for a given application. The pulse energy which reaches the sample is regulated using a computer controlled polarizer/waveplate combination for attenuation. The beam is focused to the sample using a simple telescope in order to achieve a millimeter scale beam at focus. A bare fused silica wedge is used to pick off two diagnostic beams, one for imaging the beam and the second for a energy measurement. The energy of each pulse is measured using a commercial energy meter. This meter communicates the beam energy to the computer system. The second beam pickoff is directed to a commercial beam profiling system which images the beam in an equivalent plane to the sample and determines the peak fluence once calibrated with the energy.

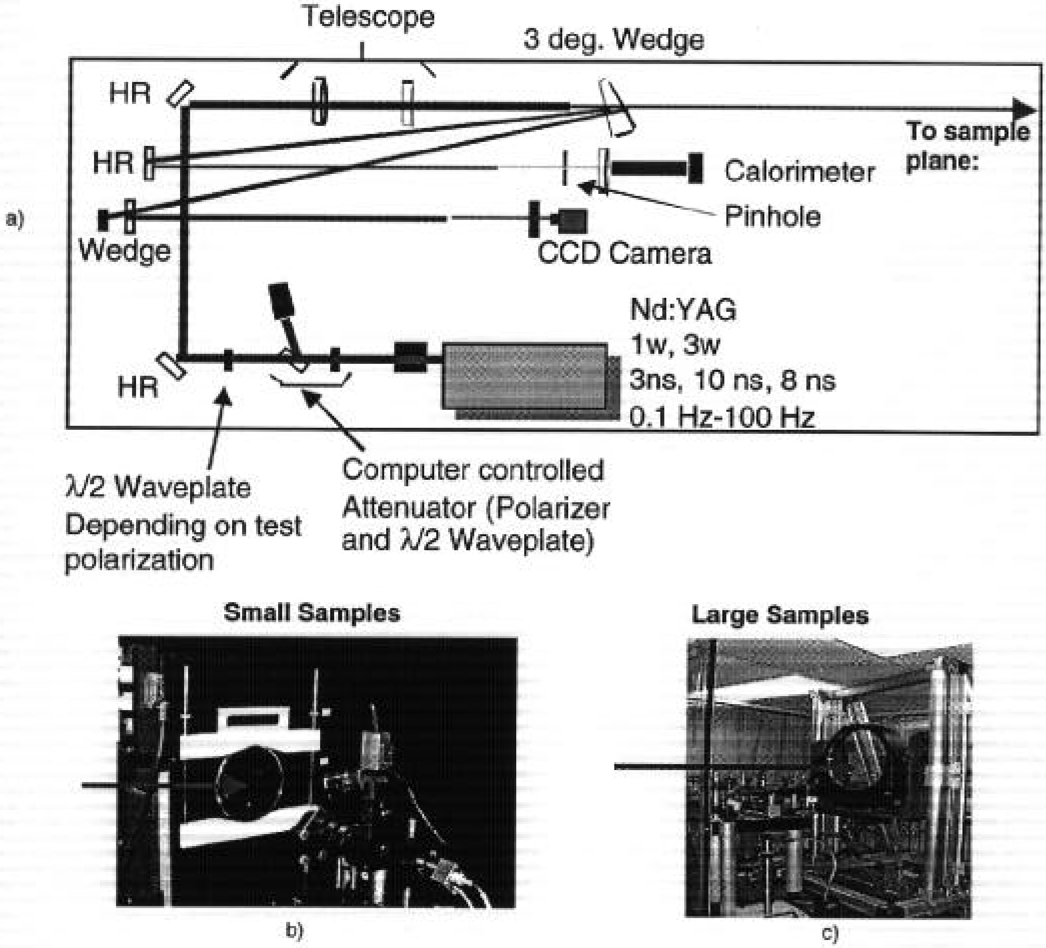

Fig 7 a) Generic damage test system layout. b) and c) are photos of example sample plane stations for small and large optic applications respectively.

The R:1 and raster scan tests are automated for fluence control, sample motion control, and damage detection. During a test the systems monitor the energy of each pulse. The energy data is combined with the beam intensity profile to calculate the peak fluence. To automate the fluence control, two empirical relations are derived from measurement. The first is the energy on the sample as a function of the beam attenuator angle. This measurement is done automatically by the computer by rotating the attenuator and measuring the beam energy as a function of angle. The second measurement is done with the assistance of the operator and derives beam fluence as a function of measured energy. The fluence is found using a commercial beam profiling unit and is defined as the peak fluence of the beam. For some systems discussed later in the section, this measurement is done automatically. For R:1 mapping, the two equations are then used to determine the starting and finishing angle of the attenuator as well as the rotation velocity required to for the appropriate ramp rate. The second equation is also used to calculate the fluence at which damage is detected. An example data set for the two measurements are shown in Fig. 8.

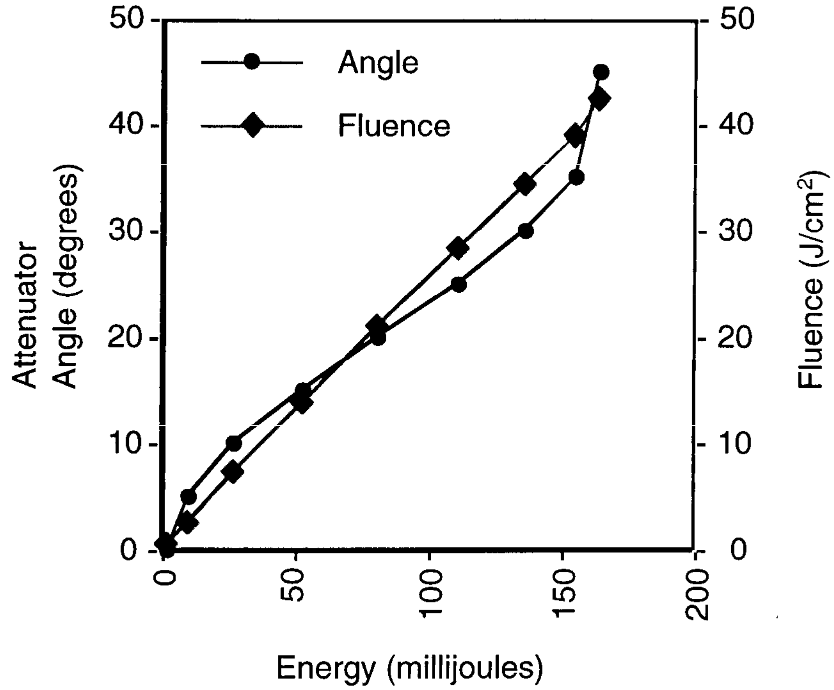

Fig. 8 For automated testing, data curves are generated before each test which allow the computer to control the energy on the sample as a function of attenuator angle as well as determine fluence base on only a measurement of energy.

The systems described above will be operating from 1 to 3 shifts a day during the NIF optics production period of 3 years. This has required extensive automation in order to allow the systems to operate safely and reliably while unattended. The system controls have also had to be automated such that little user interaction with the laser system is required.

For the LGDT, two beam measurements are needed: peak fluence in the beam and beam diameter at a fluence of 7 J/cm^2. The first is to keep the peak fluence below the level at which damage to the glass surfaces would be incurred. The second is a measure of the effective diameter of the beam at a fluence of 7 J/cm^2 as set by the damage threshold of platinum particles. The entire volume of the glass must be illuminated by this minimum fluence. This diameter becomes the step size for the scan. The system automatically monitors the effective beam diameter throughout the scan and changes the step size to compensate. The system is also able to automatically warm up at a set time of day so that it is ready for production when personnel arrive to load the glass for test.

For the LAC system, a beam profiler has been developed to diagnose the peak fluence of each pulse. The calibration measurements mentioned in the beginning of section 3 are automatically performed. This allows the system to set the pulse energies for each raster scan required for the laser conditioning. The user only sets the area to be scanned and the fluences for each consecutive scan. The system currently uses a surface scatter diagnostic to track damage on the optic so that the test can be stopped if catastrophic damage is detected.

The 3ω DT system in place at LLNL will also be automated with the beam control capabilities of the LAC system. The 3ω DT system will, however, use DMS as the primary tool for damage detection and characterization.

4. DIAGNOSTICS FOR DETECTION OF DAMAGE

Another key to the automation of the measurements is the development of diagnostics capable of automated detection of damage. The primary diagnostic used is based on scatter measurements. There are two different scatter measurement configurations used at LLNL, one for surface damage measurements (Fig 9) and one for bulk damage measurements (Fig. 10). The surface diagnostic is used on the small area tests systems (Table 1), and the Plato and LAC large area test systems (Table 2). The bulk diagnostic is employed on the Zeus small area tester for investigation of KDP/KD*P bulk damage. Both scatter diagnostics use a low power CW laser source whose wavelength varies with the application.

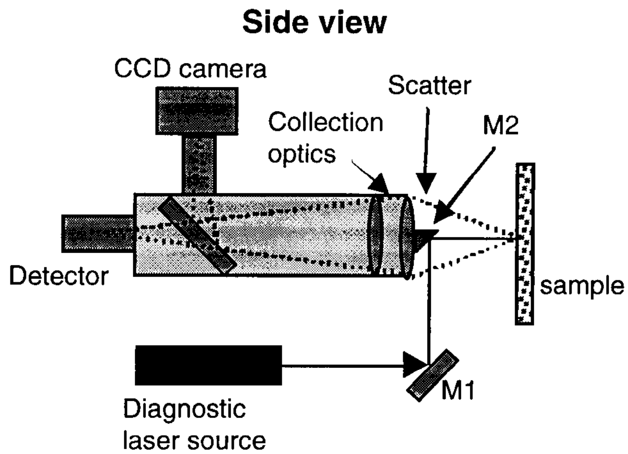

Fig. 9 Scatter diagnostic for surface damage measurements detects and images low angle scatter from the surface.

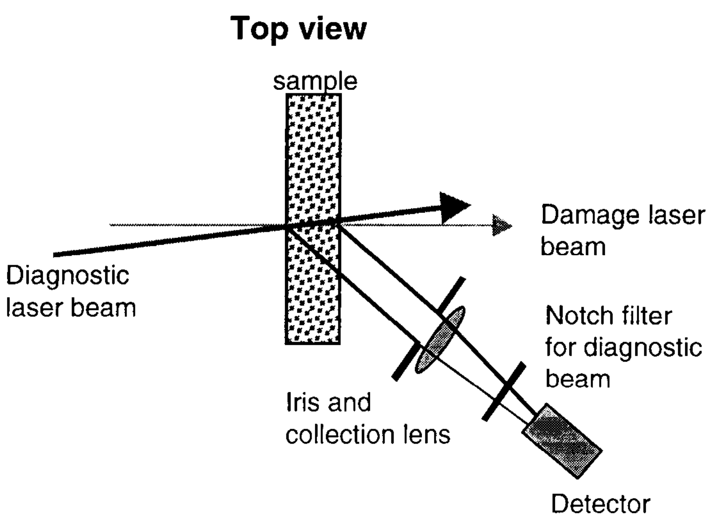

Fig. 10 Bulk damage diagnostic used for testing KDP material measures high angle scatter from bulk damage sites.

The scatter diagnostic works by comparing the scatter from a test site before laser irradiation with that measured after laser irradiation. A difference in the value indicates damage has occurred. The minimum detectable signal change corresponds to the appearance of scatter sources of 10 μm- 40 μm in size. For most materials, including fused silica surfaces, the monotonic increase in the scatter signal (Fig. 1) with damage severity makes the detection of damage initiation obvious. For some materials the signal evolution can be complicated however. This is the case for KDP crystal bulk measurements as shown in Fig. 11[2]. For this site, the bulk scatter first decreases then increases in a stepped manner as a function of increasing fluence.

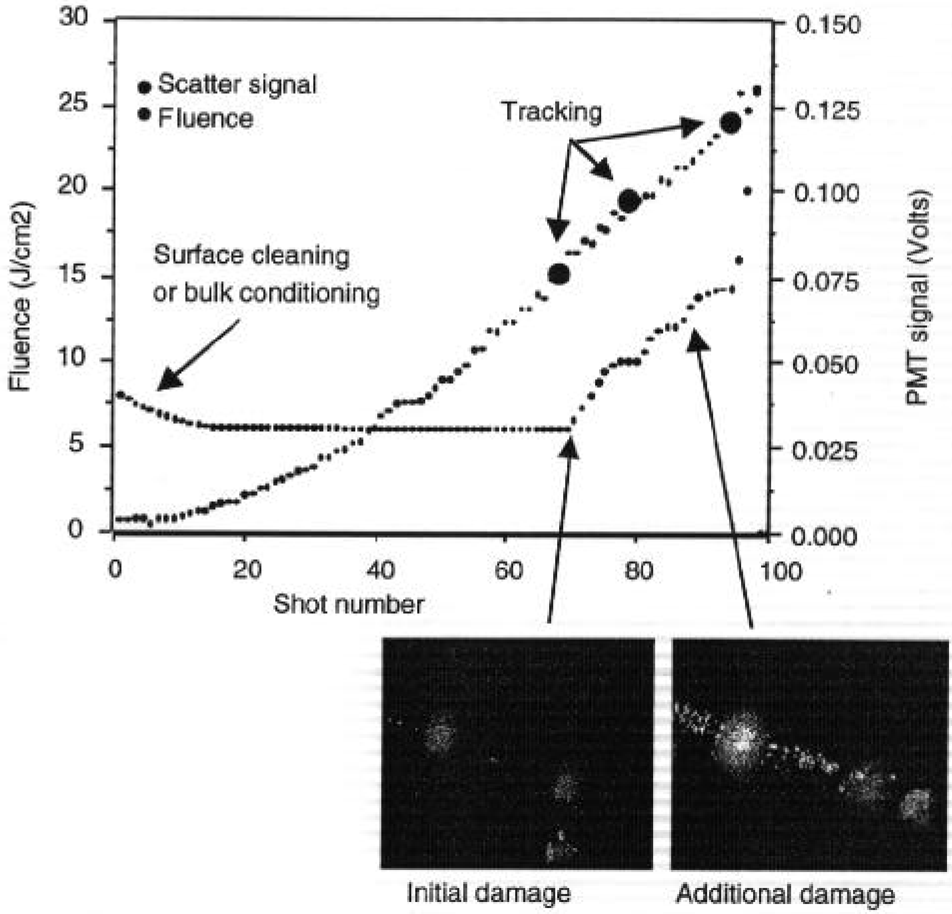

Fig. 11 Example of KDP bulk material R:1 mapping test site. Scatter is a function of pinpoint size and density in the bulk and can have a complex behavior with increasing fluence. Photos of the bulk pinpoint densities at different levels of scatter signal are shown in the lower images.

For the large transmission optics (40 cm by 40 cm), a defect mapping system (DMS) was developed[9,10]. The DMS system allows the operator to take a full aperture photograph of the optic, highlighting any defects in the surface or bulk of the material. The system has a resolution of 100 µm, but can detect defects as small as 5 µm in diameter. An example of DMS application is shown in Fig. 12. The darkened regions indicated by the arrows show damaged areas resulting from raster scan tests of increasing fluences. By analyzing the DMS image a damage concentration can be calculated at each of the scan fluences. If particular defects or damage sites need to be further understood, an optical microscope is used to take high resolution images as shown at the bottom of Fig. 12.

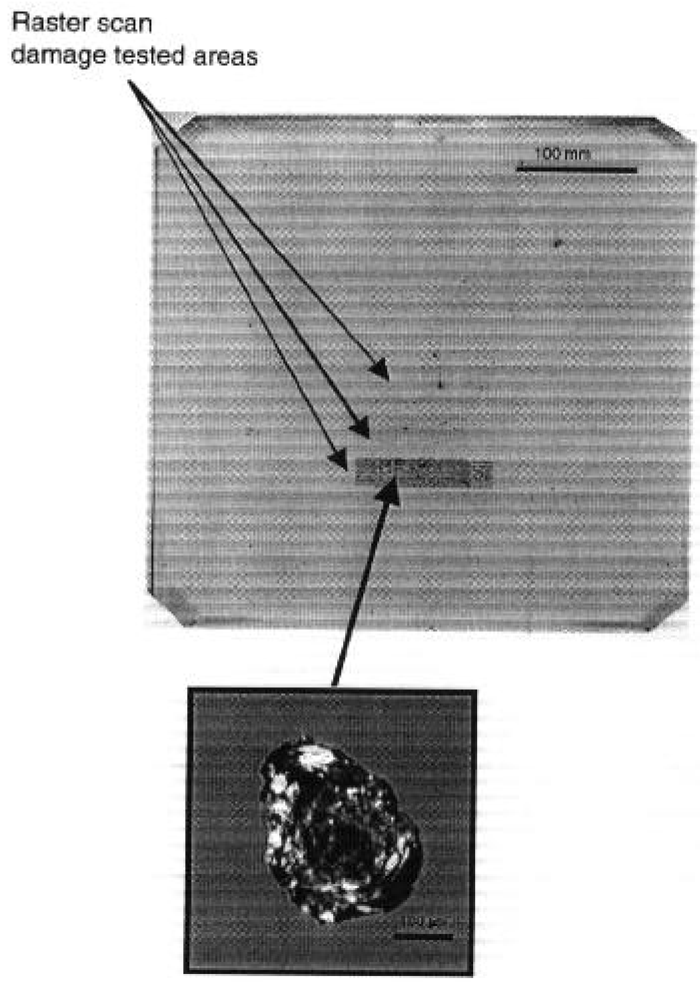

Fig. 12 DMS mapping is applied for large area transmissive optic testing allowing the determination of damage density as a function of fluence. In order to investigate damage morphology, a optical microscope is used (lower photo).

5. CONCLUSIONS

Automated damage testing facilities have been developed for both laser damage research and large optic production testing for all type of NIF optical components. Through automation of the damage measurement, statistical information can be gathered which can be used to improve our understanding of damage mechanisms, quantify the performance of optic suppliers and manufacturing processes, and predict the performance of large aperture components. This automation was in part possible due to the application of sensitive damage detection and beam characterization diagnostics.

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