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Current 3ω Large Optic Test Procedures and Data Analysis for the Quality Assurance of National Ignition Facility Optics

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ABSTRACT

A reliable metric is required to describe the damage resistance of large aperture 3ω transmissive optics for the NIF laser. The trend from single site testing to the more statistically valid Gaussian scanning test requires a well modeled experimental procedure, accurate monitoring of the test parameters, and careful interpretation of the resulting volumes of data. The methods described here provide reliable quality assurance data, as well as intrinsic damage concentration information used to predict the performance expected under use conditions. This paper describes the equipment, test procedure, and data analysis used to evaluate large aperture 3ω optics for the NIF laser.

KEYWORD LIST

Laser damage, laser damage metrology, NIF metrology, National Ignition Facility, large area testing, 3ω damage testing.

1. INTRODUCTION

Excluding spares, 768 transmissive half-meter scale UV optical elements are required to construct NIF. The final optics of NIF will be irradiated on-line by a distribution of fluences, peaking at 15 J/cm^2 (351 nm, roughly 3 ns). A single number generated by repeated irradiation of a few dozen test sites (S/1) is no longer adequate to describe the probabilistic nature of damage at high energies over large apertures. Damage probabilities generated during off-line raster scanning are dependent on the actual area irradiated which is a function of the test beam parameters. To better describe the performance of these optics, the damage sites will be treated statistically as a collection of "weak links". This technique yields the intrinsic damage density as a function of fluence for the sample under test. This predicted damage density is useful as pass/fail criteria a well as for the monitoring of material quality and variation of the finishing processes, and providing information on the performance of the optical elements under use conditions.

2. THE APPARATUS - 355 NM DAMAGE TEST SYSTEM FOR FUSED SILICA

Figure 1 schematically shows the 3ω large aperture damage test system layout, neglecting the sample plane diagnostics. The laser source is a commercially available Spectra Physics Nd:YAG operating at 10 Hz. The energy is focused to a far-field, diffraction limited focus in the sample plane. The current configuration allows for a peak fluence of 15.8 J/cm^2 (scaled from the system temporal pulse width of 7.5 ns to 3 ns by $\tau^{1/2}$). The peak fluence is held to within ±5% of target by computer control of the energy attenuator. The sample-plane beam diameter is monitored to assure that it does not vary more than 10% during a single scan. The control computer determines the scan increment by using the measured Gaussian width at 50% of peak intensity value (see Figure 2). The sample is translated through the beam to irradiate the entire surface area by raster scanning (with a scan rate of approximately 4.2 min./cm^2) The system is capable of translating one meter in both the vertical, and horizontal directions. A bare SiO_2 wedge is used to redirect a calibrated sampling of the beam to an energy meter and the CCD camera of a commercial beam profiling system. The control computer monitors these diagnostics, acting on any fluctuations. The system is capable of issuing an alpha numeric radio page alerting the operator of its status. Figure 3 shows the existing 3ω damage metrology laboratory.

The damage detection diagnostic currently consists of a scanning linear mega-pixel array[1]. The optic is mounted in a fixture which floods the bulk material with white light. The optic is imaged onto this array resulting in a full-aperture image which highlights defects within the bulk and on the surface with (for a 40 x 40 cm^2 sample) a resolution of 80 μm/pixel and a 10 μm sensitivity. These are referred to as Defect Mapping System (DMS) images. A digital micrograph can be acquired (using an in-situ 100x digital microscope) of any artifact or defect identified using a thresholded DMS image.

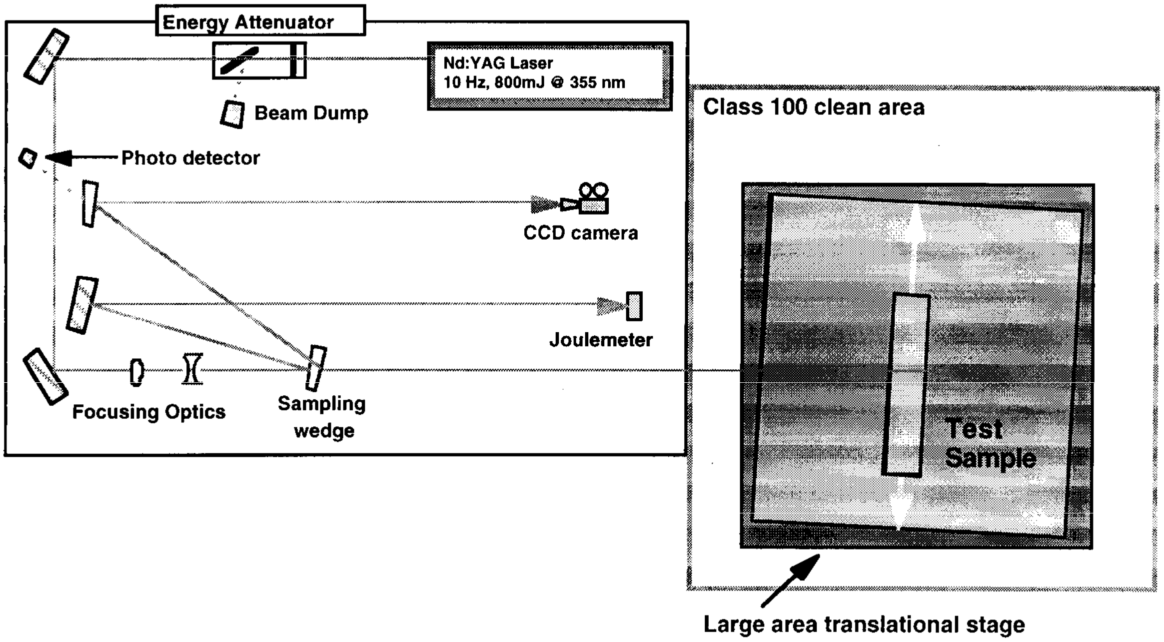

Figure 1. Large-aperture laser damage metrology system layout.

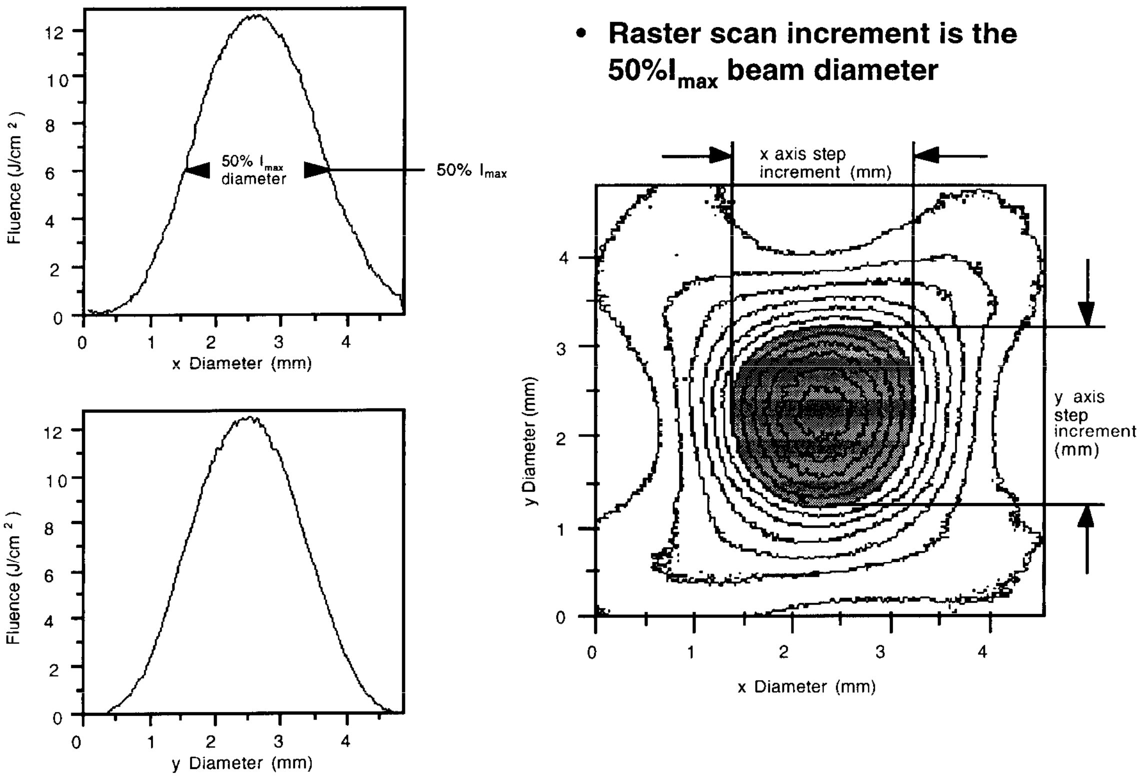

Figure 2. Far-field diffraction limited spatial beam profile in the sample plane. Step sizes during scanning are chosen to assure illumination of all points at a minimum fluence specific to the test.

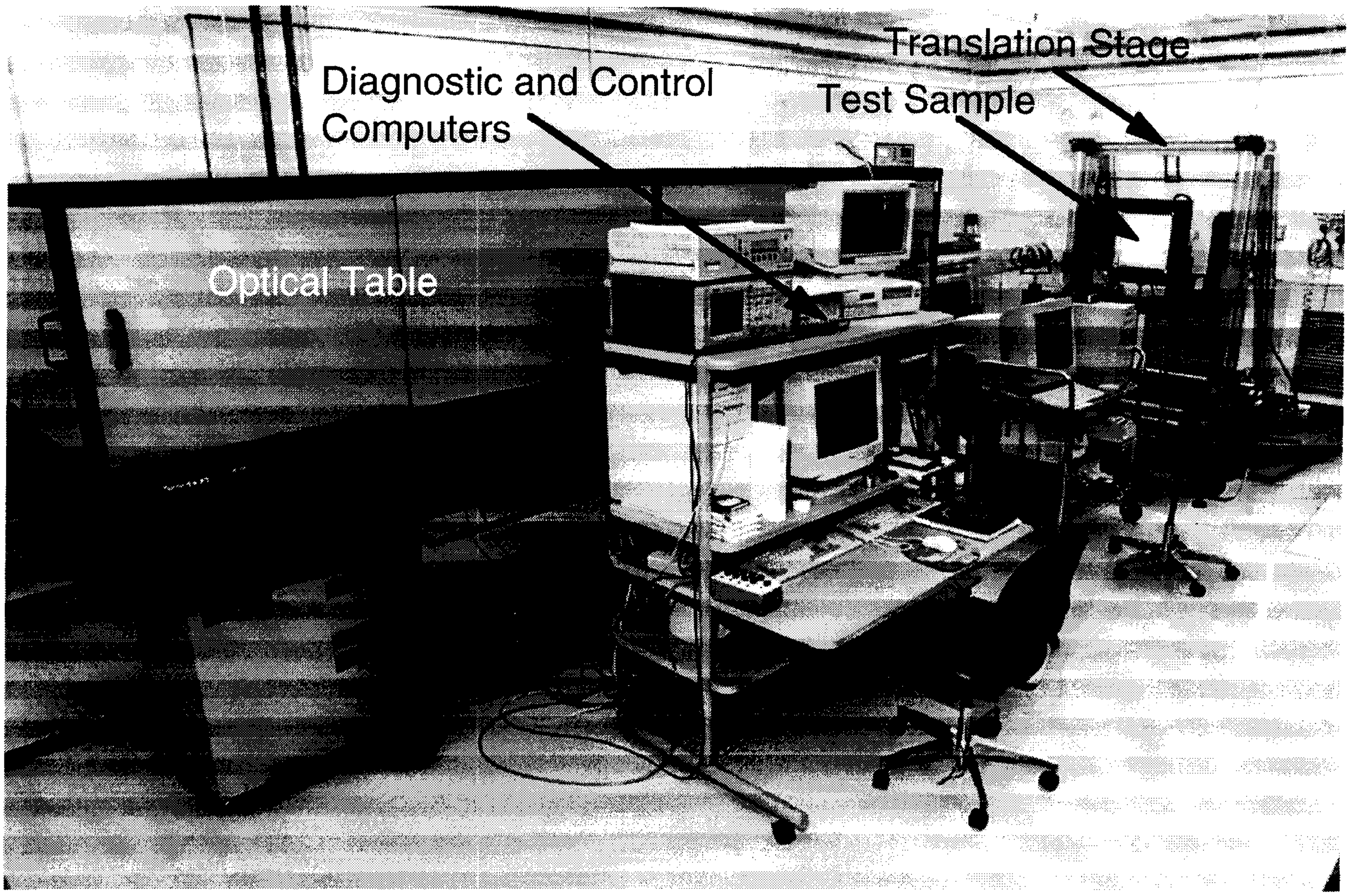

Figure 3. 3ω large aperture laser metrology system.

3. TEST PROCEDURE

A single threshold generated by repeated irradiation of a few dozen test sites (S/1) is not adequate to describe the probabilistic nature of damage to large aperture high quality laser optics. Fundamental to accurately describing a large area is an adequate volume of data to represent the entire surface. As the optical surfaces improve, the test procedure must be refined to provide a resolution appropriate to detect sample to sample variations. The test procedures discussed here are not refined to fully evaluate the sample at all fluences, but to detect initial trends by which we can build a database of results, allowing us to refine the procedures to address specific issues during production.

Prior to 3ω irradiation, a DMS image of the entire optic is acquired which highlights defects within the bulk and on the surface[1]. A digital micrograph is collected (using an in-situ 100x digital microscope) of each preexisting artifact detected within an area to be irradiated (Figure 4a). The optic is then damage tested by raster scanning a small (1-2 mm $1/e^2$ diameter) 355 nm Gaussian beam of a given peak fluence across a sub-aperture sampling of the optic. Each of the three to seven 20 cm^2 sub-aperture areas (depending on the test being performed) are scanned at a different fluence (Figure 4b). The diameter of the Gaussian beam at 50% maximum intensity (typically 0.6 - 0.8 mm) is used as the scanning increment. A micrograph of each preexisting artifact (detected in the pre-irradiation DMS image) is acquired to determine if any damage has occurred. A post irradiation DMS image is acquired and thresholded to determine the total number of sites within each test area after irradiation (Figure 4c). Micrographs can also be used to determine the size of new damage sites identified by the post irradiation DMS image. The image prior to testing is subtracted from the final image and the number of new sites within each test area are counted. In this way a damage probability can be calculated for each test fluence. Testing a typical optic in this fashion requires 10 days. Through reduction of the test areas and automation of the procedure, it is expected that system capacity will be eight hours per optic.

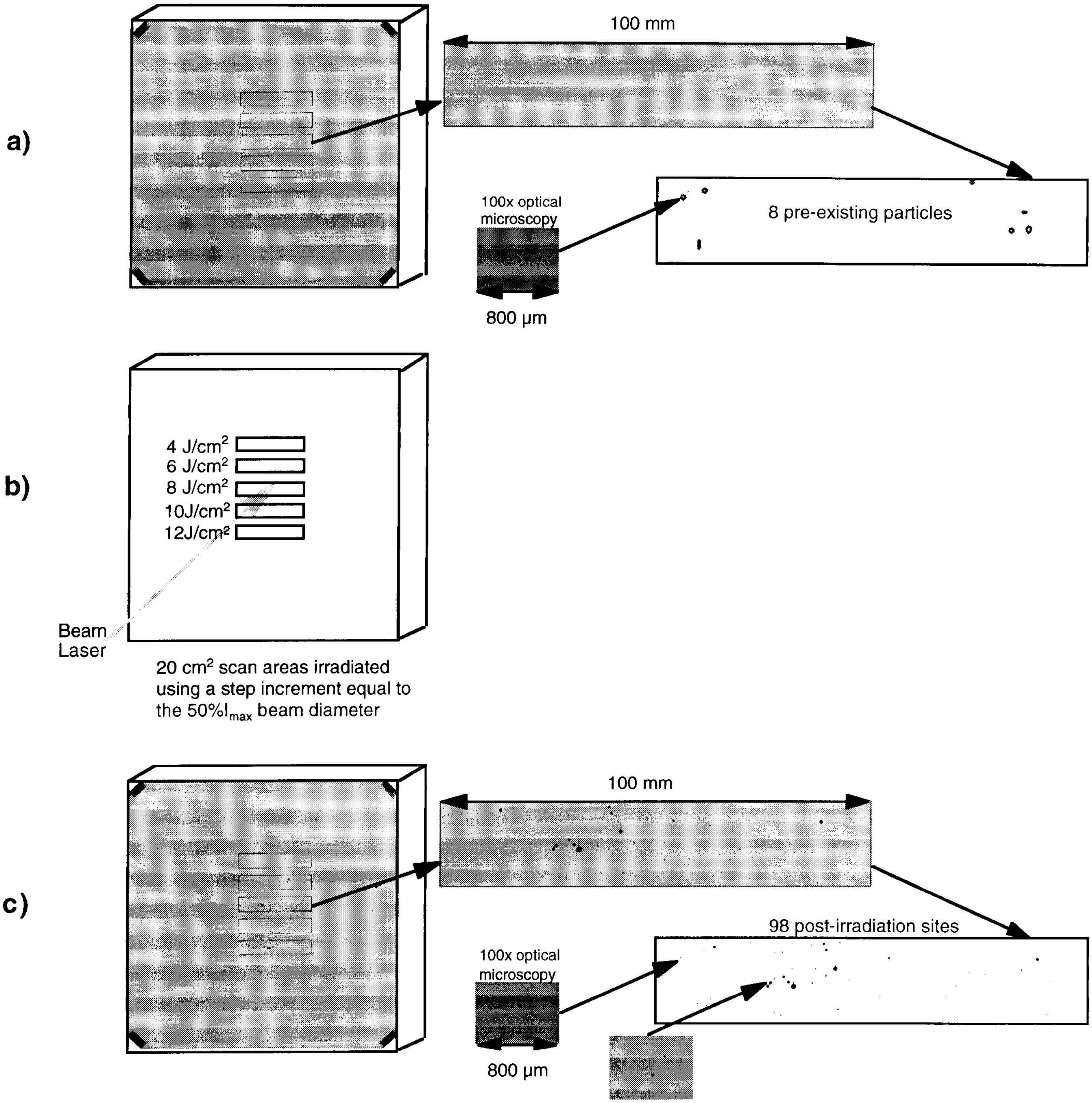

Figure 4. Graphical representation of QA verification of large aperture 355 nm damage performance.

a) A DMS image is acquired before damage testing. The areas to be irradiated are thresholded and the artifacts counted. 100x microscopy is performed on all artifact sites.

b) Each test area (typically 3-7 areas, 20 cm^2 each) is irradiated by raster scanning at a given fluence.

c) A post irradiation DMS image is acquired. Microscopy is performed on the preexisting artifacts to determine change (if any). Each test area within the post irradiation DMS image is thresholded and the total number of sites within each test area is determined. The number of damage sites within each area is found by subtracting the total number of sites within a given area from the number of preexisting artifacts which did not damage.

4. DATA ANALYSIS - THE GENERATION OF A DAMAGE CONCENTRATION CURVE

During area illumination, damage occurs at discrete sites. These sites possess a localized damage threshold at or below the irradiated peak fluence. To quantify optical damage resistance of the sample as a whole, "extreme statistics" are used which treat these localized defects as "weak links", allowing for the description of large area performance based on a sub aperture statistical sampling. It has been observed experimentally that the cumulative damaging defect density varies rapidly with fluence, often as a power or Weibull distribution[2]. The following discussion will demonstrate the progression from the measured test parameter dependent results, to a description of the expected defect density which is intrinsic to the sample under test.

Given that the off-line damage test yields the number of beam prints (S_F) and the number of damage sites (D_F) within each test area at a given fluence (F), a damage probability (P_F) can be easily calculated as

$$P_F = D_F / S_F. \tag{1}$$

This probability is valid only as a value of relative comparison, e.g. it can be used to compare samples tested under identical conditions. The probability P_F is dependent on extrinsic test parameters, particularly the fluence distribution and illuminated area. The intrinsic damage concentration (c_F) of the test sample can be obtained by determining the appropriate test area (A_{eff}) equivalent to an area irradiated by a flat beam of identical peak fluence. This effective area is the link required to use the extrinsically influenced test data to determine the intrinsic damaging defect density.

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

The effective area will be found by multiplying the area tested by discrete Gaussian irradiation (A_F) with a correction factor (A_c) relating the Gaussian raster scan area to an equivalent area of flattop irradiation.

$$A_{eff} = A_c A_F \tag{3}$$

To determine this correction factor (Ac), Weibull statistical methods are employed. In the simple case of non-overlapping beams, the effective area of the test Gaussian is determined by raising the Gaussian spatial profile to the power of the Weibull index (m), Figure 5. The calculation of an equivalent energy distribution requires further refinement when the Gaussian profiles overlap to any extent. For this case, the integration is performed on a matrix of overlapping Gaussians. This analysis requires the test scan increment and beam size to be known and constant. The step increment will be determined by specifying the fraction of the peak energy (f) at which the diameter of the energy profile will be measured. This diameter will be used as the step increment. Now the Gaussian based illuminated area matrix can be described, and the area correction determined to be

$$A_c = \pi/4 \left[\mathrm{erf} \{ \sqrt{m \ln(1/f)} \} / \sqrt{m \ln(1/f)} \ \right]^2 \tag{4}$$

Knowing this, the remaining challenge is to determine the most accurate Weibull index. To the first order, the Weibull index is simply the slope on a log-log plot of the number of defects illuminated per beam print (N_F) as a function of fluence, i.e. the slope of

$$N_F = -\ln (1 - P_F). \tag{5}$$

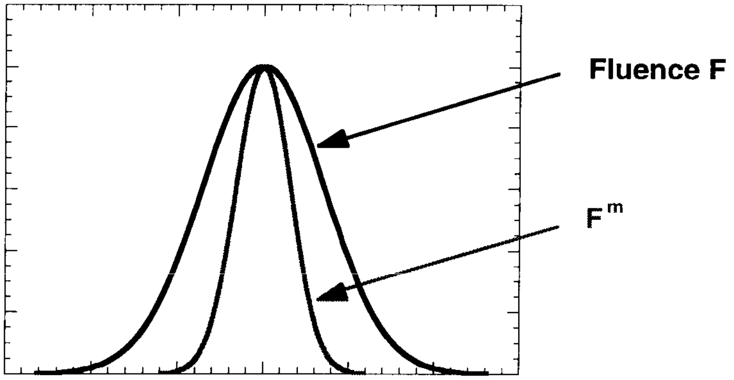

Figure 5. Since damage incidence depends on the peak fluence seen at a point, it is necessary to calculate the effective area of a flat beam with the same maximum fluence as that of the test beam[2]. For the simple case of scanning with non-overlapping Gaussian beam prints, area irradiated by a Gaussian beam profile can be related to an equivalent area illuminated by a constant (flattop) fluence, by raising the Gaussian profile to the power of the Weibull index, m.

To be more precise, the slope (m) must be carefully determined using a weighted least squares fit of the test data. This curve fit must be weighted to reflect the higher degree of statistical certainty for a fluence with many data points (damage sites) as opposed to a fluence with only a few data points. Our preliminary method to perform this weighting (W_F) is related to the statistical error for the defect concentration at each fluence level as

$$W_F = D_F^{1/2}. \tag{6}$$

This weighting factor as a function of fluence (W_F) is employed in the least squares curve fit to determine m, as

$$m = (\alpha - \beta \chi) / d \tag{7}$$

where

$$\alpha = < \ln F \ln C(F) > \tag{8}$$

$$\beta = < \ln F > \tag{9}$$

$$\chi = < \ln C(F) > \tag{10}$$

$$d = < (\ln F)^2 > \tag{11}$$

where we have used the shorthand notation

$$< y > = \frac{\sum_{i=1}^{N} y_{Fi} \, w_{Fi}}{\sum_{i=1}^{N} w_{Fi}} \tag{12}$$

y is used to represent any of the averages above, and the sums are over the *N* fluence test values F_i.

In equations (8) and (10), $C(F_n)$ is the uncorrected defect concentration, namely

$$C(F) = D_F / A_F. \qquad (13)$$

Now, knowing m, and given equations (3) and (4), the intrinsic defect concentration of the sample under test can be calculated as

$$c_F = D_F / A_{eff} \qquad (14)$$

The uncertainty (δc_F) here is related to the number of damage sites generated within each test area, as

$$\delta c_F = c_F / D_F^{1/2} \qquad (15)$$

An example of the results of this analysis are given in Figure 6.

For further reading on the origins of the statistical methods employed here, refer to *Extrapolation of damage test data to predict performance of large-area NIF optics at 355 nm*, Feit, et al, this proceedings.

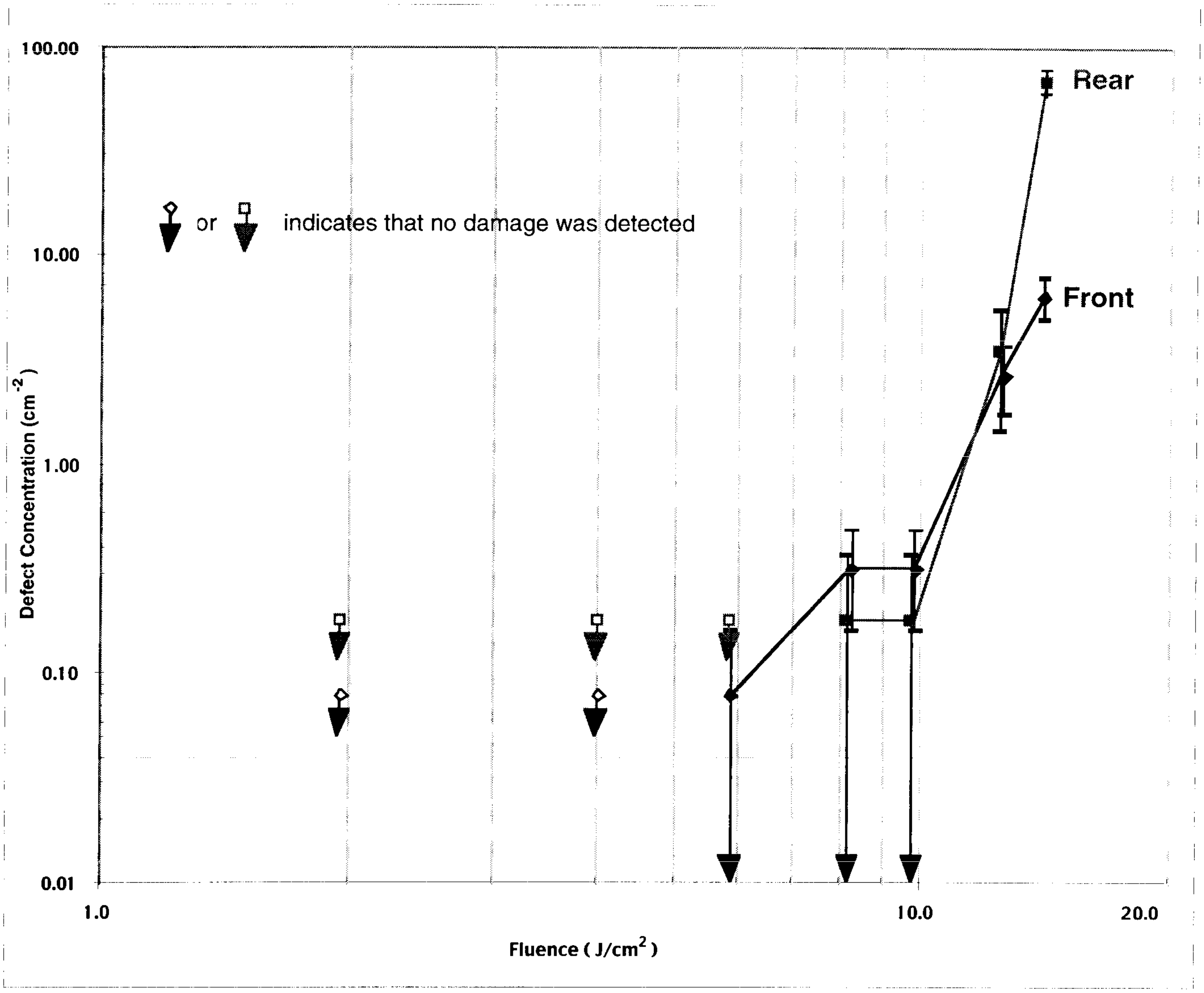

Figure 6. Sample curve showing intrinsic damage concentration as a function of fluence.

5. SUMMARY

Intrinsic damage density curves are generated off-line and used to monitor optic finishing process quality. The determination of an accurate Weibull coefficient is critical, as it determines the correction required to compare damage densities obtained by Gaussian raster scanning with densities resulting from illumination by a constant intensity. One 3ω system is required based on component production rates and testing schedules, assuming that an optic can be tested in 24 hours. Following a statistics-based optimization of the test procedure and automation of the inspection process, the testing rate is expected to be as low as 8 hours per optic. Current planning indicates that the 3ω damage test system will be operated at the Lawrence Livermore National Laboratory due to the cost of vendor site installation and the complexity of system operation and maintenance.

6. ACKNOWLEDGMENTS

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