Fluence Thresholds for Laser-induced Damage of Optical Components in the Injector Laser of the SSRL Gun Test Facility

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Damage threshold fluences for several optical components were measured at three wavelengths using the injector laser at SSRL's Gun Test Facility. Measurements were conducted using the fundamental ir wavelength at 1053 nanometers and harmonics at 526 nm and 263 nm with 3.4ps pulses ($1/e^2$ full width intensity); ir measurements were also conducted with 850 ps pulses. Practical surfaces relevant to the laser system performance are emphasized. Damage onset was evidenced by an alteration of the specular reflection of a cw probe laser (650 nm) from the irradiated region of the target surface. For the case of stretched ir pulses, damage to a Nd:glass rod was observed to begin at a site within the bulk material and to progress back toward the incident surface.

Background

The rf gun at SSRL's Gun Test Facility is a copper photocathode which is irradiated by fourth harmonic light produced by a Nd:glass based laser system. This laser utilizes the conventional chirped pulse amplification scheme for producing energetic pulses of short (picosecond) duration. Pulses in the infrared are frequency doubled to visible (526 nm) in a first BBO crystal, then doubled again to ultraviolet (263 nm) in a second BBO crystal. Because the quantum efficiency of the copper cathode is of order 10^{-5}, uv pulse energies of order 100 microJoules are needed at the cathode to generate the desired one nanoCoulomb electron bunch charge. The efficiencies of the laser pulse shaping (spatial and temporal) and transport systems necessitate the production of uv pulses with milliJoule energies. Experience with the laser system suggests that the damage thresholds of some optical components lie within the operating range of the system when spot size is not closely monitored (for uv light in particular). Because the laser system is currently being upgraded to higher pulse energy, it is important to determine relevant levels for the onset of damage and to scale the laser spot size accordingly. The efficiency of frequency conversion from the fundamental ir to the uv region increases nonlinearly with incident ir intensity, favoring the use of the highest feasible intensity. For a fixed pulse duration and energy this necessitates reducing the spot size. In addition, the beam profile transmitted through finite aperture optics is degraded when the spot size is not substantially smaller than the aperture. Determination of damage thresholds allows us to set the spot size optimally for efficient operation without damage to optics.

Laser induced damage has been studied extensively for the last three decades[1], motivated by the development of laser systems with short and ultrashort pulse capability at high pulse energies. In the short pulse regime, studies of fluence thresholds for laser induced damage in several materials indicate a $\tau^{1/2}$ scaling (where τ is the pulsewidth) of the damage threshold over a range from tens of picoseconds to a few nanoseconds. However, for pulsewidths below about 10 picoseconds, the threshold reduction with decreasing pulsewidth is weaker as optical field driven phenomena become more significant.[2-5]

Method

Determining the fluence level at which a material suffers damage requires three things: measurement of beam energy, measurement of beam size at the target surface, and a physical criterion for determining that damage associated with the incident laser pulses has occurred. Fluence threshold measurements are parameterized by the incident pulsewidth. Damage is produced using a pulsed (2.5 Hz) pump beam focussed onto the target surface with a single convex lens; the pump beam is convergent to a point behind the target surface. The energy of the pump beam is measured shot-to-shot using a pyroelectric Joulemeter (Molectron J4) and a calibrated beam splitter to sample part of the pulse. The assessed accuracy of the J4 Joulemeter is ±5%. The beam size at the target surface is measured by inserting a beam splitter between the lens and target to direct the pump beam onto a triggered CCD camera (Data-Ray WinCam PCI.) The beam splitter is positioned so that the path length from the lens to CCD sensor is the same as the path length from the lens to the target surface. During beam size measurement, the pump beam incident on the CCD is attenuated upstream of the lens using filter glass. The pump beam spatial profile is approximately Gaussian. Several single-shot images of the pump beam are saved with each data set. The target surface is monitored by illuminating the target with a cw probe laser (a diode laser at 650 nm wavelength) and imaging the specular reflection of probe light from the surface onto the same CCD that monitors the spot size. The camera is operated in free-run mode (30 Hz frame rate) during the test to ensure rapid identification of the onset of damage. After a 100-200 shot exposure to the pump beam, an image is saved and the pulse energy is increased. For ir tests, filter glass is used to regulate the pulse energy, with a minimum energy step increase of +10%. For uv and visible wavelength tests, the energy is regulated by controlling the ir energy incident on the BBO crystals using an ir half wave plate and polarizing beam splitter cube. Damage is said to have occurred when the target surface image has changed visibly. Initially, damage sites may be too small to be seen. Once damage is seeded in one region, however, that spot tends to grow with subsequent pulses. Review of saved images allows determination of the onset of damage.

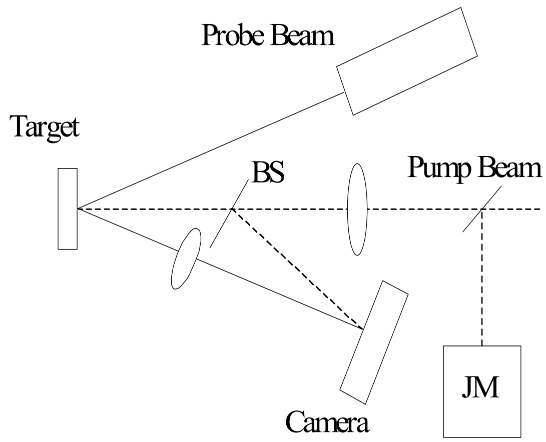
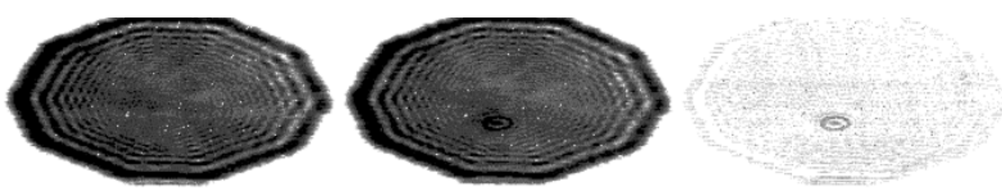


Figure 1: Test Setup. The path length from beam splitter BS to the camera equals the path length from BS to the target. Pump beam pulse energy is monitored at Joulemeter JM.

Target materials are deliberately prepared as they would be for normal use at GTF.[6] In the case of mirrors, this means an ethanol wipe with photographic lens tissue (Kodak) followed by a burst of compressed gas (1,1,1,2-tetrafluoroethane) from a power duster (CleanTex Accuduster III) and inspection with a magnifying eyepiece. The Nd:glass rods are given several careful rounds of the same treatment. Because the BBO crystals are thin and damage easily under mechanical stress, they are not cleaned beyond a power dusting.

Analysis

The onset of damage to targets was easily noted in most of the test series. Sensitivity to differences in images was enhanced by subtracting the pre-exposure image of the target from subsequent post-exposure images. An example of this is shown in Figure 2 for a case in which damage has occurred. In this case, it is clear from the post-exposure image alone that damage is present; in many other cases image subtraction was necessary because the target surface displayed preexisting damage spots in the illuminated region.



(a) (b) (c)

Figure 2: (a) Pre-Exposure, (b) Post-Exposure, and (c) Subtracted images

Numerical analysis of the damaged region for a series of images shows that as the fluence is increased, the onset of damage is abrupt. This is consistent with the anticipated highly nonlinear temporal evolution of material damage in general. This is because the damage is known to evolve from the growth of plasma attributed to laser-induced ionization.[2] Figure 3 was generated by subtracting the pre-exposure image from each post-exposure image in a series, then calculating the average pixel difference in the region illuminated by the pump laser. By plotting this average difference versus fluence at the target surface, we can assess the onset of damage. The five points with the highest average difference in Figure 3 represent target damage. This method produced the same threshold result as a simple visual assessment of the difference images.

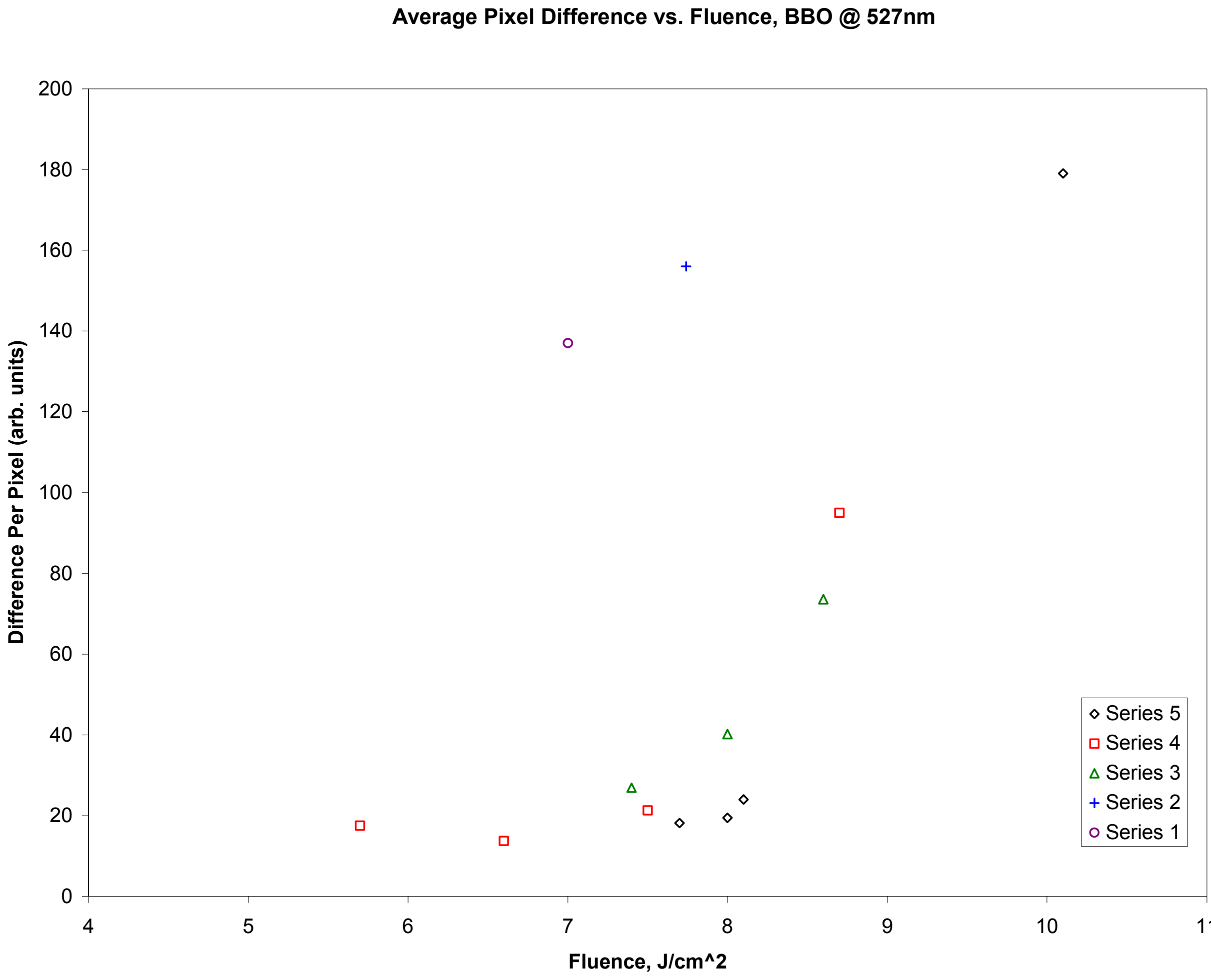


Figure 3: Numerical Method of Damage Threshold Assessment

During the Nd:Glass rod tests, a visible flash of light was observed to come from the bulk rod material with each laser pulse before any damage was apparent on the rod face. The flash site had an axial length of a few mm, and the flash site progressed back toward the surface of incidence with each subsequent laser pulse while the laser energy was held constant. When the flash site reached the face of the rod, an irregular crater of approximately 500μm diameter (substantially larger than the 70μm diameter pump beam) was produced on the rod face. Following this rod face damage each incident laser pulse generated an audible ‘snapping’ sound which apparently came from the rod surface, accompanied by a visible flash at the rod surface. Later inspection showed an opaque channel from the face damage site to the first bulk site from which the light flash was observed to originate. The generation of this light then serves as an indicator of damage to the Nd:glass material, and will be considered as the threshold of interest. The light most likely results from runaway self-focussing of the pump beam. Damage in the bulk is formed when the focused intensity of the pump beam is sufficient to ionize and consequently damage a small region within the rod. Absorption in the damaged region can heat and melt the material, establishing a ‘bulk’ reflective surface. Subsequent pulses (arriving at 2.5Hz) are reflected from this surface and cause damage to progress upstream toward the rod surface. Although the rod surface was very close to the pump beam waist, the pump beam was not well collimated at the rod surface, so it is not simple to determine the intensity dependence of self focussing in the rod bulk from the spot size and energy data. It can be said that the fluence level specified is enough to allow a convergent beam to reach damage fluence levels within the 65mm length of the rod.* Because of the limited area of the laser rod face only two measurements were made of this threshold.

For the other targets, three or more run series were used to produce the threshold values reported. Variation is likely produced by surface contamination of the target and limits on the accuracy of laser spot size measurement using the CCD camera. In the ir tests, precision is limited by a limited filter selection. In the uv and visible tests, precision is limited by energy jitter in the pump beam. Overall error in the threshold measurements is ±30%. Fluence thresholds for damage are reported in Table 1. These are peak (on-axis) values. The difference between short-pulse and long-pulse damage threshold for the Y1 mirror[φ] is notable. Also included in the table are calculations of the peak intensities and peak electric fields delivered to the target surface. The peak intensity is calculated assuming a Gaussian temporal pulse shape with the specified $1/e^2$ intensity full width. These calculations do not take into account the presence of the target surface (i.e. surface reflectivity as determined by the Fresnel equations). For reference, minimum spot diameters (2ω) based on a 1 mJ pulse energy determined by setting fluences at measured damage levels and are included in the table. A Gaussian spatial profile is assumed, and the diameter contains 86.5% of the beam energy. For a fixed fluence, the radius will increase proportional to the square root of the pulse energy.

Table 1: Damage Threshold Fluence of GTF Optics

Target	Damage Fluence, Jcm^{-2} (range)	Peak Intensity $GWcm^{-2}$	Peak Field $MVcm^{-1}$	$2\omega_{min}$ for 1mJ pulse, μm, (average)
Y1 0° Mirror (3.4ps, 1053nm)	8.5 (6.3-10.1)	4000	55	174
Y1 0° Mirror (850ps, 1053nm)	50 (48-51)	94	8.4	74
Nd:Glass Rod (850ps, 1053nm)	99, 160*	190, 300	12, 15	50, 38
BBO Crystal (3.4ps, 527nm)	8.4 (7.0-10.1)	3900	55	174
BBO Crystal (3.4ps, 263nm)	3.1 (1.9-4.0)	1500	33	286
Y4 0° Mirror (3.4ps, 263nm)	2.1 (1.7-2.8)	1000	27	348

Conclusions

The apparatus used in these measurements is adequate to measure surface damage fluence thresholds for a wide variety of samples. The method of determining the onset of damage could be enhanced by using additional energy meters to measure the transmission and reflection of pump beam energy by the sample. Dependence of damage thresholds on pump beam polarization may also be of interest in future studies. Note that the experimental method reported here is not well suited to measurement of bulk damage thresholds. Analysis of the transmitted pump beam profile would allow experimental evaluation of the effective[ξ] intensity-dependent index of refraction responsible for self-focussing and beam breakup, and is of particular interest with regard to the Nd:glass rods.

References:

[1]See references of 2 and 3 for an extensive list of papers.

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[6]For a discussion of cleaning optics with regard to damage prevention, see *DAMAGE CONTROL: A Practical Guide to Avoiding Laser Damage to Optics*, J. Doty, Alpine Research Optics (2000)

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* The measured damage threshold fluence for Nd:glass depends highly on the optical geometry of the experiment, specifically the length of the rod used in the test. Since we are studying surface damage, the number specified is the (surface) fluence at which eventual surface damage resulted. The more significant figure of merit, the fluence at which the bulk material was damaged, could not be measured in this experiment. Obviously, the threshold value will be lower for longer rods.

φ Both the Y1 and Y4 mirrors are coated optics manufactured by CVI Laser Corp.

ξ Integrated over the target length.

[7]*Damage to Fused-Silica, Spatial-Filter Lenses on the OMEGA Laser System*, LLE Review **78**, U. of Rochester (1999)
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