

Effect of laser pulse duration on damage to metal mirrors for laser IFE

John E. Pulsifer^a, Mark S. Tillack^a and S. S. Harilal^b

^aUniversity of California, San Diego, 9500 Gilman Drive, La Jolla, CA, USA 92093-0417;

^bHyperion, Inc., 455 Science Dr. Suite 100, Madison, WI 53711

ABSTRACT

A Grazing Incidence Metal Mirror (GIMM) is a chief candidate for beam delivery for Inertial Fusion Energy (IFE). The goal for GIMM survival is greater than 3×10^8 laser pulses with 5 J/cm^2 laser fluence normal to the incident beam. Laser-induced damage to metal mirrors is primarily a thermomechanical process. Long-term exposure leads to microstructural evolution analogous to fatigue. We have performed laser-induced damage experiments on high damage threshold aluminum mirrors using commercial KrF excimer (248 nm) lasers. We have studied mirror response to standard, 25 ns long-pulses as well as to IFE prototypic, 5 ns short-pulses achieved using a Pockels Cell. Short-pulse damage fluence was found to be better than predicted using simple thermal diffusion scaling from long-pulse results.

Keywords: metal mirror, final optic, inertial fusion

1. INTRODUCTION

1.1 Motivation

The Grazing Incidence Metal Mirror (GIMM) is a candidate final optic of a laser Inertial Fusion Energy (IFE) driver system where the survival goal is 3×10^8 cumulative laser pulses with a fluence of 5 J/cm^2 normal to the incident laser beam. We want to simulate an IFE prototypic laser pulse of $\sim 5 \text{ ns}$ Full Width Half Maximum (FWHM) at 248 nm (the shortest wavelength currently considered for IFE) in order to determine mirror damage fluence subject to near IFE conditions. We have already collected a large amount of mirror damage fluence data using commercial KrF excimer lasers that produce a $\sim 25 \text{ ns}$ pulse at 248 nm (FWHM is assumed for all laser pulse duration discussions herein). These long pulse results must be compared to IFE prototypic, short pulses in order to understand mirror damage fluence relevant to laser IFE.

1.2 Background

The final optic in a laser-IFE application is directly exposed to the chamber environment where fusion reactions occur. Figure 1 illustrates a design concept that locates the final optic 20-30 m from chamber center so that threats from neutrons, x-rays, high-energy ions, and debris are reduced by an order of magnitude or more compared to the threat at the chamber wall.

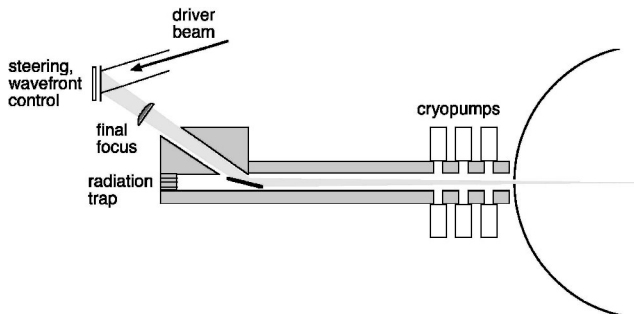


Fig. 1. Schematic of a laser-IFE power plant beamline. At a minimum, the final optic must deflect the driver beam onto the target at chamber center while protecting the upstream optics from chamber emissions. Focusing, steering, wavefront correction, or other optical functions can be achieved prior to the final optic. Despite the higher laser fluence

capability offered by multi-layer dielectric mirrors compared with metal mirrors, neutron irradiation effects such as swelling and color center formation are believed to eliminate dielectric mirrors as a final optic contender¹. A GIMM has a much lower reflectivity than a dielectric mirror, especially in the UV part of the spectrum. To overcome that limitation, we chose to use Al since it retains reflectivity below 248 nm. Figure 2 indicates that a pure Al mirror reflects over 99% of s-polarized, 248 nm light at a shallow (~85°) angle².

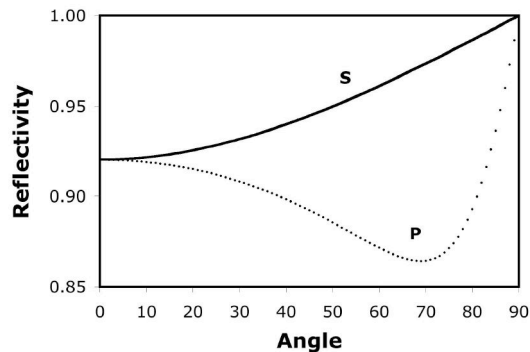


Fig. 2. Reflectivity of s- and p-polarized, 248 nm light on pure Al.

1.3 Problem and approach to solution

Laser-induced multi-pulse damage to metal mirrors is primarily a thermo-mechanical process. Thermo-mechanical stress degradation of metal mirrors was studied in detail by Musal³. An empirical model for multi-pulse damage to metal mirrors was later presented by Lee⁴ *et al*, who showed that shear stress at the mirror surface is proportional to laser pulse width. Long-term multi-pulse laser exposure leads to micro-structural evolution analogous to mechanical fatigue. We have so far studied the laser-induced damage of aluminum mirror specimens by exposing them to 248 nm light from commercial KrF excimer lasers with standard 25 ns “long” pulses. Each laser pulse produces rapid heating at the mirror surface, resulting in a steep thermal gradient and inducing high thermal stress. As an example, a fluence of 10 J/cm² will result in approximately 10 mJ/cm² absorbed into the mirror surface assuming 99% reflectivity and a factor of 10 spreading of the laser footprint due to the grazing angle of incidence. The mirror surface temperature rises tens of degrees with stresses approaching the yield point of Aluminum⁵:

$$\sigma \approx \frac{\alpha E \delta T}{3(1 - \mu)}$$

where $\alpha=2.3e-5$, $E=6.9e10$ and $\mu=0.37$ for pure Al. Depending on the laser pulse width, the thermal gradient, and therefore, thermal stress will vary. The steep thermal gradient and high stresses occur within several microns of the mirror surface and are imposed over many cycles. A successful final optic should survive more than 3×10^8 laser pulses.

To determine the effect of laser pulse width on thermal stress, we first collected long pulse damage fluence data by exposing a mirror specimen at multiple locations. Then we predicted short pulse damage fluence response using a 1-D thermal diffusion model with the long pulse fluence data as input. Finally, we produced an IFE prototypic “short” laser pulse (~5 ns) and exposed fresh locations on the same mirror specimen to collect short pulse damage fluence data for comparison.

2. THE EXPERIMENT

2.1 Overview

We performed laser-induced damage testing at the UCSD Laser Plasma and Matter Interactions Laboratory using Lambda Physik KrF (248 nm) excimer lasers. The fluence range delivered on target was 15-40 J/cm², measured perpendicular to the beam propagation direction (*not* relative to the mirror surface). The beam was polarized and attenuated using cube beamsplitters so that only s-polarized light passed to the target. To increase laser fluence on the specimen, a 1 m focal length lens converged the beam on target approach. The beam was finally reflected from the specimen at 85° from the surface normal, creating a trapezoidal footprint on target with approximate dimensions of 1

mm x 5 mm. The mirror specimen was inside a cryo-pumped chamber with a vacuum better than 1×10^{-5} Torr during testing (see Fig. 3). The spatial and temporal profiles of the beam were diagnosed using a UV imaging camera and a photodiode, respectively.

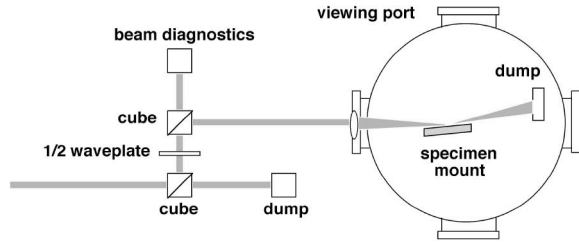


Fig. 3. General experimental setup

2.2 Test specimen

A single mirror specimen was used for both long and short pulse data collection. Many fabrication techniques have been explored to develop a mirror suitable for IFE, but one of the most successful concepts has been AlumiplateTM, a proprietary pure Al electroplate⁵. The specimen used in this work was a 2 in diameter, 0.4 in thick Al-6061 disc with a ~100 micron AlumiplateTM coating. The coated surface was single-point diamond-turned to 3 nm rms with maximum peak-to-valley of 20 nm (see Figs. 4 and 5).

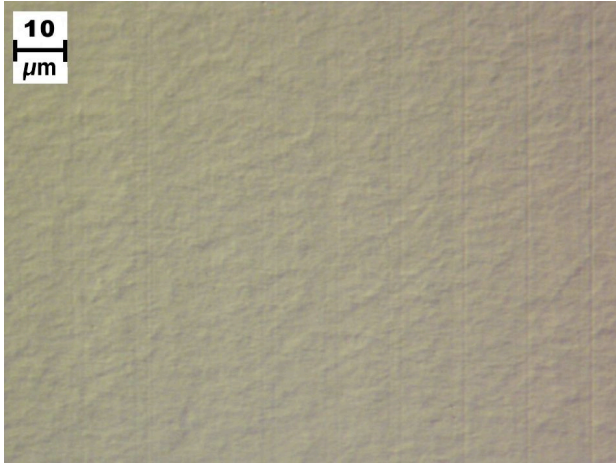


Fig. 4. Optical micrograph of the diamond-turned mirror specimen.

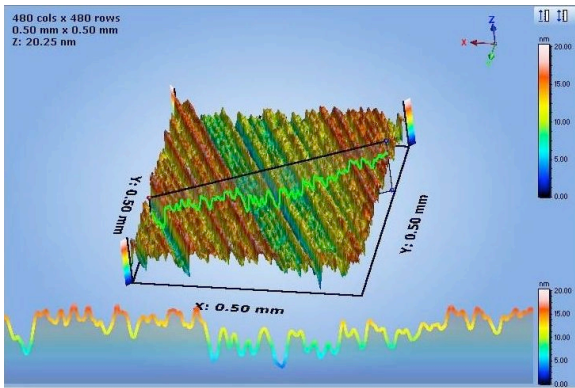


Fig. 5. Surface profile of the diamond-turned mirror specimen.

2.3 Long pulse beam

The natural laser emission from a Lambda Physik LPXPro 210 with a KrF gas fill (248 nm) and unstable resonator setup was used for long pulse testing. The LPXPro yields a ~ 25 ns pulse width (see Fig. 6) and produces a beam with approximately 0.1 mrad of divergence with the unstable resonator optics. The maximum energy output of the LPXPro is near 700 mJ, but 300 to 500 mJ was the typical range for long pulse testing.

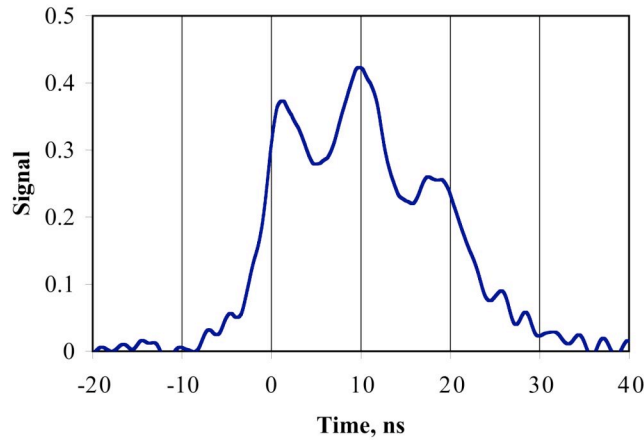


Fig. 6. Temporal profile of LPXPro beam

2.4 Short pulse beam

A Pockels cell selected part of the 25 ns excimer pulse to produce a ~ 5 ns IFE prototypic pulse. Unacceptable energy losses in the Pockels cell crystal prevented us from obtaining a short pulse beam directly from the high energy LPXPro. Thus, two KrF excimer lasers were used in an oscillator-amplifier configuration so that a short pulse could first be obtained from a lower energy source (a Lambda Physik COMPEX 201) and subsequently amplified by the LPXPro⁶. The COMPEX produces a 25 ns beam similar to the LPXPro, with the main differences being lower energy output (400 mJ maximum) and about half the cross sectional beam area. The front end COMPEX beam was polarized with cube beamsplitters, pulse sliced by the Pockels cell, and amplified by passing through the LPXPro with the resonator optics removed (see Fig. 7). A timing generator coordinated the firing of the two lasers to achieve the short pulse profile shown in Fig. 8. Nominal amplified short pulse beam energy was 100 mJ with the spatial profile shown in Fig. 9.

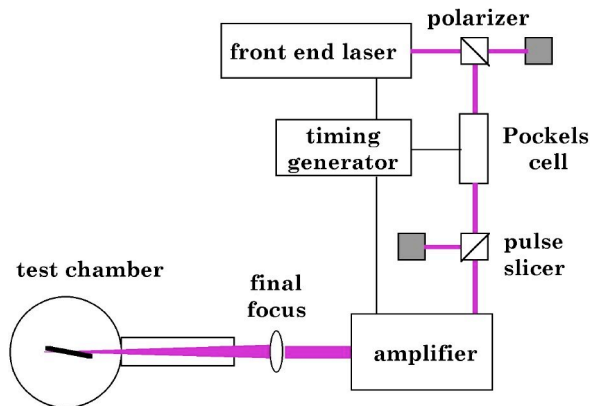


Fig. 7. Short pulse beam obtained via amplification of a pulse-sliced front end laser

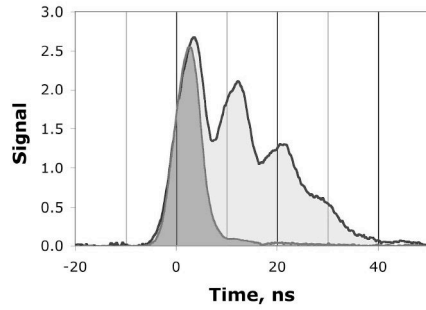


Fig. 8. Temporal profile of the front end laser with and without pulse slicing

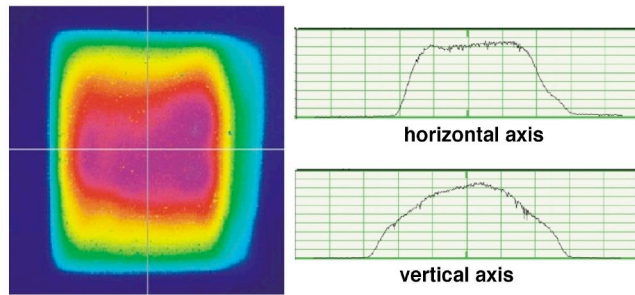


Fig. 9. Spatial profile of amplified short pulse

3. RESULTS

3.1 Long pulse damage fluence curve

The response of the mirror surface to laser energy absorption is analogous to mechanical fatigue and can be represented by a damage fluence curve that is similar to a classical stress-life curve. Laser energy absorption occurs in a shallow zone near the surface creating abrupt thermal and stress gradients that differ from classical bulk metal fatigue. Even so, by varying the fluence over a range of damage tests, a curve can be plotted that resembles a classical fatigue curve.

A mirror is exposed one location at a time with a given laser fluence until damage occurs. Damage is defined when surface defects result in a measurable roughness. Defects accumulate more rapidly as the scale length of defects approaches a considerable fraction of the laser beam wavelength, leading to increased energy absorption and finally melting. The surface roughness can be measured indirectly by viewing the brightness of the exposure site with a machine vision camera. It is preferred to terminate a test before melting occurs, but after some amount of surface roughening is visible under magnification. The camera brightness corresponding to the initial stage of damage is learned from experience, but once set, can be applied to all tests on a mirror specimen. In this way, consistent damage across all test locations yields an accurate damage fluence curve. Figure 10 is a micrograph of one test location on the specimen at 400X magnification showing typical surface roughening due to high-cycle damage. Figure 11 shows the fluence curve resulting from long pulse exposure at eight different locations on the test specimen.

3.2 Short pulse prediction

Thermal diffusion predicts that a shorter pulse length results in a higher peak surface temperature with the same total energy in the pulse. To reach the same peak temperature, Fig. 12 shows that the long-pulse COMPEX requires approximately twice the total pulse energy as the short pulse. The curve labeled “Schmitt” represents the thermal response from a prototypical laser-IFE temporal pulse shape, which matches very well with our sliced pulse response⁷. We assumed that peak temperature and stress dominated damage response and would scale like $\tau^{1/2}$. Therefore, by simply scaling fluence to match peak surface temperature and, therefore, peak thermal stress, we estimated that short pulse damage would occur at 50% lower fluence than for long pulse damage. The dashed line in Fig. 13 is the predicted short-pulse damage fluence curve.



Fig. 10. Typical high-cycle damage (400X)

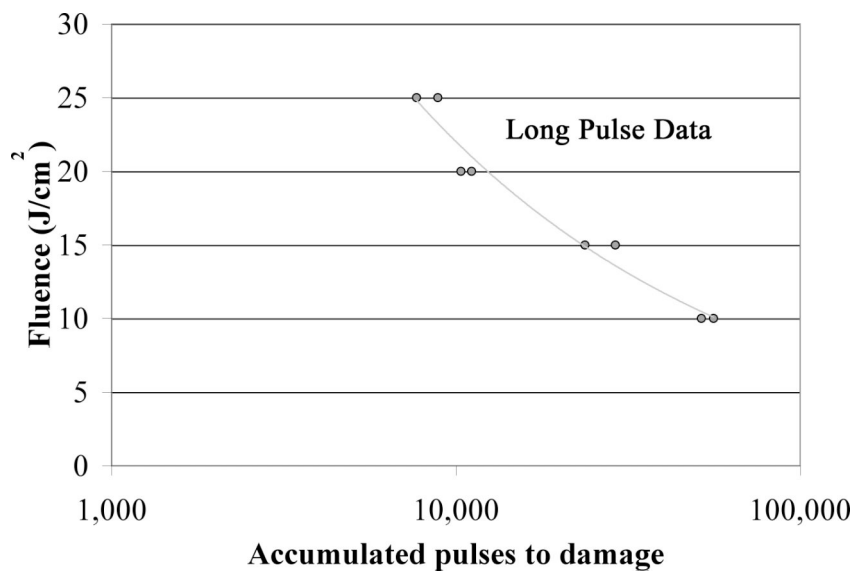


Fig. 11. Long pulse damage fluence data

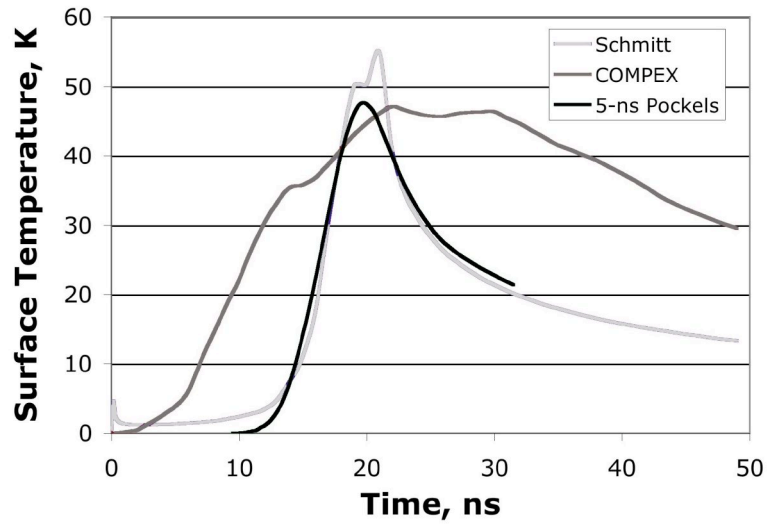


Fig. 12. Peak surface temperature due to different pulse widths; long-pulse COMPEX shown with 2X energy

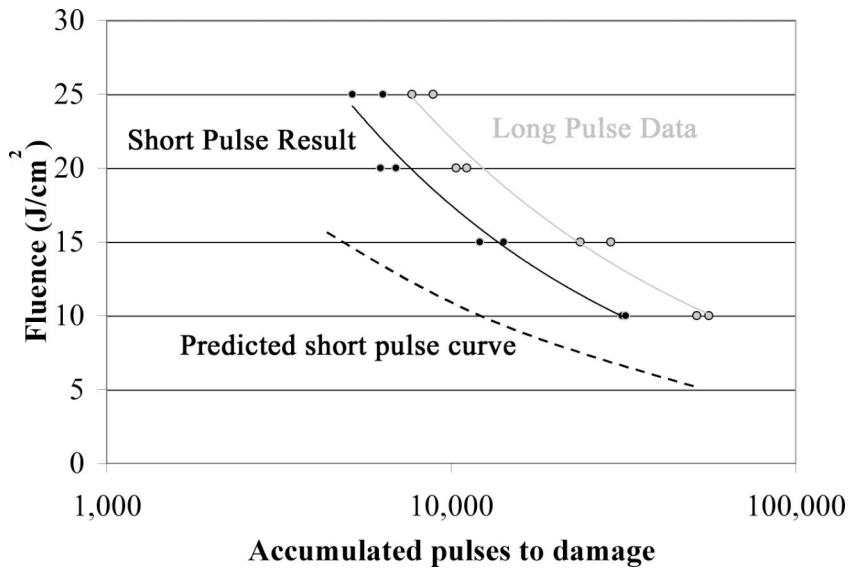


Fig. 13. Short pulse damage fluence data with prediction based on thermal diffusion

3.3 Short pulse damage fluence

After making the prediction for short pulse damage, eight more test locations were exposed to create a short pulse damage fluence curve. Short-pulse induced damage occurs at 23% less fluence than long-pulse induced damage, not the expected 50% less fluence. Therefore, damage does not scale with $\tau^{1/2}$ as expected. The short pulse damage fluence curve is the middle curve in Fig. 13.

4. CONCLUSION

Laser-induced damage to metal mirrors is primarily a thermo-mechanical process leading to micro-structural evolution analogous to fatigue. Each laser pulse creates a steep thermal gradient that results in a momentary stress at the mirror

surface. Given a fixed total laser energy, shorter pulses produce a steeper thermal gradient and higher surface temperature than longer pulses.

Our experimental result indicates that scaling fluence with respect to the peak surface temperature, and therefore peak stress, is too conservative an estimate to predict short pulse damage from existing long pulse experimental data. The result is evidence that damage to metal mirrors is likely a cumulative process where the total time above some minimum temperature and stress must be considered in addition to the peak temperature and stress.

Spatial beam profile variations may have also affected the damage fluence results. The amplified short pulse has a smoother spatial profile than the non-amplified high energy long pulse. Further experiments are being performed with a beam homogenizer to eliminate spatial profile variations and possible uncertainties related to those variations.

ACKNOWLEDGMENT

Financial support for this work was provided by the Naval Research Laboratory under contract number N00173-06-1-G903.

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