CUMULATIVE DAMAGE OF ULTRAFAST LASER PULSES

A. Hanuka[1,2,*], L. Schächter[1], K. P. Wootton[2], Z. Wu[2], K. Soong[2], I. V. Makasyuk[2], R. J. England[2],
[1]Technion–Israel Institute of Technology, Haifa 32000, Israel
[2]SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract

We present preliminary experimental results indicating that damage threshold fluence (DTF) for fused silica changes with the number of femtosecond laser (10Hz 600Hz, 65±5 fs, 800nm) shots. Based on the experimental data we were able to develop a model which indicates that the change in DTF varies with number of shots logarithmically ($\ln^p$) up to a critical value. Above this value, DTF approaches an asymptotic value. Both DTF for a single shot and the asymptotic value as well as the critical value where this happens are extrinsic parameters dependent on the configuration (repetition rate, pressure and geometry near or at the surface). Indications are that the power of this dependence (p) is an intrinsic parameter independent of the configuration.

BACKGROUND

Dielectric laser-driven accelerators (DLA) have the potential to revolutionize particle accelerators [1] due to one major advantage of dielectric structures regarding their ability to sustain accelerating gradients higher than their RF counterparts [2]. This advantage is facilitated by the high intensities available with today's lasers. In fact the limitation is not the available power, but rather the feasibility of the dielectric structure to sustain such intensity. Moreover, special attention needs to be exercised when comparing the various features at a single pulse or at low or high repetition rate. The latter operation, without damage to the dielectric structure is strictly necessary either for high energy physics applications [3], medical therapy [4] or for fabrication of precise micro-structures [5].

A convenient measure of comparison is the damage threshold fluence (DTF), being defined as the energy per unit surface that the material can sustain without irreversible effect on its optical properties. For good dielectrics e.g. Silica (SiO_2) and *single* pulse operation, the typical value is a few J/cm^2 for a sub-picoseconds long pulse. In case of exposure of the same spot to *multiple* shots, several experiments showed that the fluence is lowered [6]. This effect, known as *incubation,* was mostly investigated with *metals* for durations which vary between nanoseconds and femtoseconds. However, only a few authors considered incubation due to sub-picosecond pulses in *dielectrics* [7–9], especially Silica as it is an attractive material for DLA's [10].

When comparing the experimental accumulation dependence from different studies one needs to keep in mind that, except the various configurations examined (laser wavelength, pulse duration and pressure), the damage criterion as well as the exposure method differ from one study to another. Special attention needs to be exercised to the latter two. First, with regards to the damage criterion, DTF was mostly determined ex situ by extrapolating the *visible* geometrical damage observed using optical Nomarski microscope [11] or Scanning Electron Microscope (SEM) [12]. However, an online detection system is required in order to measure an accumulative process in real time. Second, with regards to the exposure method, most studies rely on exposing the sample to a *fixed* number of laser shots – either of increasing energy levels [13] or a fixed energy level per pulse [9] – within the same measurement. Obviously, the accumulation process will differ from one method to another. What we conceive to be the proper way to measure a time-dependent process, is to accumulate pulses *over time* while the energy per pulse is fixed. The DTF of the latter technique will be different as compared to the former two.

In the present Letter we demonstrate that the damage threshold fluence drops with the increasing number of pulses. Damage is detected in a *real-time* "pump-probe" setup. The accumulative effect on the threshold fluence of Silica's wafer is investigated in various configurations: vacuum (0.4 mTorr) and STP, at two repetition rates (10 or 600 Hz). Although the connection to underlying deterministic theories is not yet understood, we suggest a different phenomenological model where all the experimental data can be described in terms of four parameters: three extrinsic that account for the various conditions mentioned above and one intrinsic which is globally defined and it is a characteristic of the material.

EXPERIMENTAL SETUP

The back-bone of the experiment consists of a "pump-probe" measurement whereby a linear-polarized CW helium-neon (HeNe) probe laser was focused on the same spot as the pump infrared pulses (IR). Damage to the sample was manifested as a distortion to the sample's surface, and was inferred by monitoring the variations in the HeNe intensity. A schematic of the experiment is shown in Fig. 1.

The pump IR pulses generated by a Ti:sapphire laser (10Hz/ 600Hz, 800nm) were compressed to a pulse duration of $\tau_p = 65 \pm 5$ fs (FWHM) which was measured using a frequency resolved optical grating (FROG) technique [14]. After the compressor, the IR pulse intensity was adjusted with a motorized neutral density (ND) filter, and a motorized flipper was used to block or pass the IR laser. Downstream the flipper, the P-polarization was picked by a Polarizing Beam-Splitter (PBS) cube. A pellicle beam sampler directed a small fraction of the pulse energy into an off-axis parabolic mirror which focused the pulse to a pickoff silicon photodetector. Prior to each set of measurements, this detector

* Adiha@tx.technion.ac.il

ISBN 978-3-95450-147-2

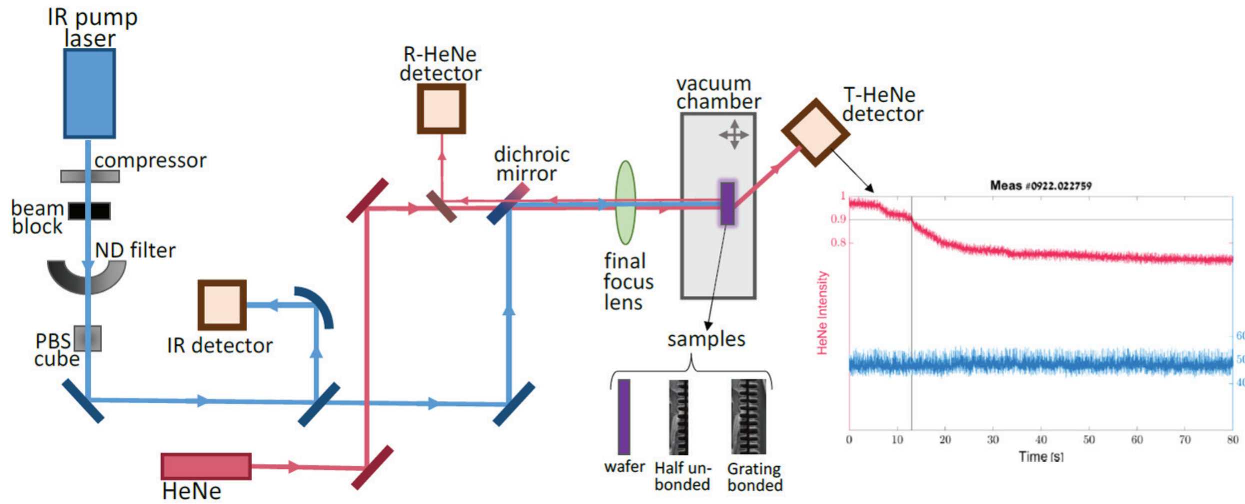

Figure 1: (color online) Schematic of the damage threshold measurement experiment. In the sub-caption there is a sample event for IR energy of 50±5 μJ where damage occurred after about 13 seconds ($\sim 10^3$ pulses). The blue line shows a trace of the acquired IR pulse energy, and the red line shows the normalized R-HeNe or T-HeNe power.

was calibrated against an Ophir energy-meter placed at the interaction point.

Downstream the energy calibration detector, the IR beam was directed by a mirror to a dichroic mirror which reflects it, but transmits the co-aligned HeNe beam. To minimize dispersion both pump and probe lasers were focused by a 80mm CaF_2 lens. The beams were perpendicularly incident on a sample which was mounted inside a (vacuum) chamber. The latter placed on a motorized two-axis stage. The reflected probe laser (R-HeNe) from the sample's surface was monitored for wafer measurements, and the second harmonic of the transmitted probe laser (T-HeNe) was monitored for grating structures. In both cases the probe laser was monitored by a shielded silicon photo-detector with a 632±10nm band pass filter to ensure no IR pulses were picked by the R-HeNe or T-HeNe detector. The transverse spot size of the laser beams was measured in the sample's plane using knife-edge scans in the horizontal and vertical dimensions.

The silica sample is a thin *plain* bulk, and the laser was focused on the sample's plain surface. For each sample, we tested hundreds of sites in which laser fluence was varied from site-to-site. At each test site we held a fixed laser fluence per pulse and laser pulses were accumulated until damage was detected. Damage criterion was adopted to be as 10% change in the HeNe's intensity, which is well above the noise level of the measurement. A sample event is plotted in sub-caption of Fig. 1. We notice that the T-HeNe decrease when damage occurs after 15 seconds. Indeed, we observed the damaged site using a CCD camera.

RESULTS

To guarantee that the accumulative process of multiple laser pulses is accurately captured, we repeat the damage experiment for a fixed laser fluence several (7-10) times. We exclude in our analysis sites where the IR energy fluctuated, and a single pulse peaked above the noise level. In these cases not the accumulated pulses but the peaked single pulse caused immediate damage. Additionally, to ensure the integrity of the experimental data, we analyze each sample with an optical microscope after the damage test, and confirm that the sites registered as damaged in the measurement show visible damage under microscopy. Finally, we note that our reported DTF values correspond to peak laser fluence, which is calculated using

$$F_{\text{th}} = \frac{2U_{\text{th}}}{\pi w_x w_y} \quad (1)$$

where U_{th} is the laser pulse energy and w_x, w_y is the rms Gaussian diameter.

Figure 2 shows the measured number of pulses (n_{sh}) that the material was exposed to when damage occurred for a preset fluence in various operating conditions (sample, vacuum/air and repetition rate). Repetition rate of 10 Hz was used for low number of shots ($n_{\text{sh}} < 10^3$) measurements, while for longer ones, we used a 600 Hz repetition rate. With this range of repetition rates in the fs regime, the fluence has weak dependance on the repetition rate [15]. In spite of this limitation, the trend for all is clear: higher DTF where damage occurs for low number of shots and conversely a lower DTF where damage occurs for high number of shots.

Silica wafer in *air* has higher threshold than in vacuum. This is consistent with previous experiments [7] which showed that multishot damage in vacuum for silica is lower since the Si-O bonds break in vacuum [16].

DISCUSSION

Analysis of the experimental data indicates that the DTF decreases with the increase in the accumulated number of

ISBN 978-3-95450-147-2

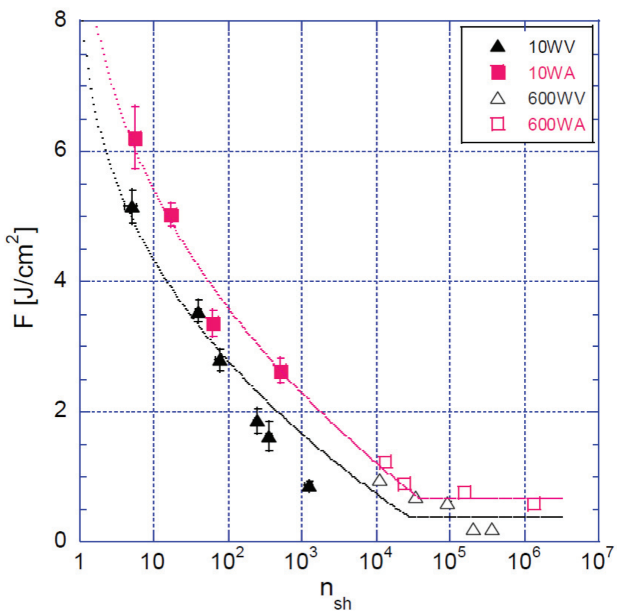

Figure 2: (color online) Measured number of pulses for 10 and 600 Hz measurements on the silica's wafer wafer in air and vacuum (A/V).

shots n_{sh} and it follows the equation

$$F_{th}(n_{sh}) = \begin{cases} F_1 - \Delta F(\ln n_{sh})^p & n_{sh} \le n_{cr} \\ F_\infty & n_{sh} \ge n_{cr} \end{cases} \quad (2)$$

where F_1 is the DTF for a *single* shot, ΔF represents the slope of the dependence on the number of shots, and $n_{cr} = \exp\left\{[(F_1 - F_\infty)/\Delta F]^{\frac{1}{p}}\right\}$ is the critical number of shots for which the fluence reaches its asymptotic value F_∞. While our analysis indicates that F_1, ΔF, F_∞ are *extrinsic* parameters dependent on the operating conditions (repetition rate, sample's configuration and environment), the power p is an *intrinsic* variable independent of the experimental conditions.

The proposed model differs from other similar models [6, 17] in that it assumes a logarithmic rather than power-law dependence $F_{th} = F_\infty - (F_\infty - F_1)\, n_{sh}{}^{\xi-1}$ where ξ is an incubation coefficient. The latter is similar to the parameter p introduced by Eq. 2, which therefore appears to be intrinsic. However our model better fits the experimental data compared to the power-law model with errors of 0.5% and 5% respectively. We find the power p to vary in the range 0.4 ± 0.07, and typical values of F_∞ were found in the range between 0.5 - 0.7 J/cm^2, and n_{cr} in the range $3 \cdot 10^4 - 1 \cdot 10^5$ pulses.

CONCLUSION

In conclusion, damage threshold fluence (DTF) for fused silica changes with the accumulated number of femtosecond laser shots. Based on the experimental data we were able to develop a model which indicates that the change in DTF varies with the number of shots like $(\ln n_{sh})^p$ up to a critical value ($n_{sh} \le n_{cr}$). Above this value, DTF reaches an asymptotic value. Both DTF for a single shot (F_1), the asymptotic value F_∞ and the critical value where this happens $n_{sh} = n_{cr}$ are extrinsic parameters dependent on the configuration (repetition rate, pressure and geometry near or at the surface). The results provide some evidence that the power of this dependence (p) is independent of the experimental conditions that were systematically varied in this experiment. However, it may have dependence upon other experimental conditions that were not varied, such as laser wavelength, material composition, or surface preparation. Current models cannot explain the experimental data, specifically damage accumulation over pulse separation in excess of milliseconds.

ACKNOWLEDGEMENT

This work was supported by the U.S. Department of Energy under Contracts DE-AC02-76SF00515 (SLAC) and Israel Science Foundation. The authors acknowledge J. Spencer for helpful discussions, A. Ceballos for providing the wafer samples, E. Peralta for fabricating the grating samples, and K. Leedle for building the vacuum chamber.

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