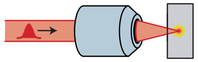
FEMTOSECOND LASER-INDUCED MICROEXPLOSIONS

Chris B. Schaffer, Nozomi Nishimura, and Eric Mazur
Harvard University, Department of Physics, Cambridge, MA 02138

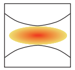
Introduction



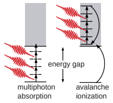
Femtosecond laser pulses are tightly focused inside a transparent sample.

These pulses produce a highly-excited plasma that is confined to a micrometer-sized region. This tight confinement of extreme conditions is the hallmark of our work.

Due to the short pulsewidth and tight focusing, the intensity in the focal volume is in excess of 10^{14} W/cm^2. The laser can be focused beneath the surface of the material, so this high intensity can be concentrated in the bulk, rather than at the surface.

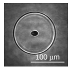


intensity at laser focus

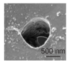


The high intensity leads to absorption of the laser energy through non-linear processes. The result is a micrometer-sized, highly-excited plasma, trapped inside the material.

The hot plasma rapidly expands into the surrounding material, producing a microscopic explosion — a microexplosion. See the Microexplosion Dynamics section.



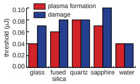
pressure wave in water at 35 ns



microstructure in sapphire

In solid materials, a microexplosion leaves behind a sub-micron-sized region of permanent damage — a microstructure. See the Microstructures section.

The threshold for producing a microexplosion are remarkably similar for a wide variety of transparent materials. See the Thresholds section.



laser-induced microexplosion thresholds

see also:
http://mazur-www.harvard.edu

Acknowledgments

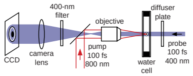
We thank Eli N. Glezer and André Brodeur for help with the experiments. This work was supported, in part, by MRSEC seed funding from the National Science Foundation.

Microexplosion Dynamics

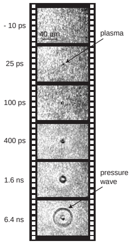
Using time-resolved imaging and scattering measurements, we monitor the evolution of a microexplosion following excitation.

Time-resolved imaging

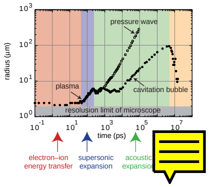
setup



images



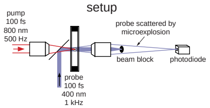
microexplosion radius



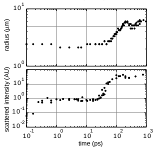
Ask to see the movie!

Time-resolved scattering

setup



early-time imaged radius and scattering signal



scattering = scattering coefficient × cross-sectional area
~ plasma density and plasma size

the similarity of the radius vs. time and scattering vs. time data suggests the scattered intensity is determined primarily by the plasma size

Results

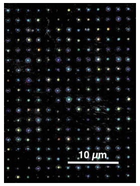
- the rapid expansion velocity (> 30 km/s) from 20 ps to 200 ps indicates high temperature and pressure characterize the plasma
- after reaching a radius of 7 µm, all subsequent dynamics are acoustic or slower
- **extreme conditions confined to micrometer scales**

Microstructures

Using optical and electron microscopy, we examine the damage structures produced by microexplosions in bulk materials.

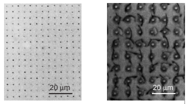
Optical microscopy

microstructure array



100 fs, 0.3 µJ, 0.65 NA, fused silica

100-fs vs. 200-ps pulses

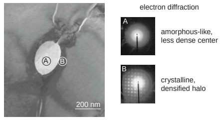


100 fs
small structures, no cracks

200 ps
larger structures, cracks

Electron microscopy

transmission electron microscopy

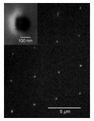


amorphous-like, less dense center

crystalline, densified halo

100 fs, 2 µJ, 0.65 NA, sapphire

scanning electron microscopy



100 fs, 0.3 µJ, 0.65 NA, fused silica

Results

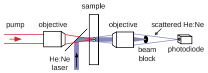
- microstructures with a 150-nm diameter have been produced
  — self-focusing reduces the beam waist at the focus
- large Δn (> 5%) between damaged and undamaged material

Thresholds

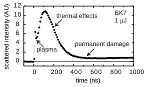
Using scattering techniques in solids and acoustic detection in water, we measure the microexplosion threshold in a variety of materials.

Solid samples

setup

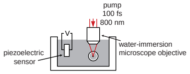


scattered He:Ne

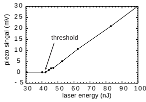


Water

setup



piezoelectric measurement



Results

thresholds for 100-fs and 200-ps pulses

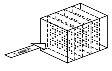
material	100 fs plasma formation (µJ)	100 fs permanent damage (µJ)	200 ps plasma formation (µJ)	200 ps permanent damage (µJ)
glass (BK7)	0.04	0.07	0.9	1.2
fused silica	0.06	0.08	1.7	1.8
quartz	0.08	0.08	2.9	2.9
sapphire	0.07	0.1	1/N	1/N
water	0.04	N/A	2.0	N/A

- 100-fs thresholds similar for many different materials.
- plasma and permanent damage produced well below the threshold for the changes described in the Microstructures section.

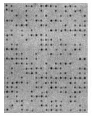
Applications

In applications we make use of the micrometer-scale confinement of extreme conditions. Examples are three-dimensional microstructuring and laser surgery.

three-dimensional binary data storage



- small damage size, localized in three dimensions means high data density
- high contrast means fast, easy, parallel readout

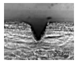


2-µm spaced binary data pattern
100-fs, 0.5-µJ pulses

photodisruptive microsurgery

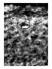
histology of damage in a human skin model

surface incision



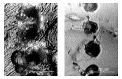
100 fs, 4 µJ

sub-surface damage



100 fs, 20 µJ

surface ablation: 200 ps and 100 fs



200 ps, 40 µJ

100 fs, 40 µJ

- femtosecond pulses produce less collateral effects than longer pulses
- we have demonstrated damage 600 µm beneath the surface in pig skin

http://mazur-www.harvard.edu