Laser-Induced Microexplosions:
creating stellar conditions on an optical bench

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Introduction
Introduction

- microstructuring of transparent materials
Introduction

- microstructuring of transparent materials
- laser surgery
Introduction

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- laser surgery
- electronic and structural transitions
Introduction

- microstructuring of transparent materials
- laser surgery
- electronic and structural transitions
- laser assisted chemistry
Introduction
Introduction

focus laser beam inside material...

100 fs

transparent material

objective
Introduction

high intensity at focus…

100 fs

objective
transparent material
... causes nonlinear ionization...
Introduction

and microscopic bulk damage
Introduction

laser field ionization

multiphoton...
Introduction

laser field ionization

...or tunneling
Introduction

avalanche ionization

free carrier absorption...
Introduction

avalanche ionization

...and impact ionization
Introduction

Damage mechanisms:

- explosive
- thermal
- defect forming
Applications:

- data storage
Introduction

Applications:

- data storage
Introduction

Applications:

- data storage
- photonic devices
Introduction

Applications:

- data storage
- photonic devices
- internal micromachining
Outline

- Damage morphology
- Energy deposition
- Dynamics
Damage morphology

3 µm

40 nJ, 120 fs
0.65 NA
Corning 0211
Damage morphology

3 µm distance (µm)

intensity

0 6 24

0 2 4 6
distance (µm)

top view

250 nm

3 µm

intensity

0 100 200 300
Damage morphology

3 µm

40 nJ, 120 fs
0.65 NA
Corning 0211
Damage morphology

3 µm distance (µm)

side view

intensity

distance (µm)

2 µm
Damage morphology

more shots

more energy

10 µm

100 fs
1.4 NA
Corning 0211
Damage morphology

25,000 shots at 25 MHz
4.5 nJ, <100 fs
1.4 NA
Corning 0211
Damage morphology

Electron Microscopy:
explosive damage
forms voids

100 fs, 500 nJ
0.65 NA
fused silica
## Damage morphology

### Summary of damage mechanisms

<table>
<thead>
<tr>
<th></th>
<th>Single shot</th>
<th>Multiple shot (25 MHz)</th>
</tr>
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<tbody>
<tr>
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### Damage morphology

**Summary of damage mechanisms**

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Outline

- Damage morphology
- Energy deposition
- Dynamics
Energy deposition

Determine threshold for damage:

- Optical microscopy
- Transmission
- Dark field scattering
Energy deposition

optical microscopy
Energy deposition

optical microscopy

6.6 nJ
Energy deposition

transmission of pump beam in fused silica

800 nm, 110 fs
0.65 NA
fused silica

damage critical self-focusing
Energy deposition

Dark-field scattering

objective sample
Energy deposition

block probe beam...

Diagram showing a probe, objective, sample, and detector.
Energy deposition

...bring in pump beam...
...damage scatters probe beam
Energy deposition

- Energy deposition for fused silica with a signal of 1.0 µJ.
Energy deposition

vary numerical aperture in Corning 0211

![Graph showing energy deposition vs numerical aperture.](image)
minimal self focusing, so spot size determined by:

\[
I = \frac{E}{\tau A} = \frac{E}{\tau} (\text{NA})^2
\]

and thus

\[
E = \frac{I\tau}{(\text{NA})^2}
\]
fit gives threshold intensity: $I_{th} = 2.5 \times 10^{17} \text{ W/m}^2$
Energy deposition

<table>
<thead>
<tr>
<th>bandgap (eV)</th>
<th>threshold intensity ($10^{17}$ W/m²)</th>
<th>threshold fluence (kJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
<td></td>
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<tr>
<td>4</td>
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<tr>
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Inset graph:
- Numerical aperture on the x-axis.
- Threshold intensity ($10^{17}$ W/m²) on the y-axis.
- Threshold fluence (kJ/m²) on the right y-axis.

Arrow indicating data point.
Energy deposition

vary material...

- SF11
- 0211
- CaF$_2$
- fused silica

threshold intensity ($10^{17}$ W/m$^2$)

threshold fluence (kJ/m$^2$)

bandgap (eV)
Energy deposition

threshold increases with bandgap...

![Graph showing the relationship between bandgap (eV) and threshold intensity (10^17 W/m^2) for CaF_2, fused silica, 0211, and SF11. The threshold intensity increases with bandgap.](image-url)
Energy deposition

...but not very much
Energy deposition

same trend at 400 nm
Outline

- Damage morphology
- Energy deposition
- Dynamics
Dynamics

imaging setup

sample

objective
Dynamics

imaging setup

sample

objective

pump
Dynamics

imaging setup

sample

objective
Dynamics

imaging setup

probe → sample → objective → CCD
sapphire

3 \mu J pulse

3.8 ns delay

40 \mu m radius
Dynamics

- water ("self-healing")
- 1.0 µJ pulse
- 35 ns delay
- 58 µm radius
Dynamics

![Graph showing the dynamics of sapphire with a radius of 11.4 µm/ns. The graph plots radius (µm) against time (ns). The trend line indicates a linear relationship with a slope of 3 µJ.](image)
Dynamics

**Graph:**
- **X-axis:** Time (ns)
- **Y-axis:** Radius (µm)
- **Label:** water
- **Marker:** 1 µJ
- **Label on graph:** 1.48 µm/ns

Table:
- **Radius (µm):**
  - 500
  - 400
  - 300
  - 200
  - 100
  - 0
- **Time (ns):**
  - 0
  - 1
  - 2
  - 3
  - 4
  - 5

Legend:
- Black square: 1 µJ
**Dynamics**

- Water radius (µm)
  - 100
  - 80
  - 60
  - 40
  - 20
  - 0

- Time (ns)
  - 0
  - 1
  - 2
  - 3
  - 4
  - 5

Graph showing the dynamics of water radius over time with 1 µJ.
Dynamics

water

1 µJ

radius (µm)

0 1 2 3 4 5 6 7 8 9 10

time (ps)

0.1 1 10 100 1000
Dynamics

Time-resolved scattering setup
Dynamics

time-resolved scattering setup

- pump
- objective
- sample
- detector
Dynamics

time-resolved scattering setup
Dynamics

time-resolved scattering setup
Dynamics

time-resolved scattering setup

signal proportional to area of scatterer
Dynamics

radius (µm)

water

1 µJ

0.1 1 10 100 1000

time (ps)
Dynamics

water

1 \mu J

100 \mu m/ns!

radius (\mu m)

time (ps)

100 \mu m/ns!
Conclusions

- submicron-scale bulk micromachining
- weak bandgap and wavelength dependence
- only a few nanojoules required
Laser micromachining simplified

5-nJ threshold: unamplified micromachining
Laser micromachining simplified

5-nJ threshold: unamplified micromachining
Laser micromachining simplified

waveguide machining
Laser micromachining simplified

waveguide machining
Future applications

Photonic devices
Future applications

- Photonic devices
- Wavelength-selective splitter
Future applications

wavelength selective splitter
Future applications

wavelength selective splitter
Future applications

wavelength selective splitter
Future applications

wavelength selective splitter
Future applications

- Photonic devices
- Wavelength-selective splitter
- Photonic bandgap materials
Open questions

- Propagation of pulses
- Mechanisms
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For a copy of this talk and additional information, see:

http://mazur-www.harvard.edu