Laser-induced microexplosions: creating stellar conditions on an optical bench

Chris B. Schaffer
Nozomi Nishimura
André Brodeur
Eric Mazur

Old Dominion University
9 April 1999
Introduction

focus laser beam inside material...

Introduction

High intensity at focus...

... causes nonlinear ionization...

and microscopic bulk damage

Introduction

What are the conditions at focus?

objective

transparent material
Introduction

What are the conditions at focus?

Laser deposits energy in $\sim 1 \mu m^3$
Introduction

What temperature?
What temperature?

$$\Delta E = C_V \rho V \Delta T$$
What temperature?

\[ \Delta E = C_V \rho V \Delta T \]

\[ C_V = 0.75 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1} \]

\[ \rho = 2.2 \times 10^3 \text{ kg/m}^3 \]
What temperature?

\[ \Delta E = C_V \rho V \Delta T \]

\[ C_V = 0.75 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1} \]

\[ \rho = 2.2 \times 10^3 \text{ kg/m}^3 \]

So, 1 \( \mu \text{J} \) in 1 \( \mu \text{m}^3 \) gives

\[ \sim 1,000,000 \text{ K!} \]
Introduction

What pressure?
Introduction

What pressure?

Treat ionized material as an ideal gas:

\[ pV = nRT \]
What pressure?

Treat ionized material as an ideal gas:

\[ pV = nRT \]

Gives

\[ p = 10 \text{ MBar!} \]
So:

<table>
<thead>
<tr>
<th>microexplosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T \approx 1$ MK</td>
</tr>
<tr>
<td>$p \approx 10$ MBar</td>
</tr>
<tr>
<td>$\rho = 2.2 \times 10^3$ kg/m$^3$</td>
</tr>
</tbody>
</table>
### Introduction

So:

<table>
<thead>
<tr>
<th></th>
<th>microexplosion</th>
<th>sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>$\approx 1$ MK</td>
<td>2–15 MK</td>
</tr>
<tr>
<td>$p$</td>
<td>$\approx 10$ MBar</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>$2.2 \times 10^3$ kg/m$^3$</td>
<td>0.15–150 $\times 10^3$ kg/m$^3$</td>
</tr>
</tbody>
</table>
So:

<table>
<thead>
<tr>
<th>microexplosion</th>
<th>sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>$\approx 1 \text{ MK}$</td>
</tr>
<tr>
<td>$p$</td>
<td>$\approx 10 \text{ MBar}$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$2.2 \times 10^3 \text{ kg/m}^3$</td>
</tr>
</tbody>
</table>

creating stellar conditions in lab!
Outline

- Post-mortem analysis
- Energy deposition
- Microexplosion dynamics
Post-mortem analysis

optical microscopy

2 x 2 µm array

fused silica

0.5 µJ, 100 fs, 800 nm

Post-mortem analysis

optical microscopy

2 x 2 µm array

fused silica

0.5 µJ, 100 fs, 800 nm

optical microscopy

2 x 2 µm array

fused silica

0.5 µJ, 100 fs, 800 nm

Post-mortem analysis

optical microscopy

2 x 2 \( \mu \text{m} \) array

fused silica

0.5 \( \mu \text{J} \), 100 fs, 800 nm

Post-mortem analysis

optical microscopy

2 x 2 µm array

fused silica

0.5 µJ, 100 fs, 800 nm

Post-mortem analysis

200 ps

100 fs
Post-mortem analysis

- Optical microscopy
- 10 x 10 µm array
- Fused silica
- 9 µJ, 200 ps, 800 nm
Post-mortem analysis

3 µm

40 nJ, 120 fs
0.65 NA
Corning 0211
Post-mortem analysis

3 µm distance (µm)

Intensity

Top view

250 nm

3 µm
Post-mortem analysis

3 µm

40 nJ, 120 fs
0.65 NA
Corning 0211
Post-mortem analysis

![Image of a laser beam with a side view graph showing intensity vs. distance (µm)]

- Distance: 3 µm
- Intensity
  - 0
  - 100
  - 200
  - 300
- Distance (µm)
  - 0
  - 2
  - 4
  - 6
- Intensity
  - 0
  - 100
  - 200
  - 300

**Side View**

- Length: 2 µm
Post-mortem analysis

SEM:

bumps & pits!
Post-mortem analysis

AFM scans of pits
Post-mortem analysis

AFM scans of bump
Post-mortem analysis

TEM picture

sapphire

200 nm
Post-mortem analysis

electron diffraction: amorphous?
Post-mortem analysis

electron diffraction: crystalline

100 nm
Post-mortem analysis

TEM picture

quartz

400 nm
Post-mortem analysis

electron diffraction: amorphous

100 nm
Post-mortem analysis

electron diffraction: crystalline
Post-mortem analysis

SEM microscopy

200 nm
how little energy produces permanent changes?
Energy deposition

laser field ionization

multiphoton
Energy deposition

laser field ionization

tunneling
Energy deposition

impact ionization
Energy deposition

impact ionization
Energy deposition

Dark-field scattering

objective

sample
Energy deposition

block probe beam...
Energy deposition

...bring in pump beam...
Energy deposition

...damage scatters probe beam
Energy deposition

![Graph showing energy deposition for fused silica with 0.1 µJ of signal in arbitrary units (a.u.) over time (µs).]
Energy deposition

![Graph showing energy deposition over time for fused silica with a peak at 1.0 μJ.](image)
Energy deposition

signal (a.u.)

plasma

fused silica

1.0 µJ

time (µs)
Energy deposition

- Energy deposition time: \( 1.0 \, \text{µJ} \)
- Curve for fused silica
- Signal (a.u.) vs. time (µs)
  - Permanent change
  - Time range: \([-0.2, 0.8]\) µs
  - Signal range: \([0, 3]\) a.u.
Energy deposition

signal (a.u.)

fused silica
1.0 µJ

thermal transient

time (µs)

0 0.2 0.4 0.6 0.8
transmission of pump beam in fused silica
Energy deposition

transmission of pump beam in fused silica

![Graph showing transmission as a function of energy (J)]

- 55 nJ
- Plasma
- Fused silica 800 nm

Energy deposition

Transmission of pump beam in fused silica
transmission of pump beam in fused silica

Energy deposition

78 nJ

no recovery

fused silica
800 nm
transmission of pump beam in fused silica

Energy deposition

visible damage

300 nJ

fused silica
800 nm

transmission

energy (J)

10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4}

0.1 1
Energy deposition

vary numerical aperture in Corning 0211
Energy deposition

fit gives threshold intensity: $I_o = 2.7 \times 10^{17} \text{ W/m}^2$
Energy deposition

other materials...

![Plot showing the relationship between energy deposition and numerical aperture for different materials.](image)
Energy deposition

... give other thresholds
Energy deposition

threshold increases with bandgap

![Graph showing threshold intensity (10^17 W/m^2) vs. bandgap (eV) for various materials: LiF, CaF_2, FS, 0211, BK7, SF11, with a trend indicating that the threshold intensity increases with bandgap.]
Energy deposition

- plasma below damage threshold
- damage with only tens of nanojoules
- weak dependence on bandgap
- no shot-to-shot variation
what happens after the energy is deposited?
Microexplosion dynamics

imaging setup

sample

objective
Microexplosion dynamics

imaging setup
Microexplosion dynamics

imaging setup

sample  objective
Microexplosion dynamics

Imaging setup

probe → sample → objective → CCD
Microexplosion dynamics

sapphire

3 µJ pulse

3.8 ns delay

40 µm radius
Microexplosion dynamics

- Water
- 1.0 µJ pulse
- 35 ns delay
- 58 µm radius
Microexplosion dynamics

- Water
- 14 µJ pulse
- 35 ns delay
- 64 µm radius
Microexplosion dynamics

Graph showing the relationship between time (ns) and radius (µm) for sapphire with an input of 3 µJ. The graph plots a linear relationship with a gradient of 11.4 µm/ns.
Microexplosion dynamics

Water

- 1 μJ

Radius (μm) vs. Time (ns)

- 1.48 μm/ns
Microexplosion dynamics

- **Water**
  - 1 µJ

![Graph showing the relationship between time (ns) and radius (µm) for water.](graph.png)
Microexplosion dynamics

![Graph showing the dynamic radius (µm) over time (ns) for water with different energy inputs]
Microexplosion dynamics

![Graph showing the dynamics of water radius over time for different laser energies: 1 µJ (squares), 10 µJ (triangles), and 30 µJ (circles).]
Microexplosion dynamics

water

1 μJ

radius (μm)

time (ps)

0.1 1 10 100 1000

$10^\text{8}$ $10^\text{6}$ $10^\text{4}$ $10^\text{2}$ $10^\text{0}$
Microexplosion dynamics

radius (µm)

water

1 µJ

time (ps)

0.1 1 10 100 1000

0 2 4 6 8 10
Microexplosion dynamics

water

1 µJ

100 µm/ns!

radius (µm)

0 1 2 3 4 5 6 7 8 9 10

time (ps)

0.1 1 10 100 1000

0.1 1 10 100 1000
Summary

- extreme conditions with only nanojoules
- microstructuring without amplifiers
- view into dynamics
Applications

- data storage (17 GBits/cm$^3$)
- internal microstructuring
- microsurgery
Questions

- stellar conditions?
- material dependence?
- models?
Funding: National Science Foundation

Acknowledgments:
Prof. N. Bloembergen
W. Leigh
Carl Zeiss, Inc

For a copy of this talk and additional information, see:

http://mazur-www.harvard.edu