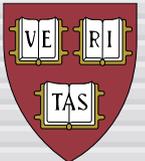


Femtosecond Laser Micromachining: Applications in Biology

**Sam Chung
Raffael Gattass
Iva Maxwell
Jonathan Ashcom
Chris Schaffer
Limin Tong**

**Eli Glezer
Nan Shen
Debjoyoti Datta
Philip LeDuc
Sam Aravi
Donald E. Ingber**



Introduction

Laser-Induced Electric Breakdown in Solids

NICOLAAS BLOEMBERGEN, FELLOW, IEEE

Abstract—A review is given of recent experimental results on laser-induced electric breakdown in transparent optical solid materials. A fundamental breakdown threshold exists characteristic for each material. The threshold is determined by the same physical process as dc breakdown, namely, avalanche ionization. The dependence of the threshold on laser pulse duration and frequency is consistent with this process. The implication of this breakdown mechanism for laser bulk and surface damage to optical components is discussed. It also determines physical properties of self-focused filaments.

I. INTRODUCTION

THE history of laser-induced electric breakdown is almost as old as the history of lasers itself. Early in 1963 Maker *et al.* [1] reported damage to transparent dielectrics and the production of a spark in air by focusing a pulsed ruby laser beam. The importance of these experiments in the production of laser-induced dense

plasmas and for the propagation characteristics of high-power laser beams through solids, liquids, and gases was quickly recognized. The subject of electric breakdown in transparent optical solids, including laser materials, windows, and other optical components, remained, until recently, largely an empirical or engineering science. Although a vast amount of theoretical and experimental effort was expended in the economically and experimentally important problem of optical damage, quantitative reproducible breakdown thresholds with unambiguous theoretical interpretations have been obtained only during the last two years. The situation was somewhat analogous to the development of our understanding of the problem of dc breakdown in electrical insulators. There, too, the field developed largely by engineering trial and error. Basic quantitative understanding was not achieved until reproducible experimental results on well-defined materials were obtained [2]. The difficulties in dc breakdown experiments were manifold: the influence of space charges, the occurrence of heating due to the effects of heating due to a few elec-

Introduction

Laser-Induced Electric Breakdown in Solids

NICOLAAS BLOEMBERGEN, ILLINOIS, U.S.A.

Abstract: A review is given of present experimental results on laser-induced electric breakdown in transparent optical solid materials. A fundamental breakdown threshold exists characteristic for each material. The threshold is determined by the same physical process, as in breakdown, namely, avalanche ionization. The dependence of the threshold on laser pulse intensity and frequency is consistent with this process. The implication of this breakdown mechanism for laser bulk and surface damage components is discussed. It also determines physical properties of self-focused beams.

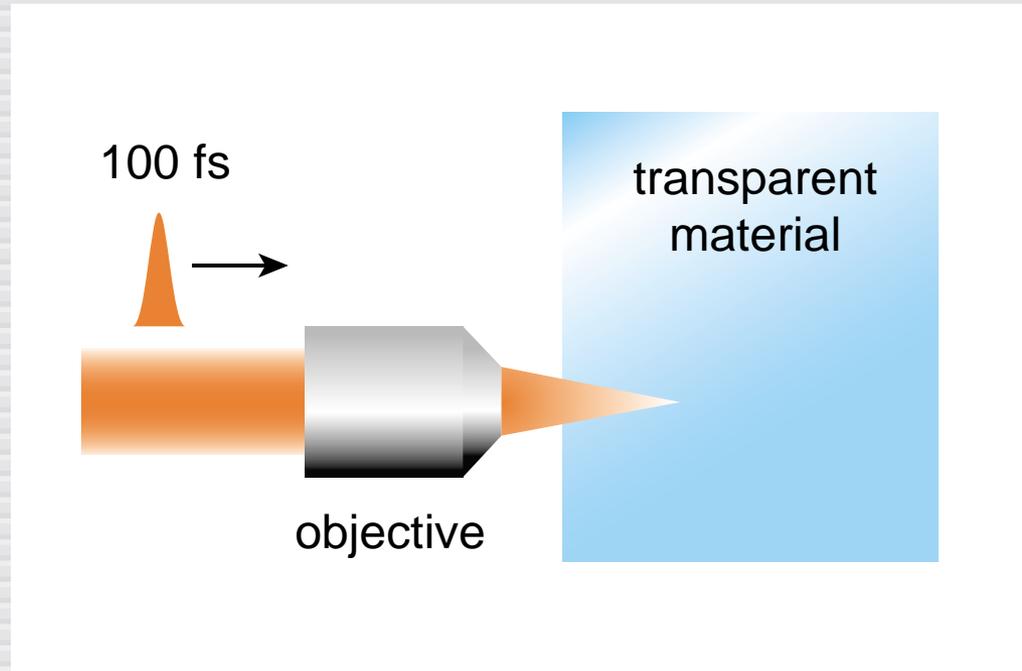
1. INTRODUCTION

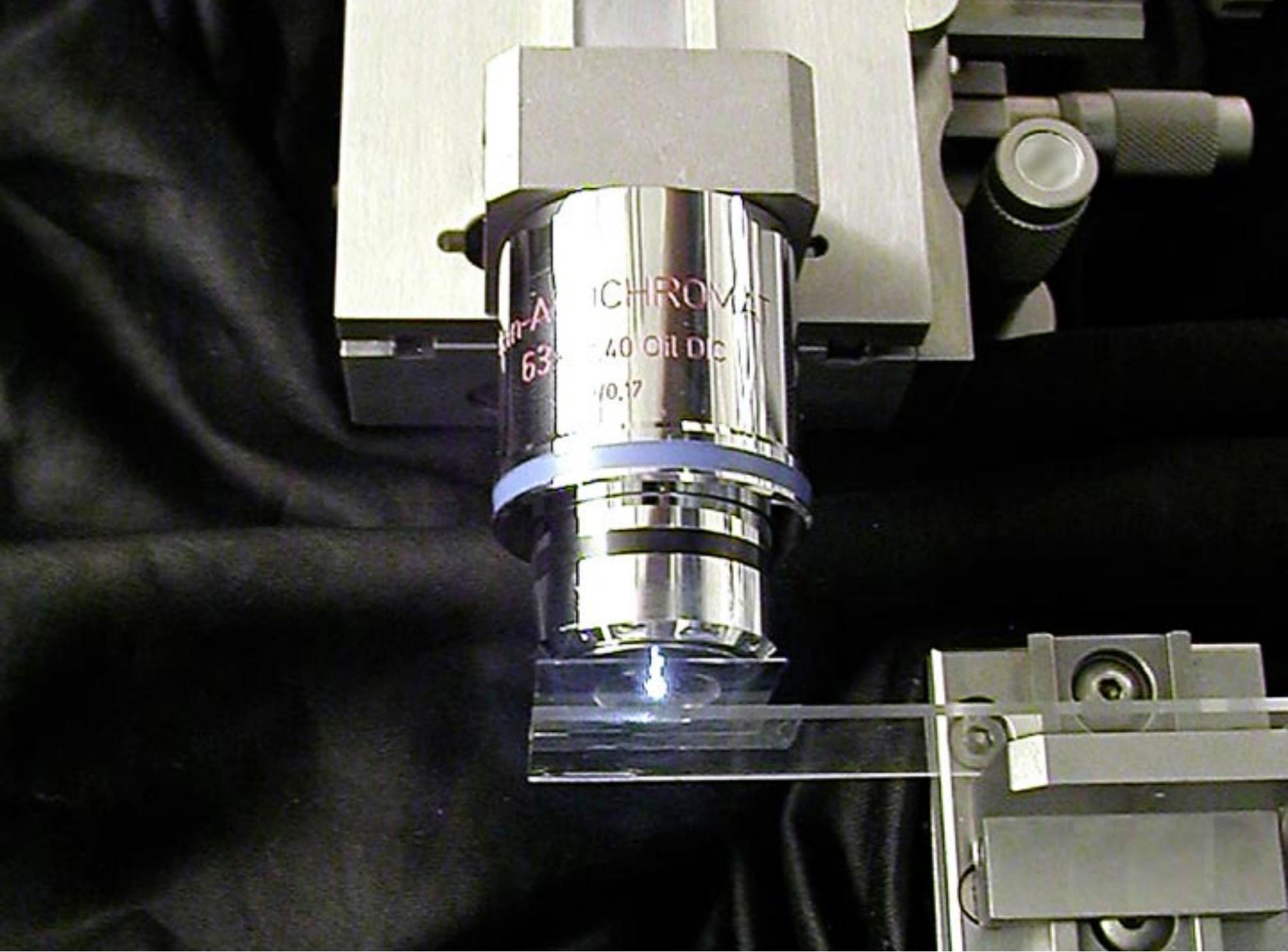
THE history of laser-induced electric breakdown is almost as old as the history of lasers itself. Early in 1963 Mallet et al. reported the production of a spark in an optically transparent dielectric and the production of a striation in an optically transparent solid by laser beams. The importance of these laser-induced electric breakdown processes in the production of laser-induced surface damage

plasmas and for the propagation characteristics of high-power laser beams through solids, liquids, and gases was quickly realized. The subject of electric breakdown in transparent optical solids, including laser materials, was done, and other optical components, remained, and recently, largely an empirical or engineering science. Although a lot of work in theoretical and experimental studies was expended in the economically and technically important problem of optical damage thresholds, reproducibly breakdown thresholds with unambiguous theoretical interpretations have been obtained only during the last two years. The situation was somewhat analogous to the development of our understanding of the problem of dielectric breakdown in electrical insulators. There, too, the breakdown levels by experimental trial and error. Basic quantitative understanding was not achieved until reproducibly experimental results on well-defined materials were obtained [2]. The difficulties in obtaining quantitative experimental results on well-defined materials were manifold: the influence of the breakdown process on the occurrence of space charge, the effects of heating and

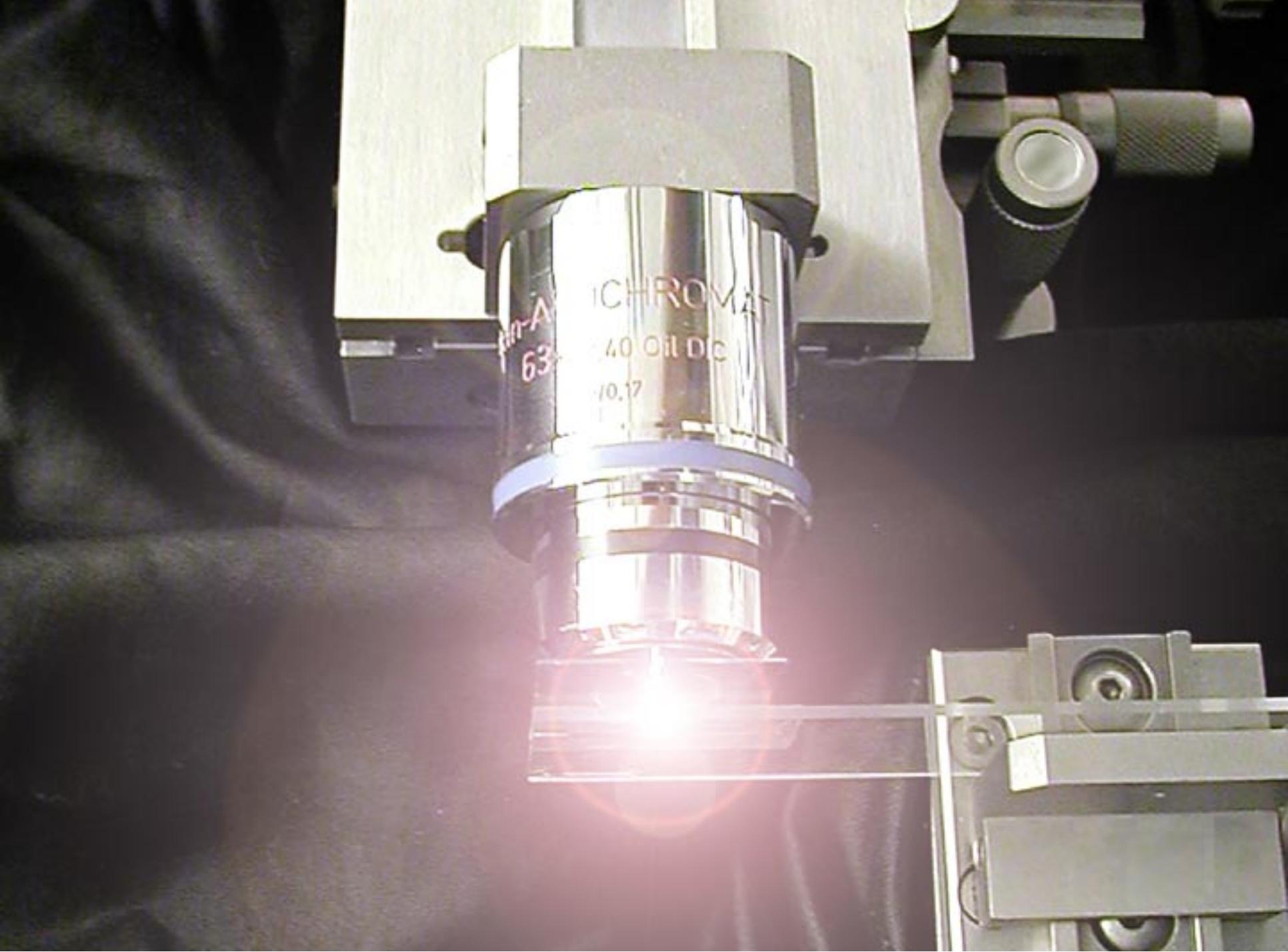
Processing with fs pulses

focus laser beam inside material





Mikro-A
63x
ACHROMAT
40 Oil DC
10.17



10x/0.25
63

ACHROMAT
40 Oil DC
10.17

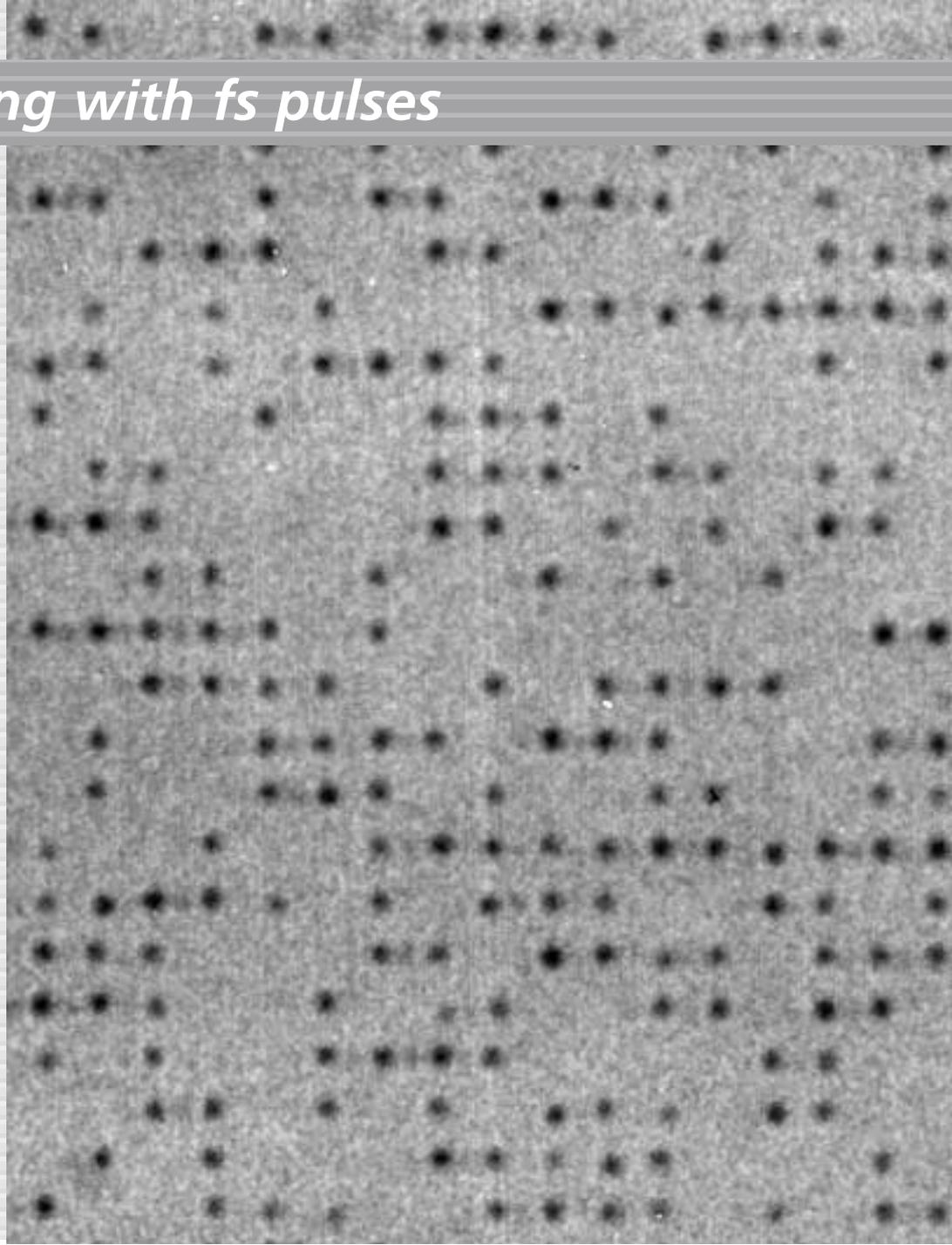
Processing with fs pulses

2 x 2 μm array

fused silica, 0.65 NA

0.5 μJ , 100 fs, 800 nm

***Opt. Lett.* 21, 2023 (1996)**

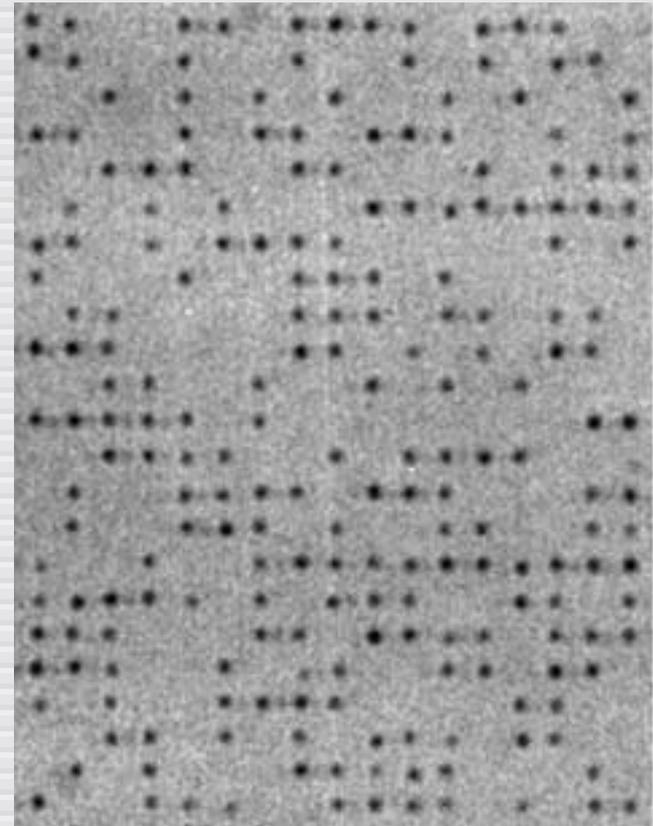


Processing with fs pulses

2 x 2 μm array

fused silica, 0.65 NA

0.5 μJ , 100 fs, 800 nm

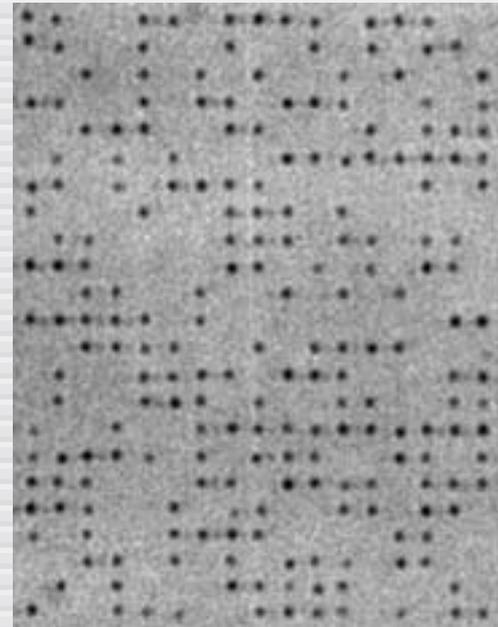


Processing with fs pulses

2 x 2 μm array

fused silica, 0.65 NA

0.5 μJ , 100 fs, 800 nm

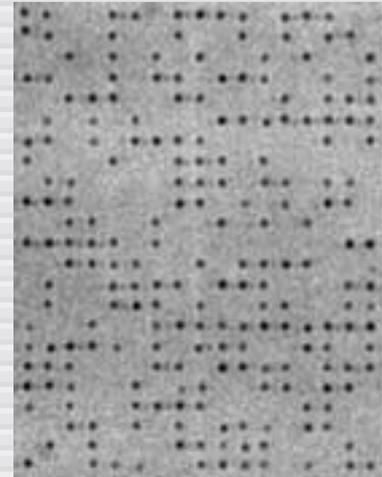


Processing with fs pulses

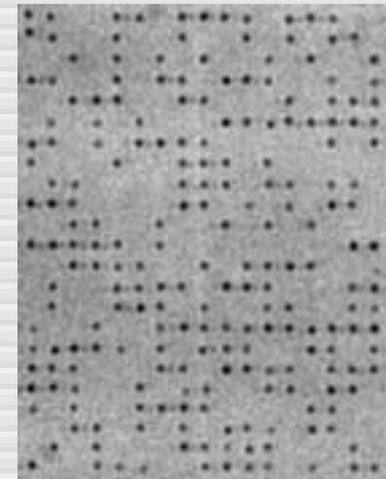
2 x 2 μm array

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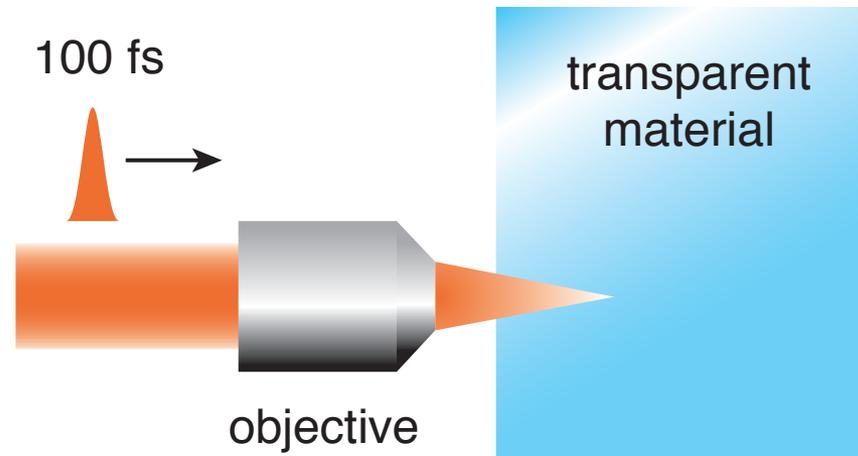
Processing with fs pulses



100 fs
0.5 μ J

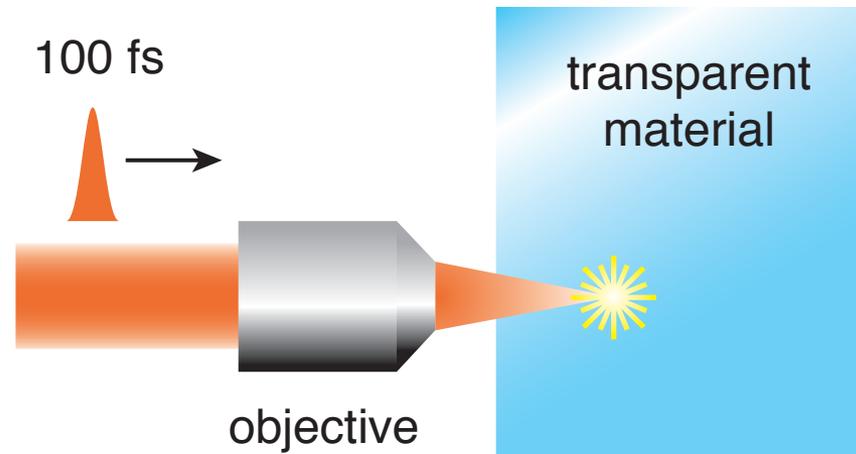
200 ps
9 μ J

Processing with fs pulses



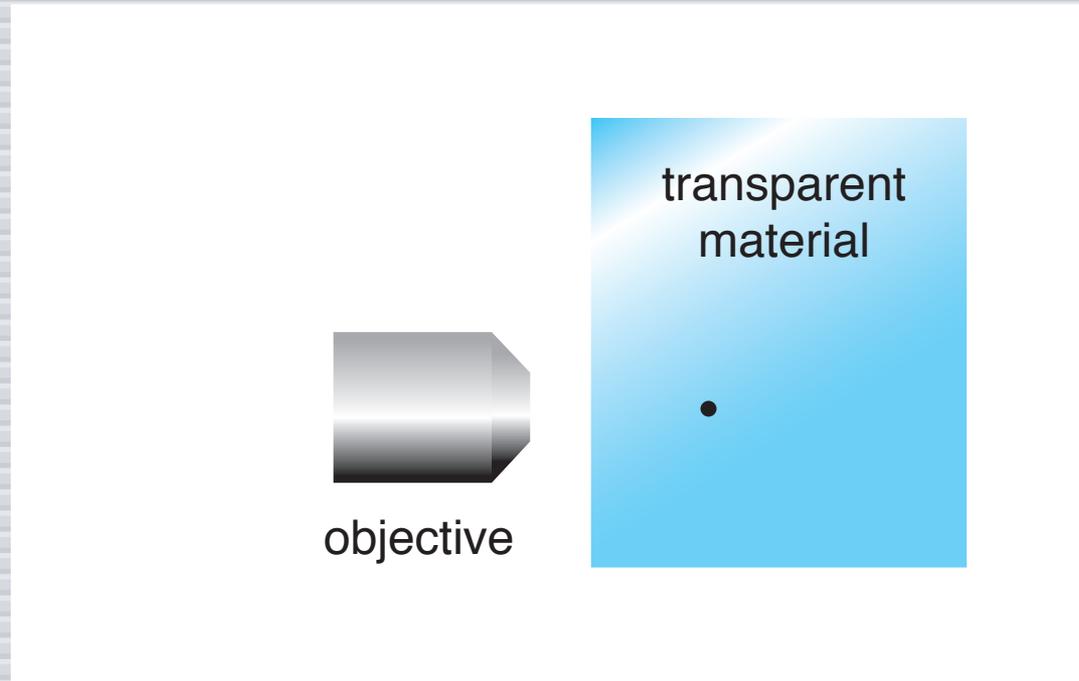
high intensity at focus...

Processing with fs pulses



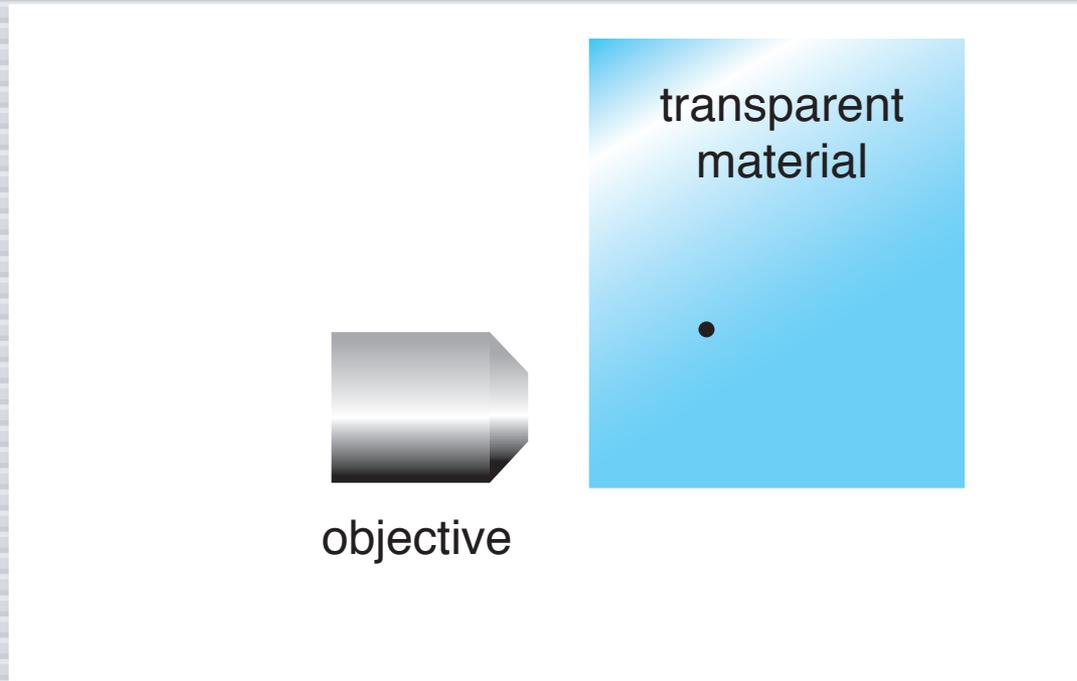
...causes nonlinear ionization...

Processing with fs pulses



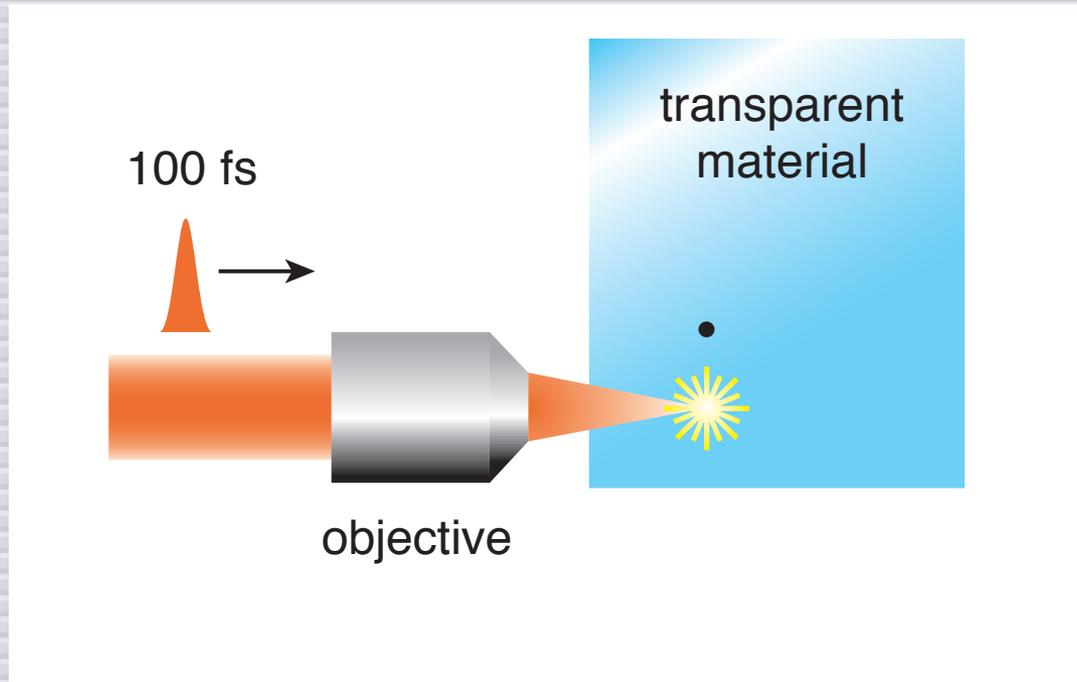
and 'microexplosion' causes microscopic damage

Processing with fs pulses



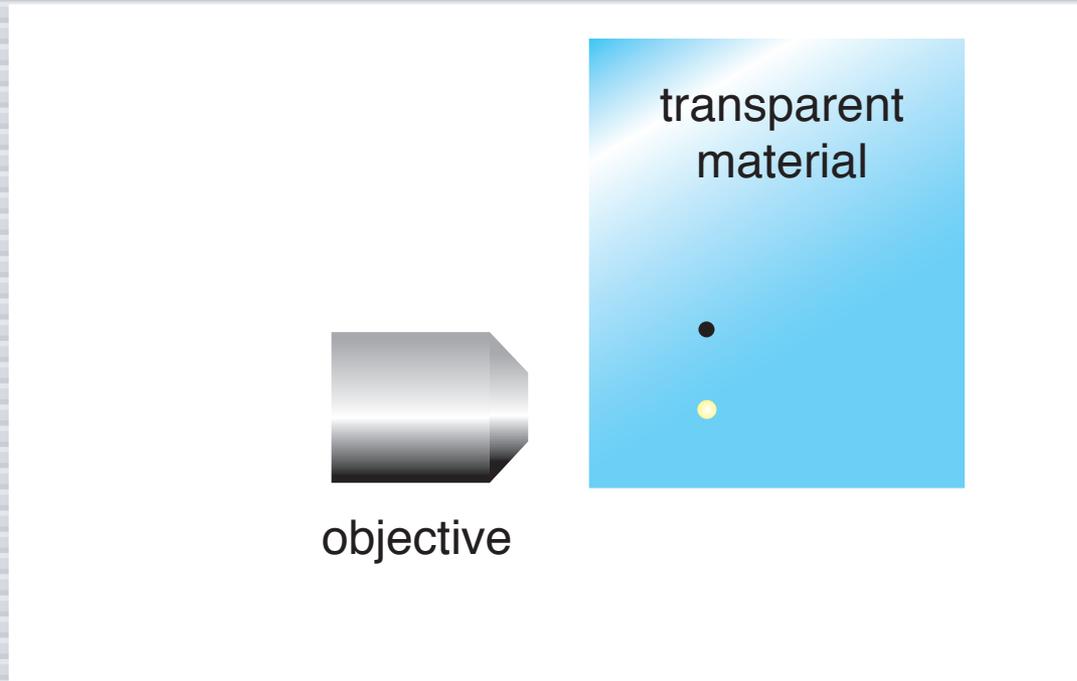
translate sample

Processing with fs pulses



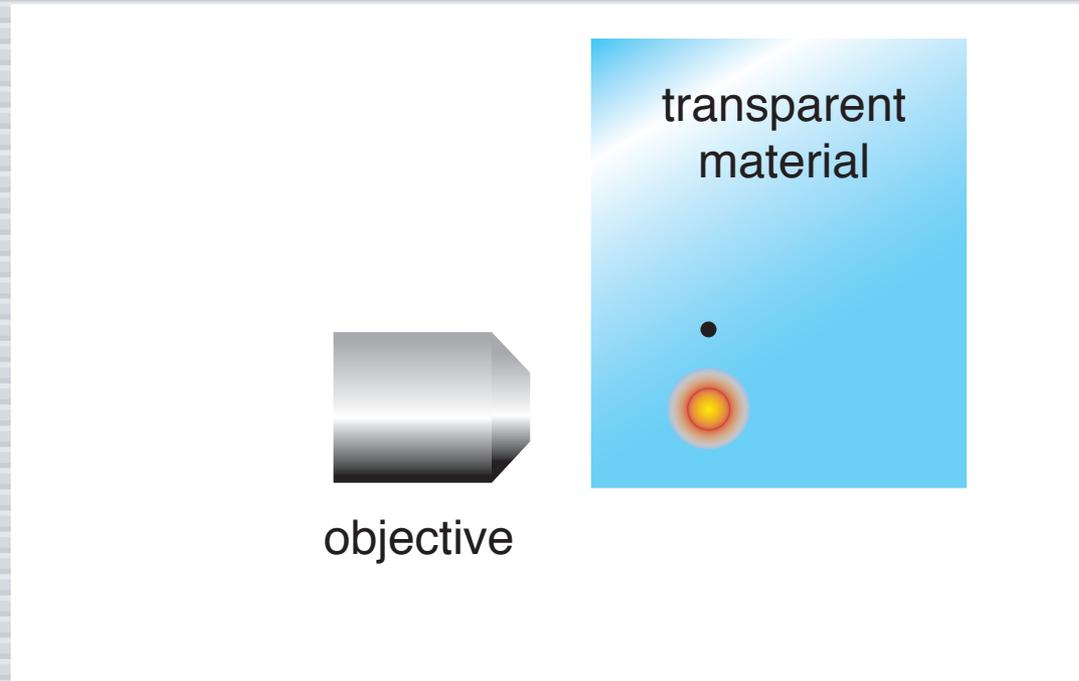
100 fs: laser energy transferred to electrons

Processing with fs pulses



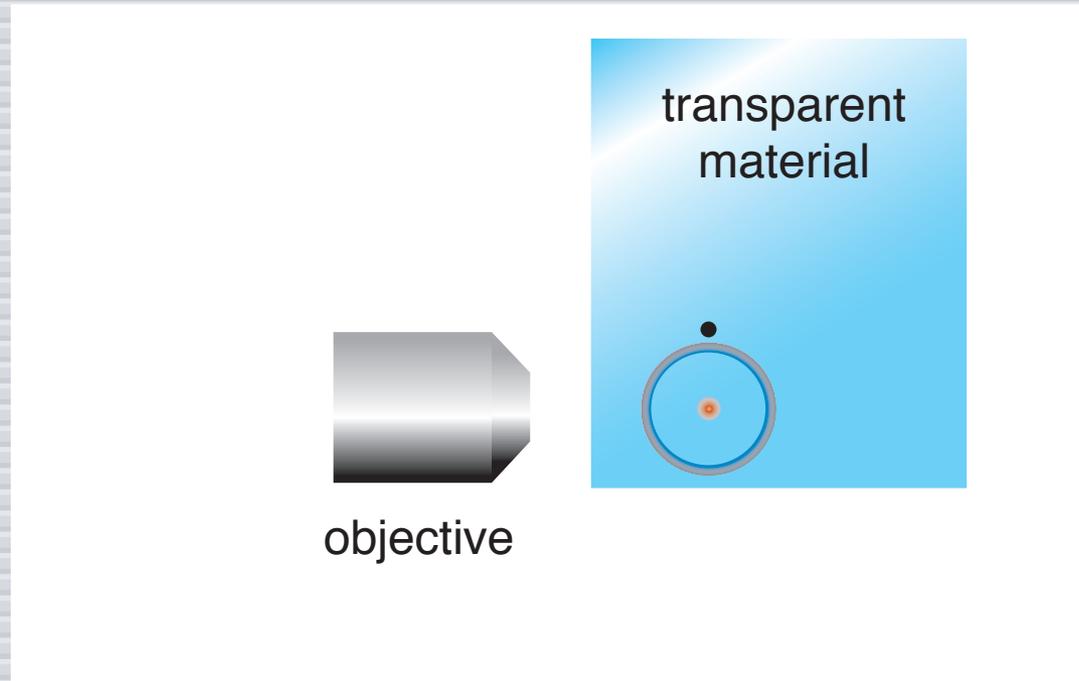
10 ps: energy transfer to ions

Processing with fs pulses



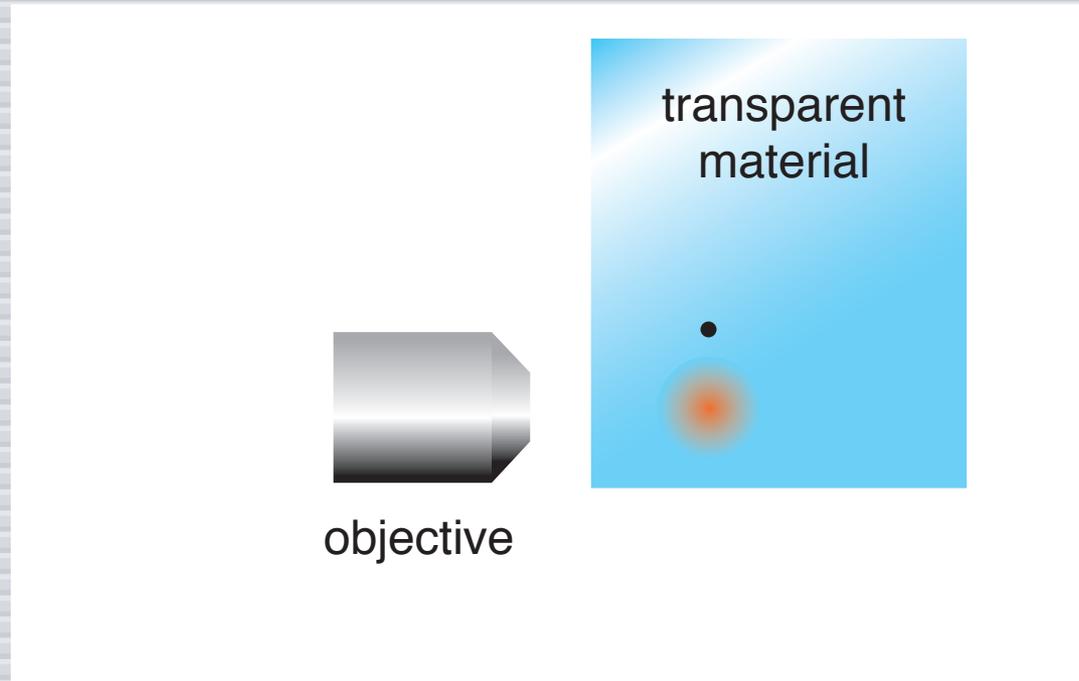
100 ps: plasma expansion

Processing with fs pulses



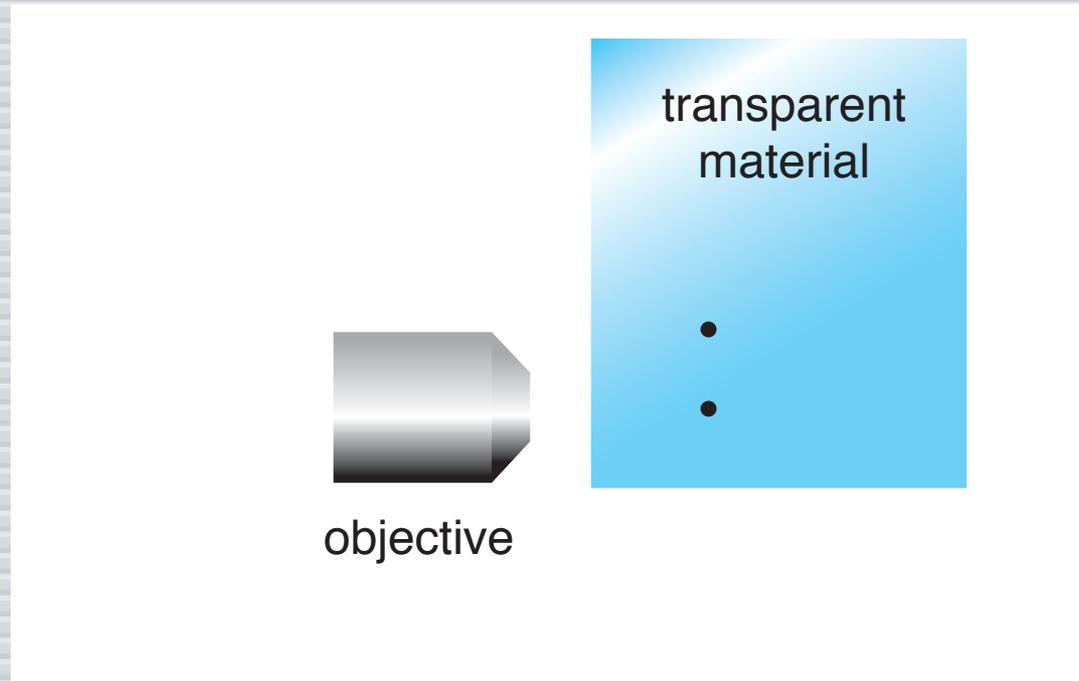
10–100 ns: shock propagation

Processing with fs pulses



1 μ s: thermal expansion

Processing with fs pulses



1 ms: permanent structural damage

Processing with fs pulses

Points to keep in mind:

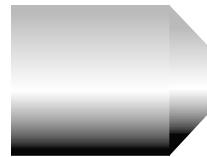
- ▶ **fs laser processing works**
- ▶ **focusing very important**
- ▶ **no collateral damage**

Outline

- ▶ Processing with fs pulses
- ▶ Role of focusing
- ▶ Low-energy processing

Role of focusing

Dark-field scattering



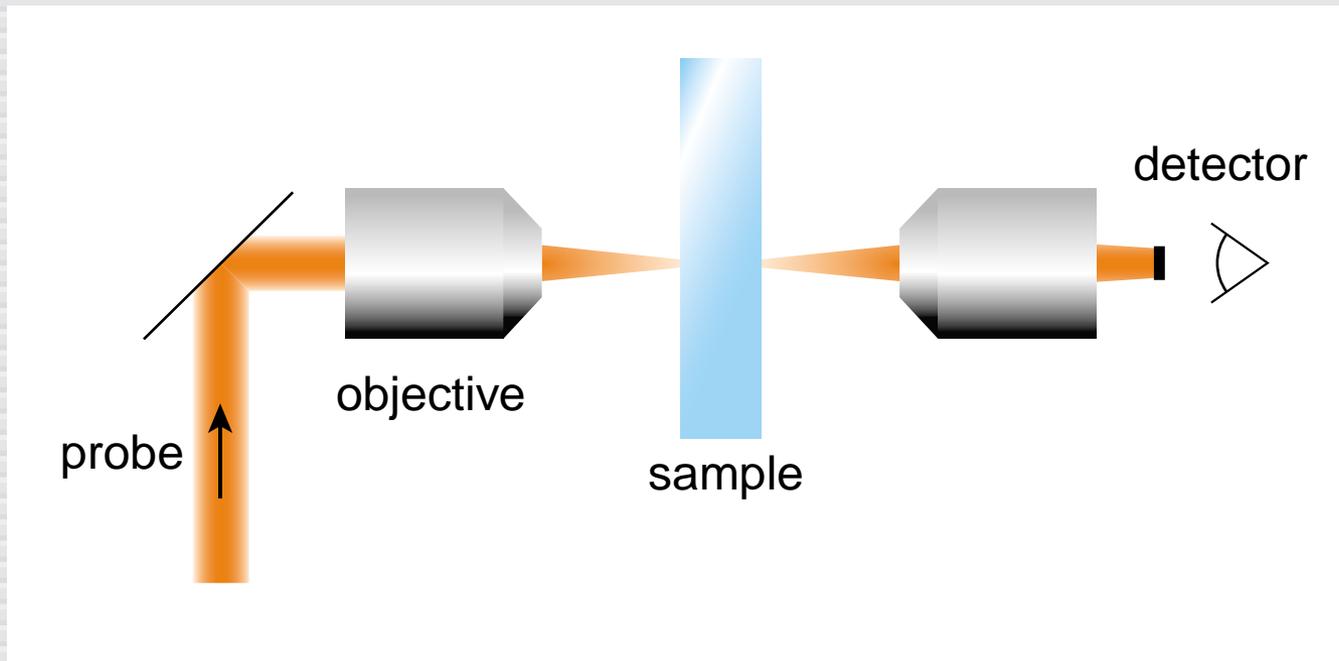
objective



sample

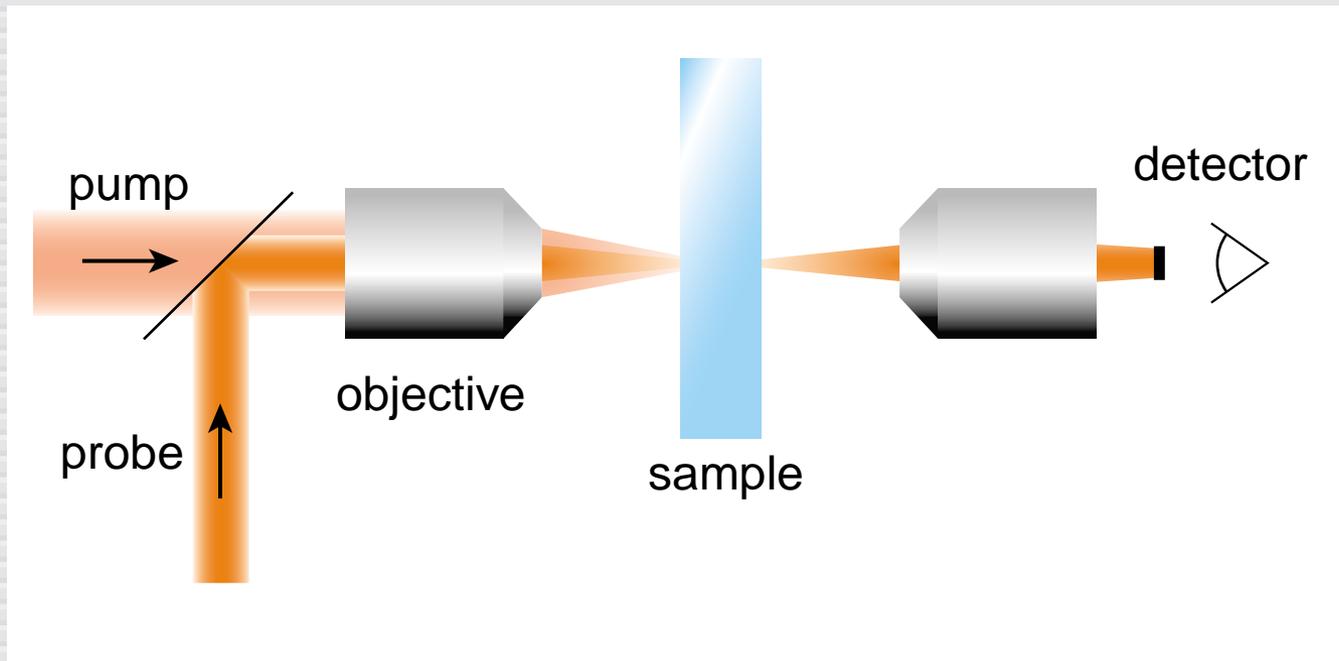
Role of focusing

block probe beam...



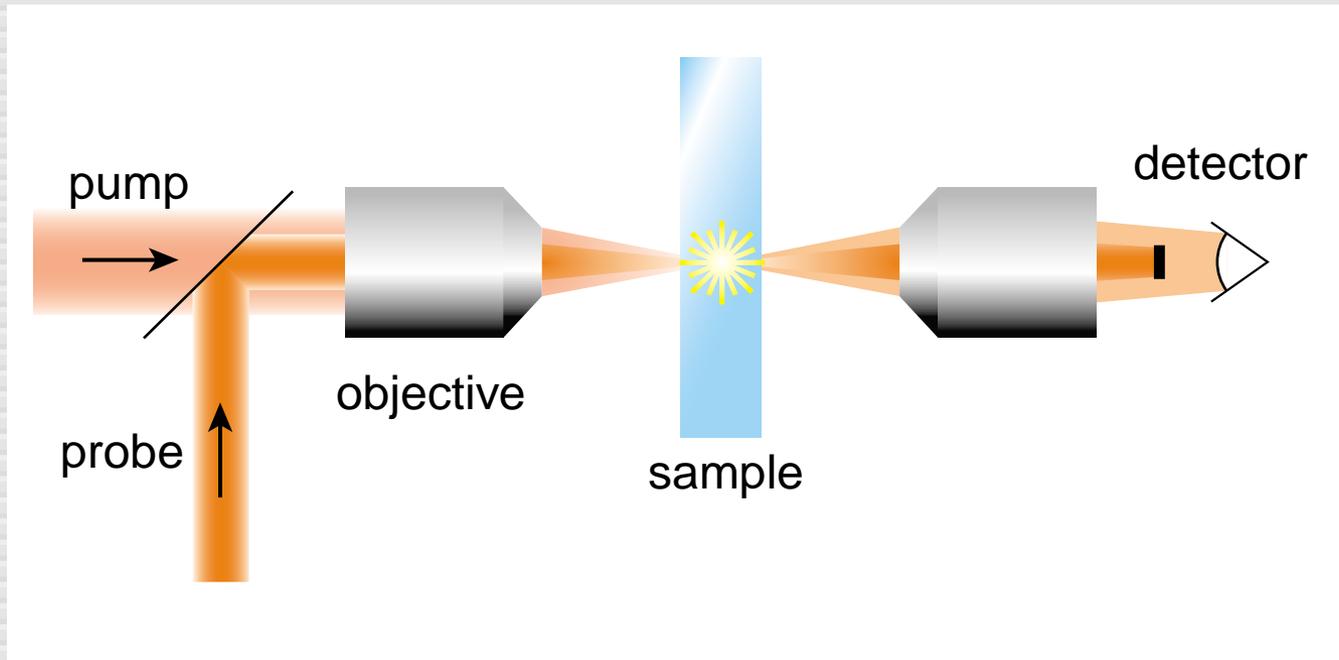
Role of focusing

... bring in pump beam...



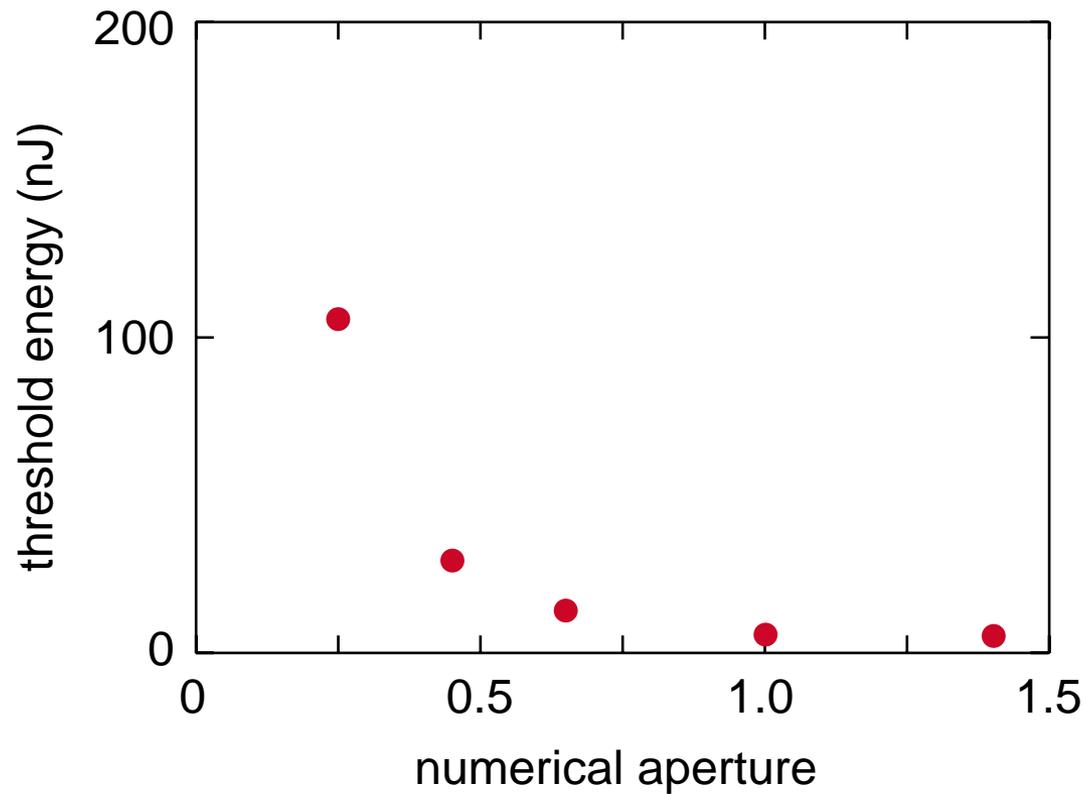
Role of focusing

... damage scatters probe beam



Role of focusing

vary numerical aperture in Corning 0211

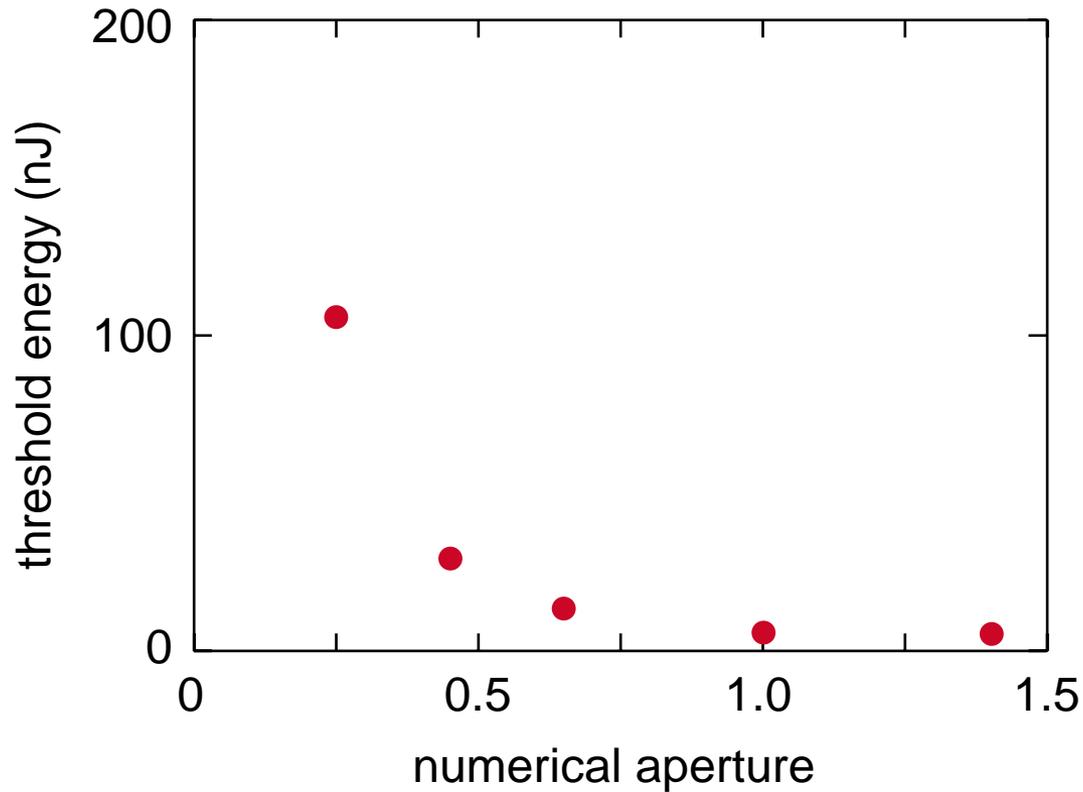


Outline

- ▶ Processing with fs pulses
- ▶ Role of focusing
- ▶ **Low-energy processing**

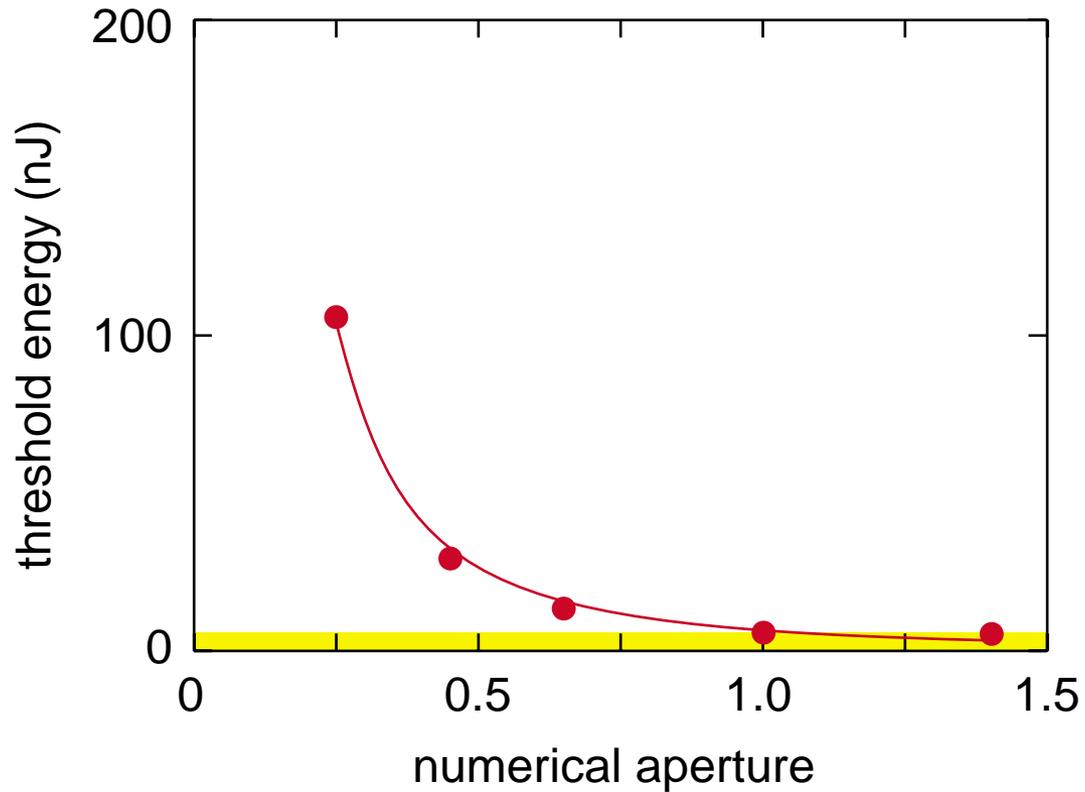
Low-energy processing

threshold decreases with increasing numerical aperture



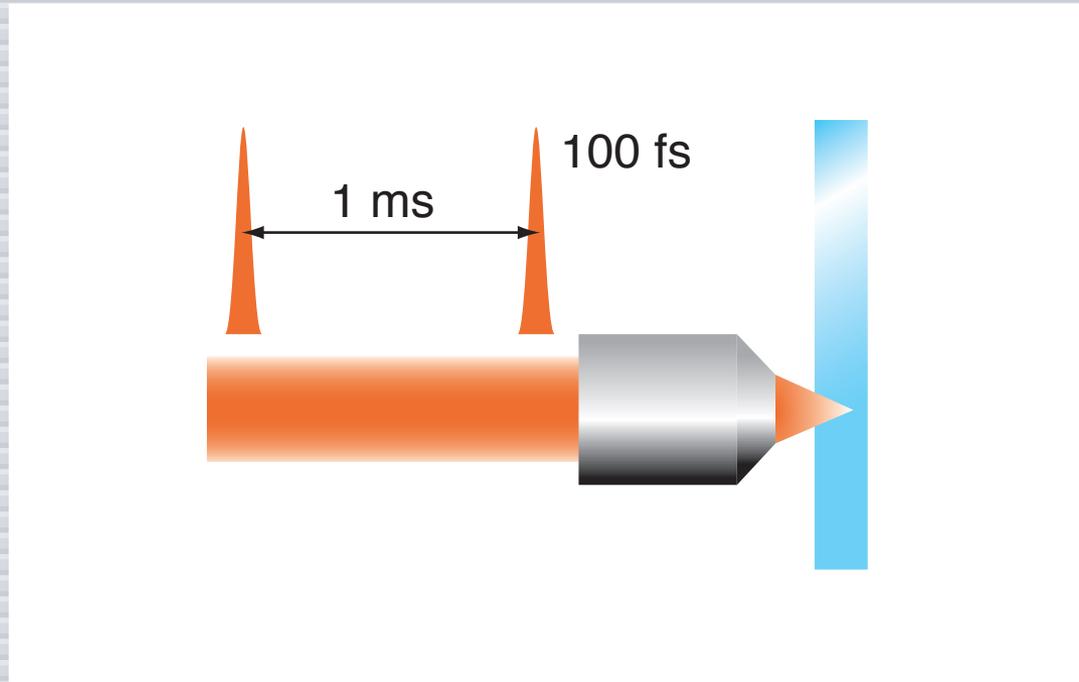
Low-energy processing

less than 10 nJ at high numerical aperture!



Low-energy processing

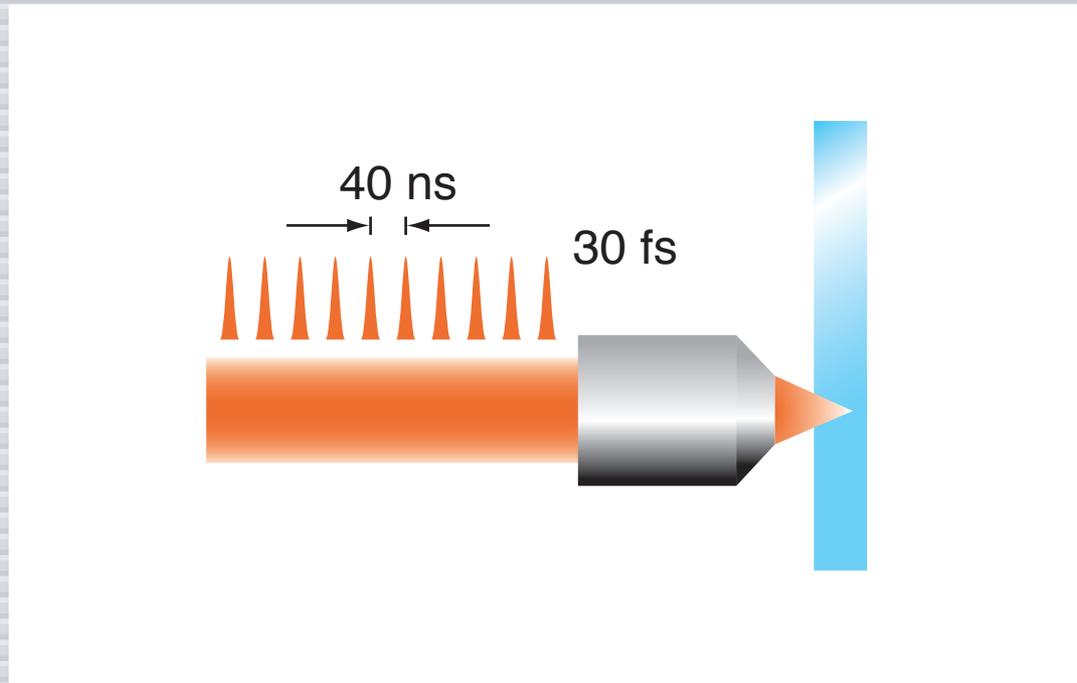
amplified laser: 1 kHz, 1 mJ



heat diffusion time: $\tau_{diff} \approx 1 \mu\text{s}$

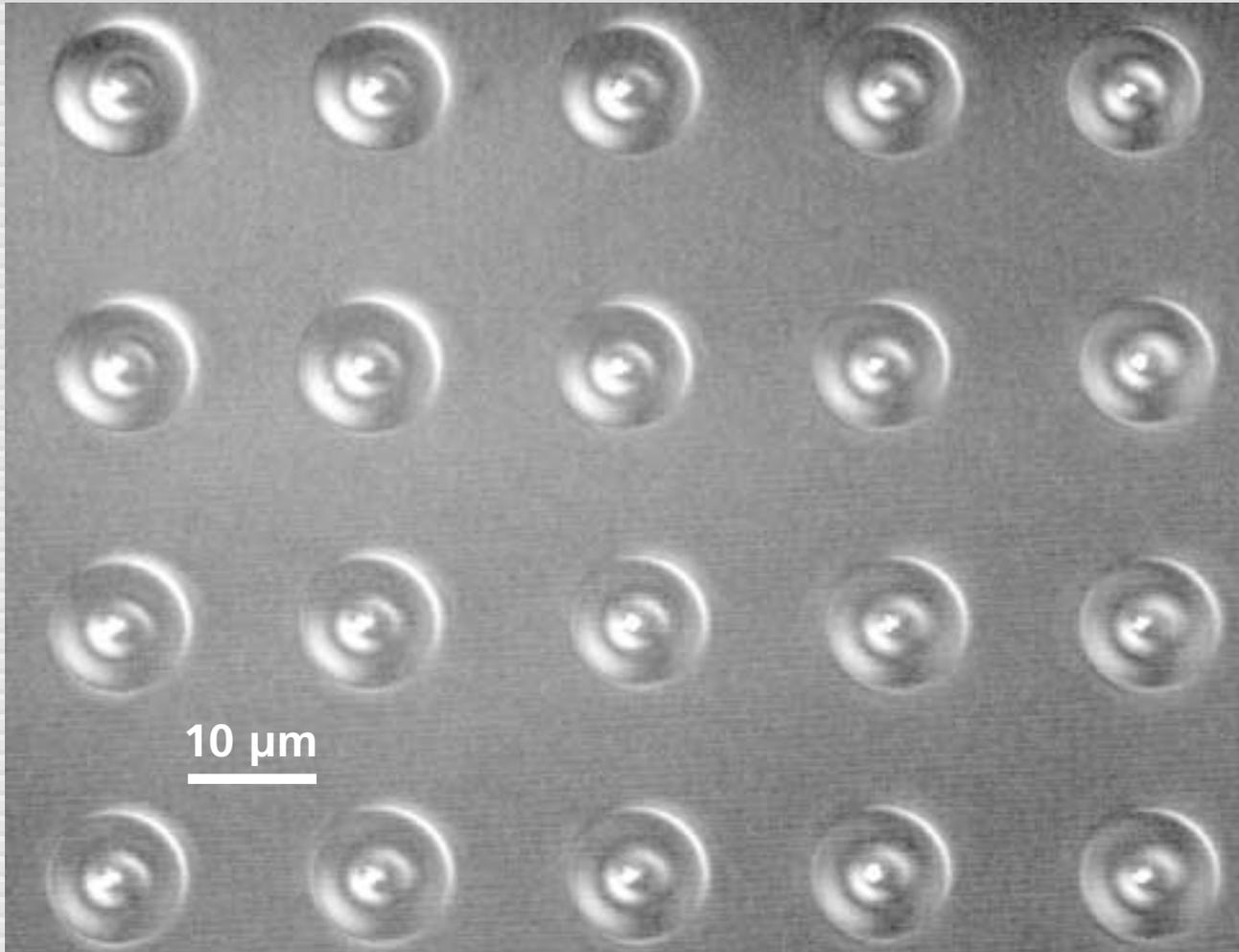
Low-energy processing

long cavity oscillator: 25 MHz, 25 nJ



heat diffusion time: $\tau_{diff} \approx 1 \mu\text{s}$

Low-energy processing

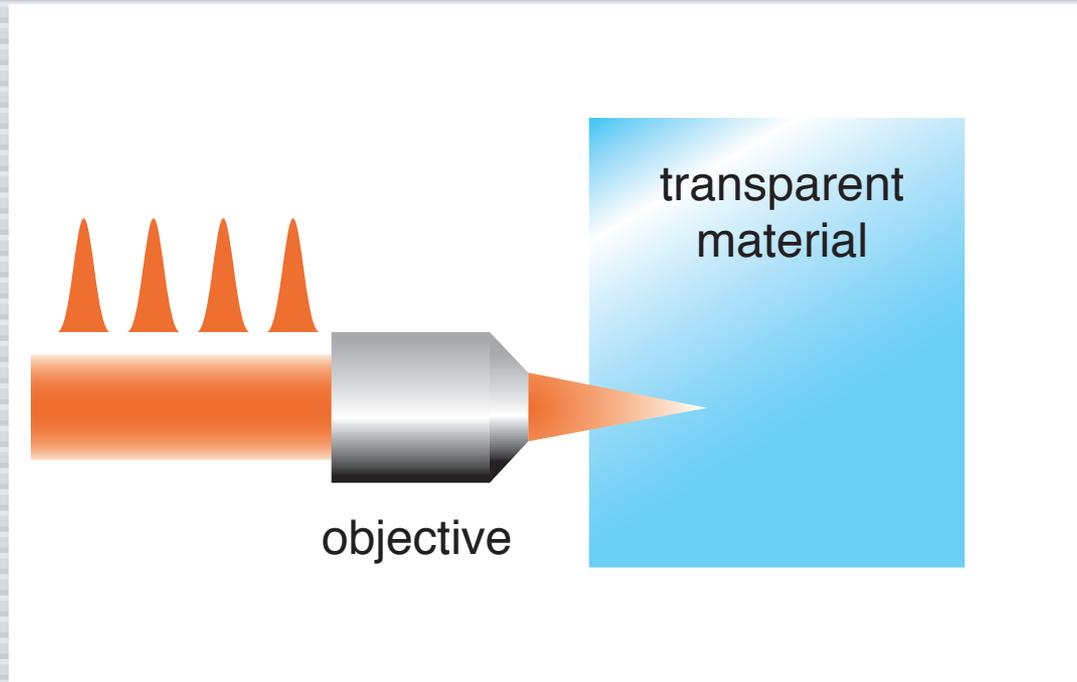


Low-energy processing

high repetition-rate micromachining:

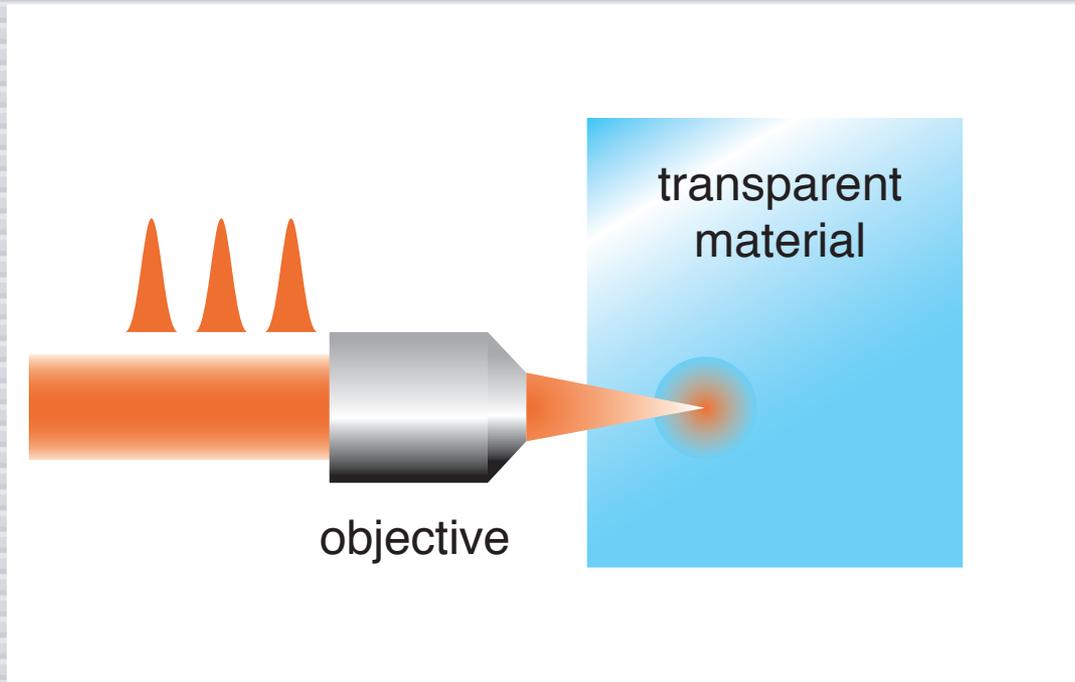
- ▶ **structural changes exceed focal volume**
- ▶ **spherical structures**
- ▶ **density change caused by melting**

Low-energy processing



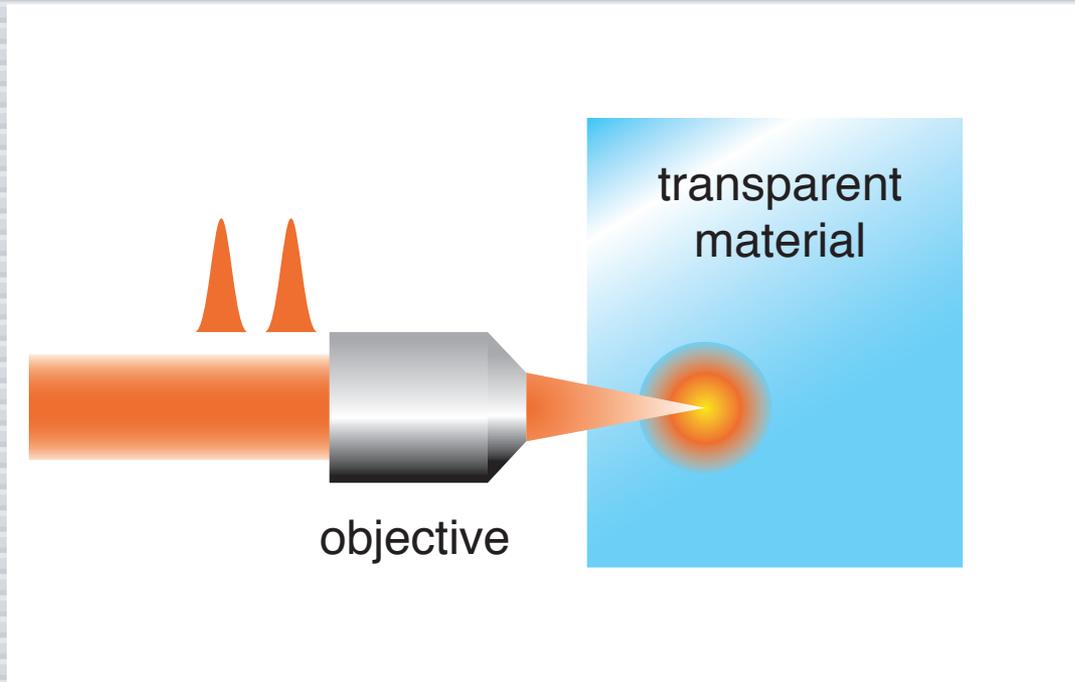
cumulative energy deposition

Low-energy processing



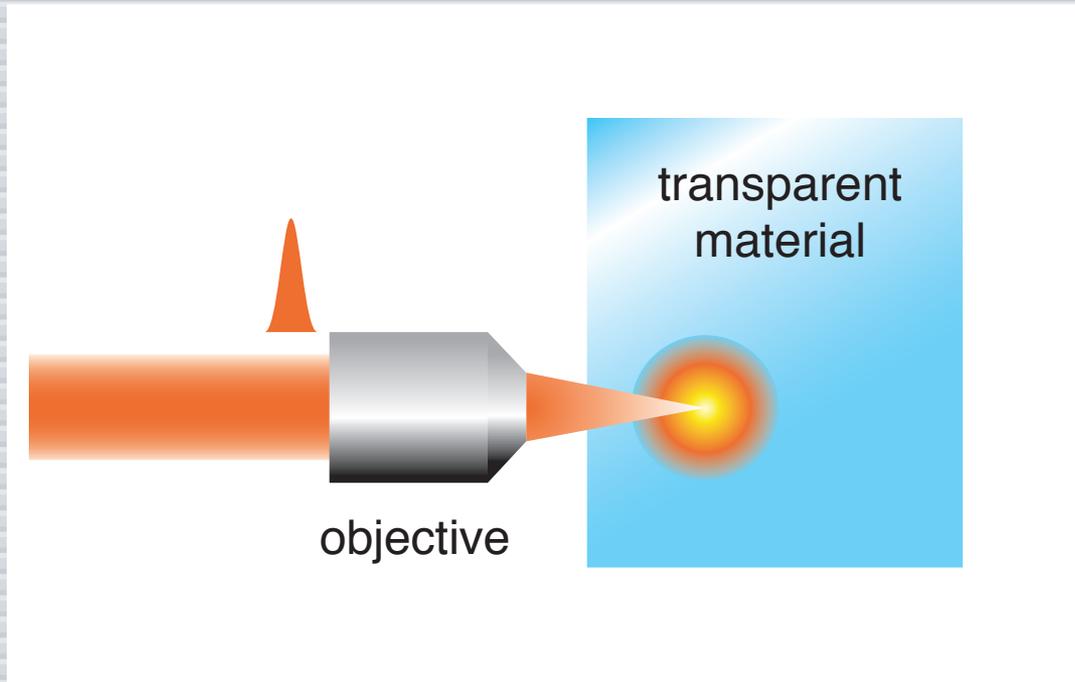
cumulative energy deposition

Low-energy processing



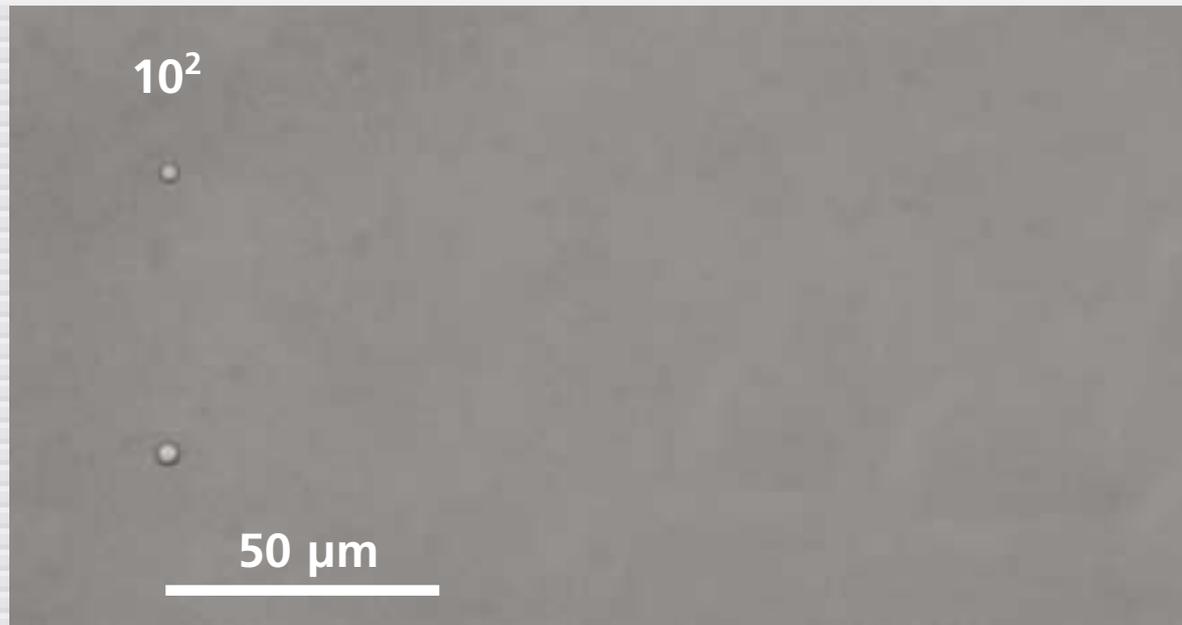
cumulative energy deposition

Low-energy processing

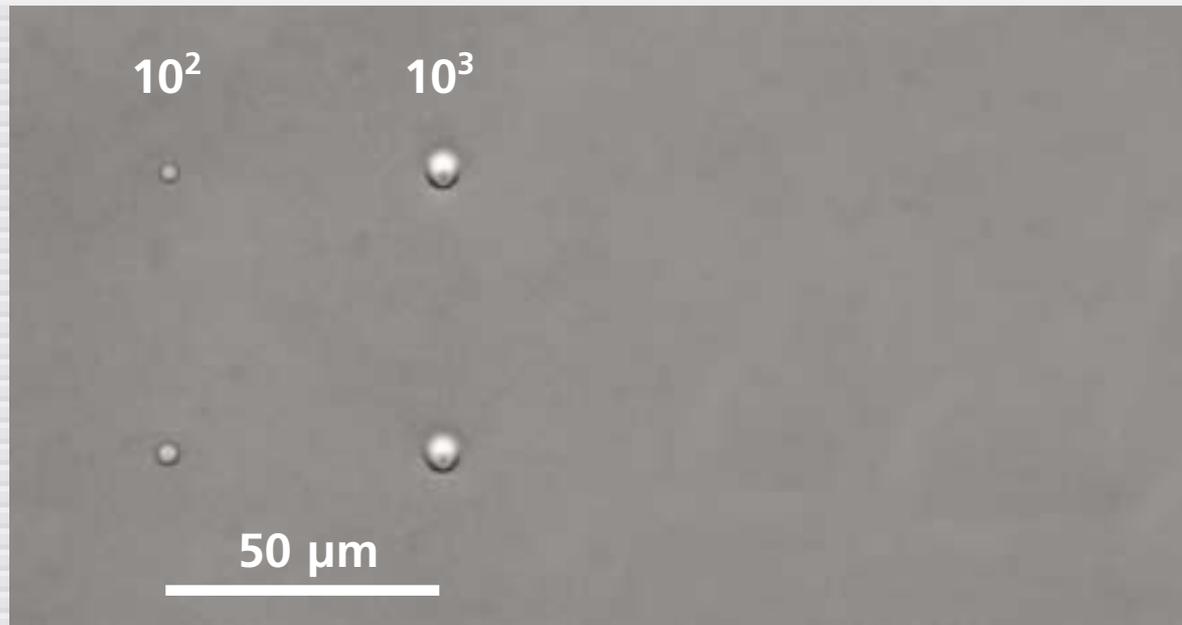


cumulative energy deposition

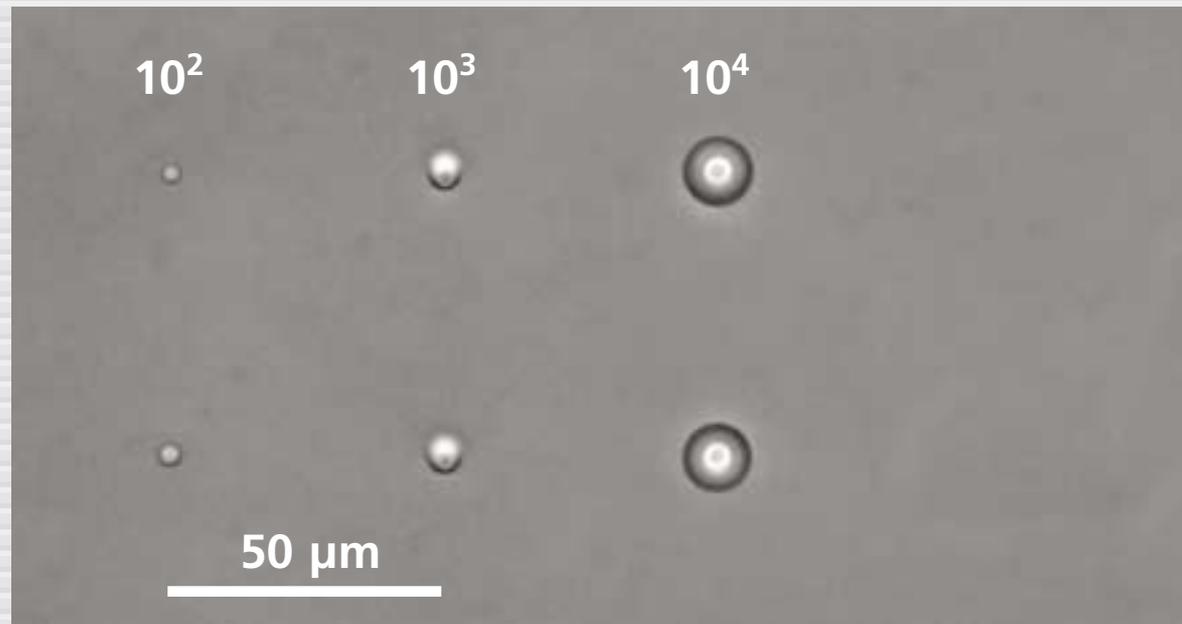
Low-energy processing



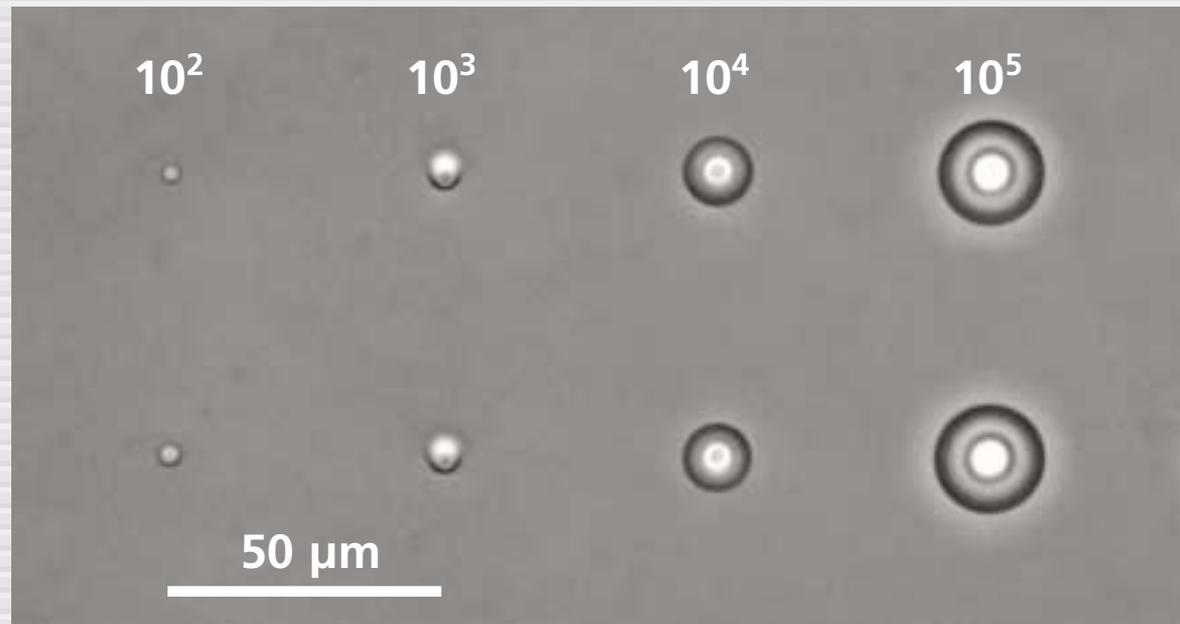
Low-energy processing



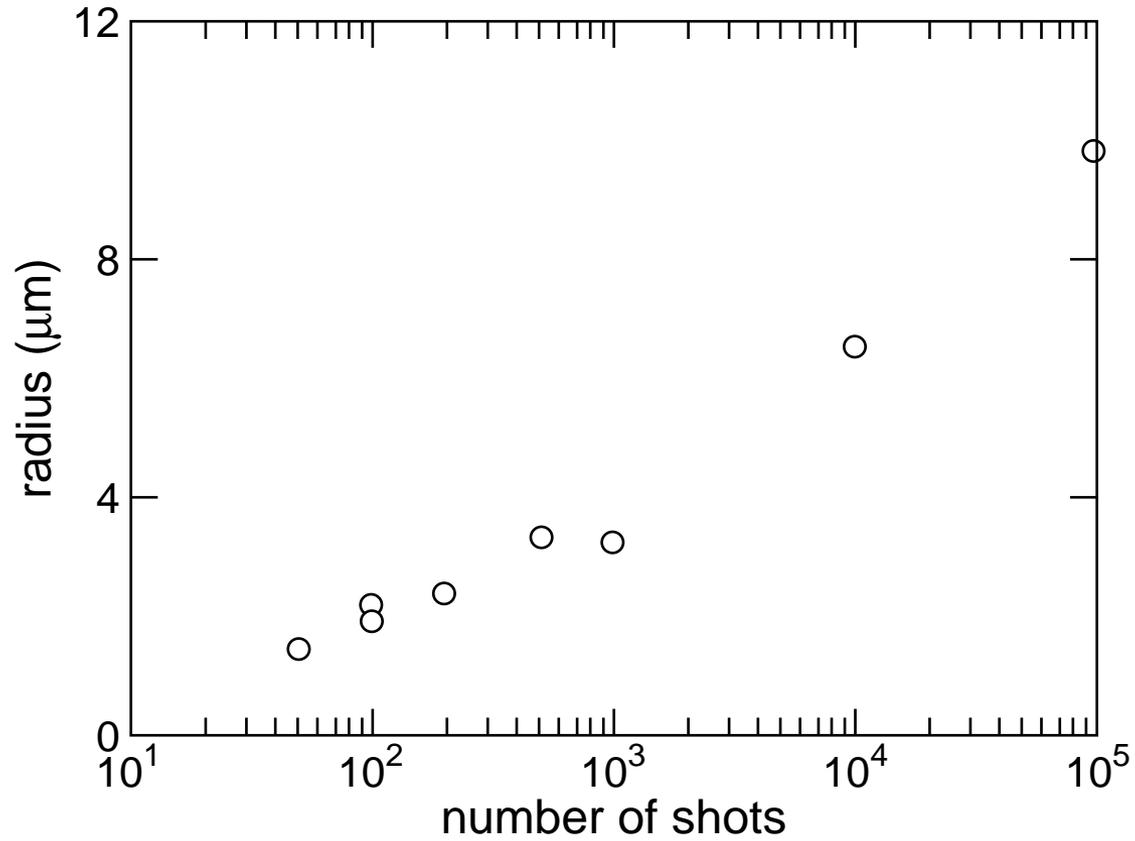
Low-energy processing



Low-energy processing



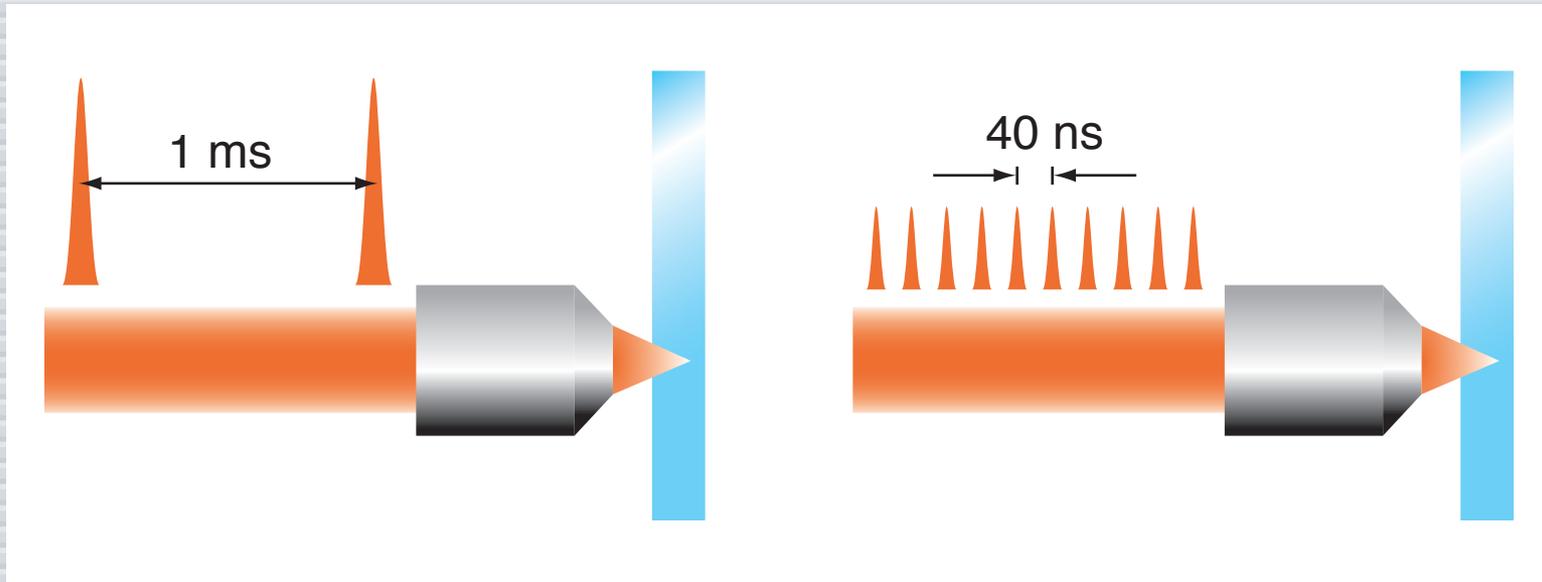
Low-energy processing



Low-energy processing

amplified laser

oscillator

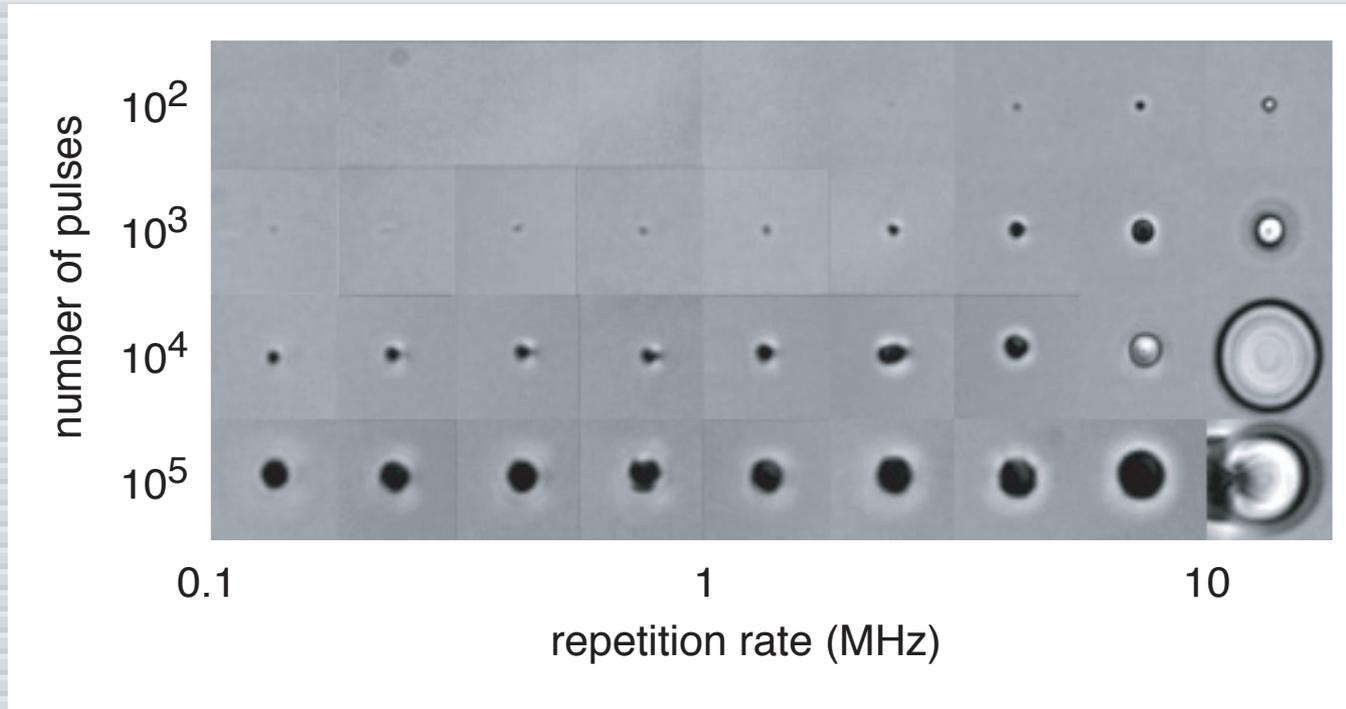


repetitive

cumulative

Low-energy processing

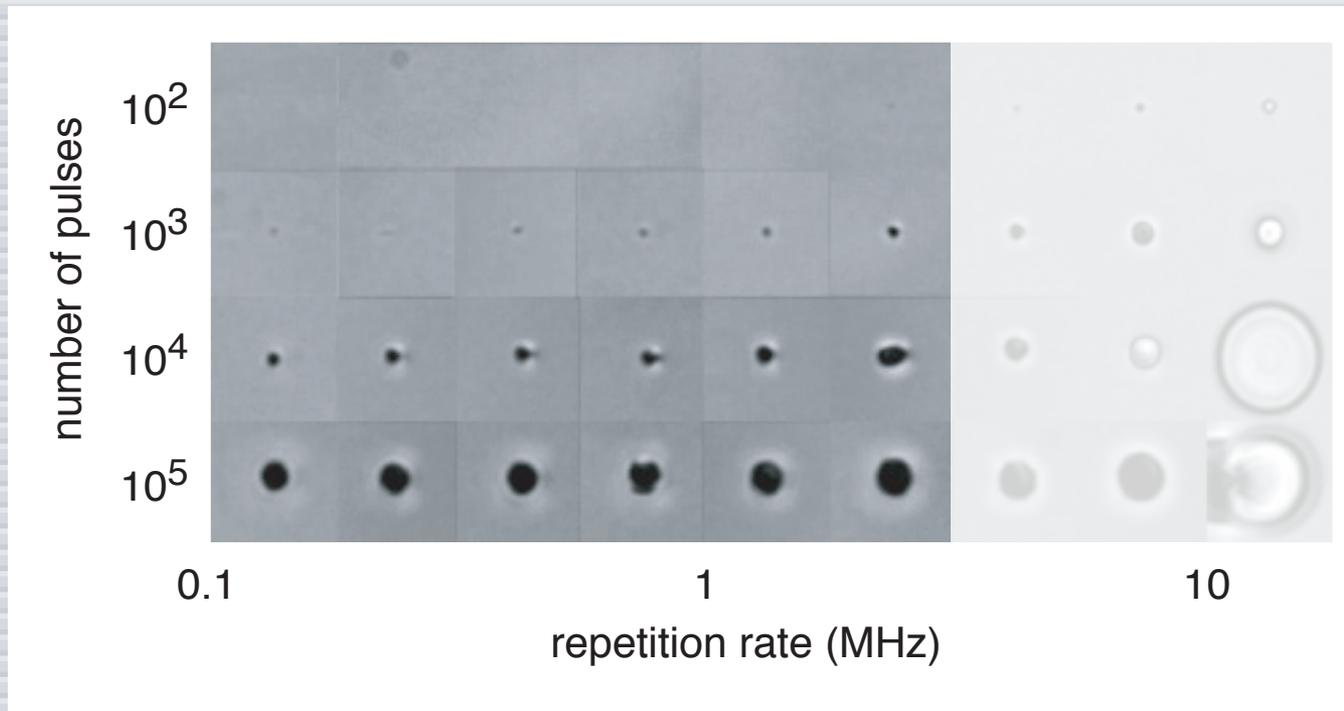
repetition-rate dependence



As_2S_3 , 100 fs, 7 nJ

Low-energy processing

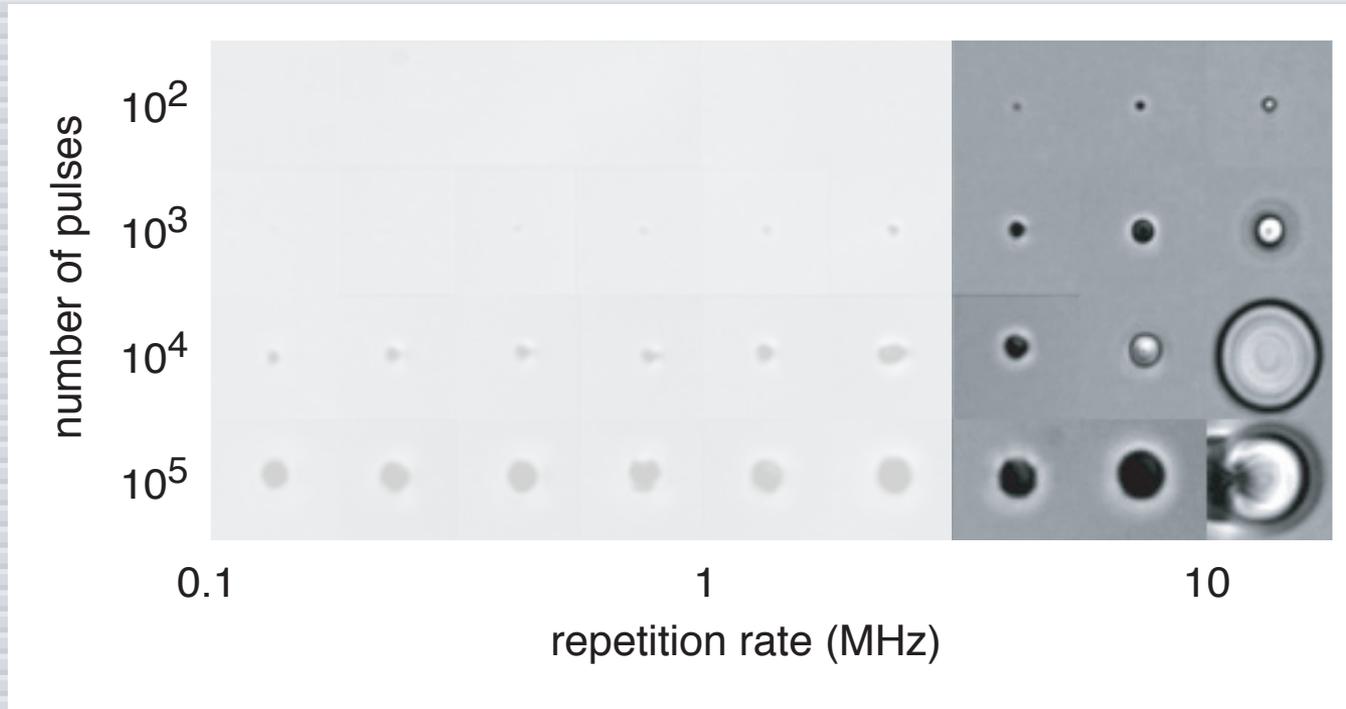
repetition-rate dependence



As_2S_3 , 100 fs, 7 nJ

Low-energy processing

repetition-rate dependence

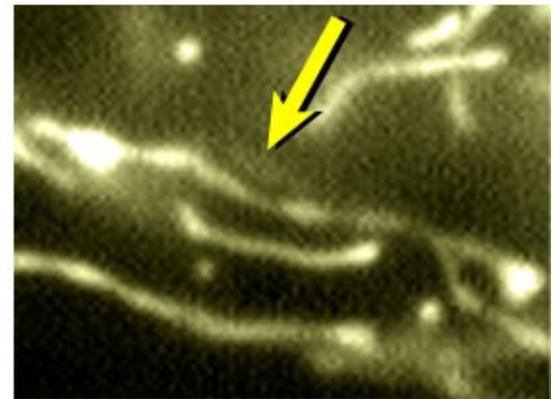
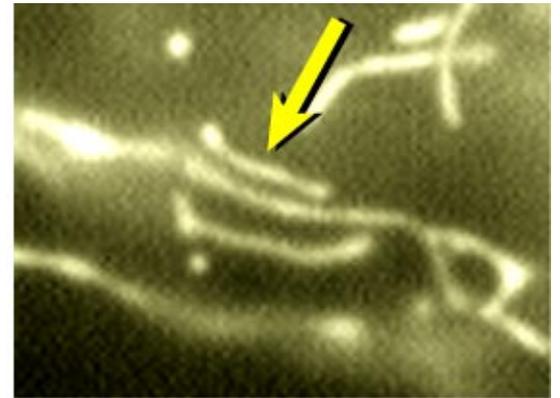
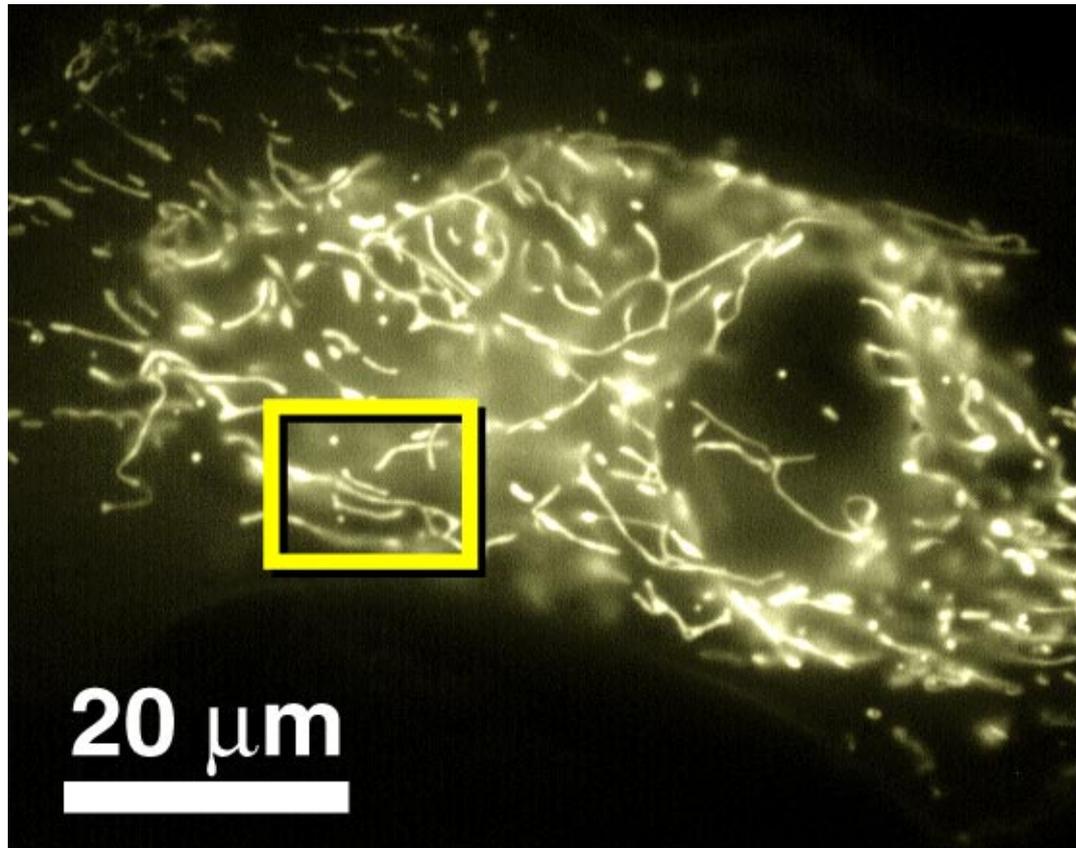


As₂S₃, 100 fs, 7 nJ

Low-energy processing

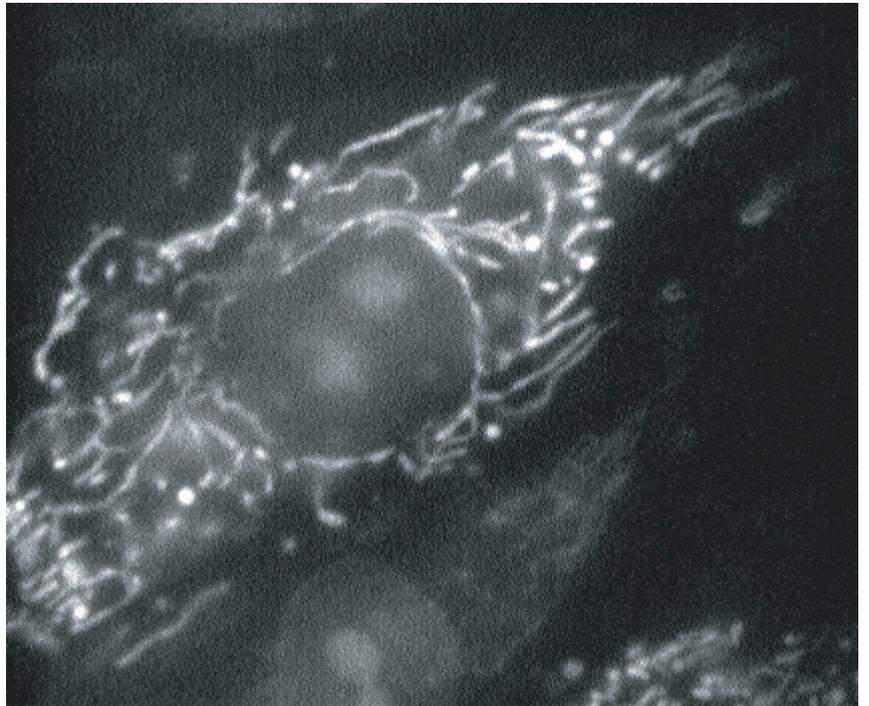
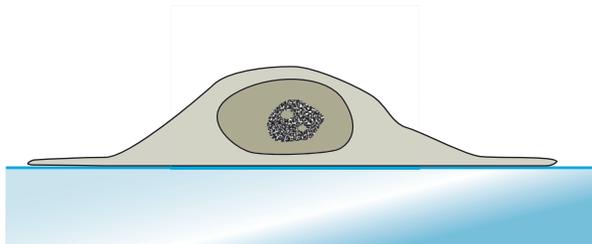
- ▶ **standard biochemical tools: species selective**
- ▶ **fs laser nanosurgery: site specific**

Low-energy processing



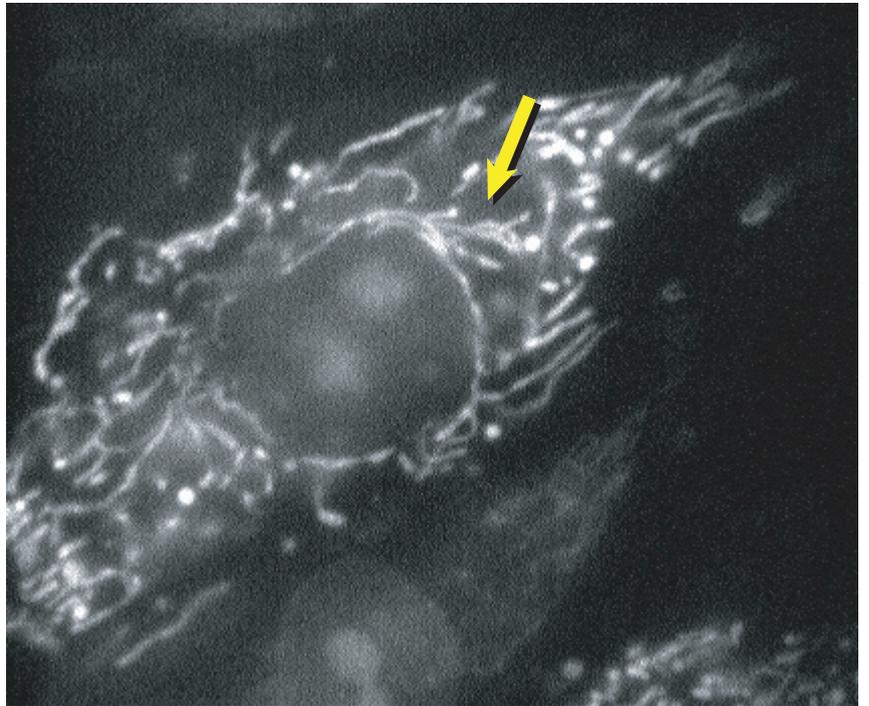
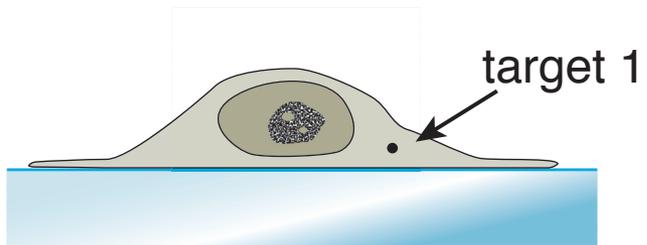
Low-energy processing

Ethydium bromide test



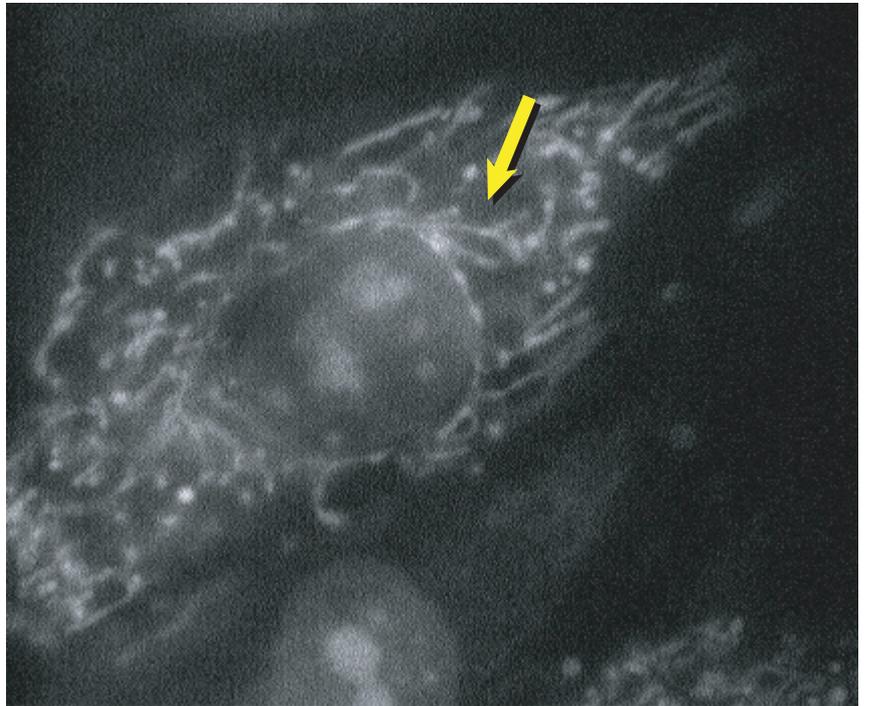
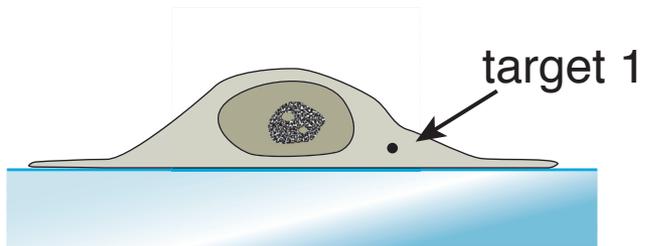
Low-energy processing

Ethydium bromide test



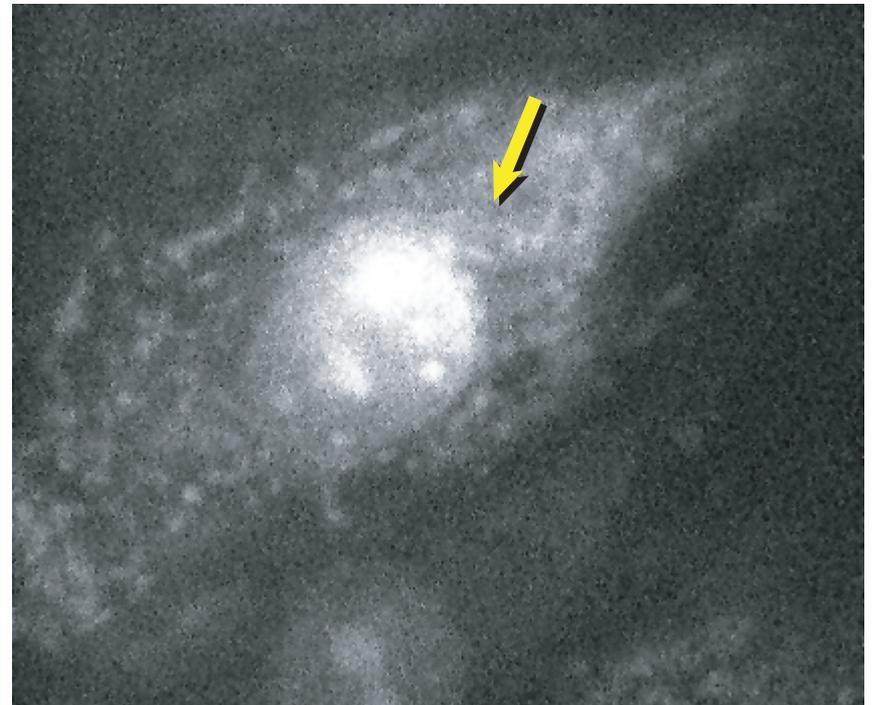
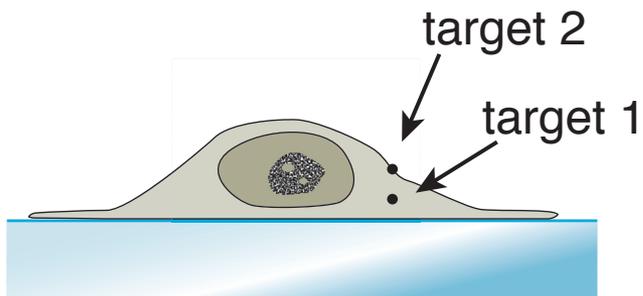
Low-energy processing

Ethydium bromide test



Low-energy processing

Ethydium bromide test



Nanoneurosurgery

Caenorhabditis Elegans



Juergen Berger & Ralph Sommer
Max-Planck Institute for Developmental Biology

Nanoneurosurgery

Caenorhabditis Elegans

- ▶ **simple model organism**

Nanoneurosurgery

Caenorhabditis Elegans

- ▶ **simple model organism**
- ▶ **similarities to higher organism**

Nanoneurosurgery

Caenorhabditis Elegans

- ▶ **simple model organism**
- ▶ **similarities to higher organism**
- ▶ **genome fully sequenced**

Nanoneurosurgery

Caenorhabditis Elegans

- ▶ **simple model organism**
- ▶ **similarities to higher organism**
- ▶ **genome fully sequenced**
- ▶ **easy to handle**

Nanoneurosurgery

Caenorhabditis Elegans

▶ 80 μm x 1 mm

Nanoneurosurgery

Caenorhabditis Elegans

- ▶ **80 μm x 1 mm**
- ▶ **about 1300 cells**

Nanoneurosurgery

Caenorhabditis Elegans

- ▶ **80 μm x 1 mm**
- ▶ **about 1300 cells**
- ▶ **302 neurons**

Nanoneurosurgery

Caenorhabditis Elegans

- ▶ **80 μm x 1 mm**
- ▶ **about 1300 cells**
- ▶ **302 neurons**
- ▶ **invariant wiring diagram**

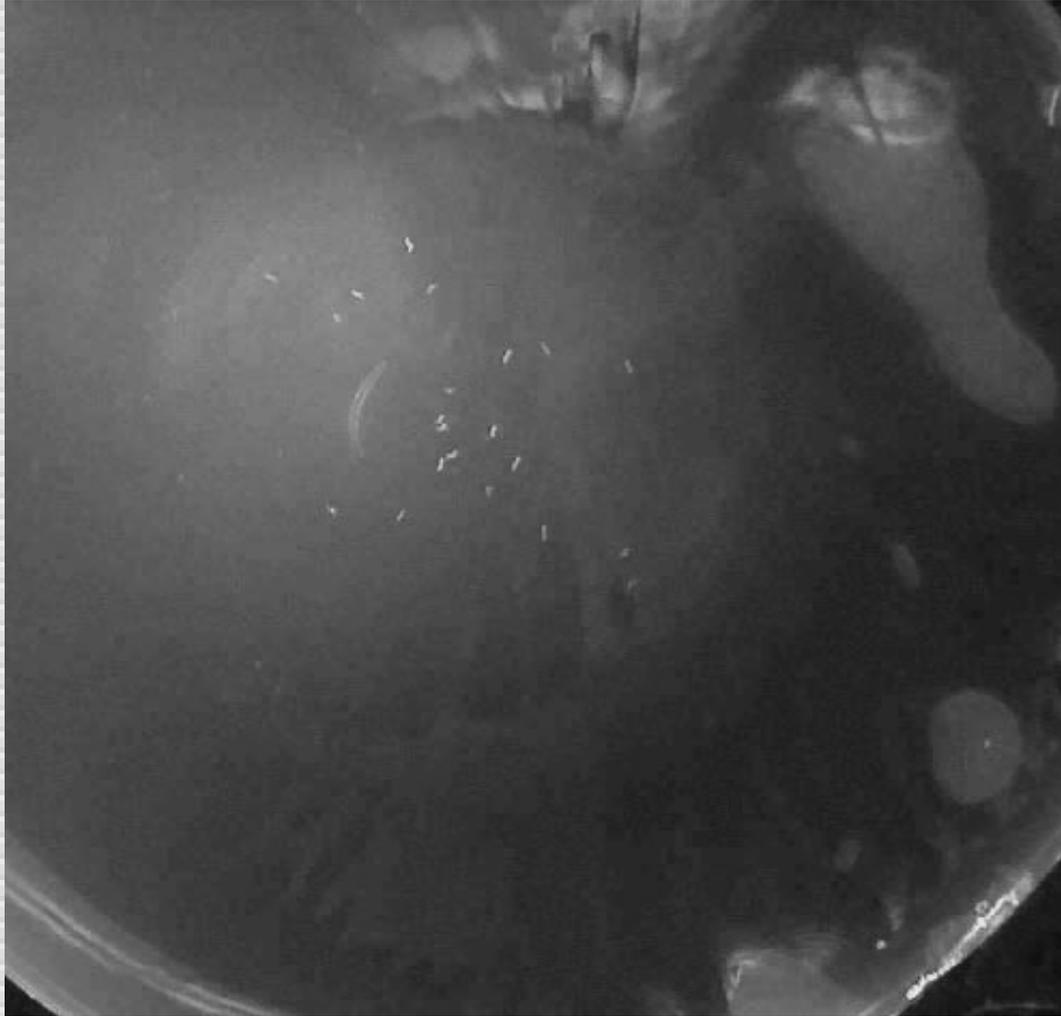
Nanoneurosurgery

Caenorhabditis Elegans

- ▶ **80 μm x 1 mm**
- ▶ **about 1300 cells**
- ▶ **302 neurons**
- ▶ **invariant wiring diagram**
- ▶ **neuronal system completely encodes behavior**

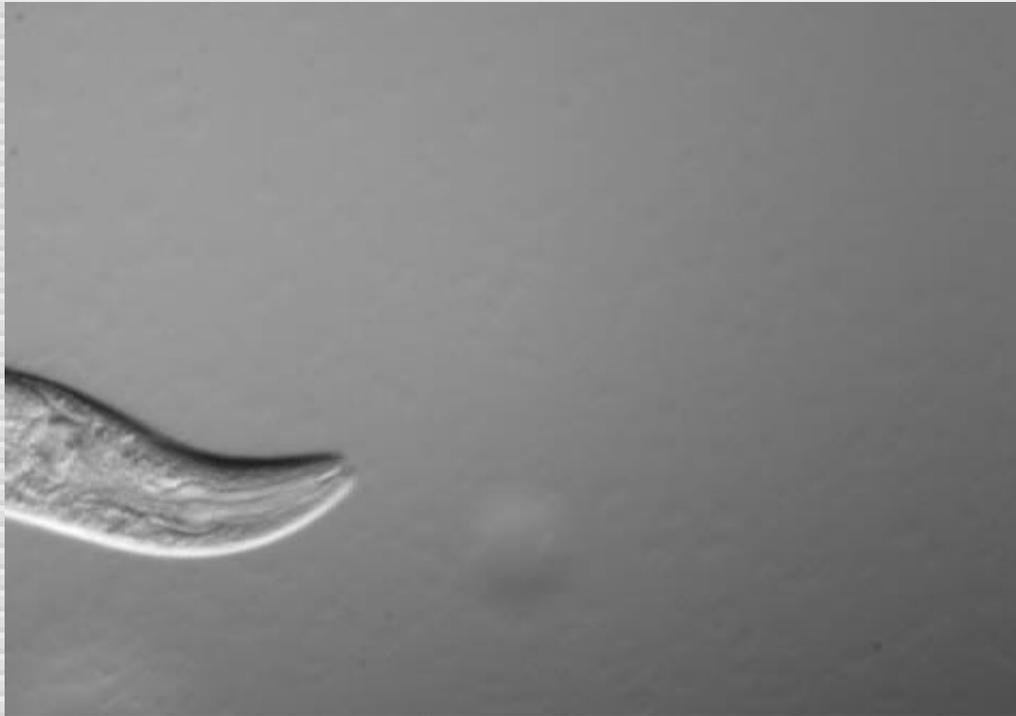
Nanoneurosurgery

Caenorhabditis Elegans



Nanoneurosurgery

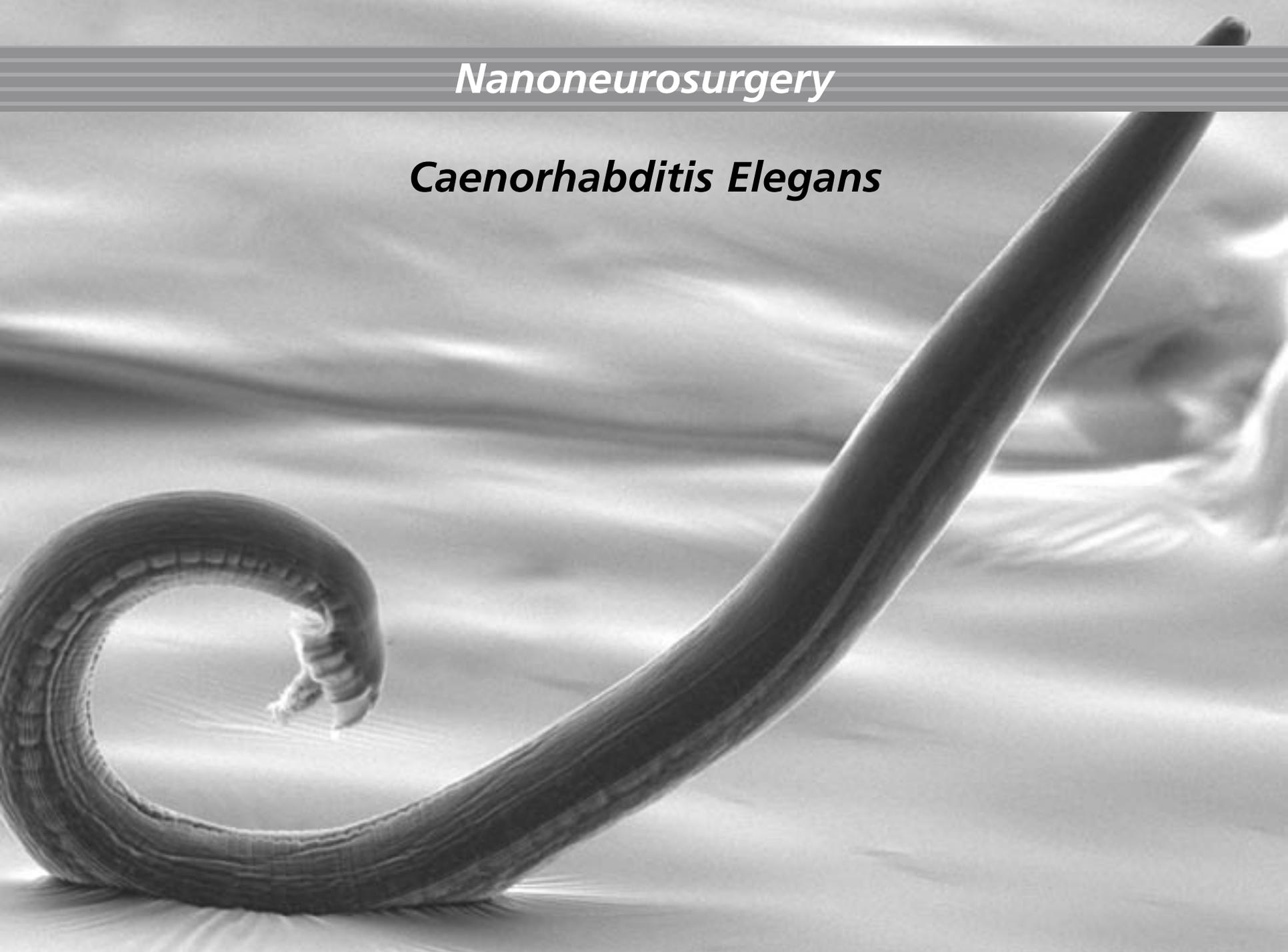
Caenorhabditis Elegans



Bob Goldstein, UNC Chapel Hill

Nanoneurosurgery

Caenorhabditis Elegans



Nanoneurosurgery



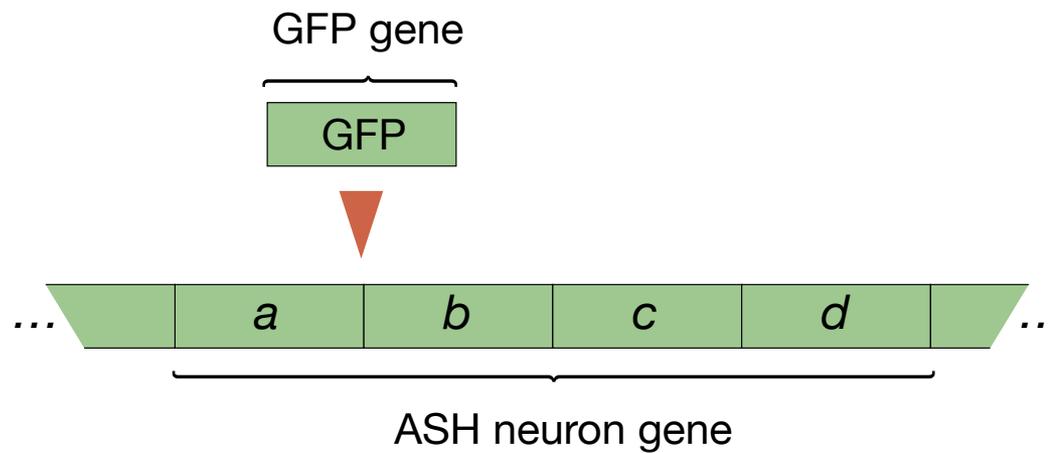
Nanoneurosurgery

ASH neurons

- ▶ **responsible for osmotic avoidance**
- ▶ **ciliary projections extend through skin**
- ▶ **one on each side**

Nanoneurosurgery

make ASH neurons express GFP



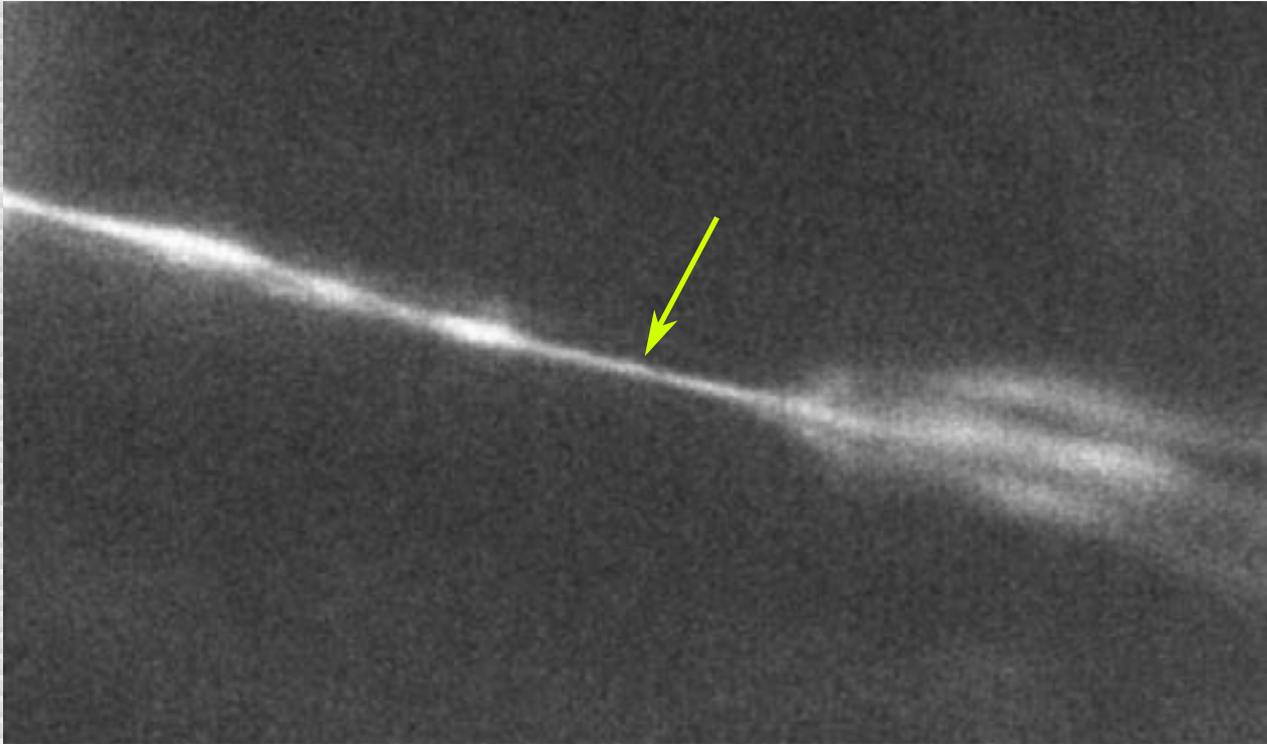
Nanoneurosurgery

GFP: absorbs UV, emits green



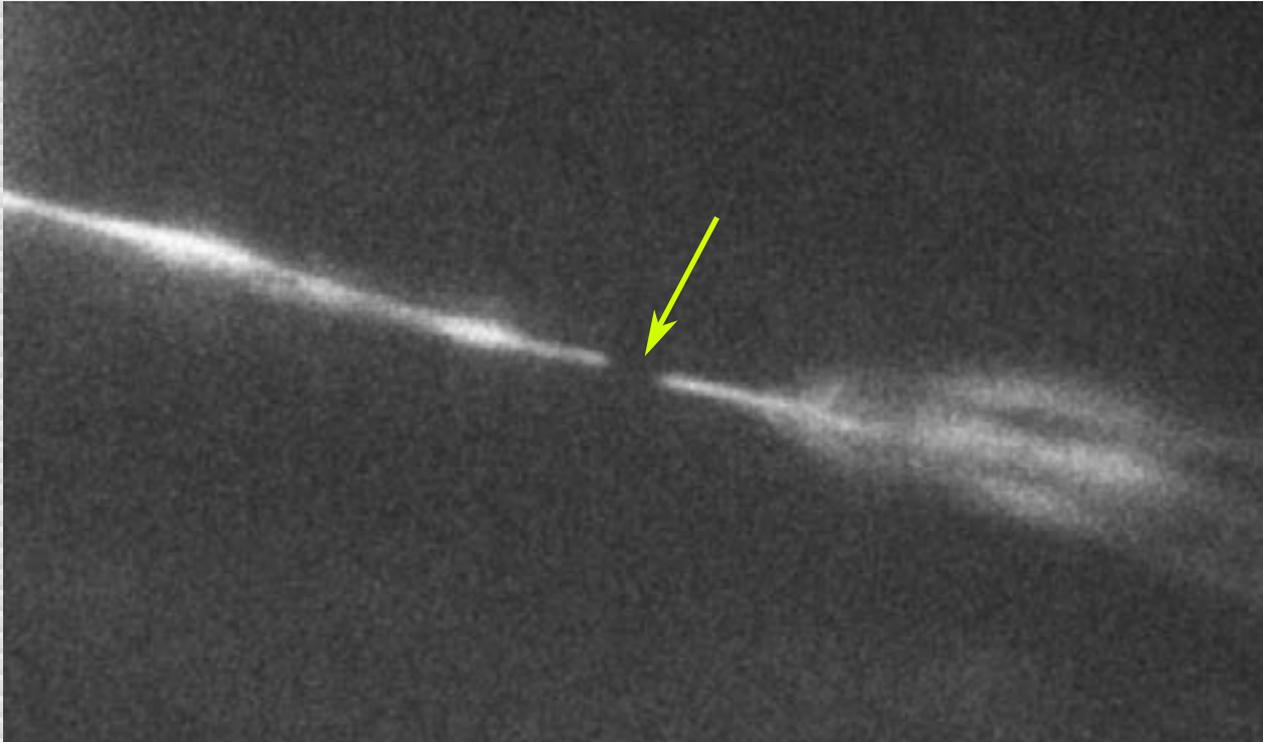
Nanoneurosurgery

cutting an axon



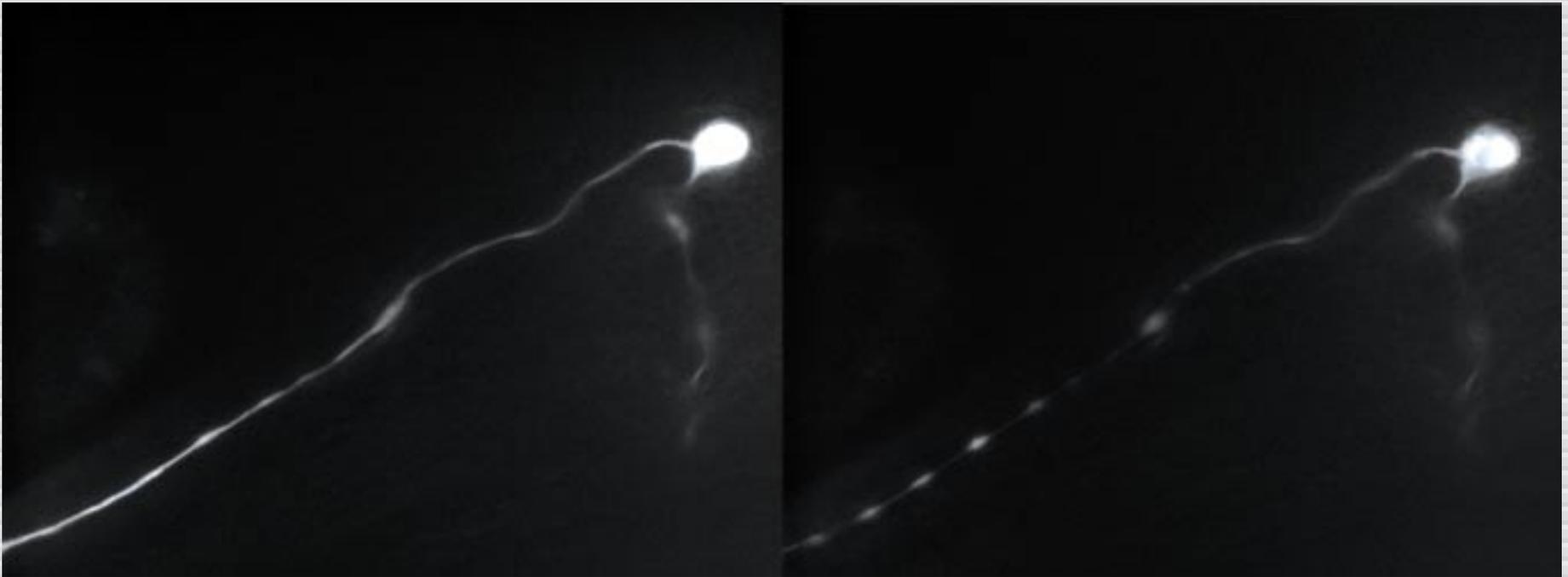
Nanoneurosurgery

cutting an axon



Nanoneurosurgery

pearling instability



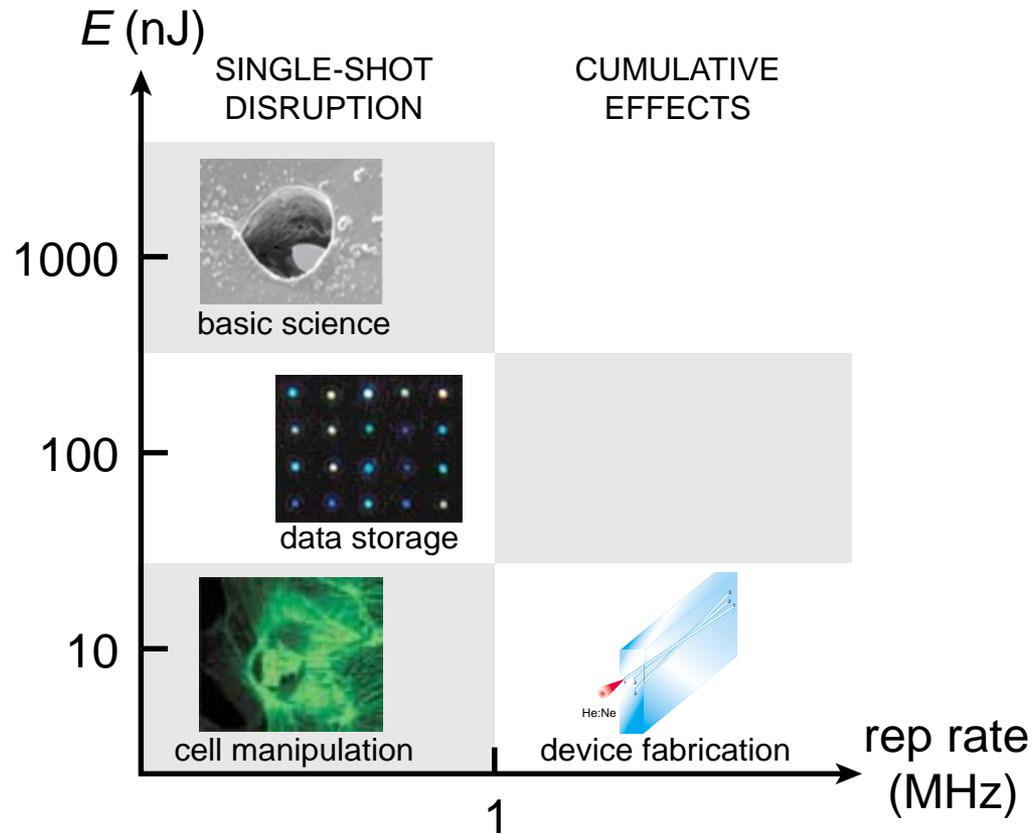
Summary

important parameters

- ▶ **focusing**
- ▶ **energy**
- ▶ **repetition rate**

nearly material-independent!

Summary



GORDON MCKAY
LABORATORY OF
APPLIED SCIENCE



A group of approximately 15 people, including men and women of various ethnicities, are standing in a line in front of a red brick wall. The wall has some graffiti, including the name "GORDON VICKY" and "APRIL 2004". The people are dressed in casual attire like t-shirts and jeans. The scene is outdoors during the day.

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