Femtosecond laser micromachining

1st International Workshop on Multiphoton Processes in Glass and Glassy Materials
University of Sydney, Australia, 11 December 2006


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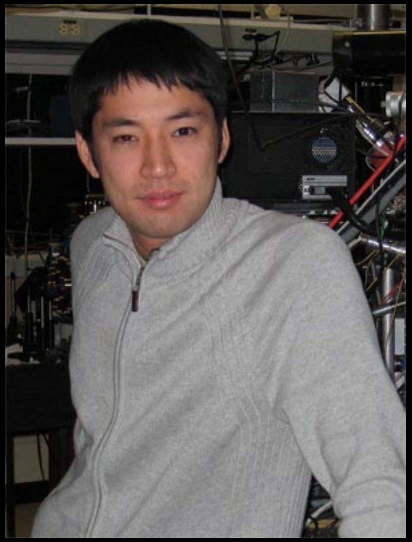
Masanao Kamata

and also....

Iva Maxwell
San Chung
Eli Glezer
Chris Schaffer
Nozomi Nishimura
Jonathan Ashcom
Jeremy Hwang
Nan Shen
Dr. André Brodeur
Dr. Sanjoy Kumar
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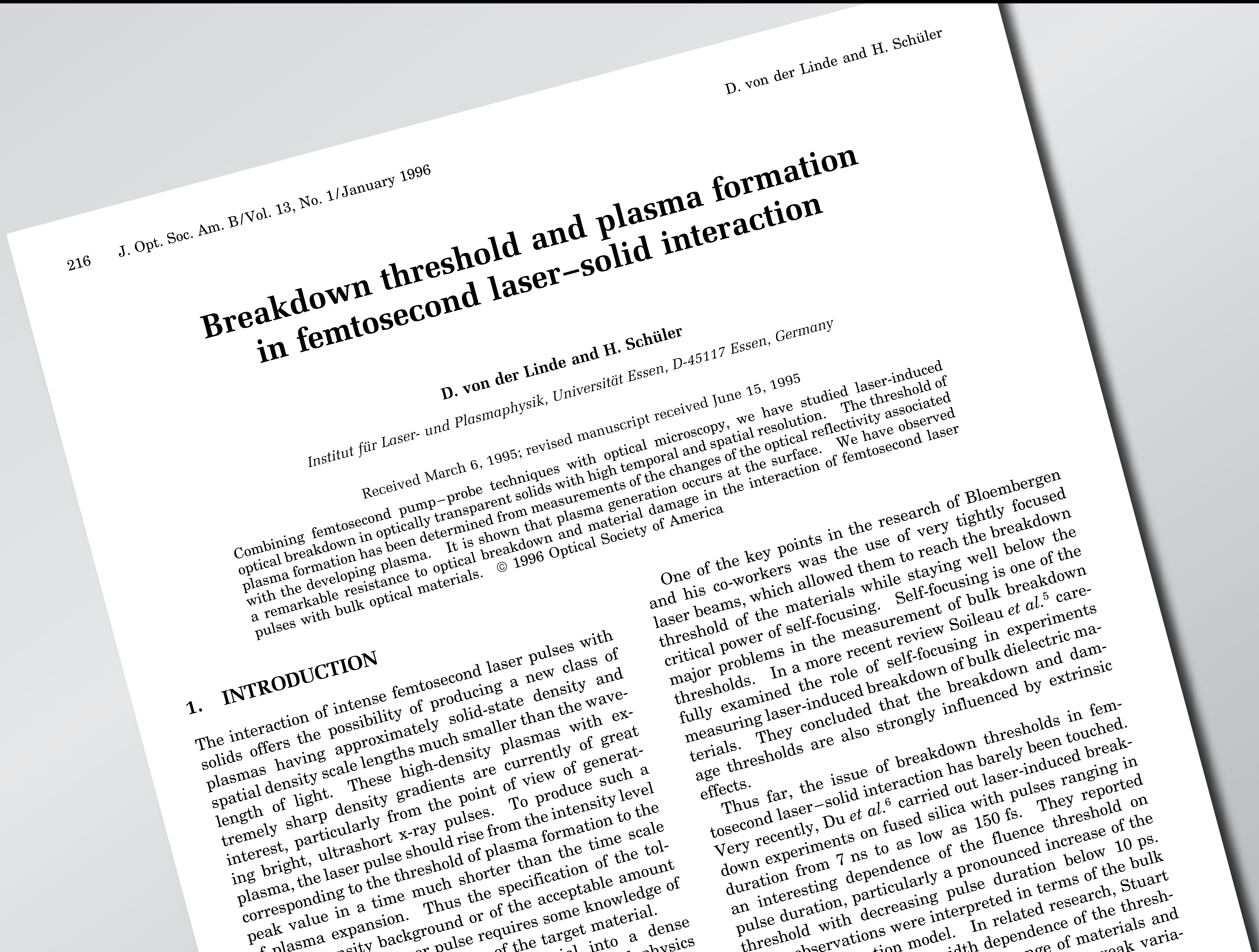
Prof. Aravi Samuel (Harvard)

My message

fs micromachining: great technique for manipulating matter

Introduction

Introduction



Breakdown threshold and plasma formation in femtosecond laser–solid interaction

D. von der Linde and H. Schüler

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Received March 6, 1995; revised manuscript received June 15, 1995

Combining femtosecond pump–probe techniques with optical microscopy, we have studied laser-induced optical breakdown in optically transparent solids with high temporal and spatial resolution. The threshold of plasma formation has been determined from measurements of the changes of the optical reflectivity associated with the developing plasma. It is shown that plasma generation occurs at the surface. We have observed a remarkable resistance to optical breakdown and material damage in the interaction of femtosecond laser pulses with bulk optical materials. © 1996 Optical Society of America

1. INTRODUCTION

The interaction of intense femtosecond laser pulses with solids offers the possibility of producing a new class of plasmas having approximately solid-state density and spatial density scale lengths much smaller than the wavelength of light. These high-density plasmas with extremely sharp density gradients are currently of great interest, particularly from the point of view of generating bright, ultrashort x-ray pulses. To produce such a plasma, the laser pulse should rise from the intensity level corresponding to the threshold of plasma formation to the peak value in a time much shorter than the time scale of plasma expansion. Thus the specification of the tol- … background or of the acceptable amount … pulse requires some knowledge of … of the target material. … into a dense … physics

One of the key points in the research of Bloembergen and his co-workers was the use of very tightly focused laser beams, which allowed them to reach the breakdown threshold of the materials while staying well below the critical power of self-focusing. Self-focusing is one of the major problems in the measurement of bulk breakdown thresholds. In a more recent review Soileau *et al.*[5] carefully examined the role of self-focusing in experiments measuring laser-induced breakdown of bulk dielectric materials. They concluded that the breakdown and damage thresholds are also strongly influenced by extrinsic effects.

Thus far, the issue of breakdown thresholds in femtosecond laser–solid interaction has barely been touched. Very recently, Du *et al.*[6] carried out laser-induced breakdown experiments on fused silica with pulses ranging in duration from 7 ns to as low as 150 fs. They reported an interesting dependence of the fluence threshold on pulse duration, particularly a pronounced increase of the threshold with decreasing pulse duration below 10 ps. … observations were interpreted in terms of the bulk … model. In related research, Stuart … dependence of the thresh- … of materials and … weak varia-

Introduction

"… clear evidence that no bulk plasmas…

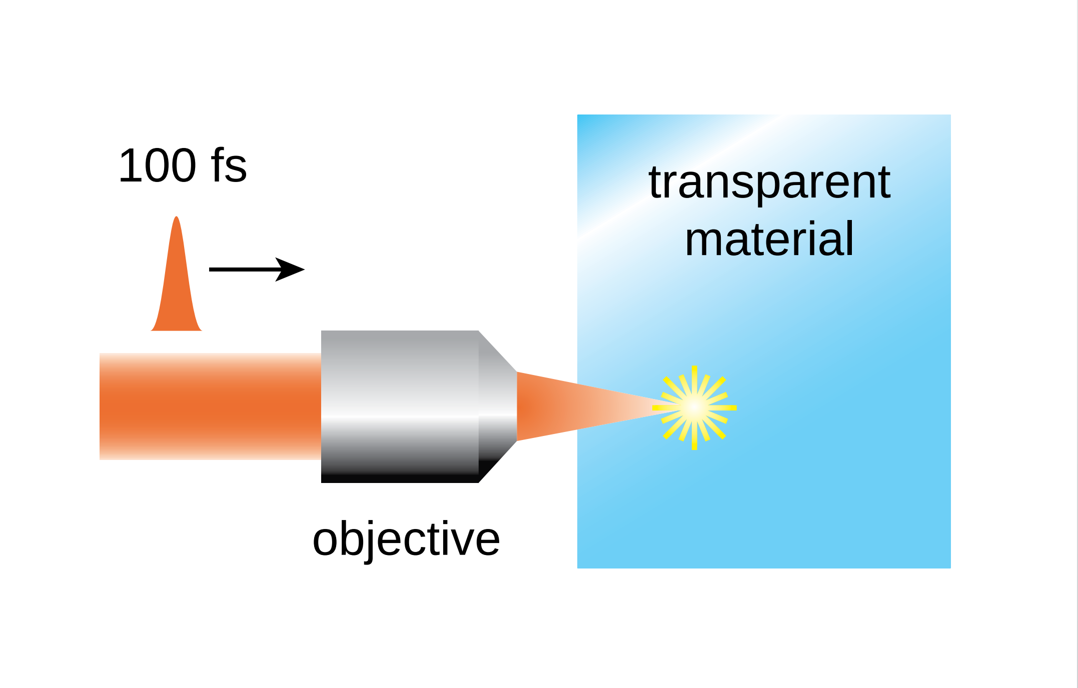
[and] … no bulk damage could be produced

with femtosecond laser pulses"

von der Linde, *et al*., *J. Opt. Soc. Am*. B **13**, 216 (1996)

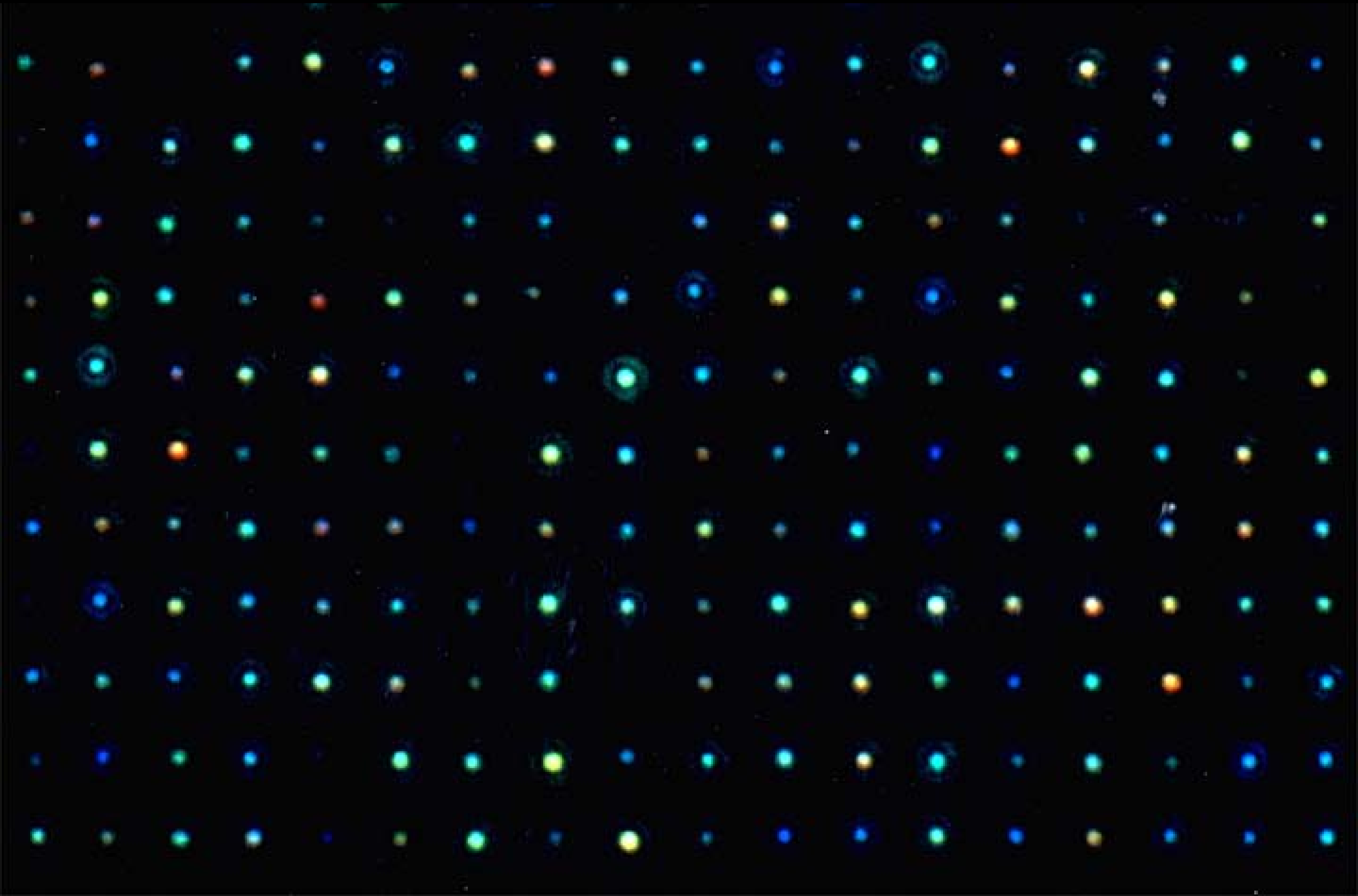
Introduction

focus laser beam inside material



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

Introduction

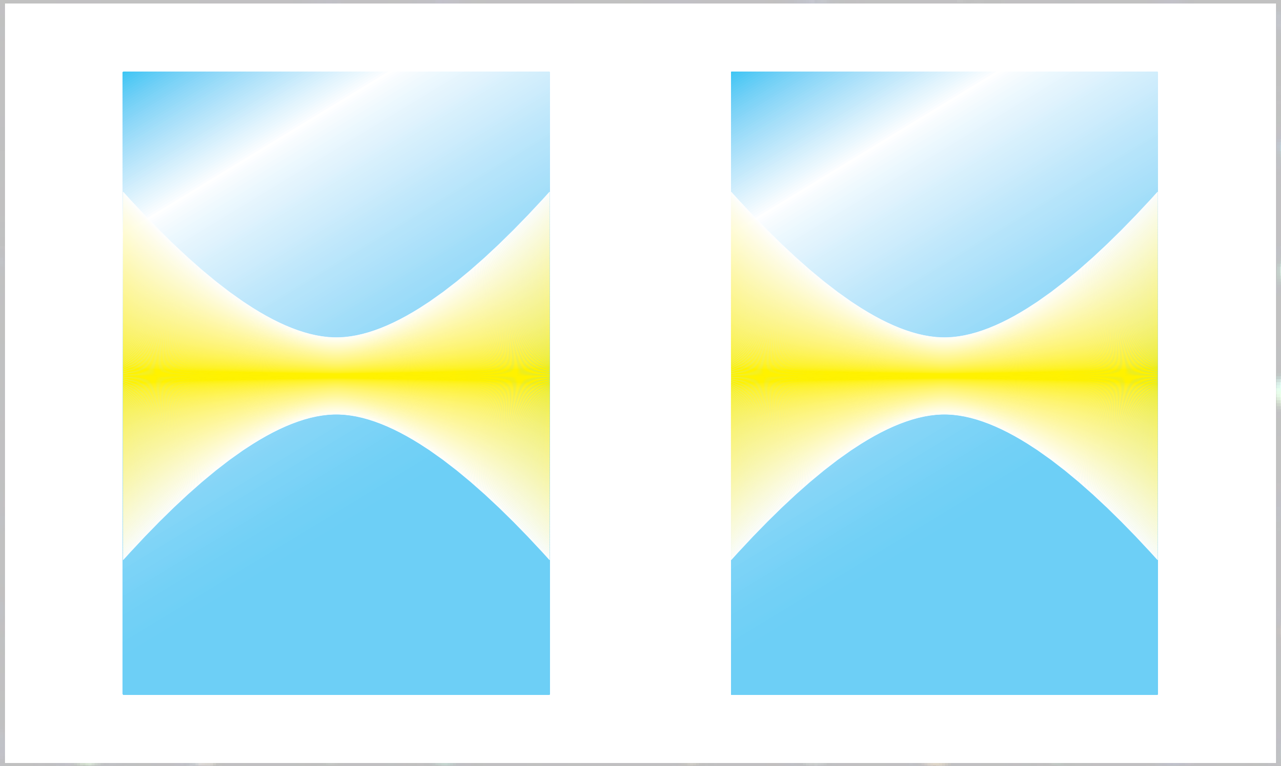


Introduction

photon energy $<$ bandgap $\longrightarrow$ nonlinear interaction

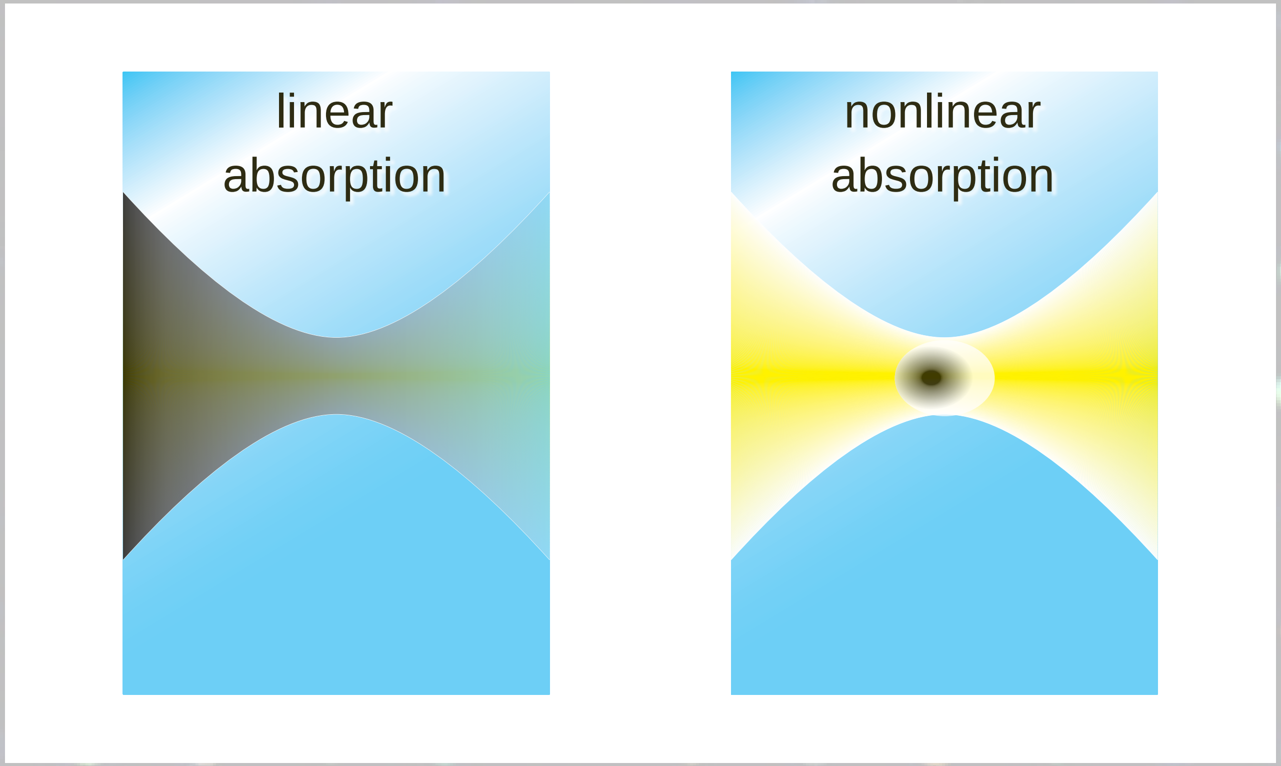
Introduction

nonlinear interaction provides bulk confinement



Introduction

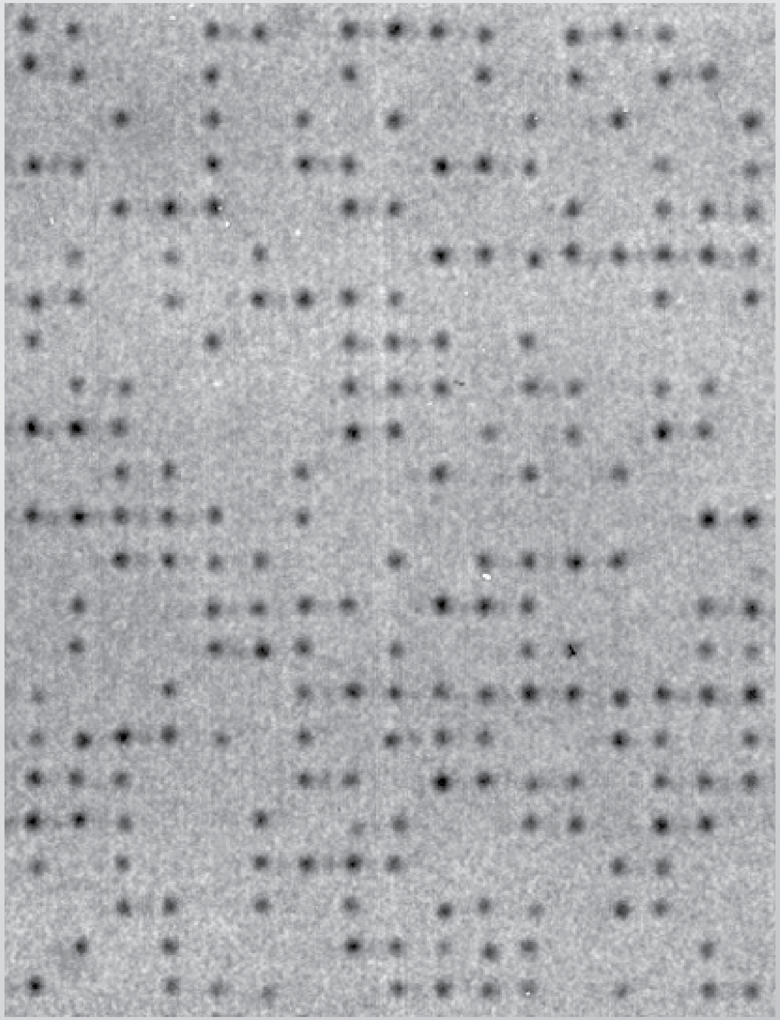
nonlinear interaction provides bulk confinement



Femtosecond micromachining

Some applications:

- data storage
- waveguides
- microfluidics

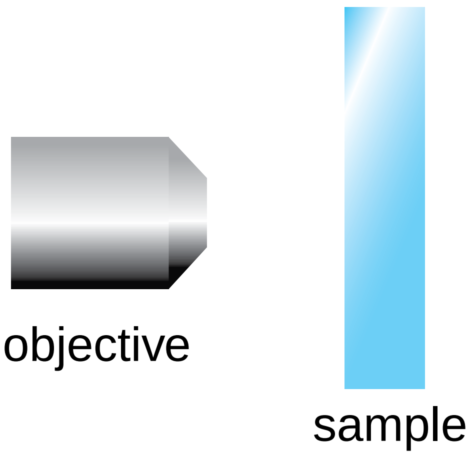


Outline

- femtosecond micromachining
- low-energy machining
- applications

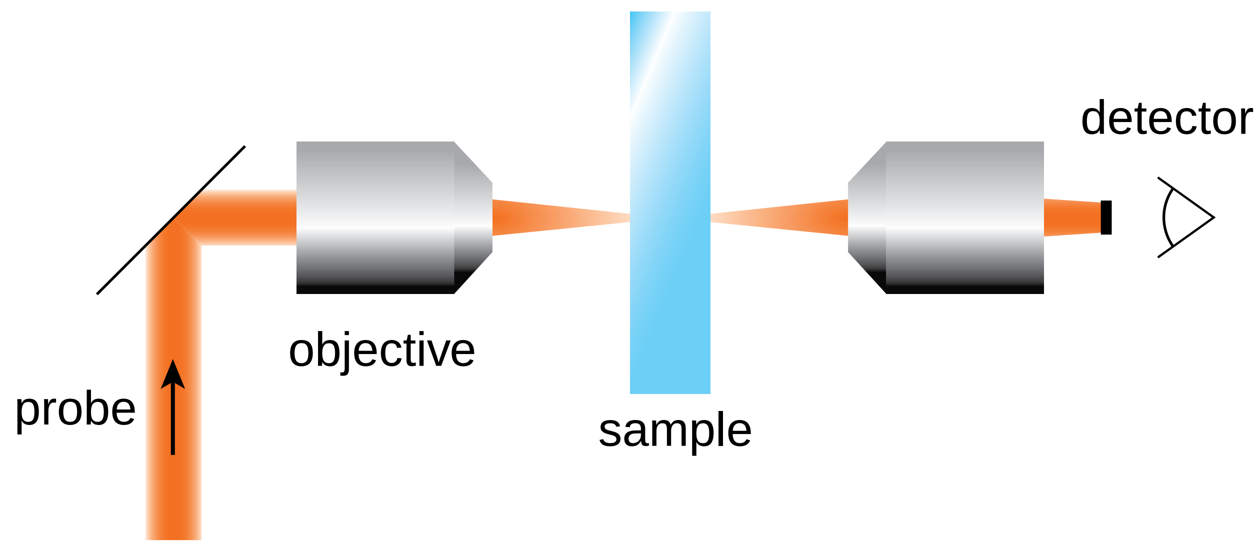
Femtosecond micromachining

Dark-field scattering



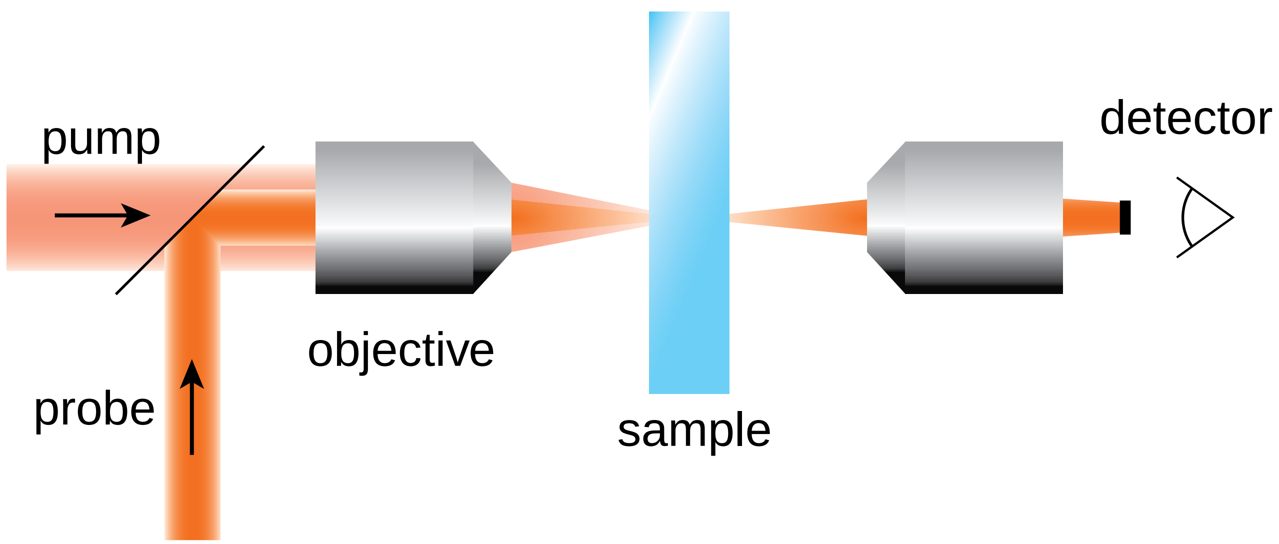
Femtosecond micromachining

block probe beam…



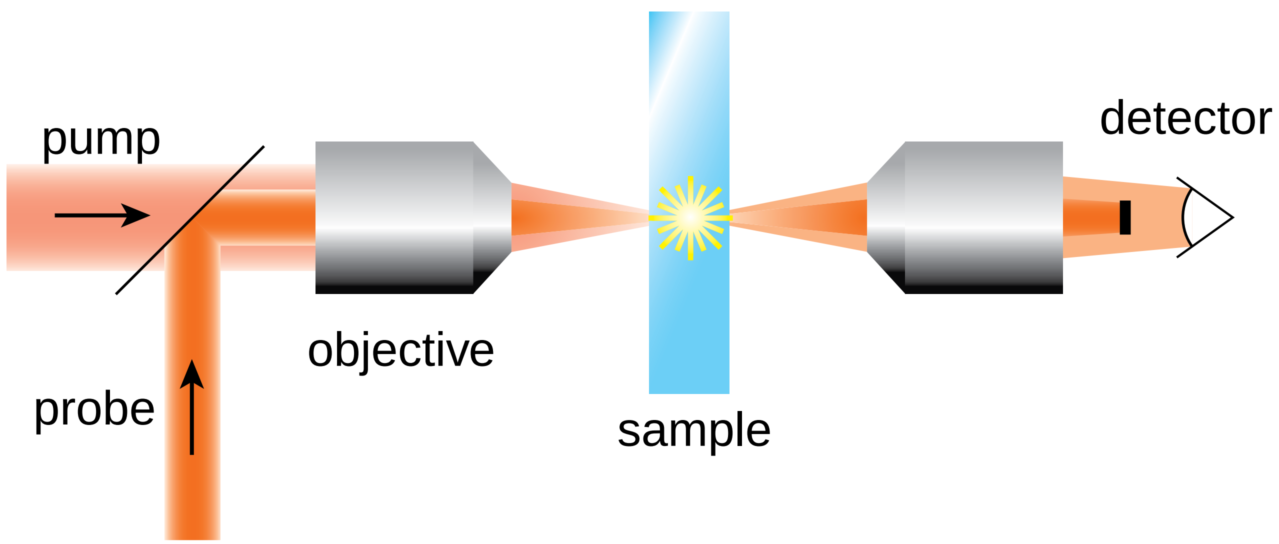
Femtosecond micromachining

… bring in pump beam…



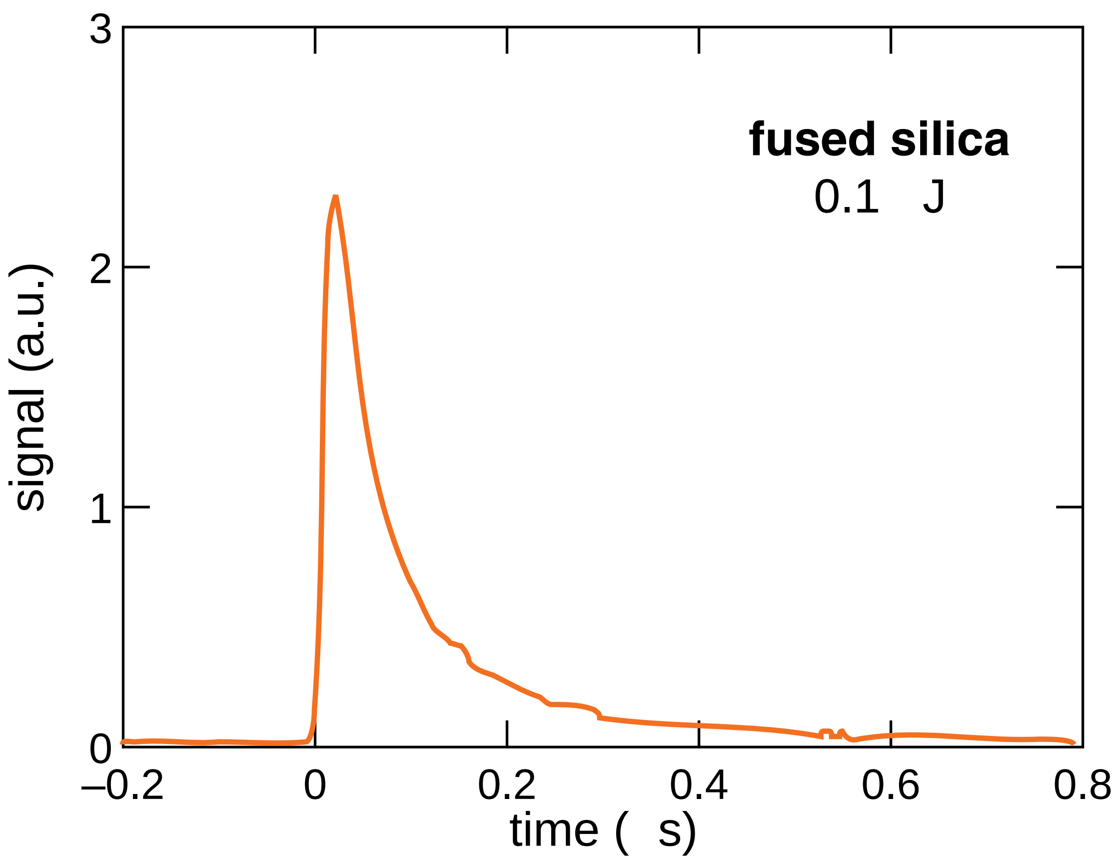
Femtosecond micromachining

... damage scatters probe beam



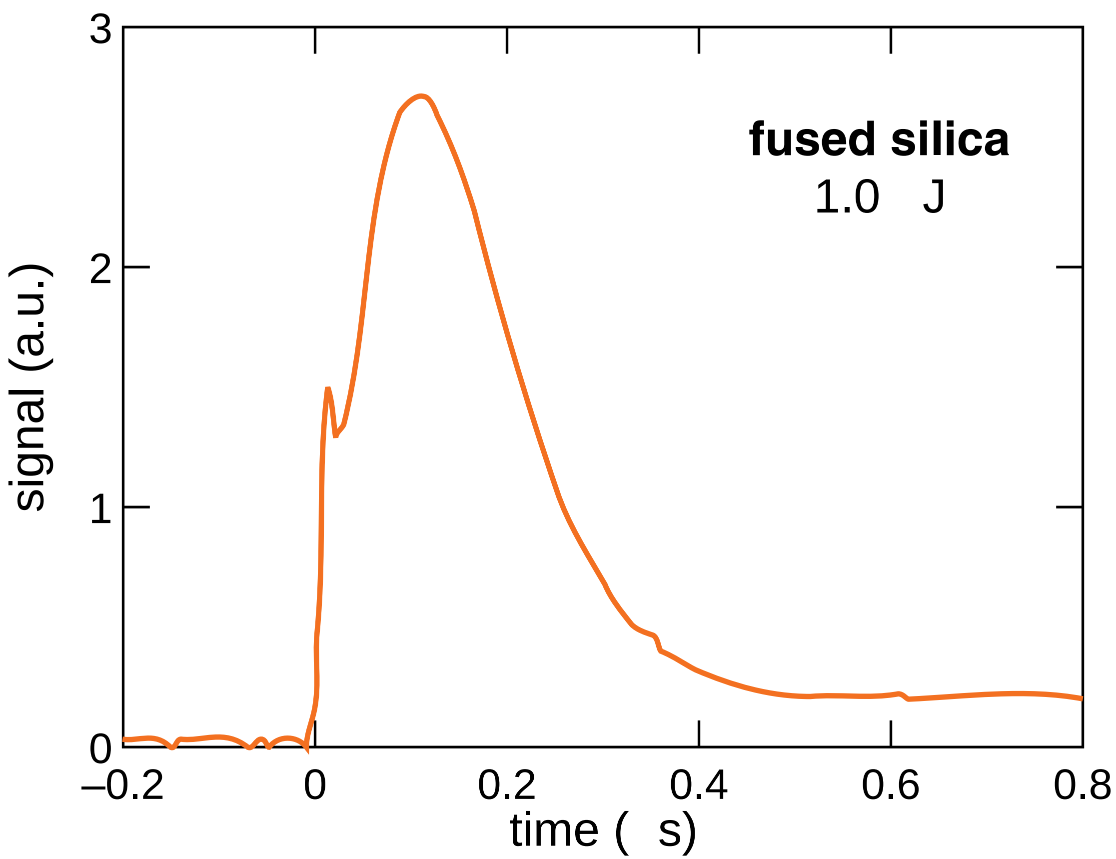
Femtosecond micromachining

scattered signal



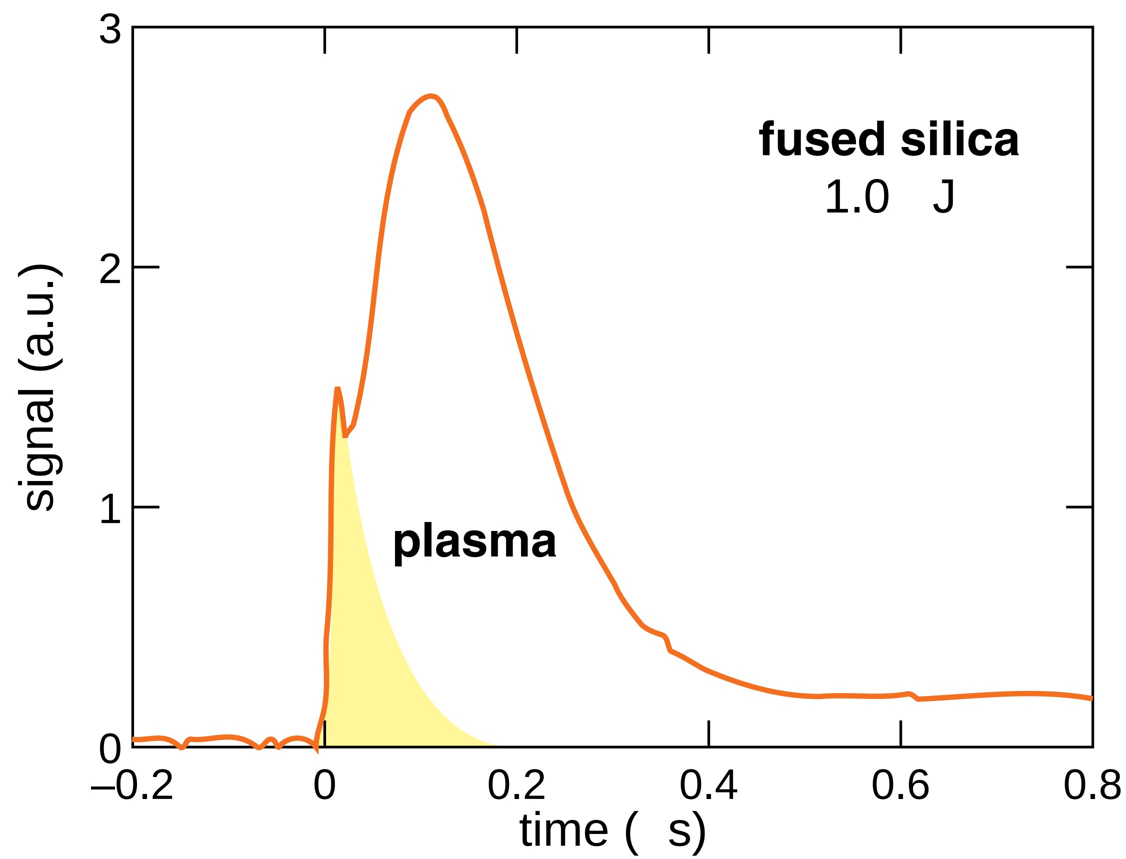
Femtosecond micromachining

scattered signal



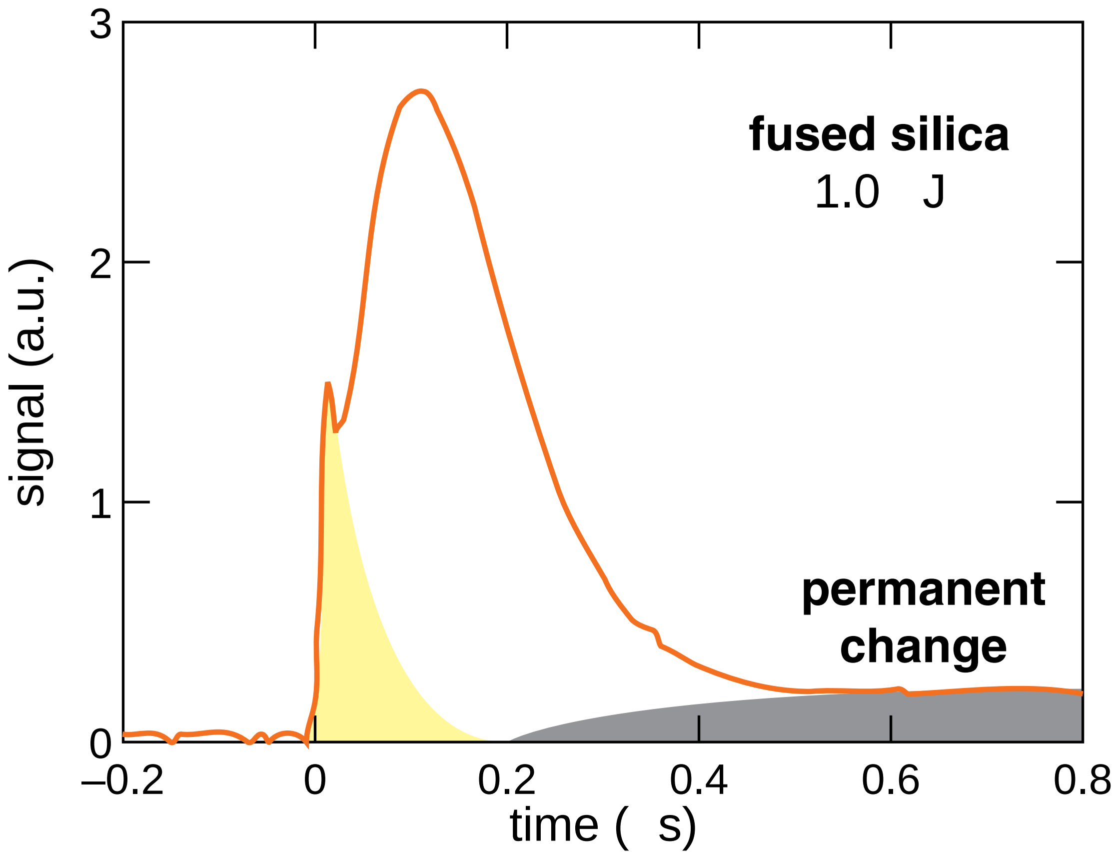
Femtosecond micromachining

scattered signal



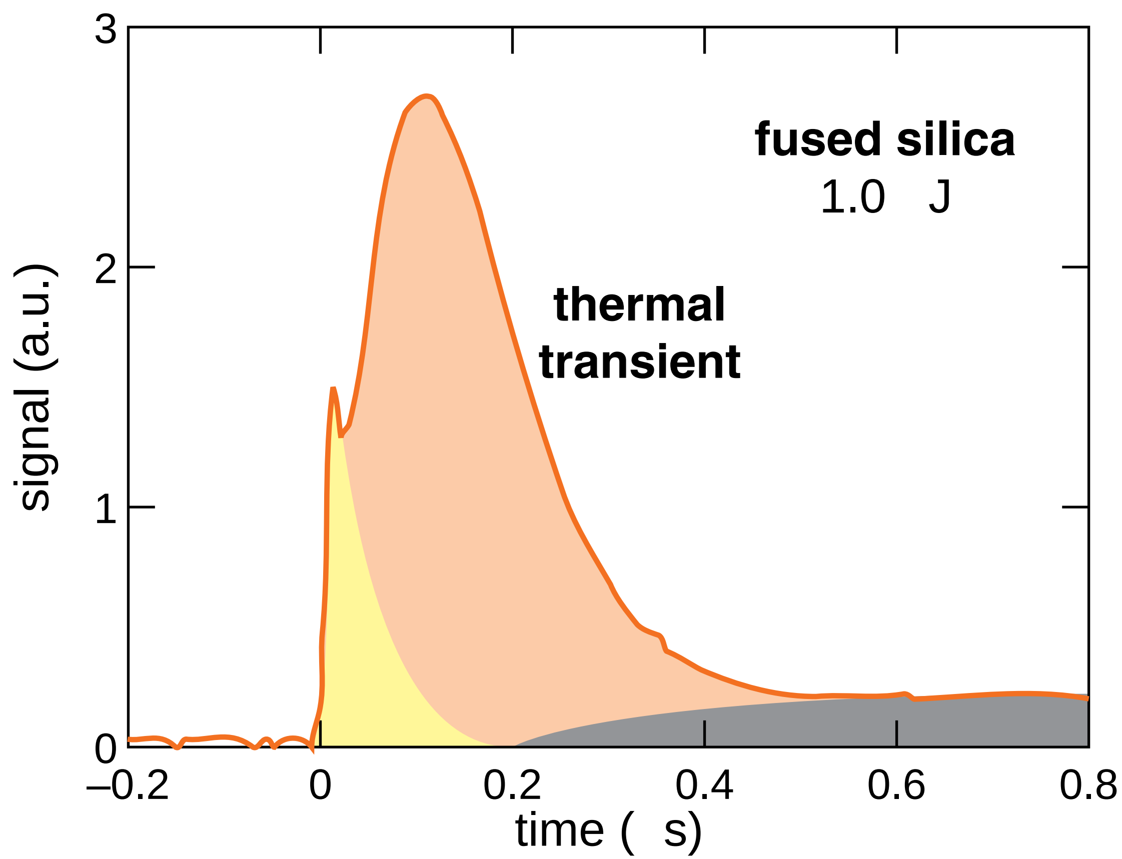
Femtosecond micromachining

scattered signal



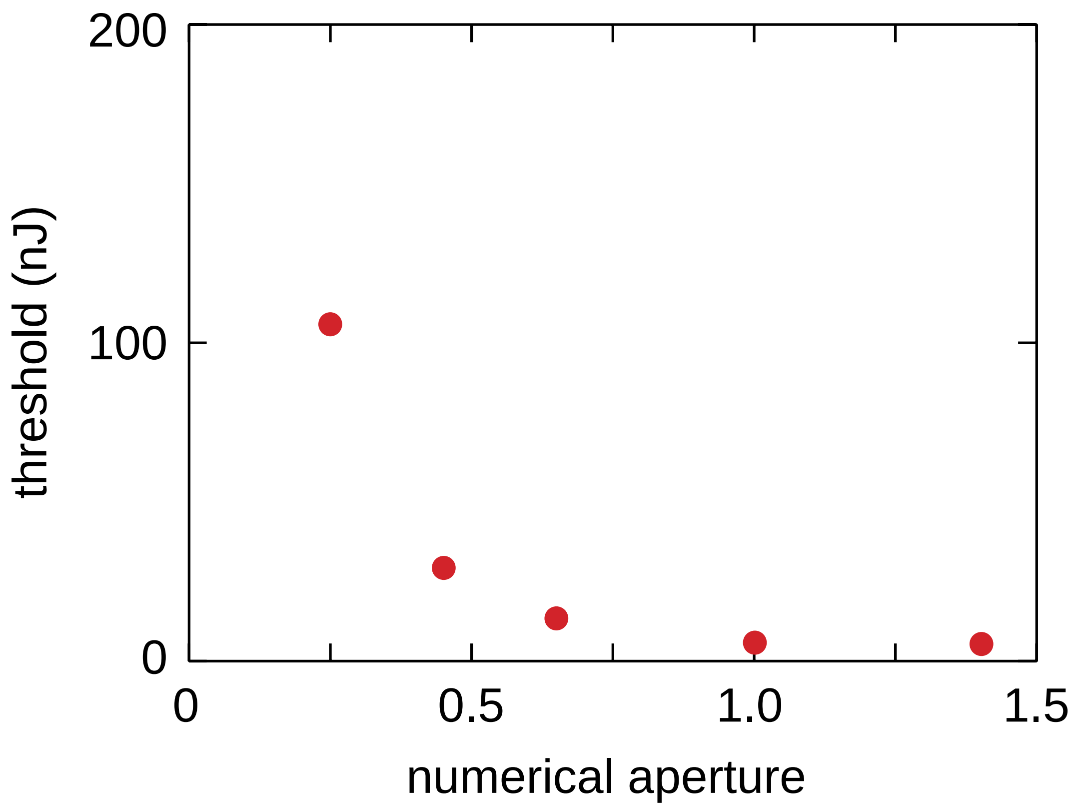
Femtosecond micromachining

scattered signal



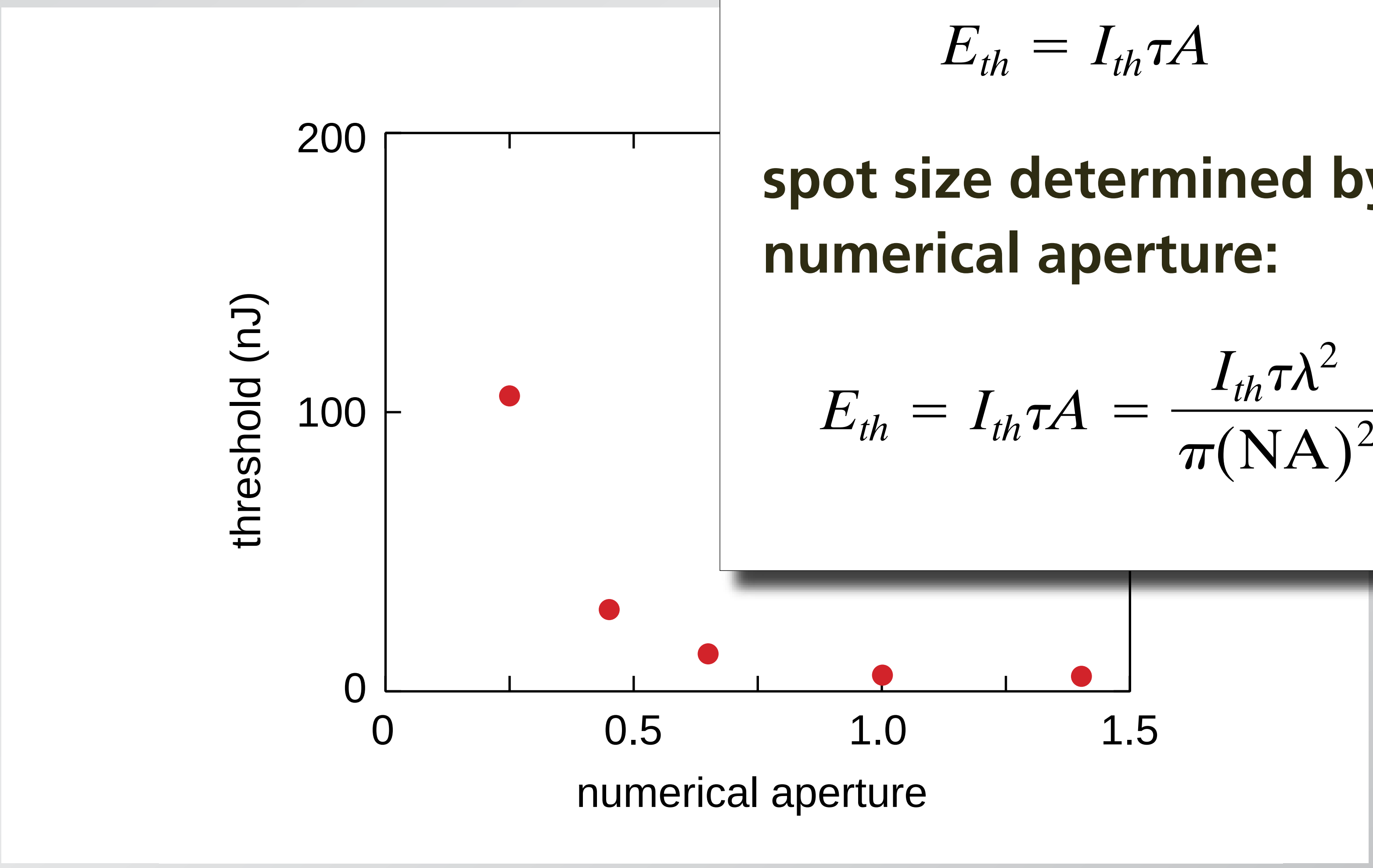
Femtosecond micromachining

vary numerical aperture



Femtosecond micromachining

vary numeric



intensity threshold:

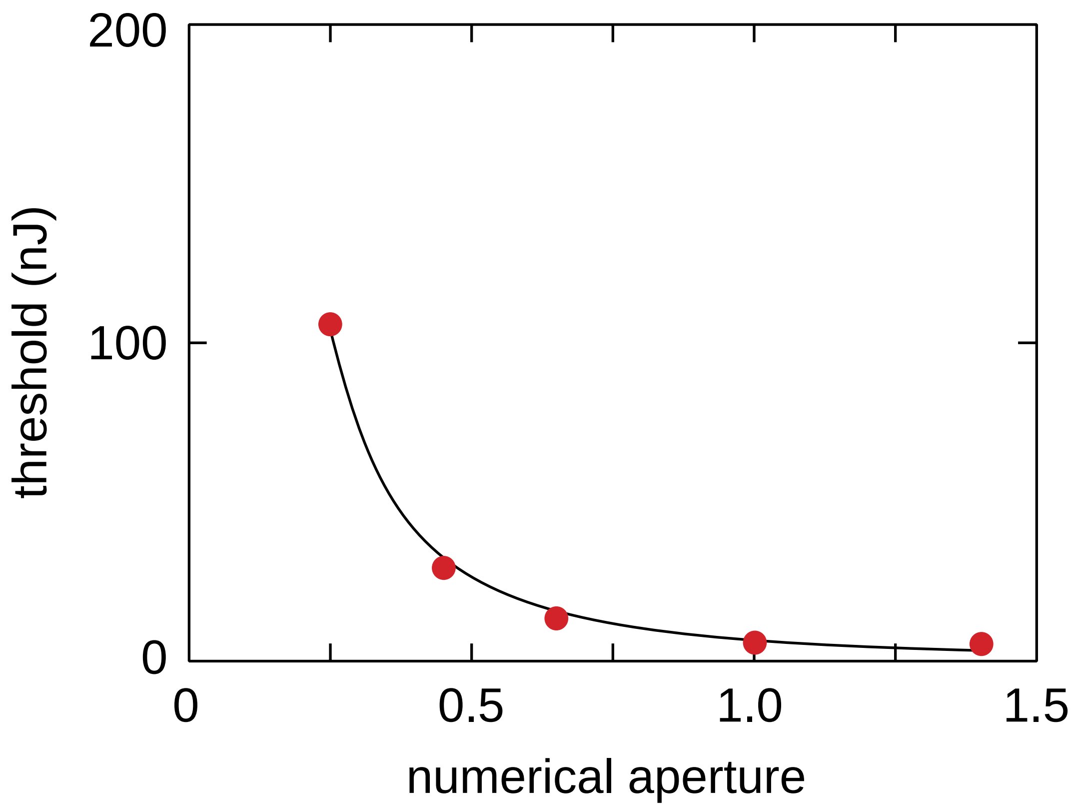
$$E_{th} = I_{th}\tau A$$

spot size determined by numerical aperture:

$$E_{th} = I_{th}\tau A = \frac{I_{th}\tau\lambda^2}{\pi(\mathrm{NA})^2}$$

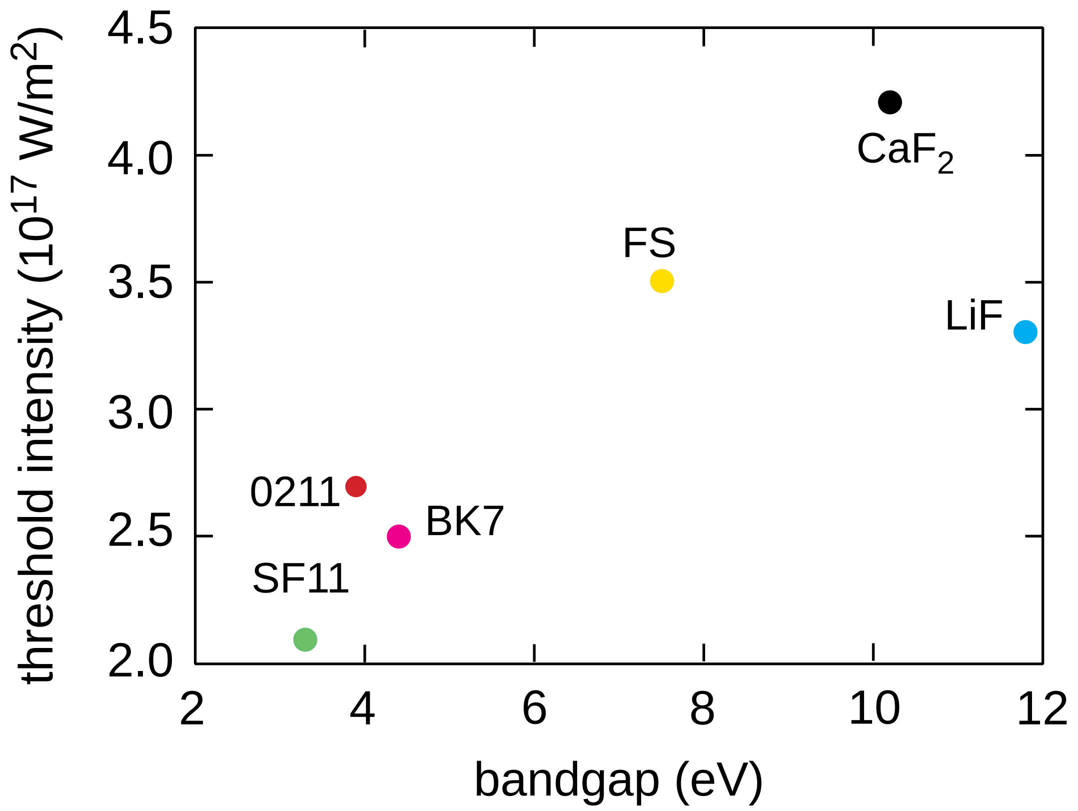
Femtosecond micromachining

fit gives threshold intensity: I_{th} = 2.5 x 10^{17} W/m^2



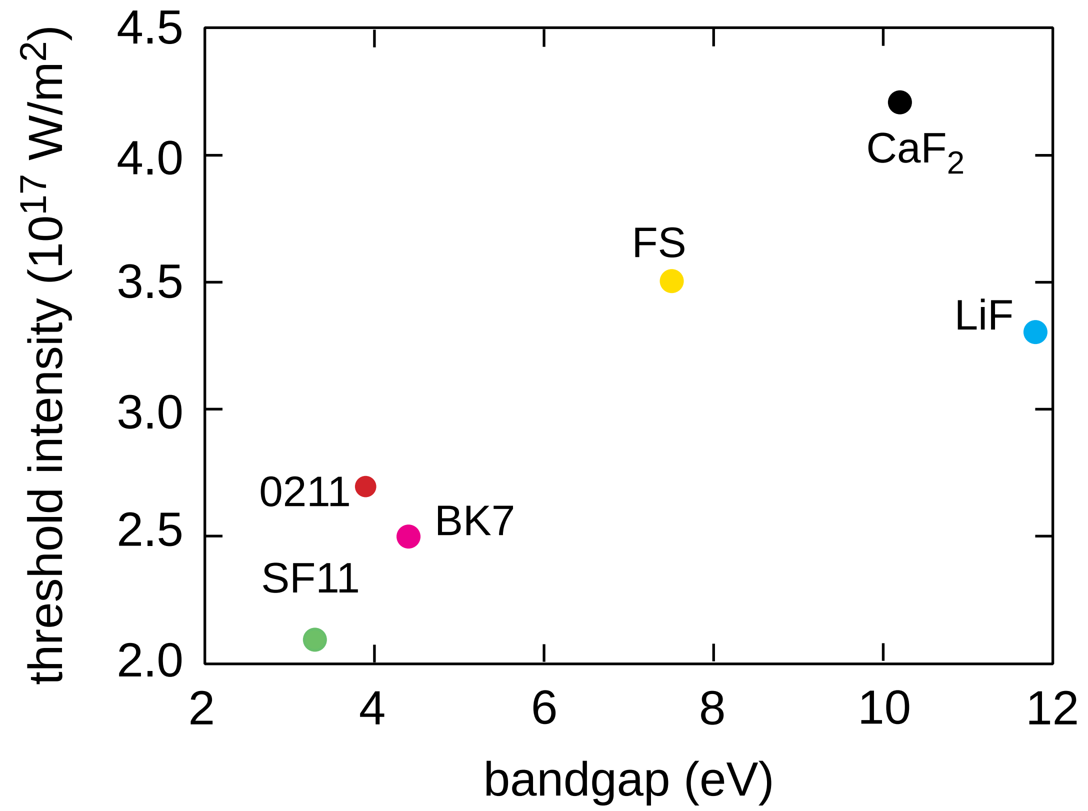
Femtosecond micromachining

vary material…



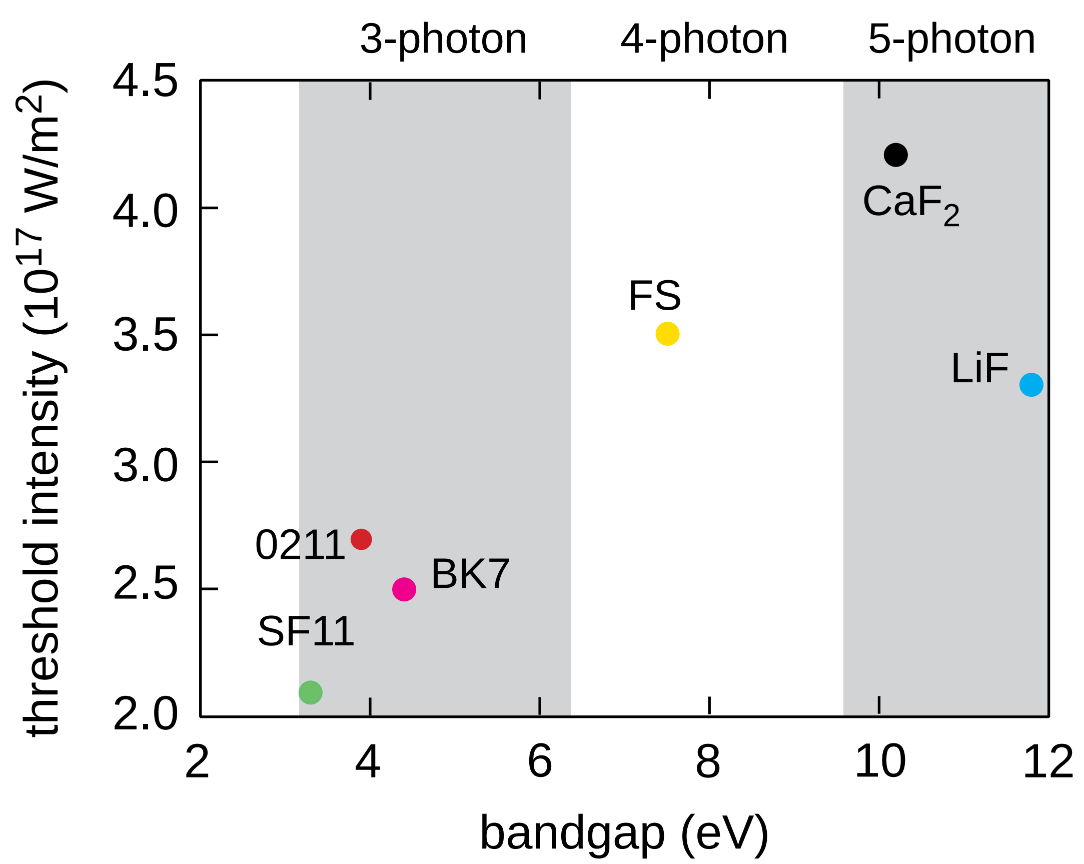
Femtosecond micromachining

…threshold varies with band gap (but not much!)



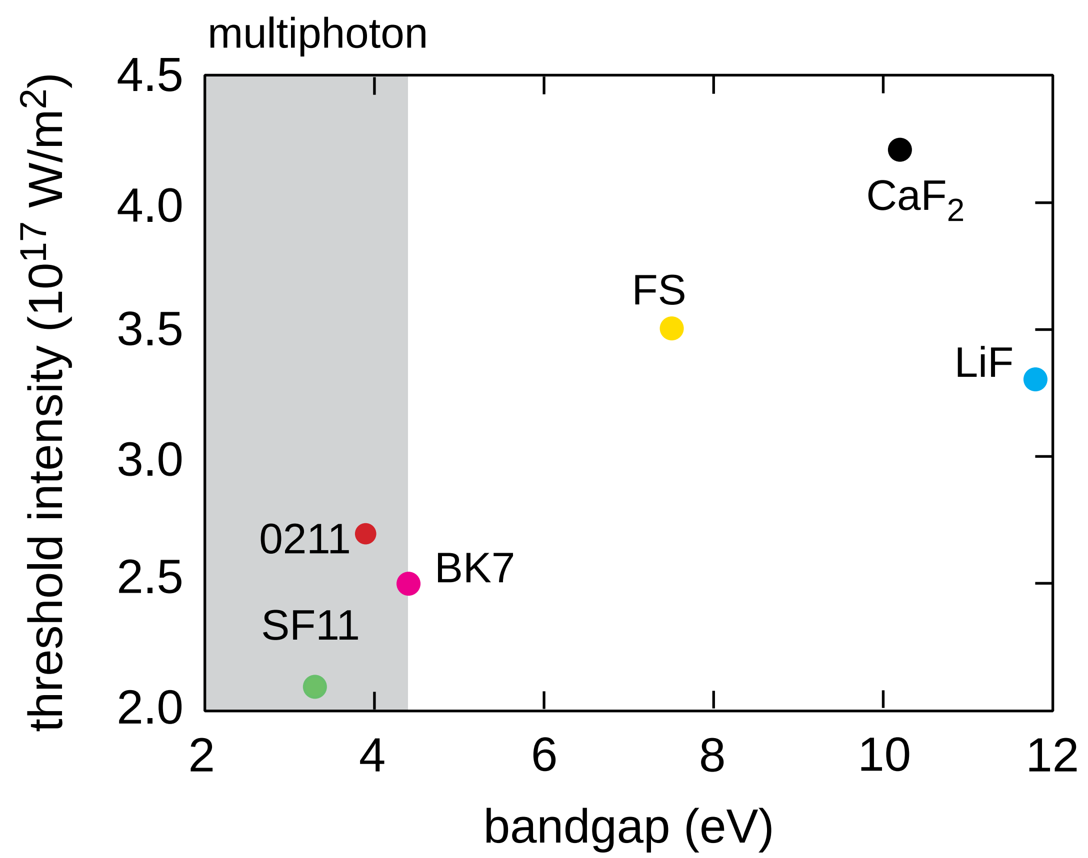
Femtosecond micromachining

would expect much more than a factor of 2



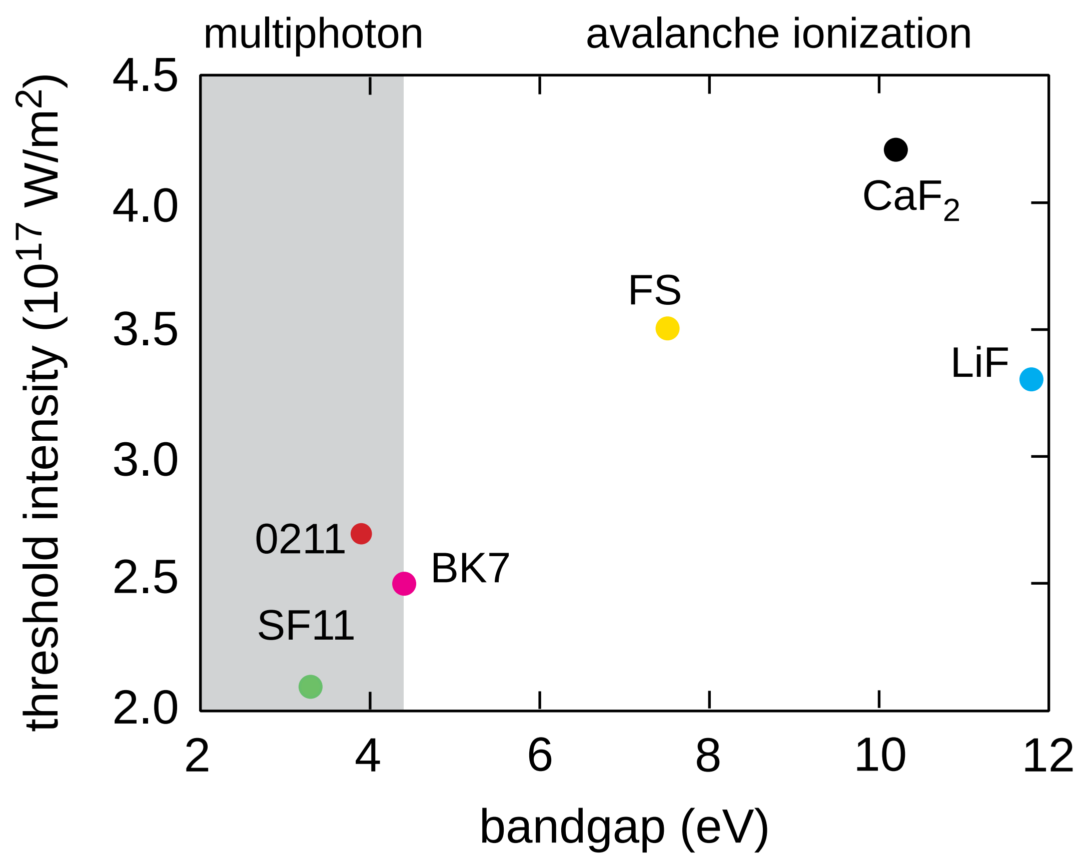
Femtosecond micromachining

critical density reached by multiphoton for low gap only



Femtosecond micromachining

avalanche ionization important at high gap



Femtosecond micromachining

what prevents damage at low NA?

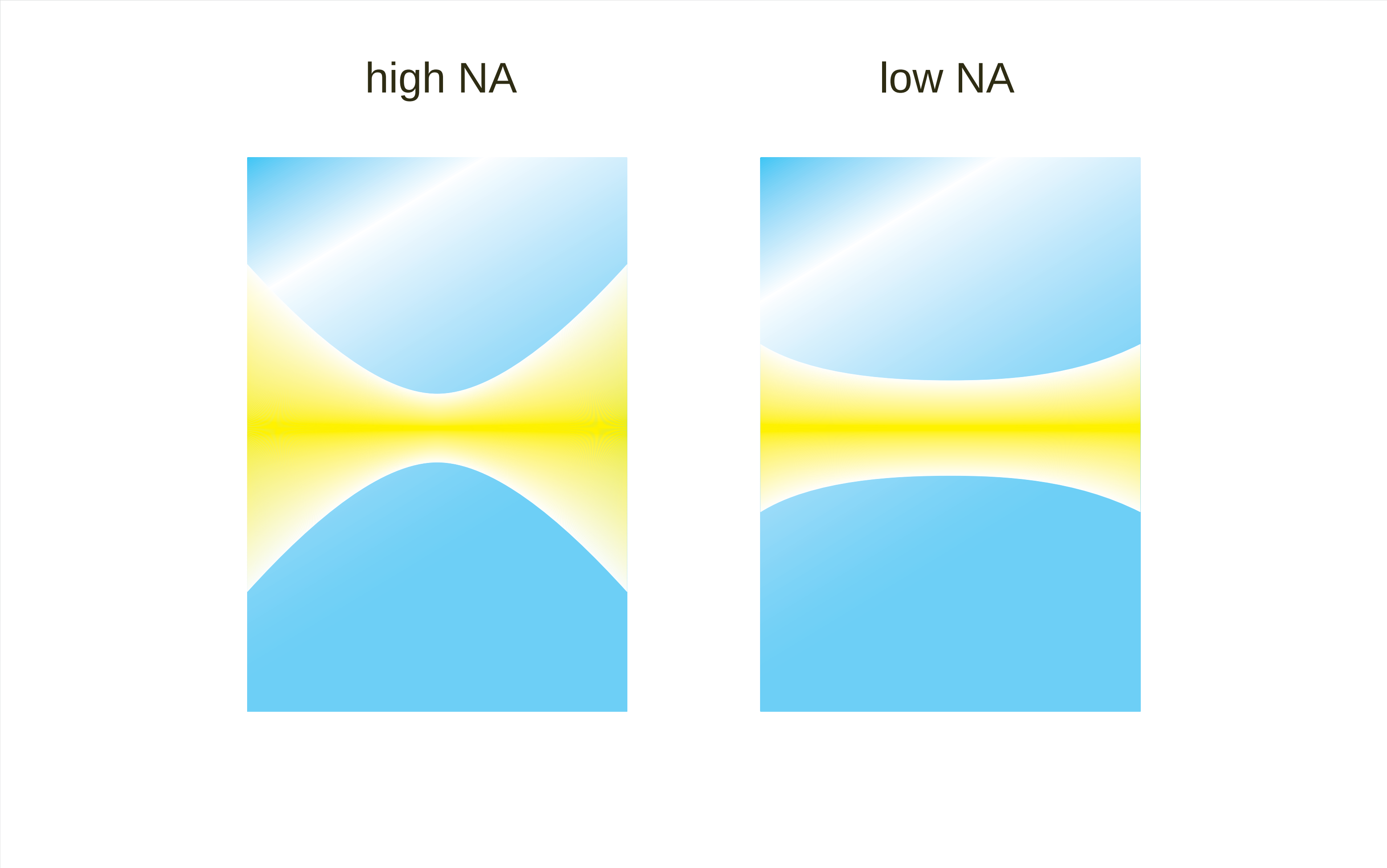
Femtosecond micromachining

Competing nonlinear effects:

- multiphoton absorption
- supercontinuum generation
- self-focusing

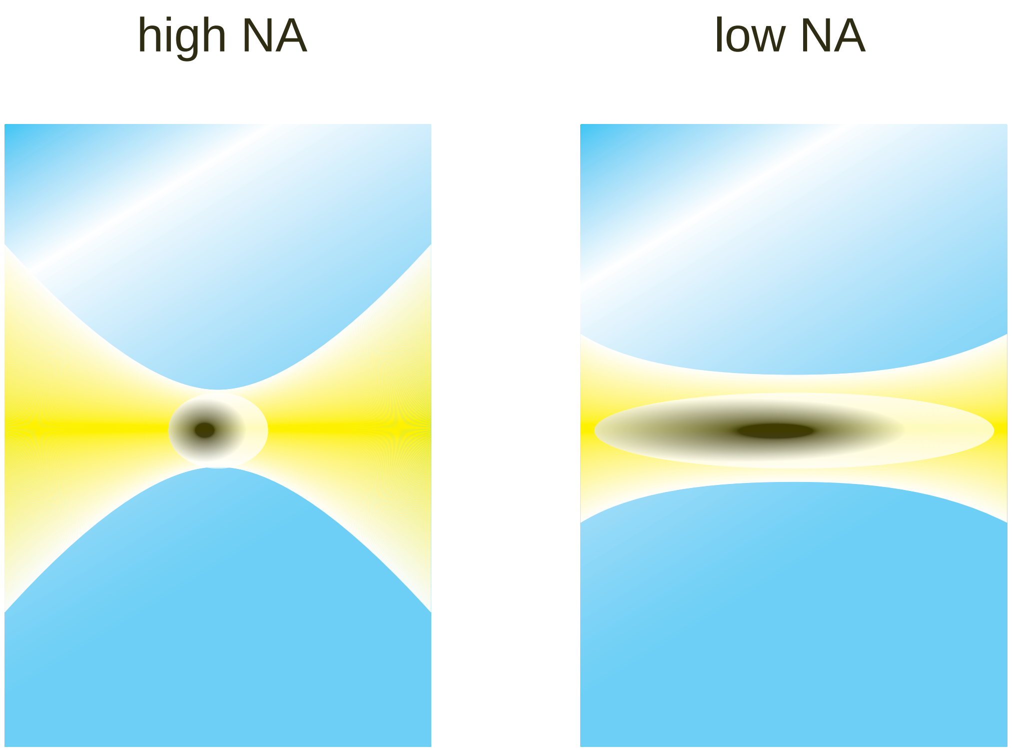
Femtosecond micromachining

why the difference?



Femtosecond micromachining

very different confocal length/interaction length

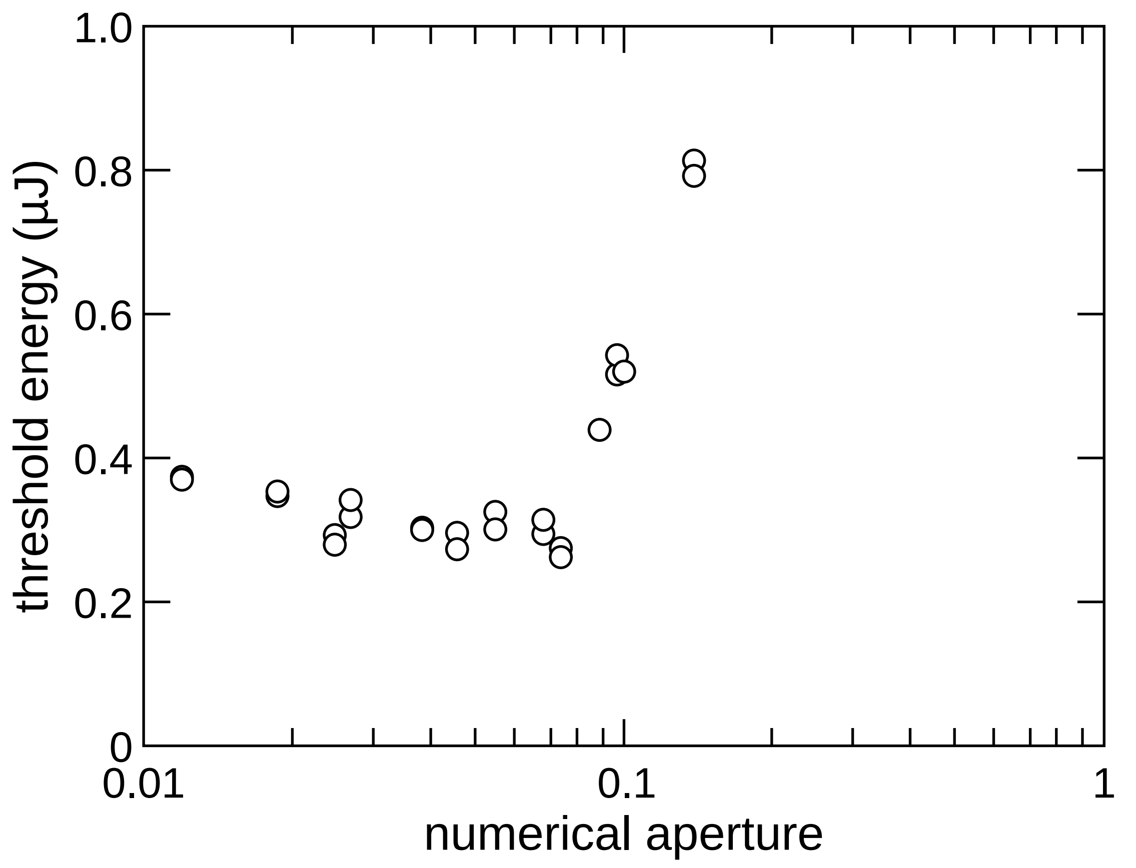


Femtosecond micromachining

high NA: interaction length too short for self-focusing

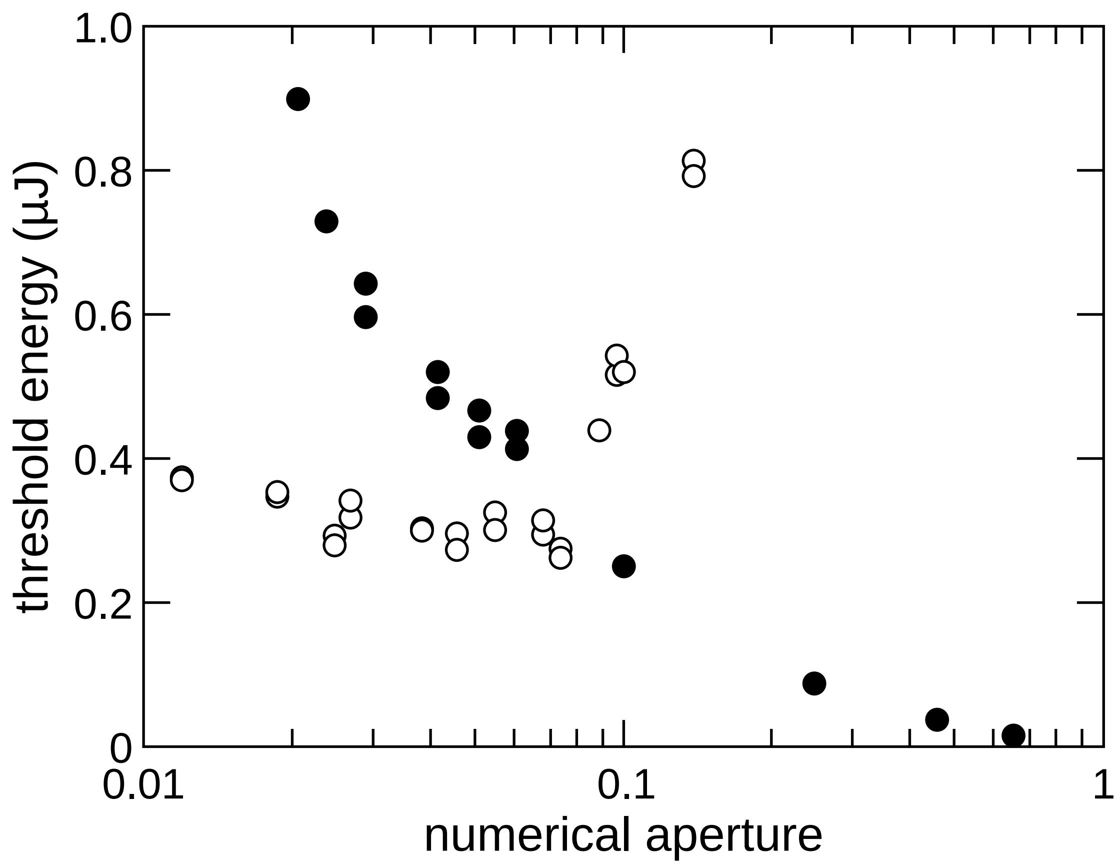
Femtosecond micromachining

threshold for supercontinuum generation



Femtosecond micromachining

threshold for damage



Femtosecond micromachining

Points to keep in mind:

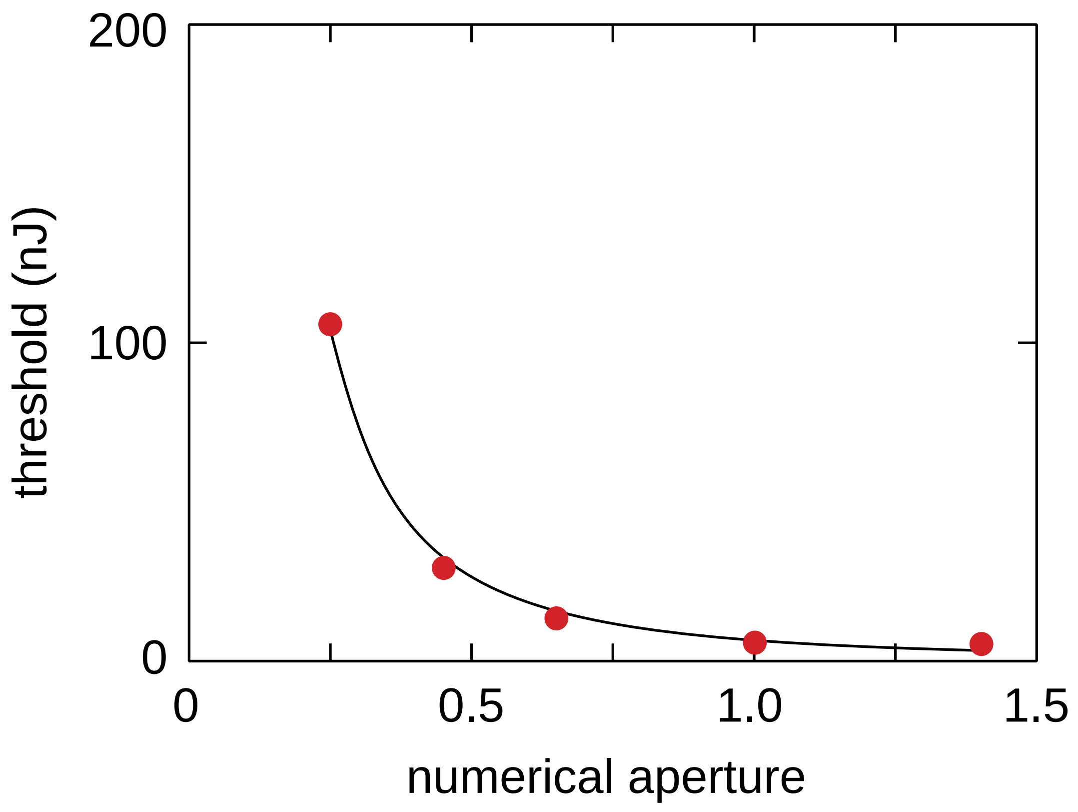
- threshold critically dependent on NA
- surprisingly little material dependence
- avalanche ionization important

Outline

- femtosecond micromachining
- **low-energy machining**
- applications

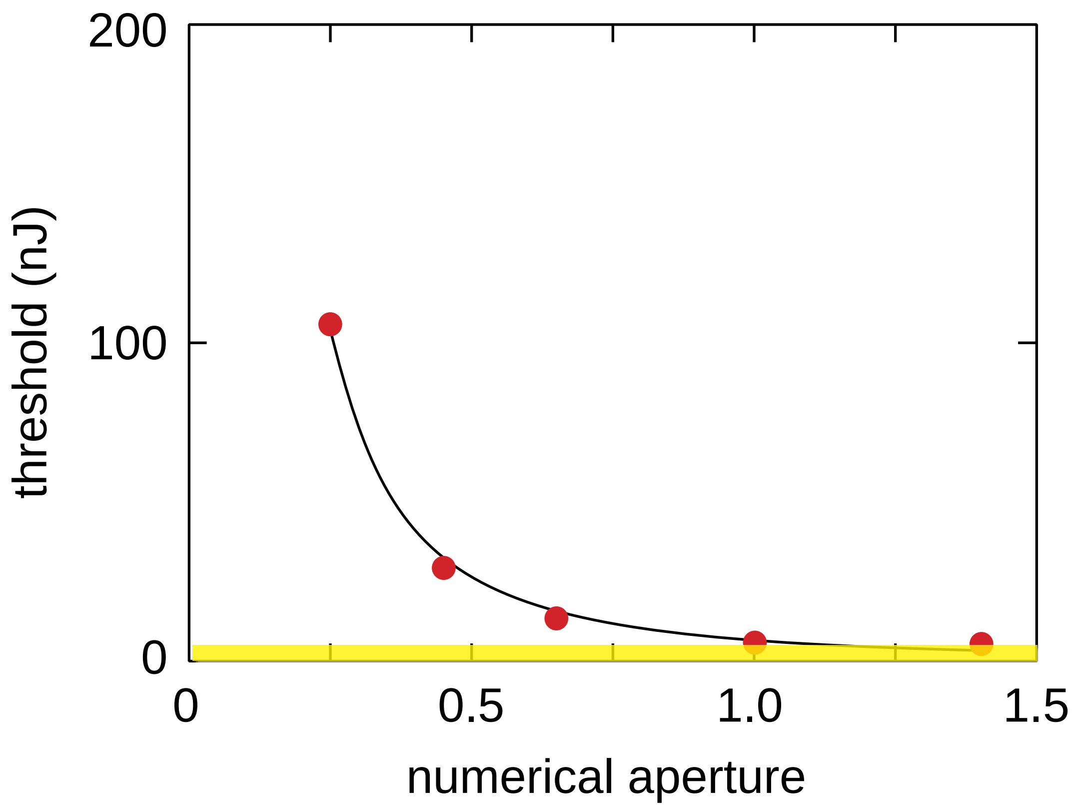
Low-energy machining

threshold decreases with increasing numerical aperture



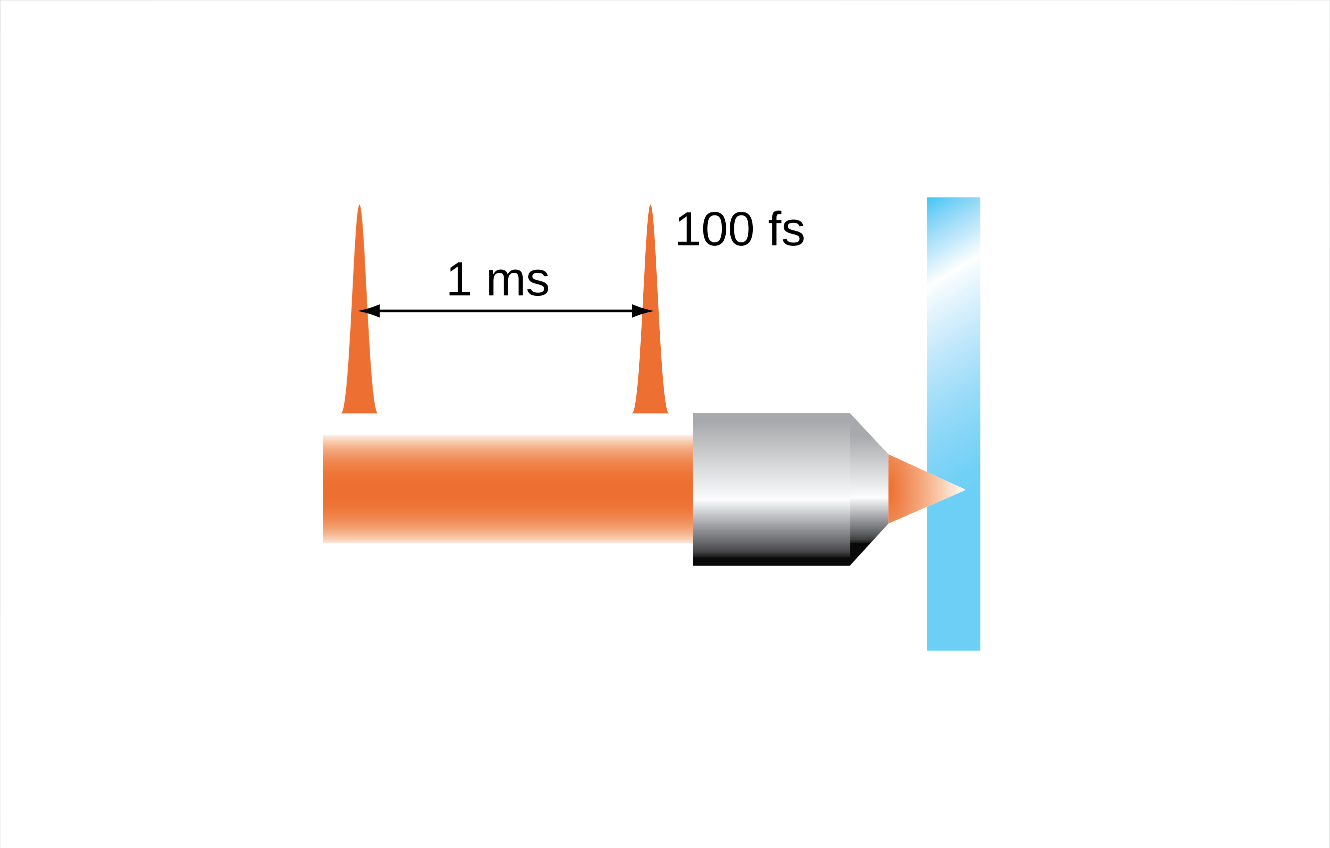
Low-energy machining

less than 10 nJ at high numerical aperture!



Low-energy machining

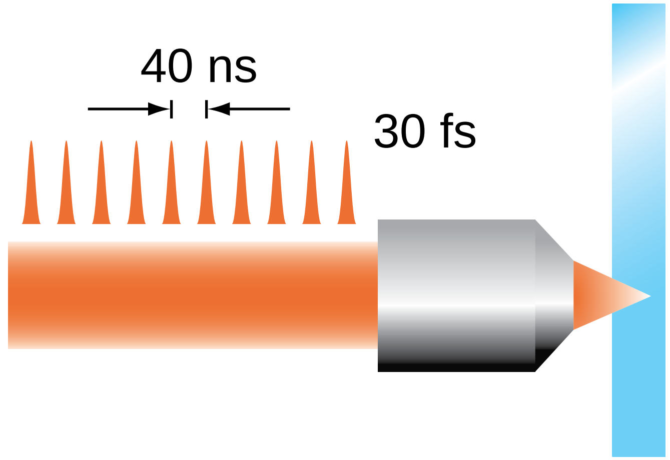
amplified laser: 1 kHz, 1 mJ



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

Low-energy machining

long cavity oscillator: 25 MHz, 25 nJ



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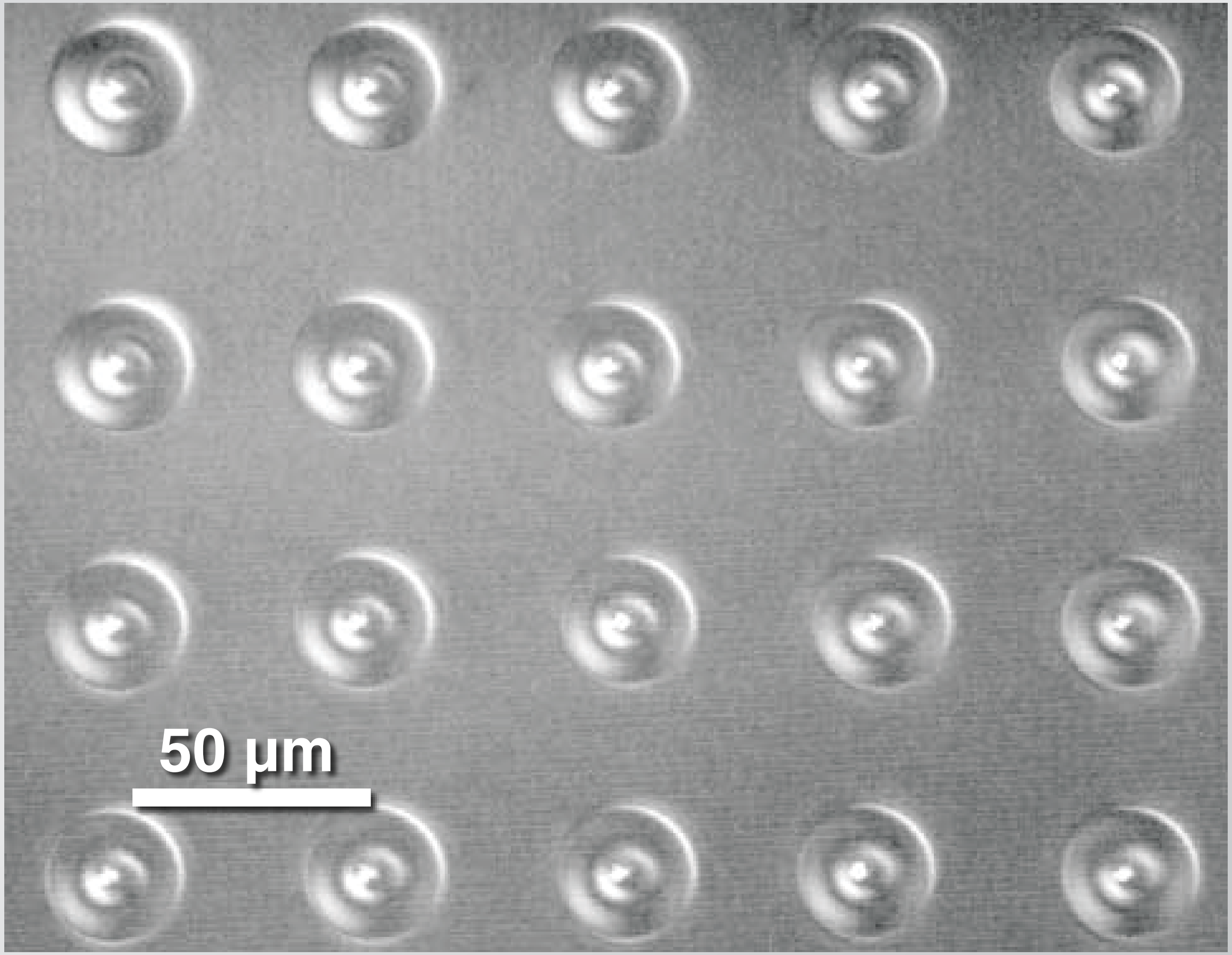
Low-energy machining



Low-energy machining

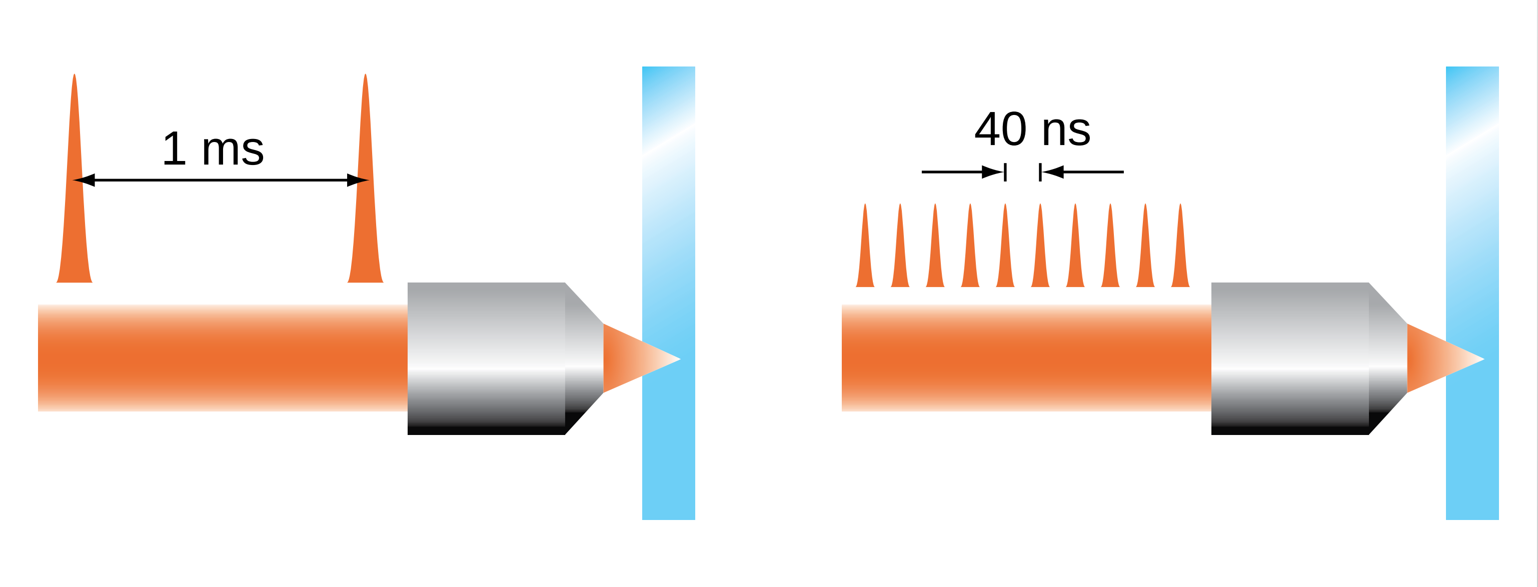
High repetition-rate micromachining:

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

Low-energy machining

amplified laser

oscillator

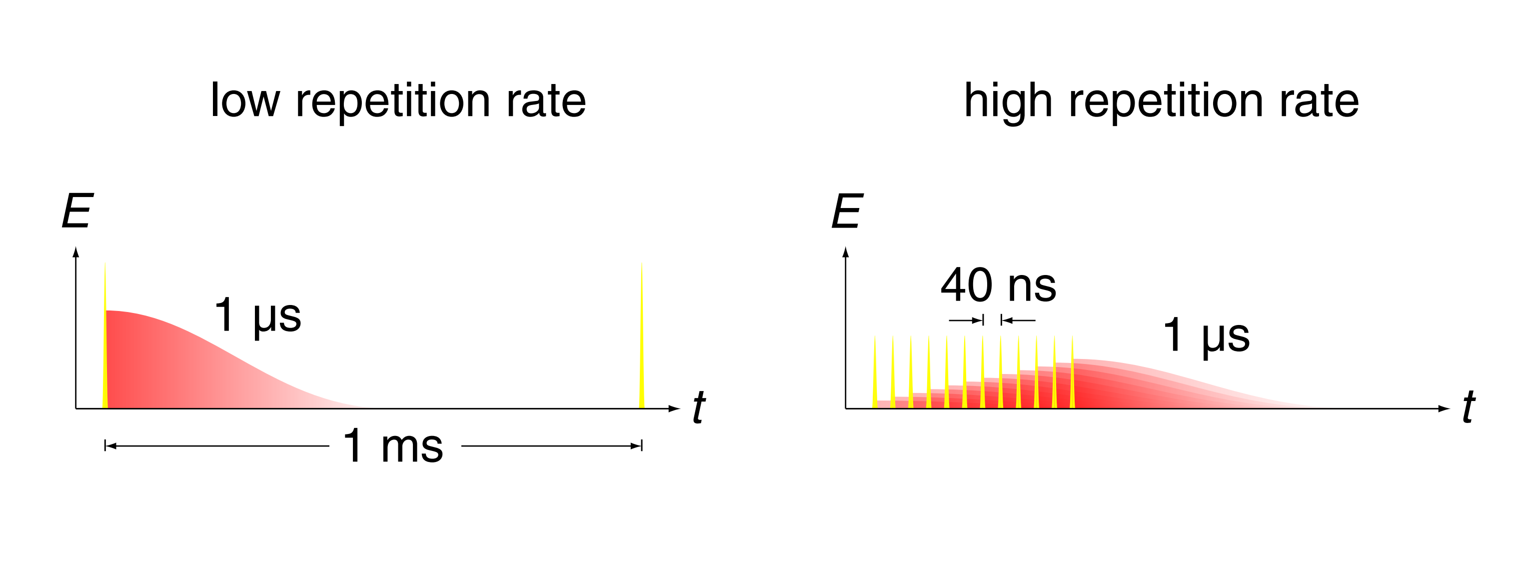


repetitive

cumulative

Low-energy machining

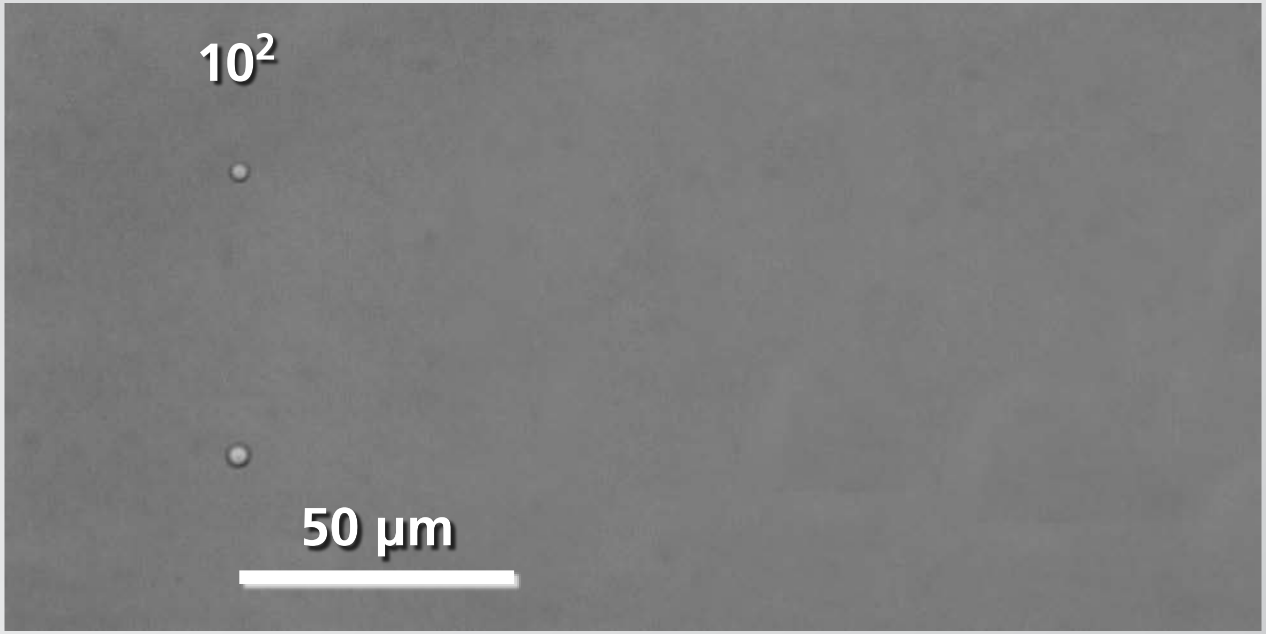
amplified laser | **oscillator**



repetitive | **cumulative**

Low-energy machining

the longer the irradiation…



Low-energy machining

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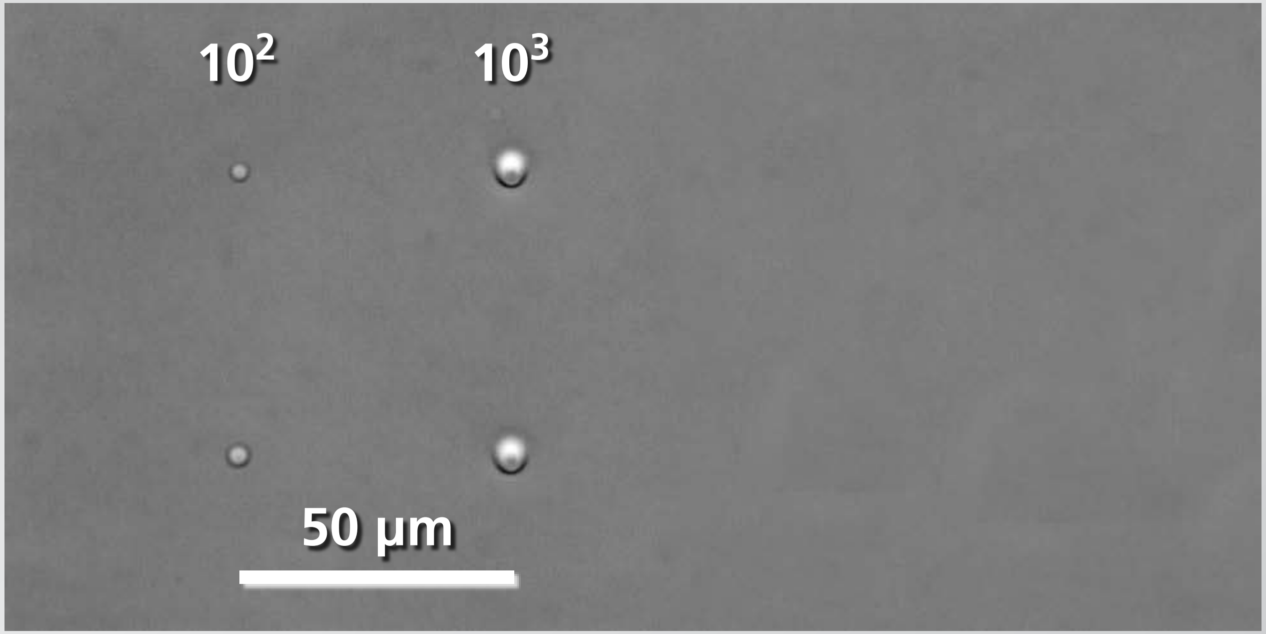

Low-energy machining

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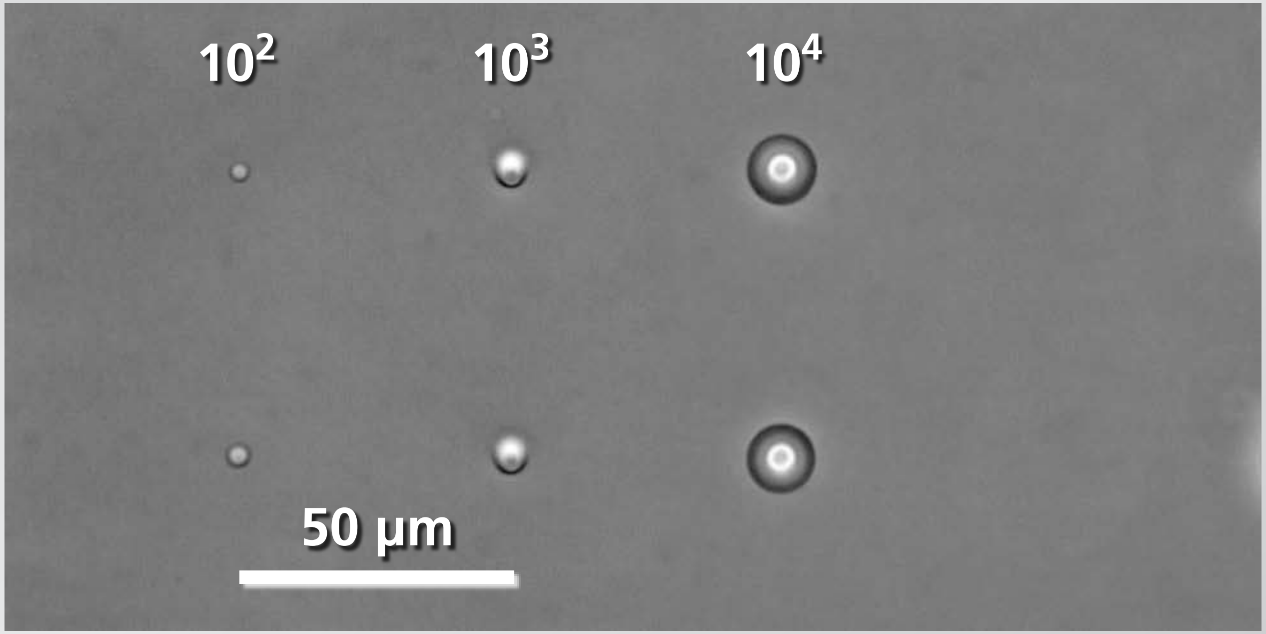

Low-energy machining

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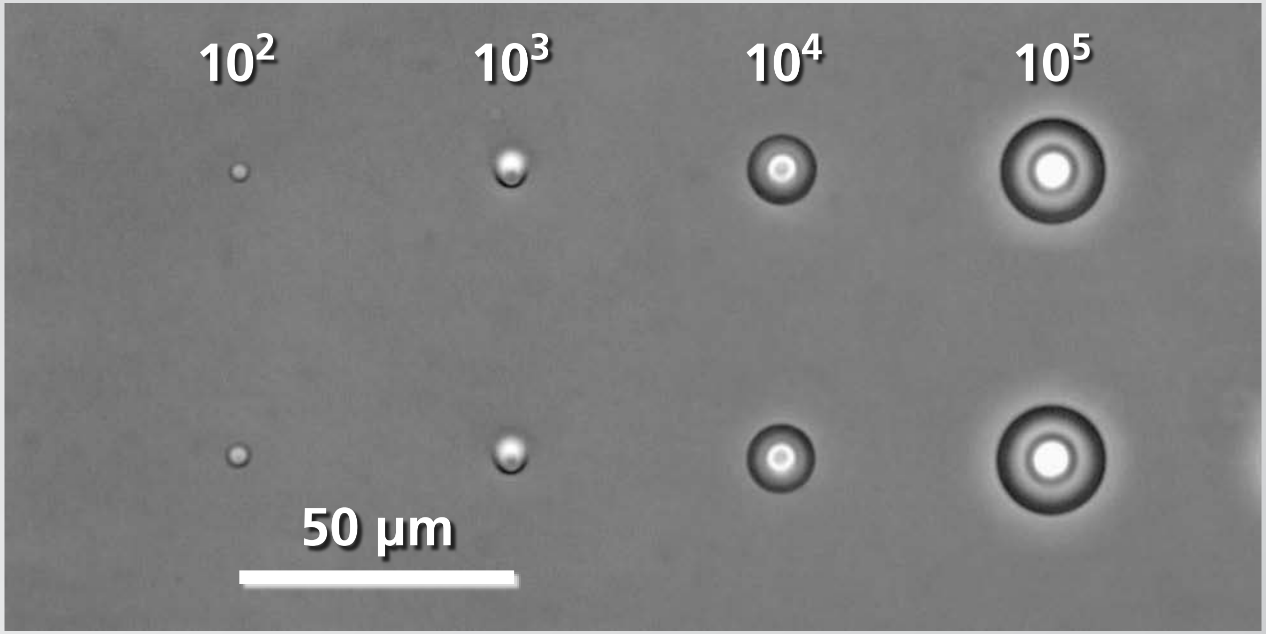
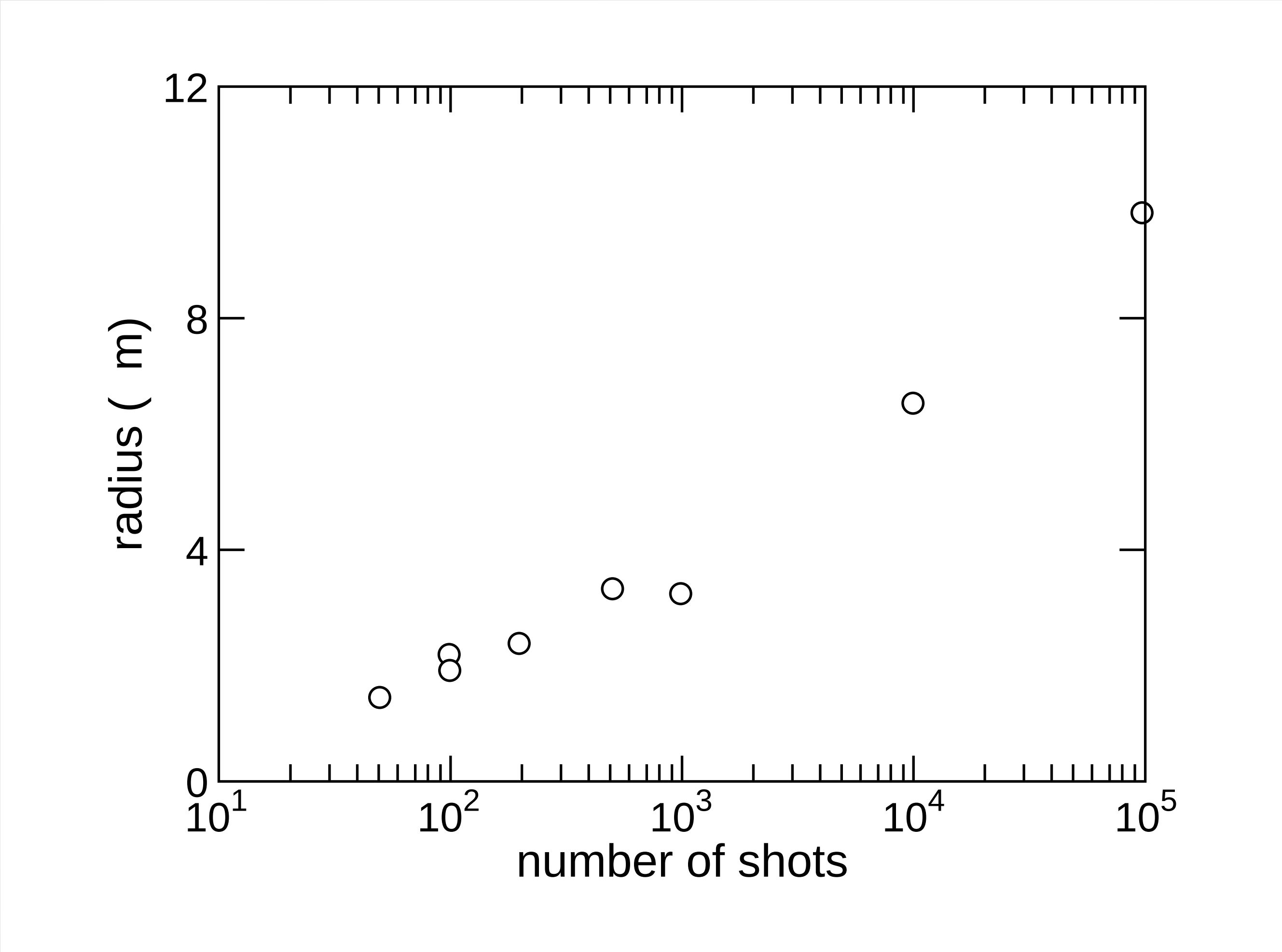


… the larger the radius

Low-energy machining

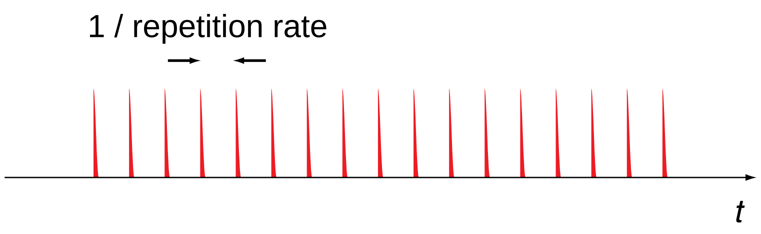


Low-energy machining

at high-rep rate: internal “point-source of heat”

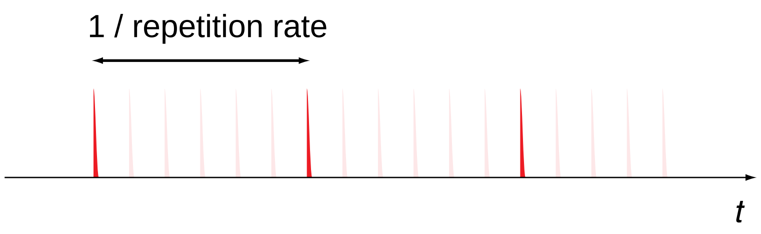
Low-energy machining

repetition-rate control



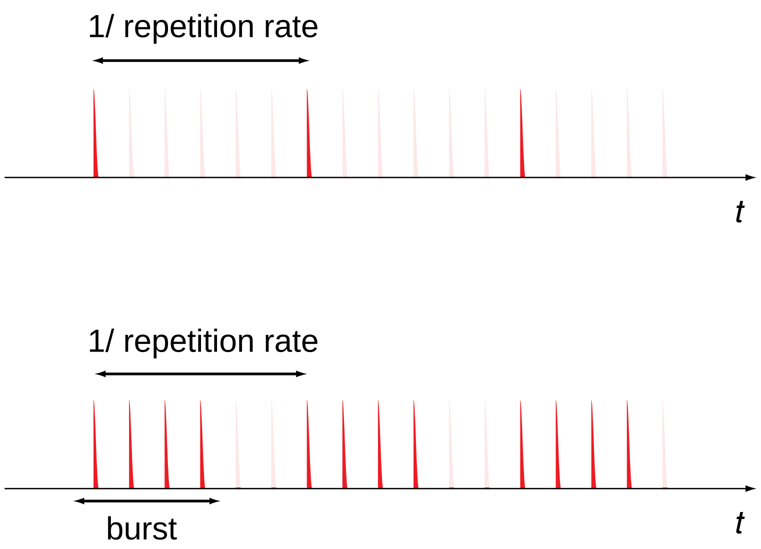
Low-energy machining

repetition-rate control

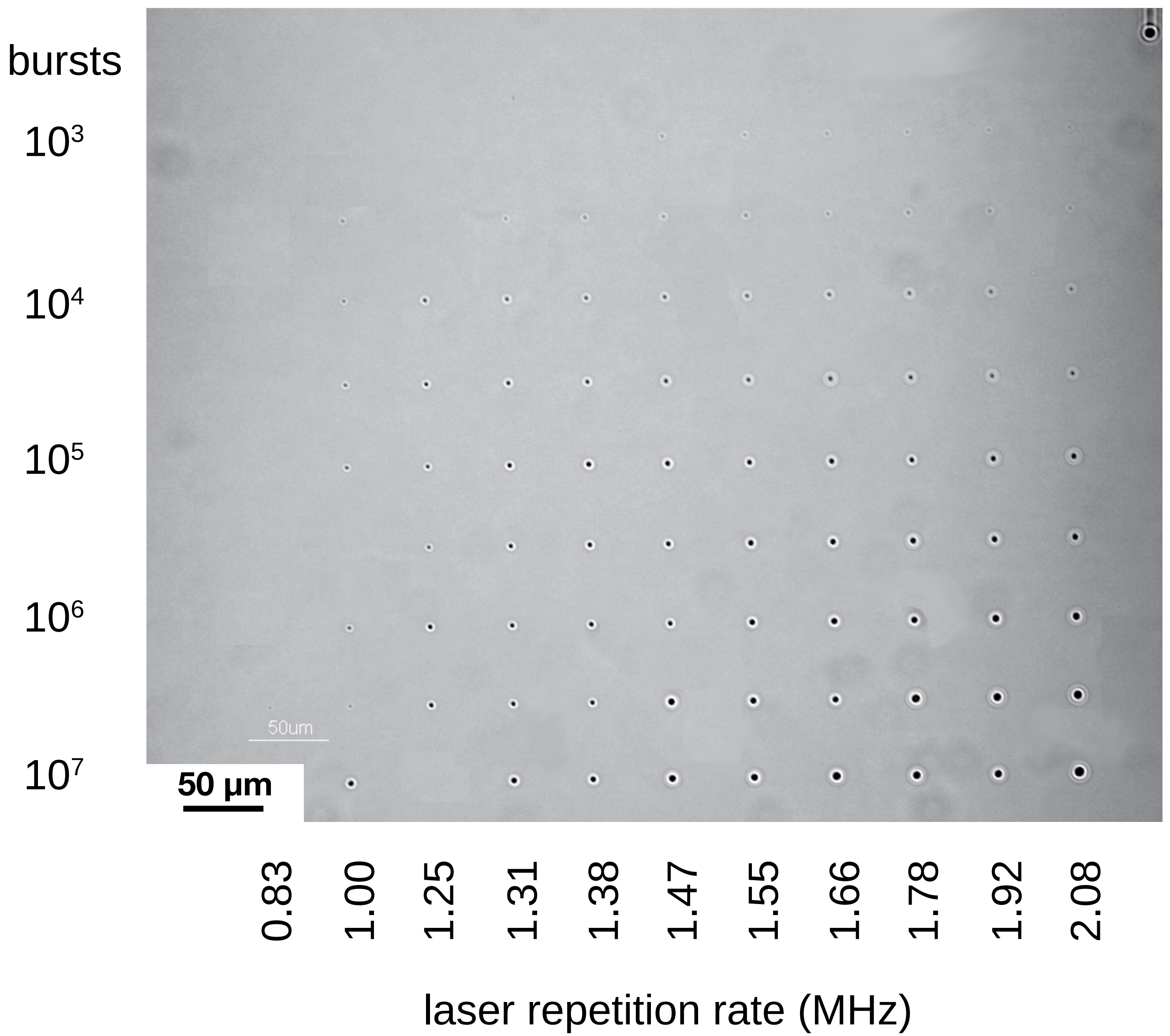


Low-energy machining

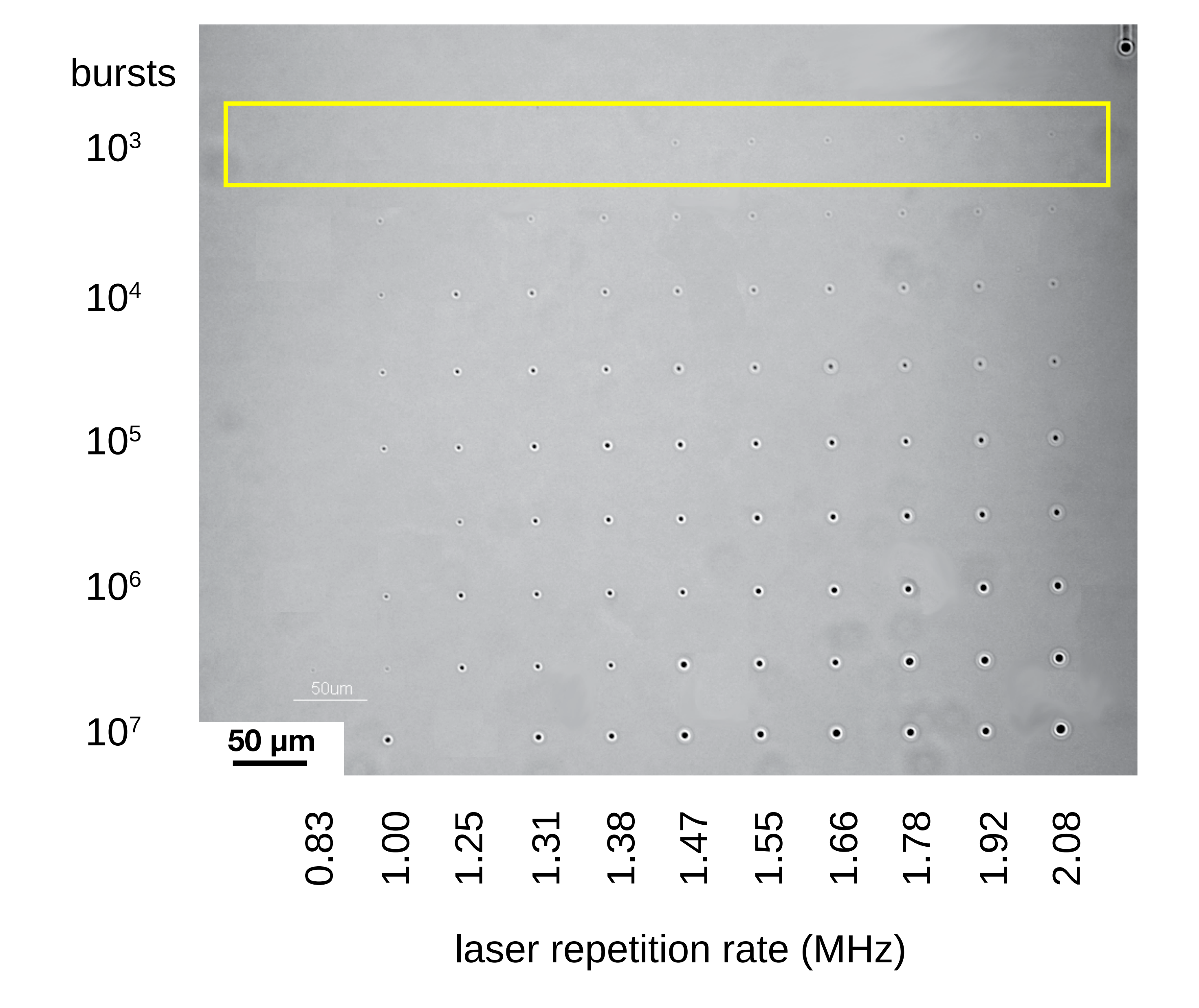
repetition-rate control



Low-energy machining

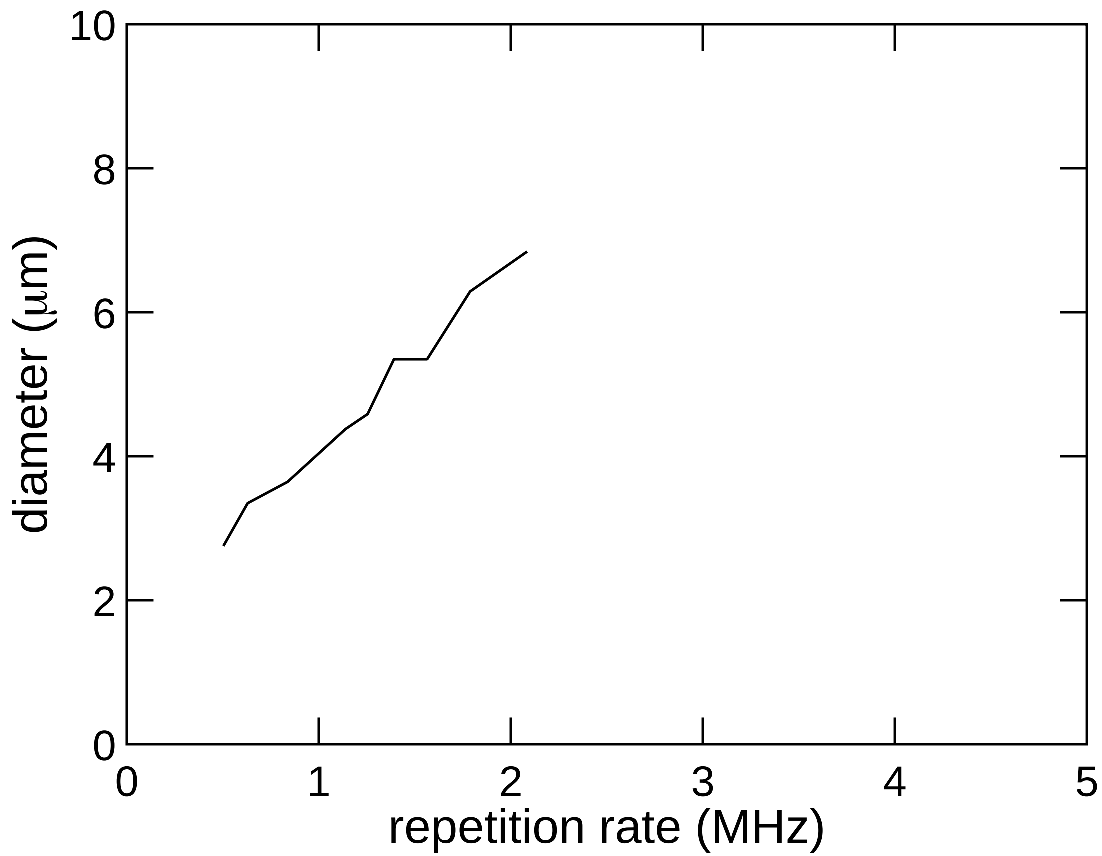


Low-energy machining



Low-energy machining

repetition-rate dependence of diameter



Low-energy machining

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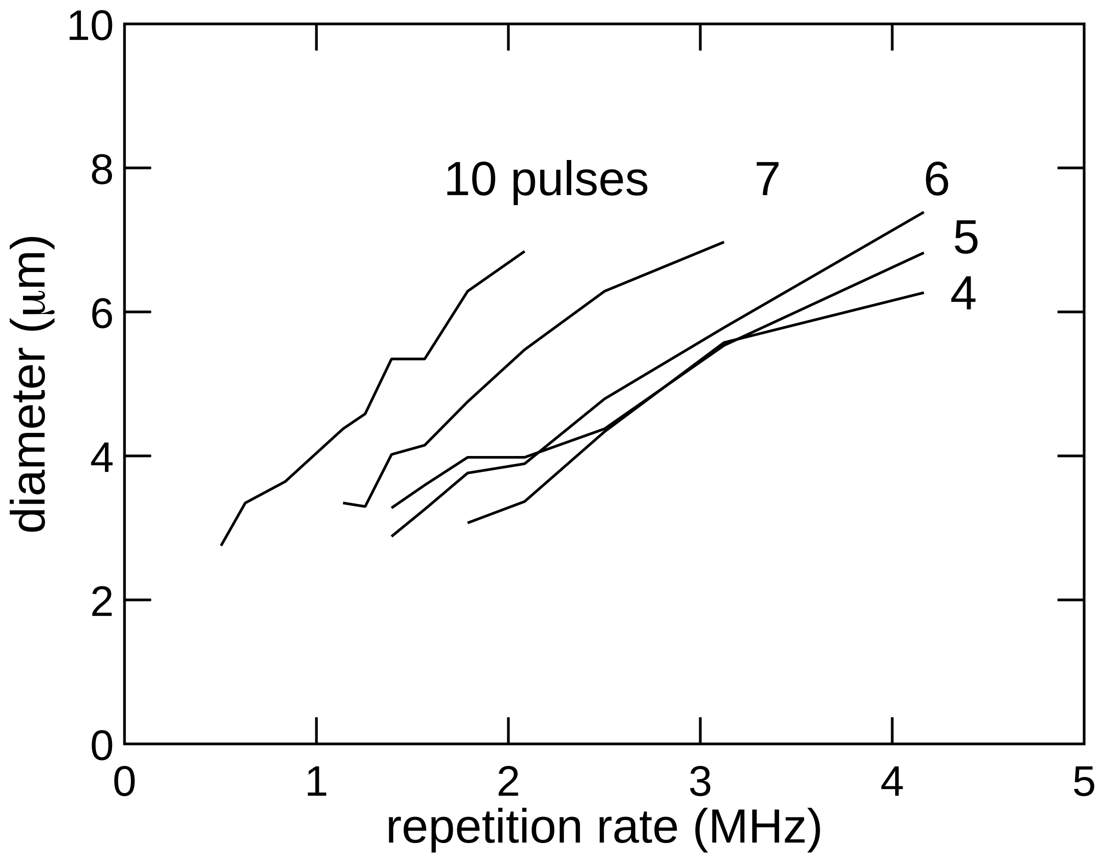
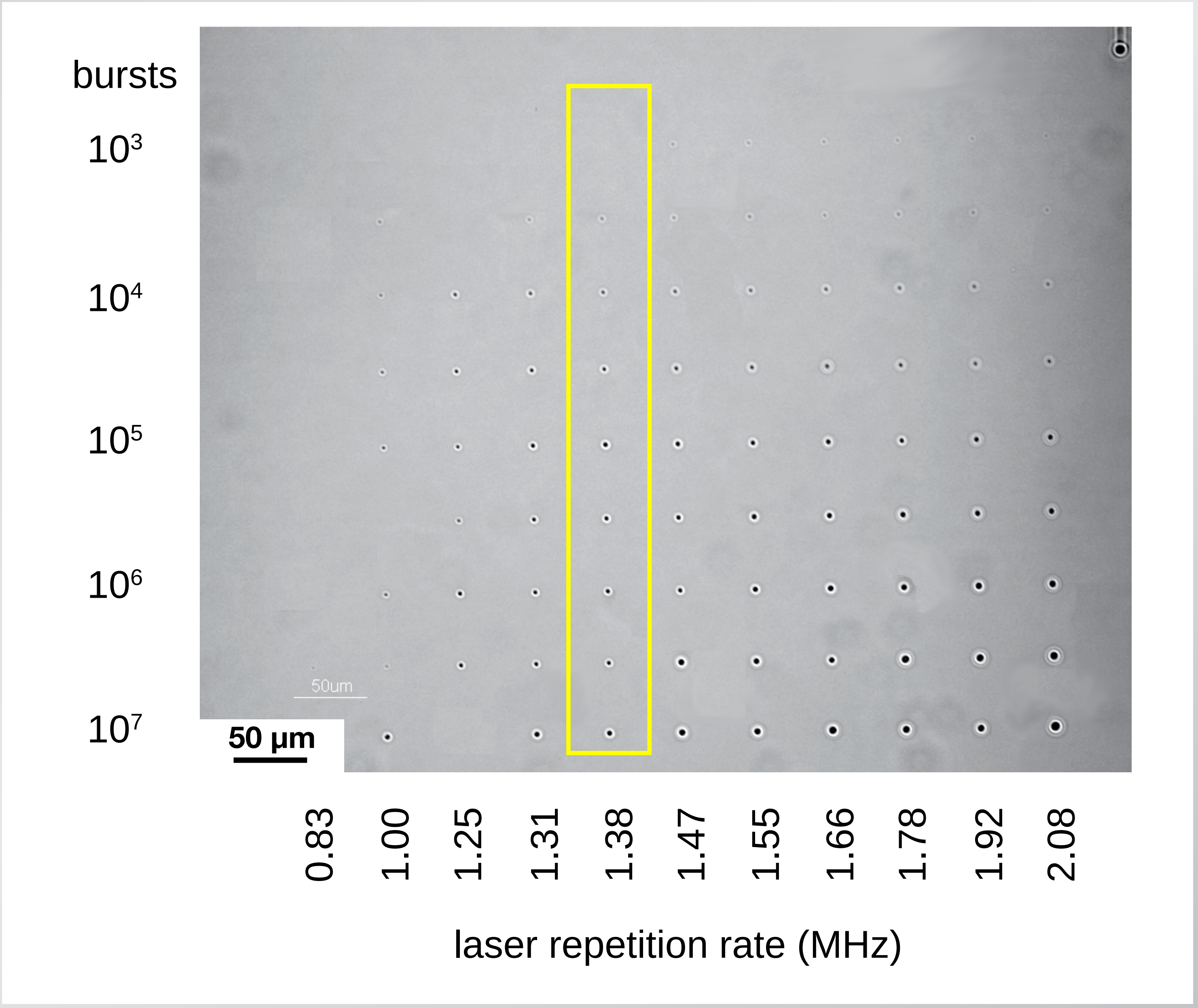
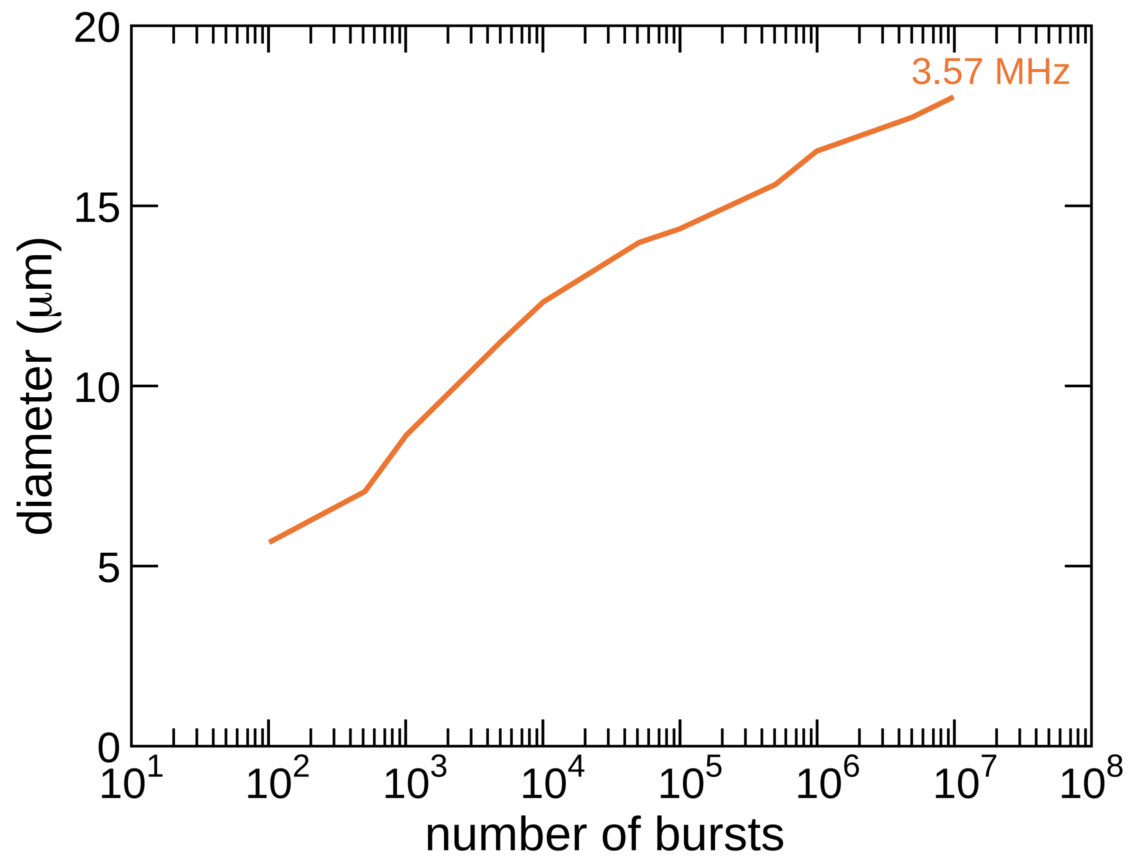


Low-energy machining



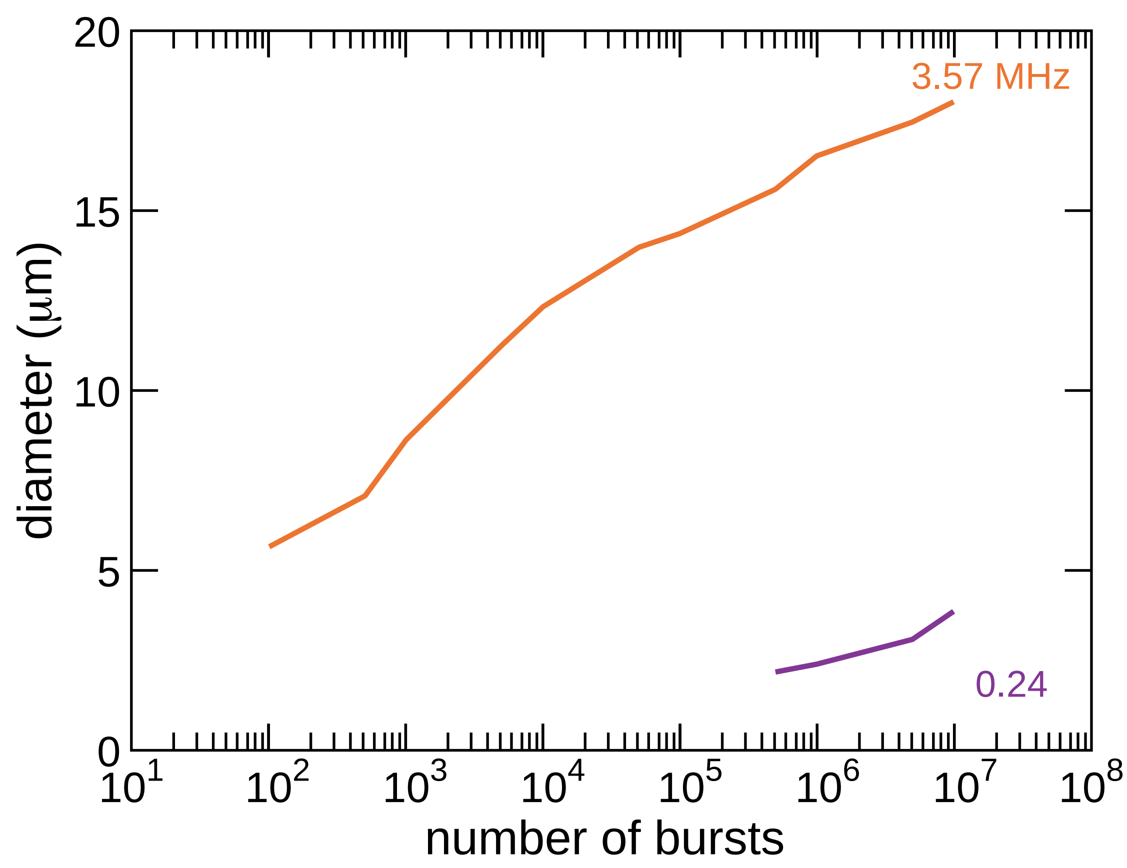
Low-energy machining

burst number dependence of diameter



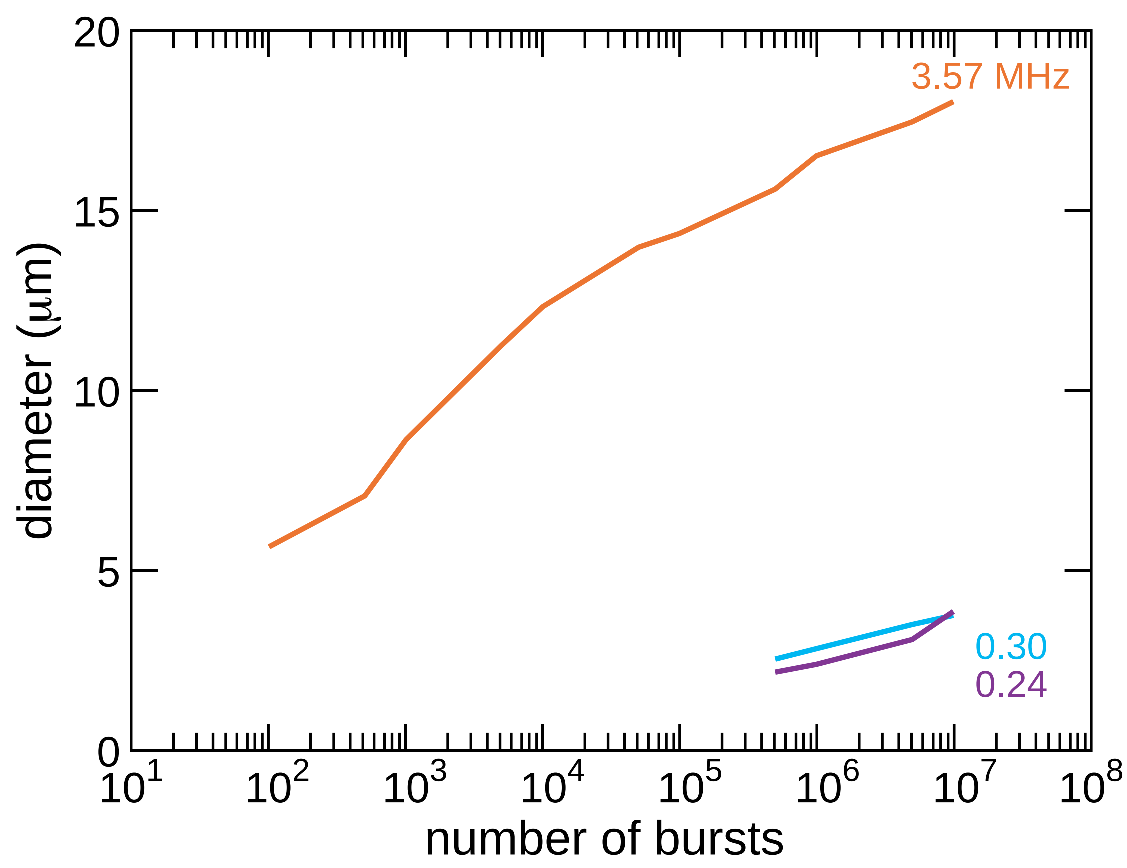
Low-energy machining

burst number dependence of diameter



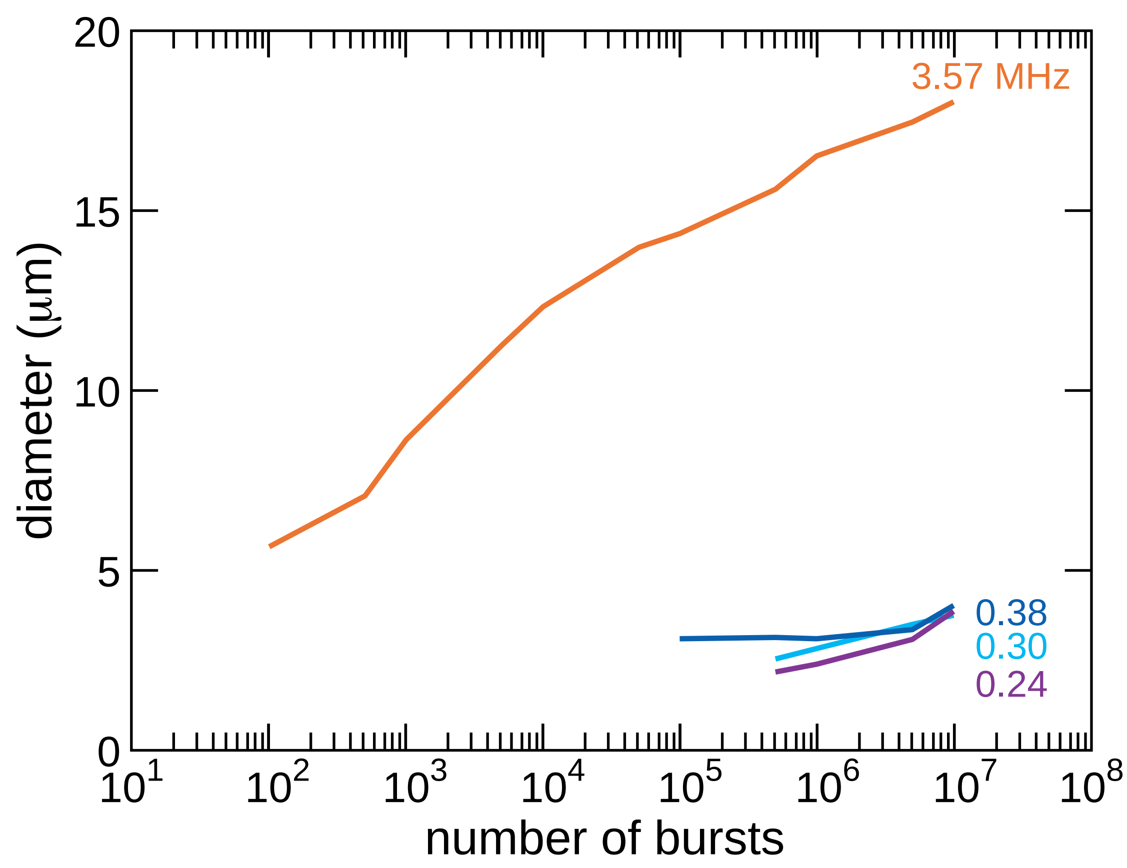
Low-energy machining

burst number dependence of diameter



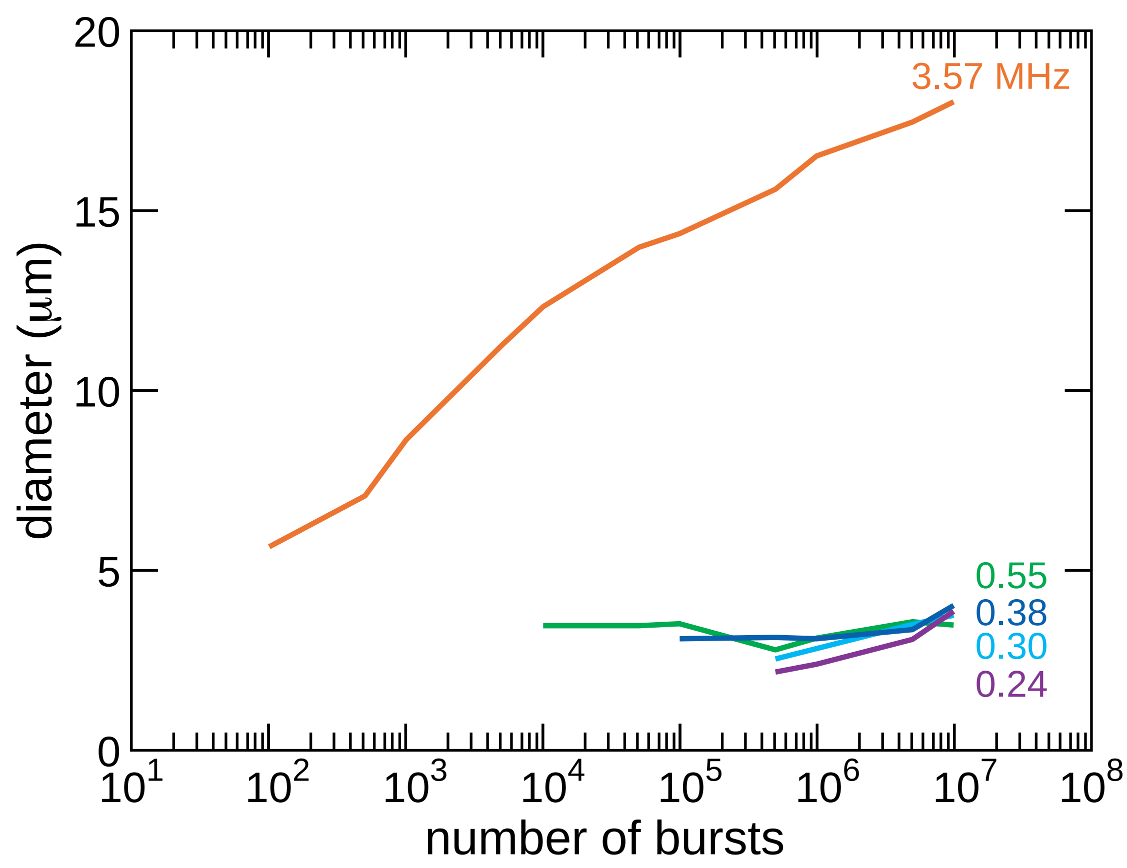
Low-energy machining

burst number dependence of diameter



Low-energy machining

burst number dependence of diameter



Low-energy machining

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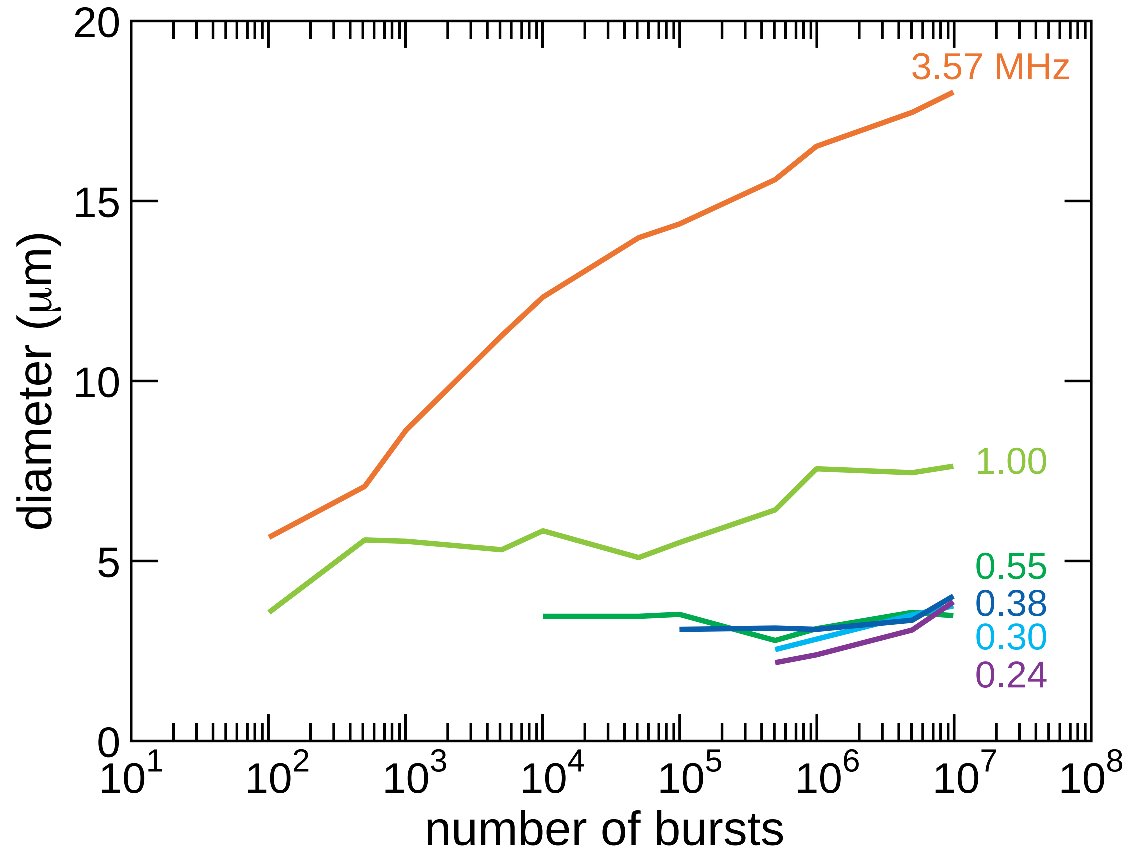

Low-energy machining

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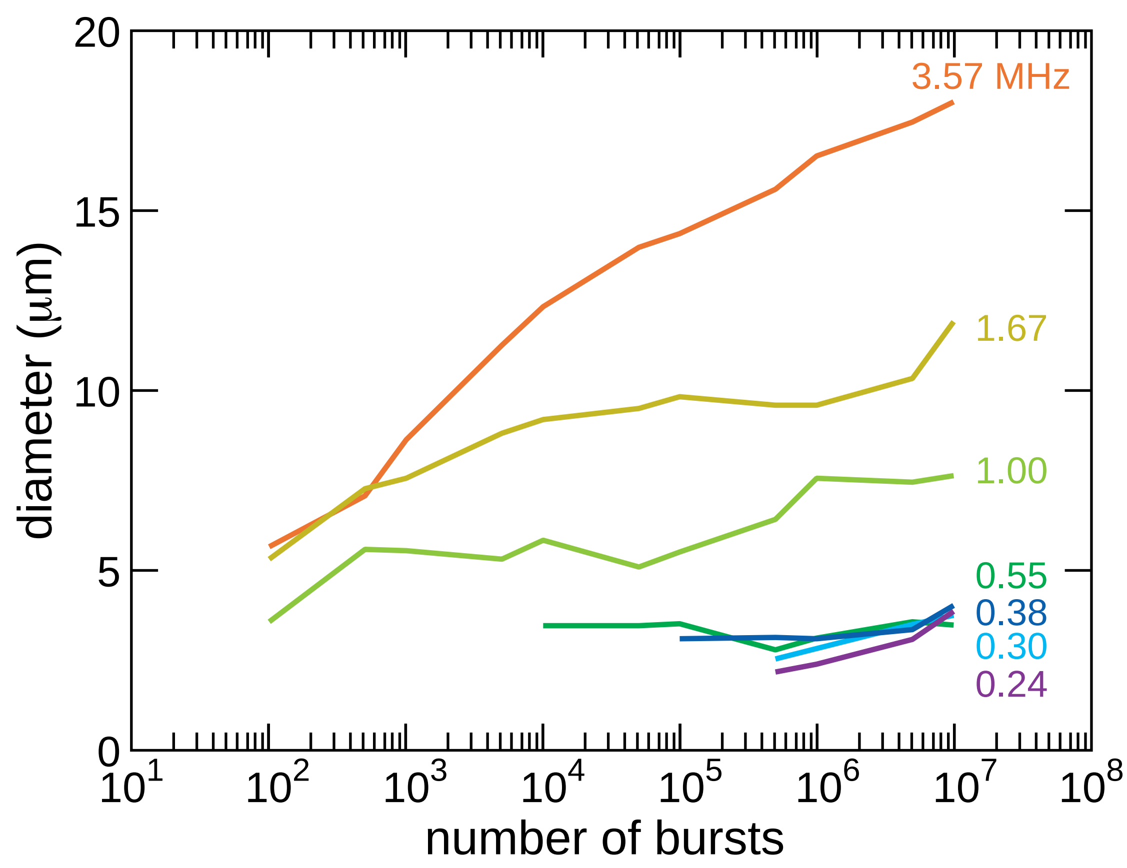

Low-energy machining

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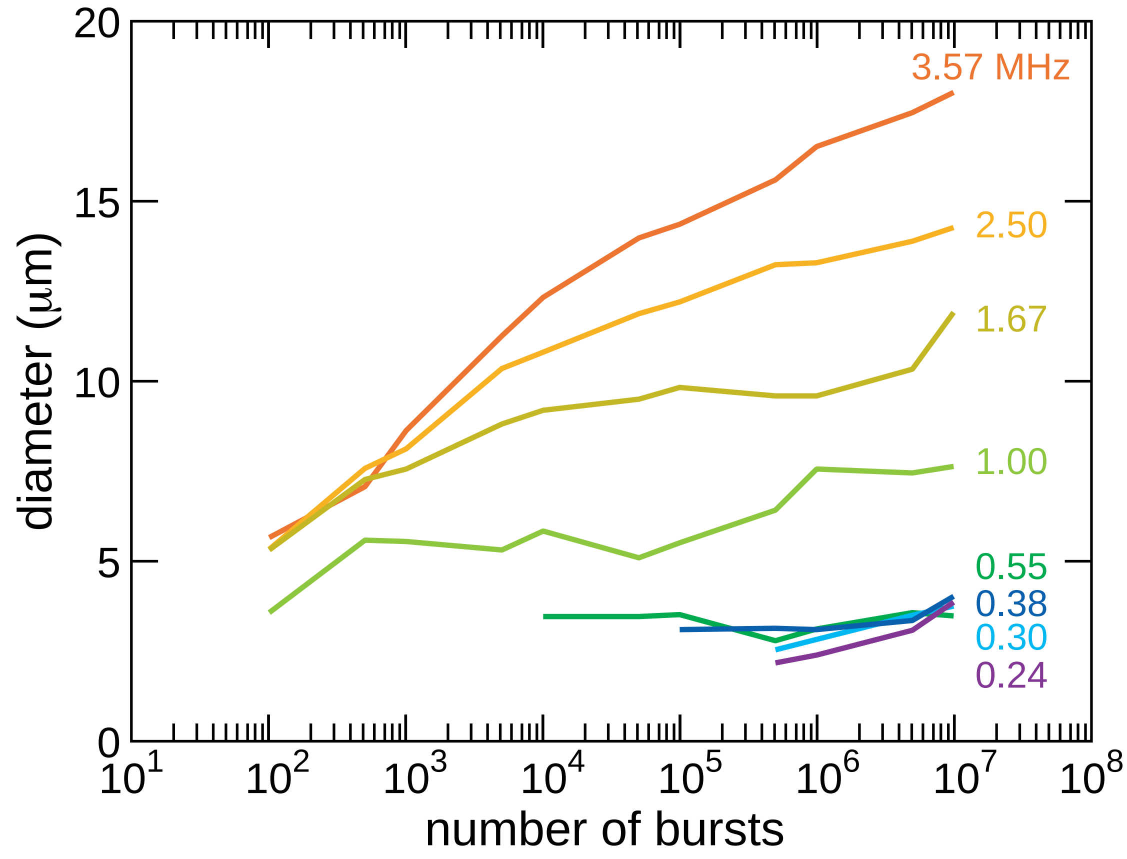
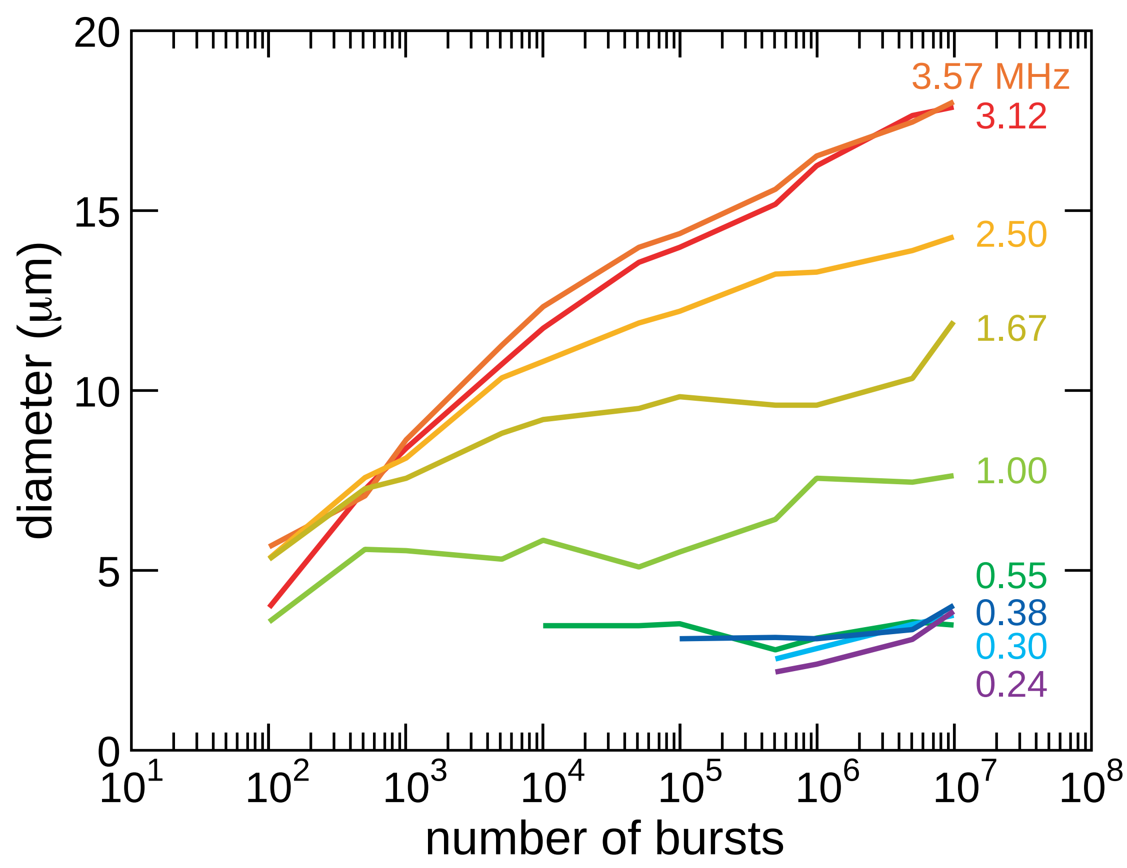


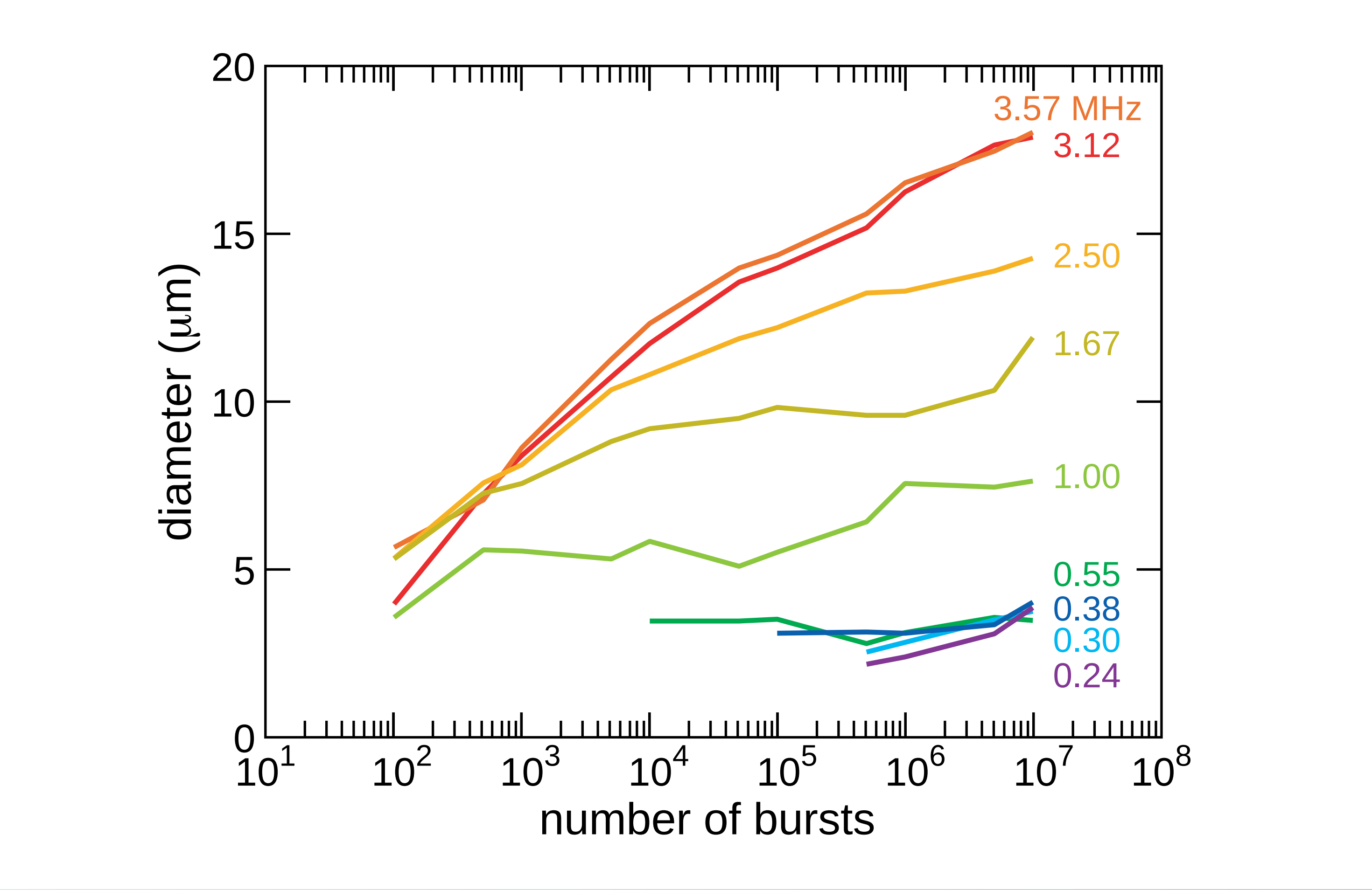
Low-energy machining

burst number dependence of diameter



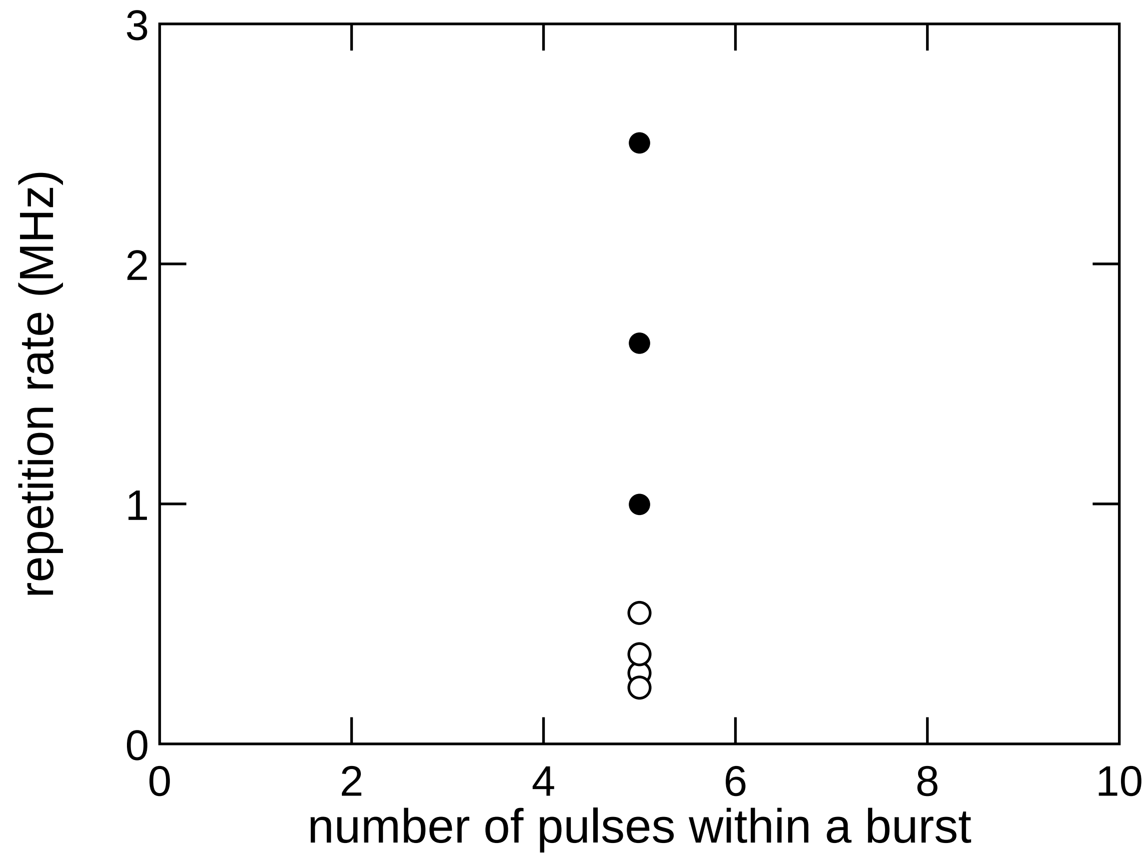
Low-energy machining

5-pulse burst: diameter grows above 1 MHz



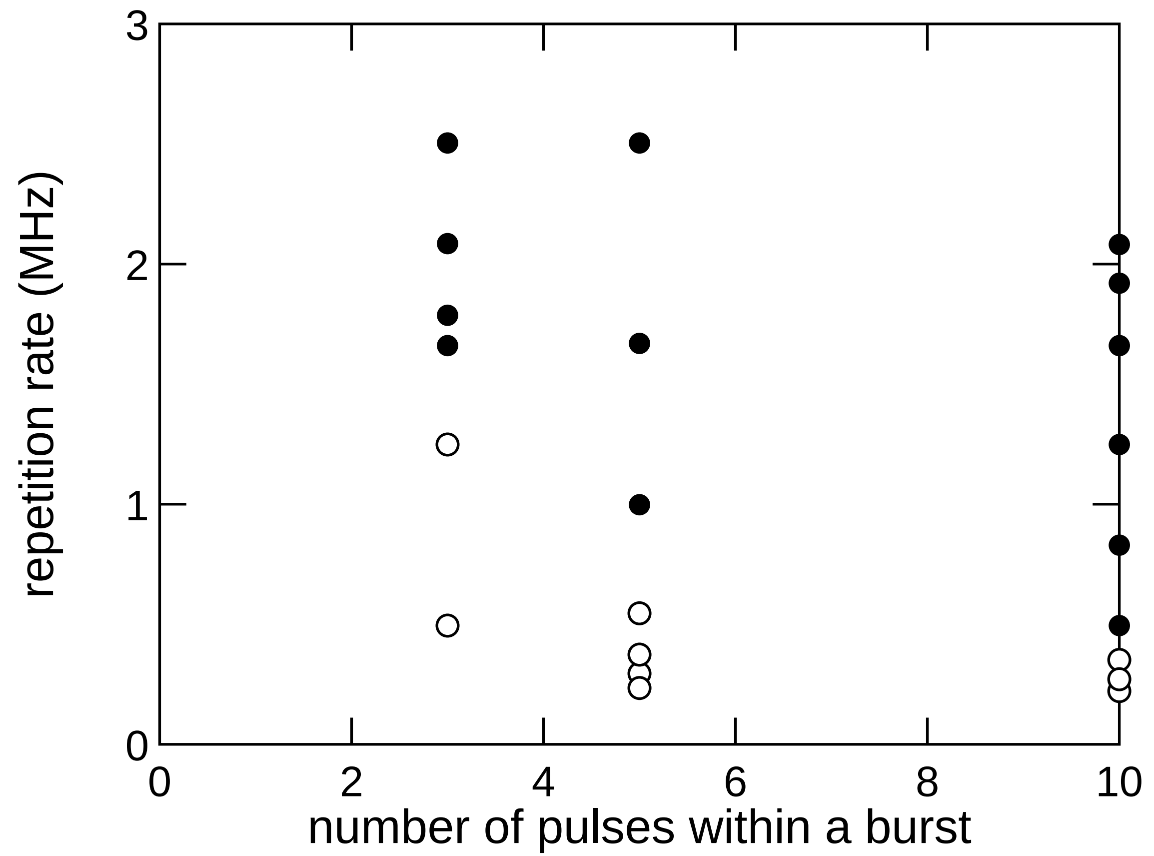
Low-energy machining

5-pulse burst: diameter grows above 1 MHz



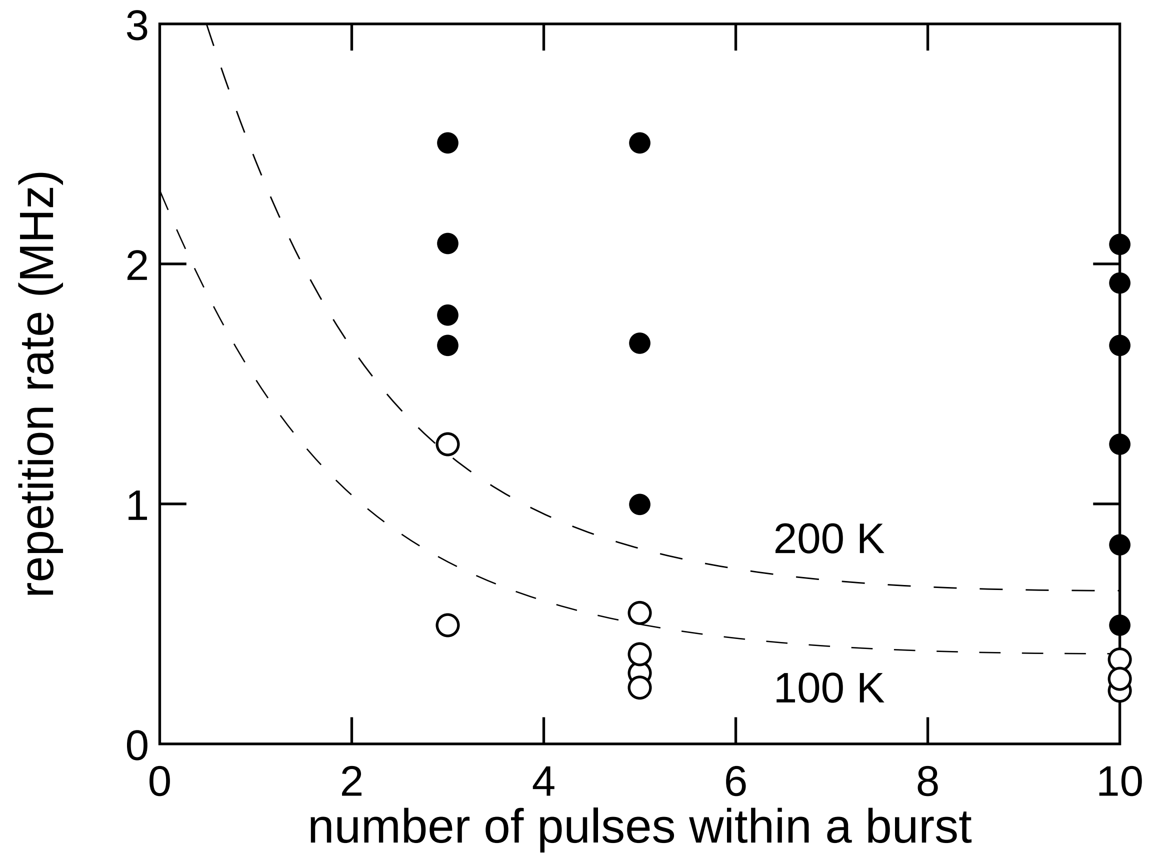
Low-energy machining

add data for 3 and 10-pulse bursts



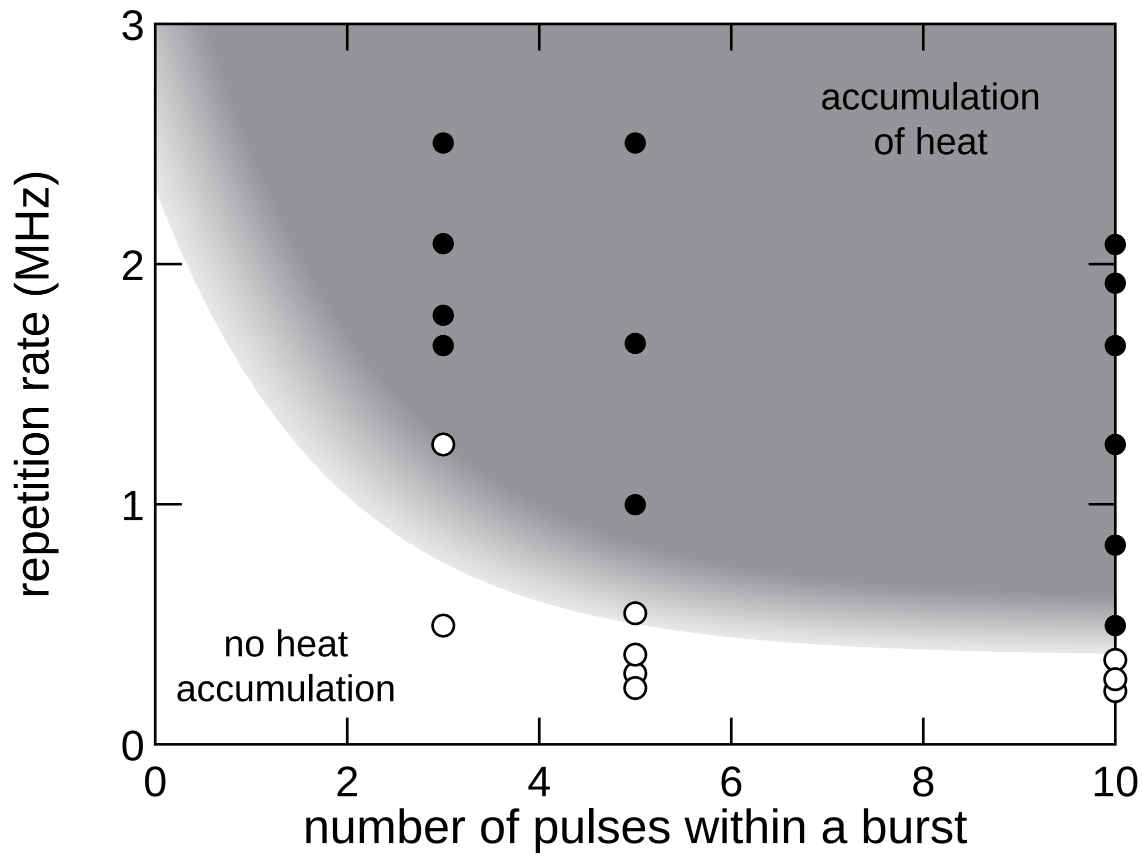
Low-energy machining

calculate heat accumulation between bursts



Low-energy machining

transition occurs for 150 K residual temperature rise

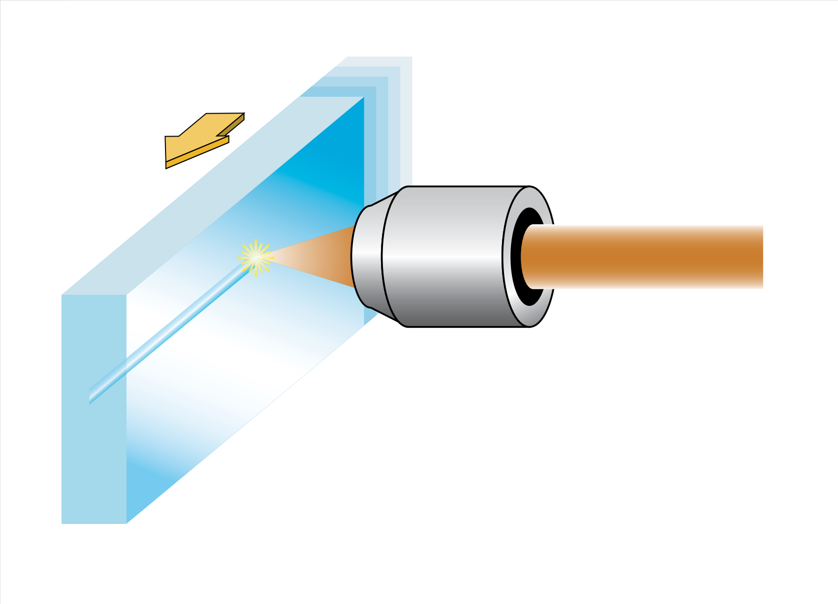


Outline

- femtosecond micromachining
- low-energy machining
- **applications**

Low-energy machining

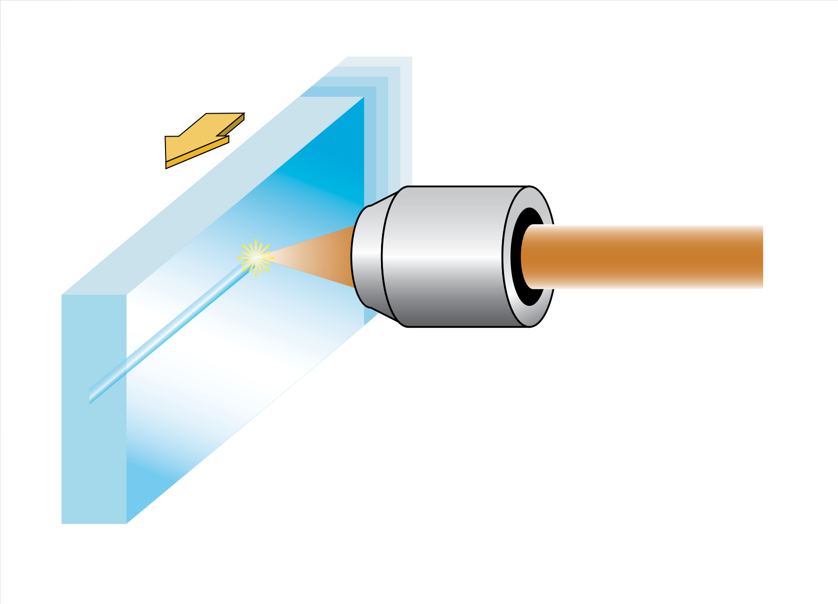
waveguide micromachining

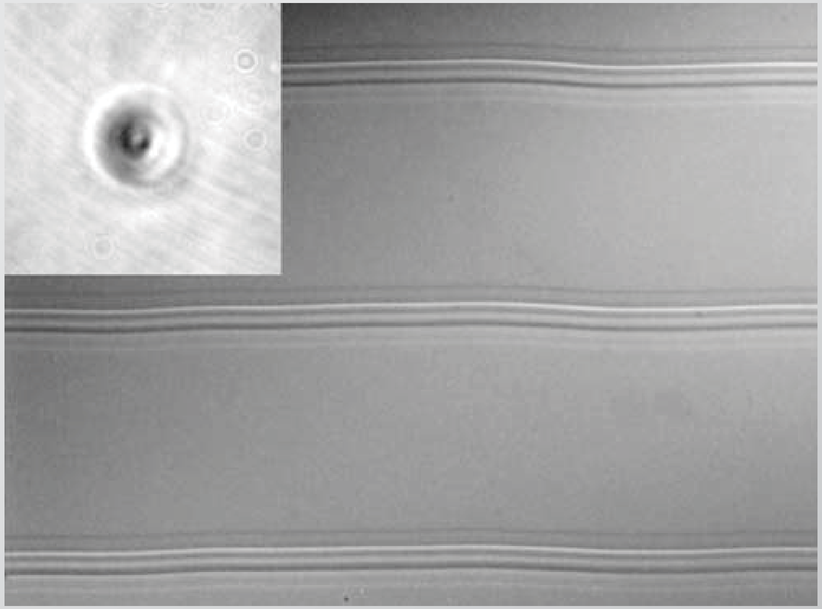


Opt. Lett. **26**, 93 (2001)

Low-energy machining

waveguide micromachining

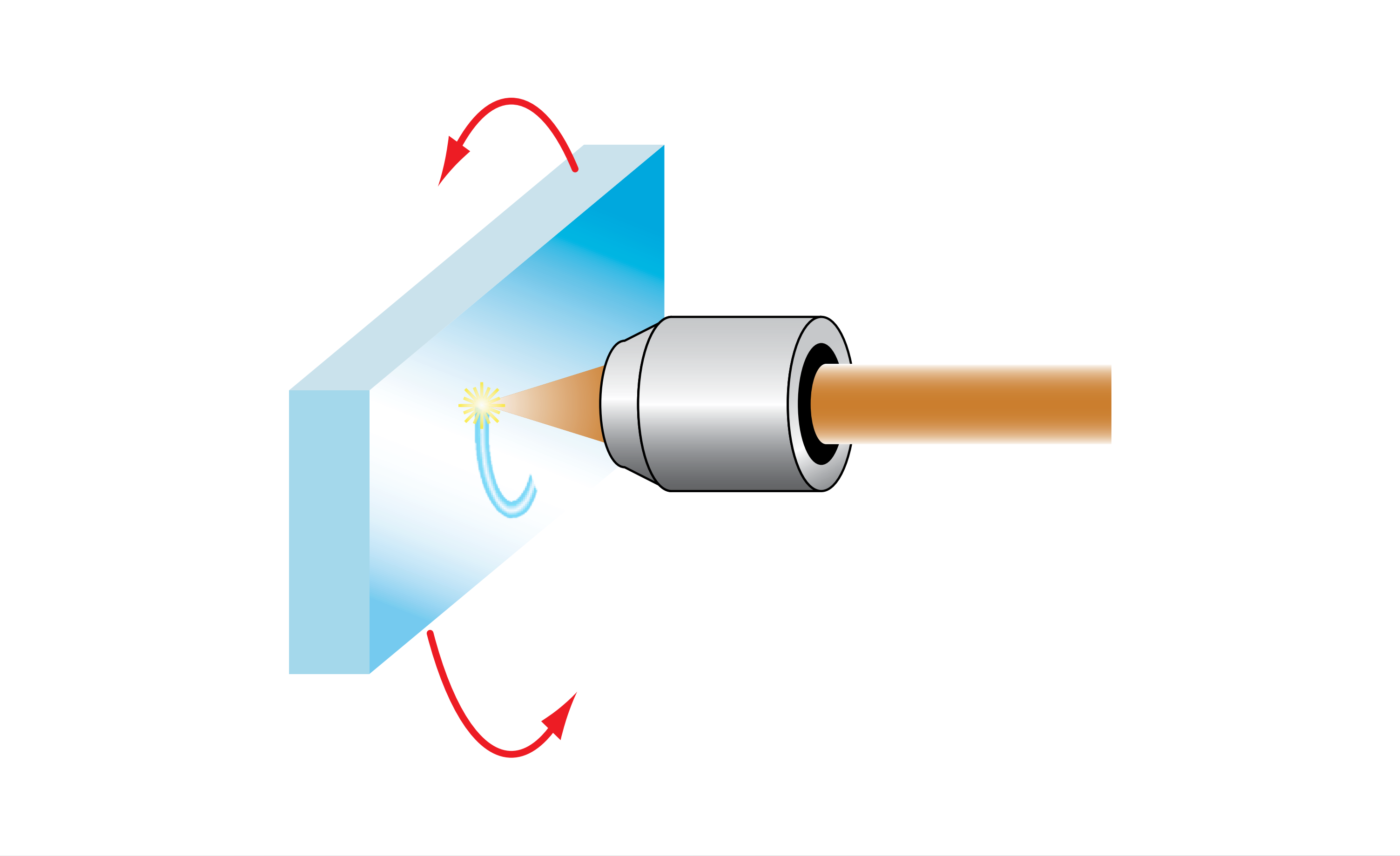




Opt. Lett. **26**, 93 (2001)

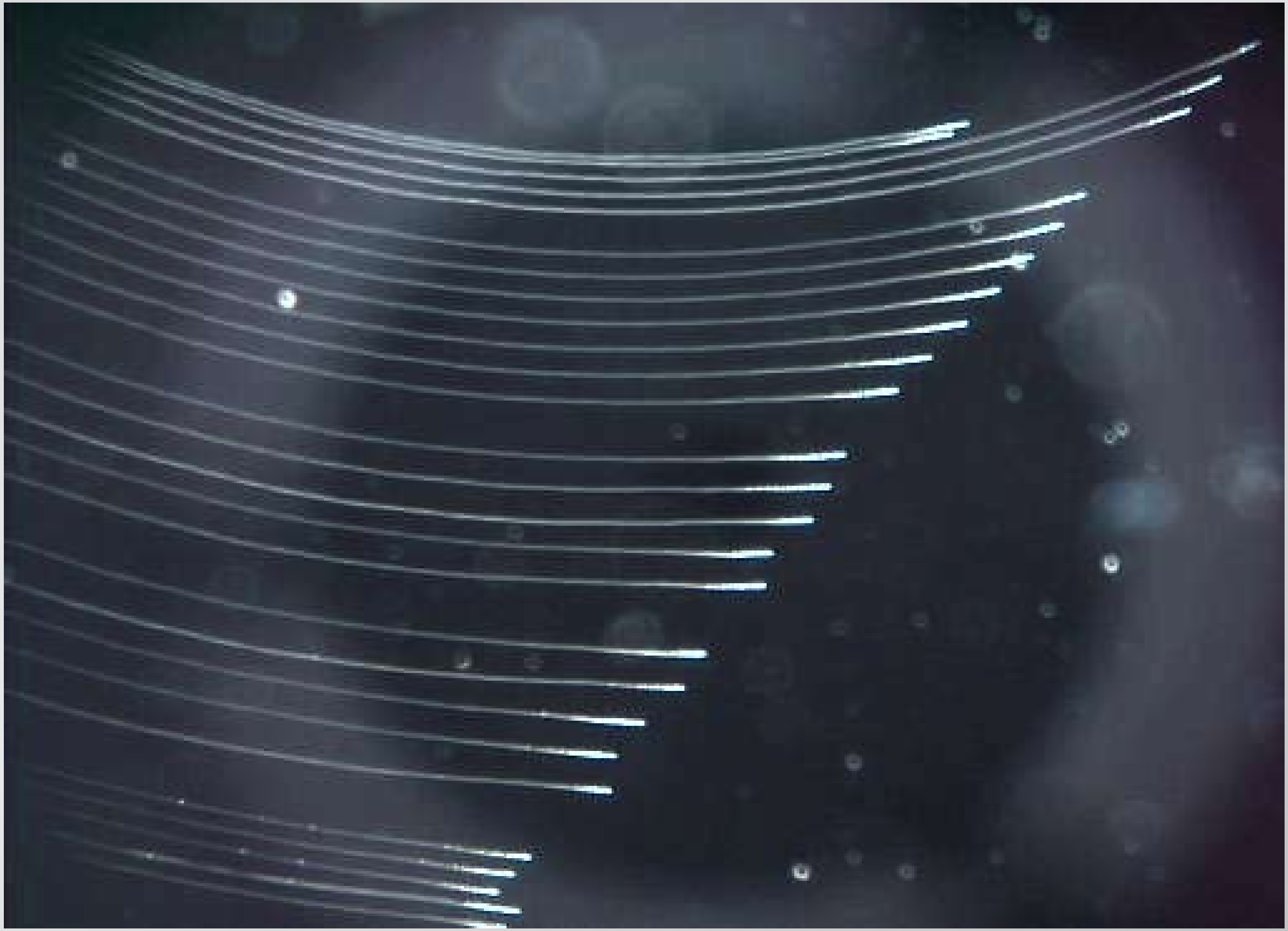
Applications

curved waveguides



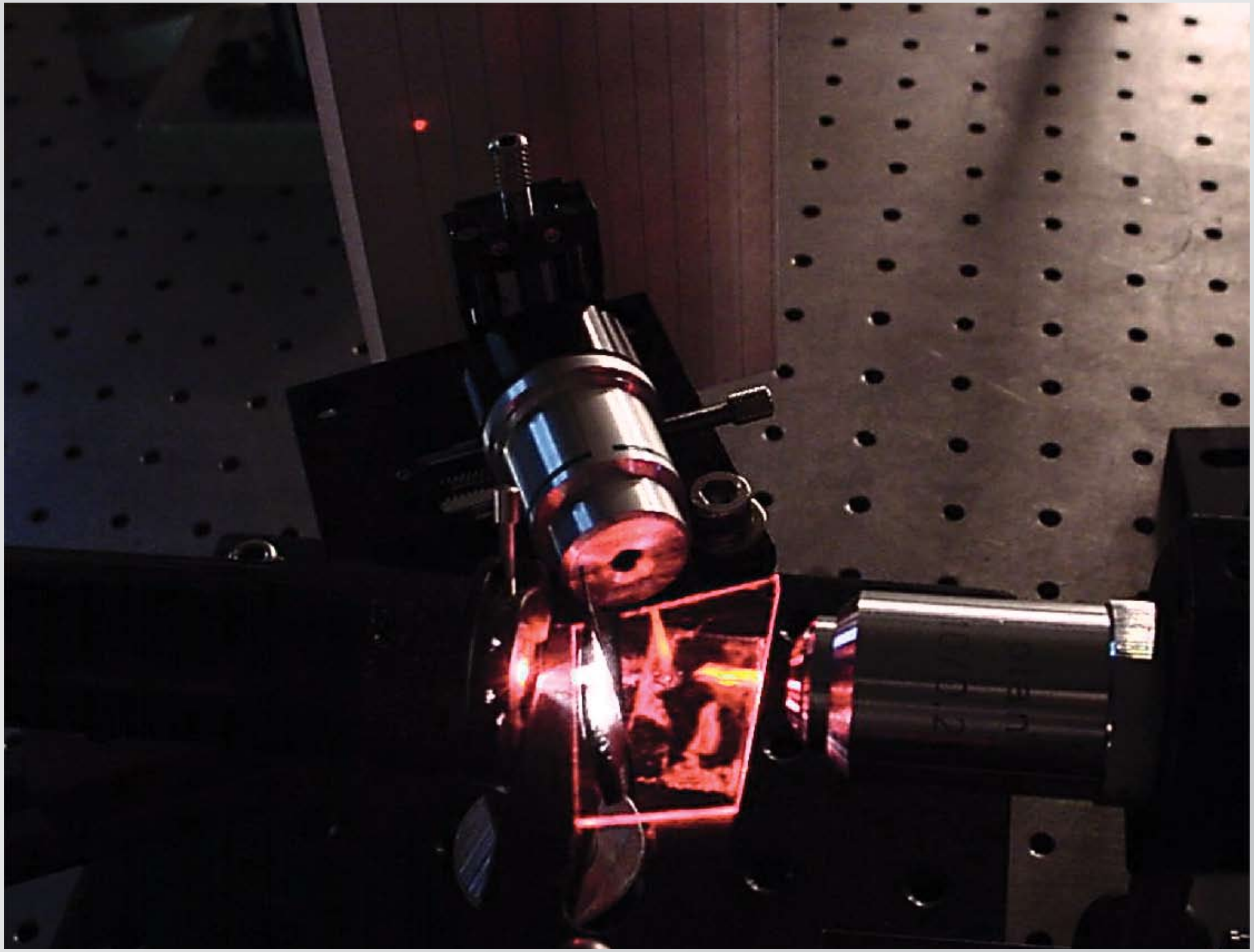
Applications

curved waveguides



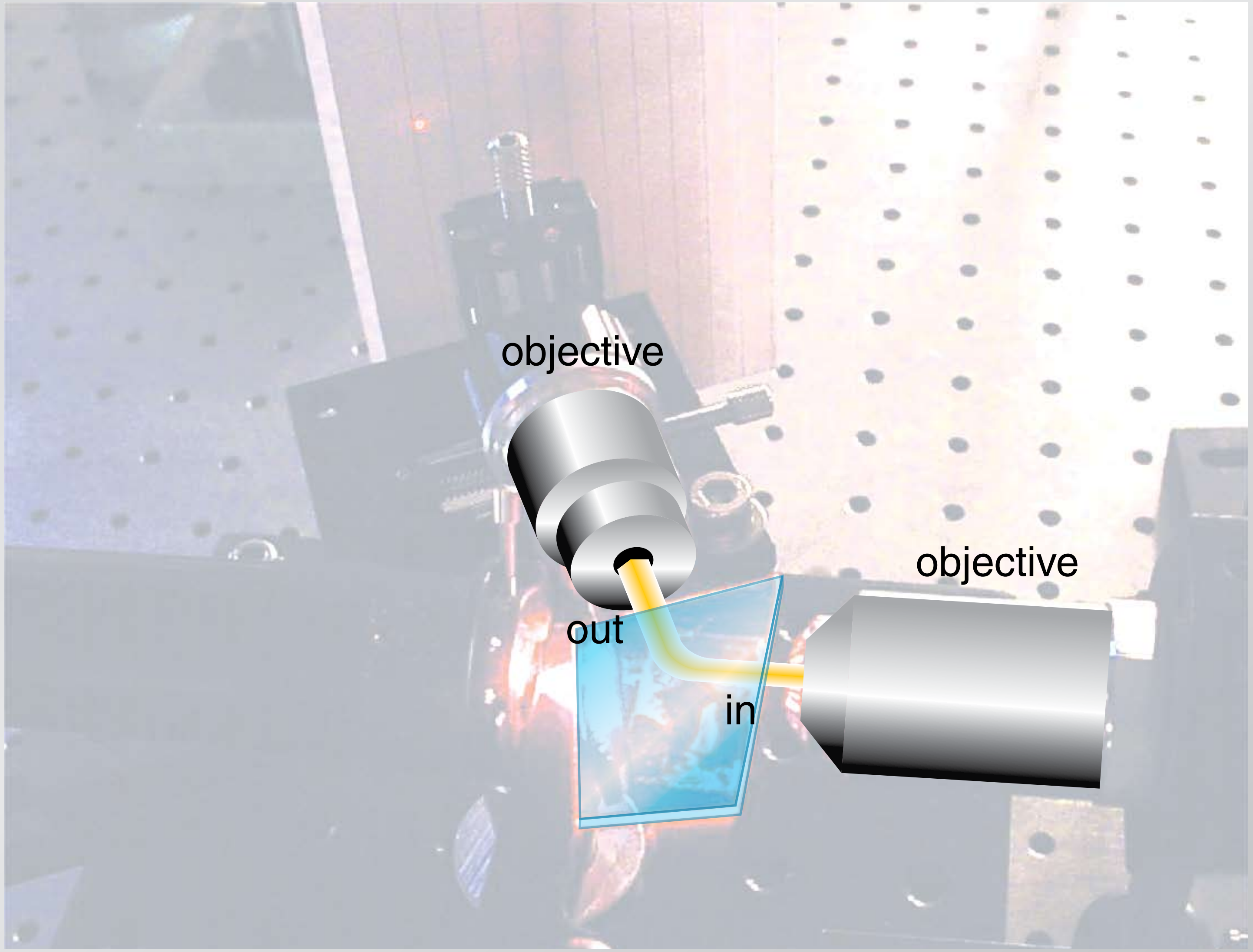
Applications

curved waveguides



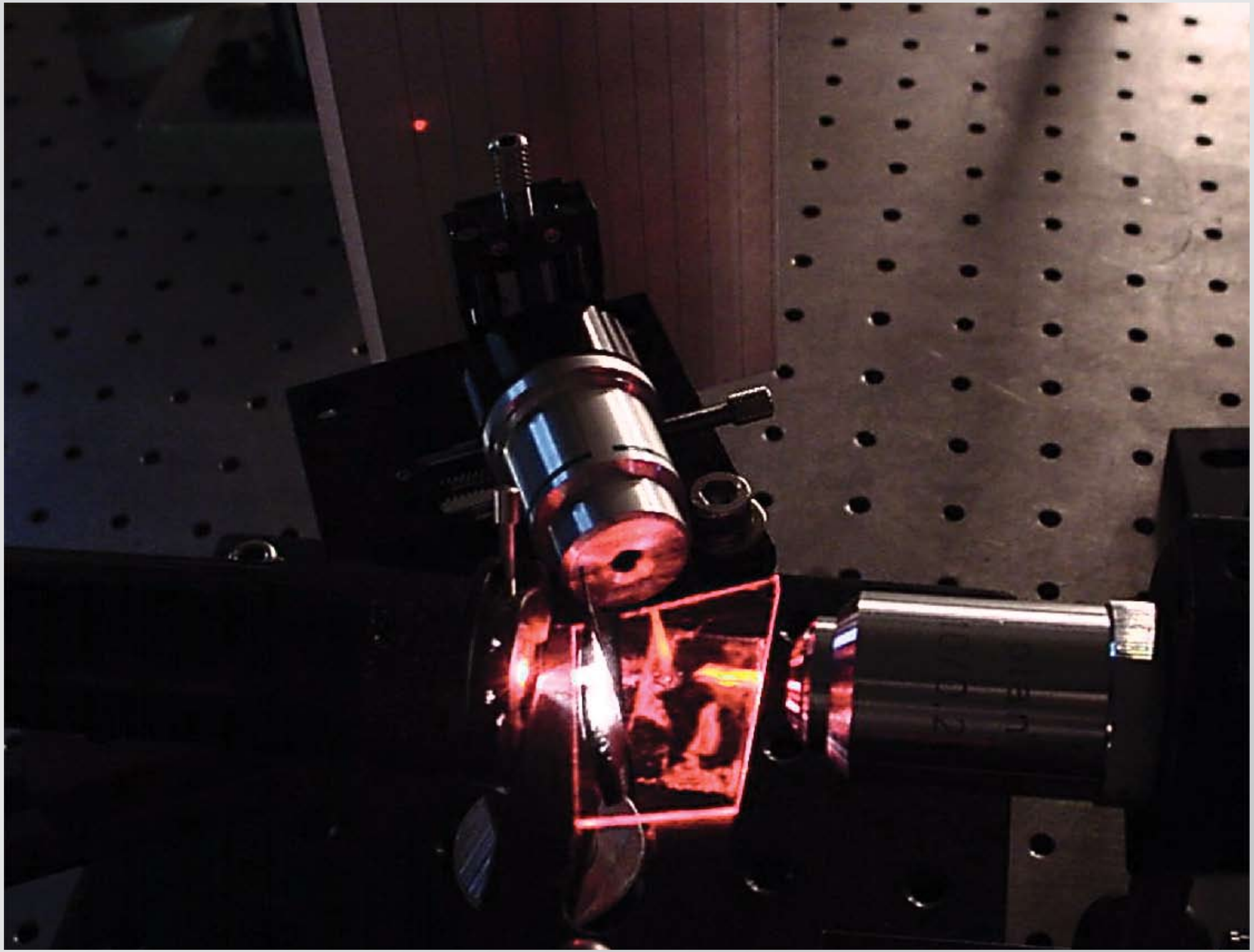
Applications

curved waveguides



Applications

curved waveguides



Applications

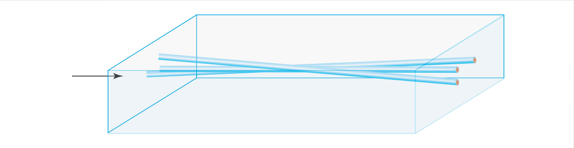
photonic fabrication techniques

	fs micromachining	other
loss (dB/cm)	< 3	0.1–3
bending radius	36 mm	30–40 mm
Δn	2×10^{-3}	10^{-4} – 0.5
3D integration	Y	N

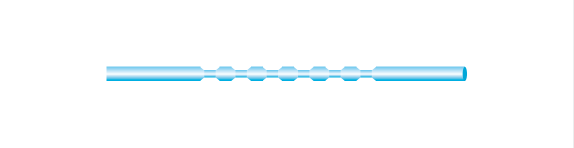
Applications

photonic devices

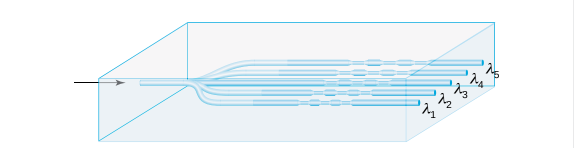
3D splitter



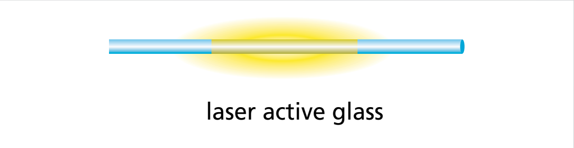
Bragg grating



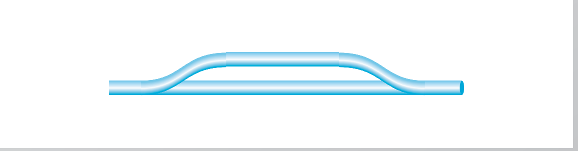
demultiplexer



amplifier



interferometer



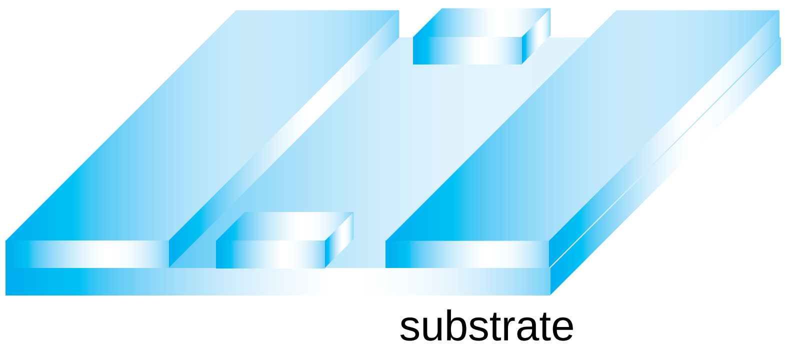
Applications

all-optical sensor

Appl. Phys. Lett. **87**, 051106 (2005)

Applications

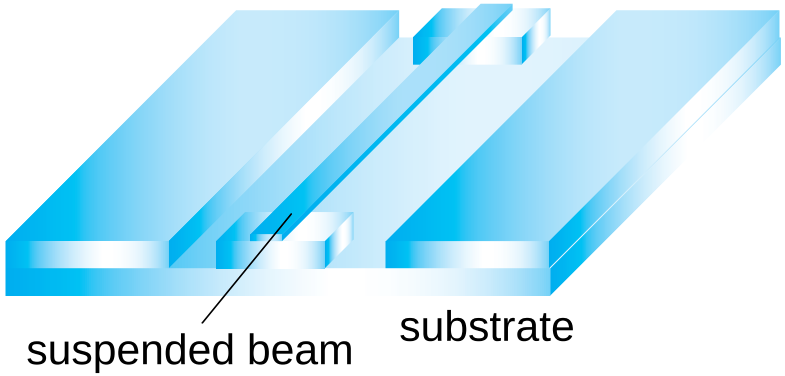
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

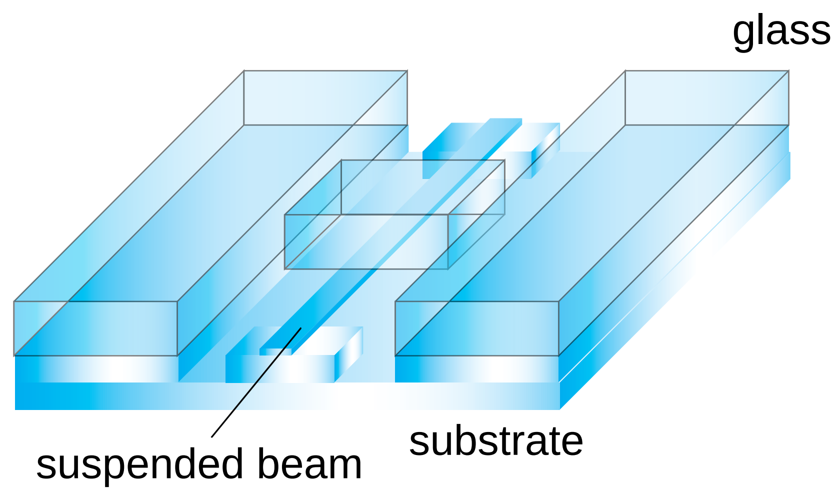
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

all-optical sensor



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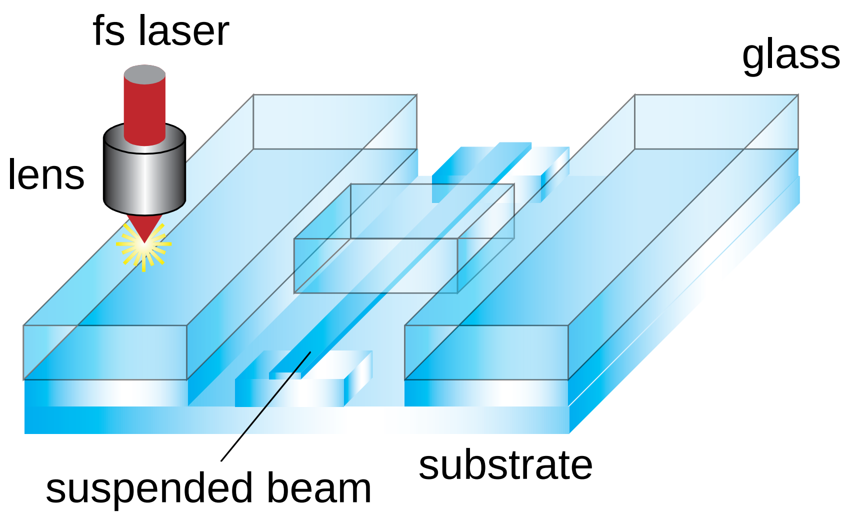
Applications

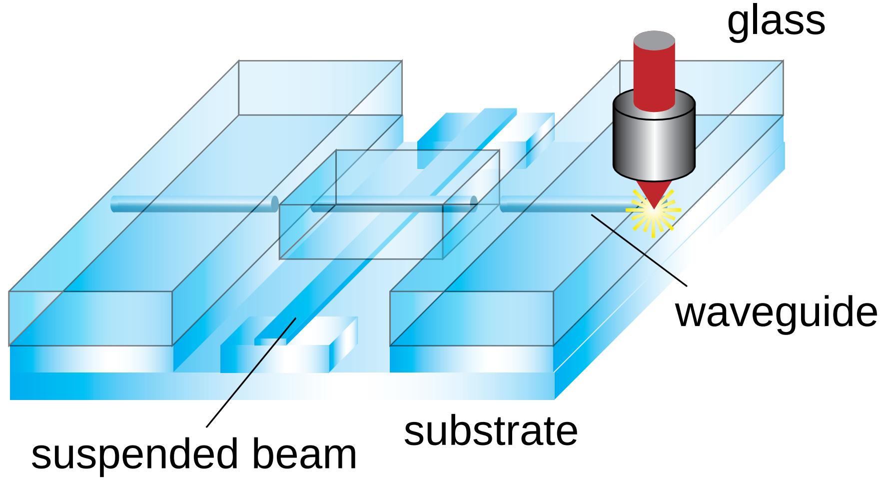
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

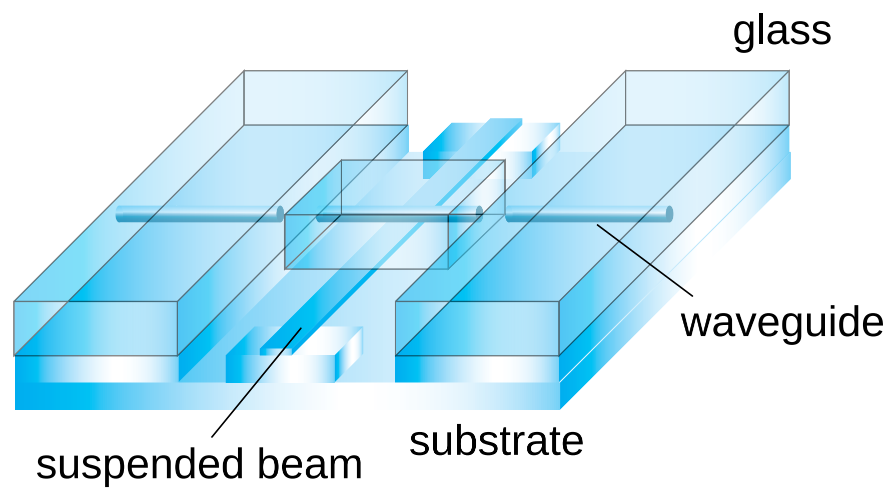
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

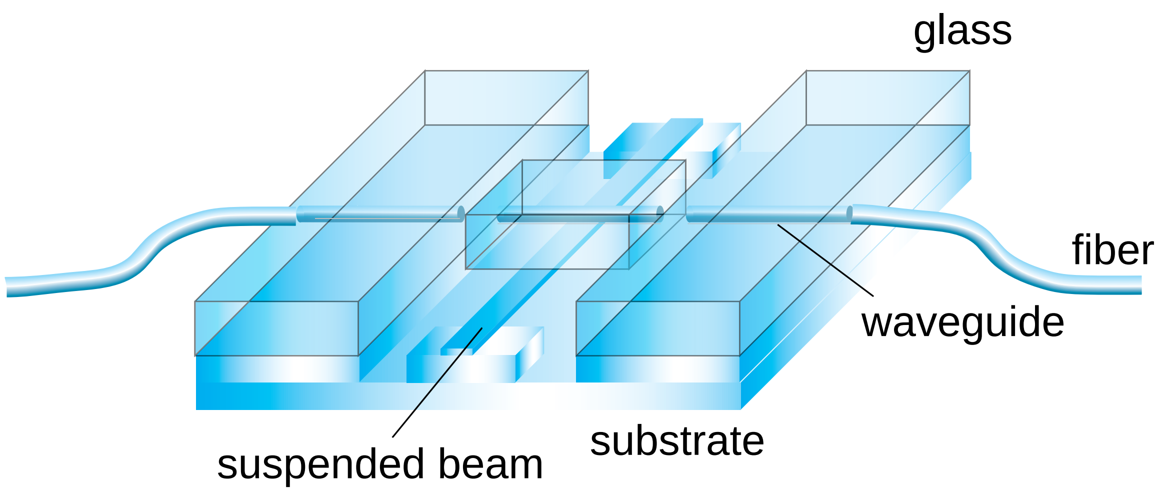
all-optical sensor



Appl. Phys. Lett. **87**, 051106 (2005)

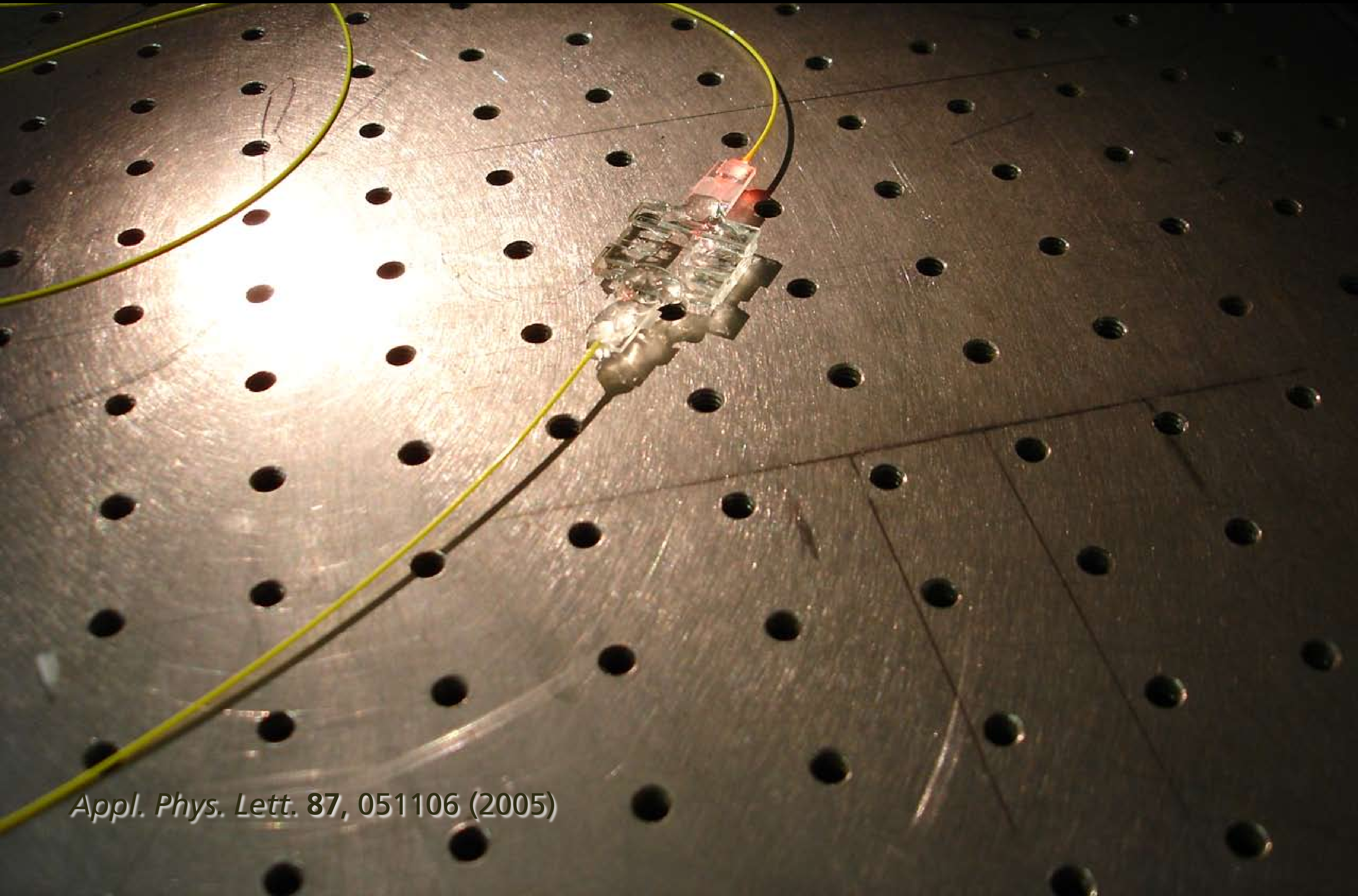
Applications

all-optical sensor



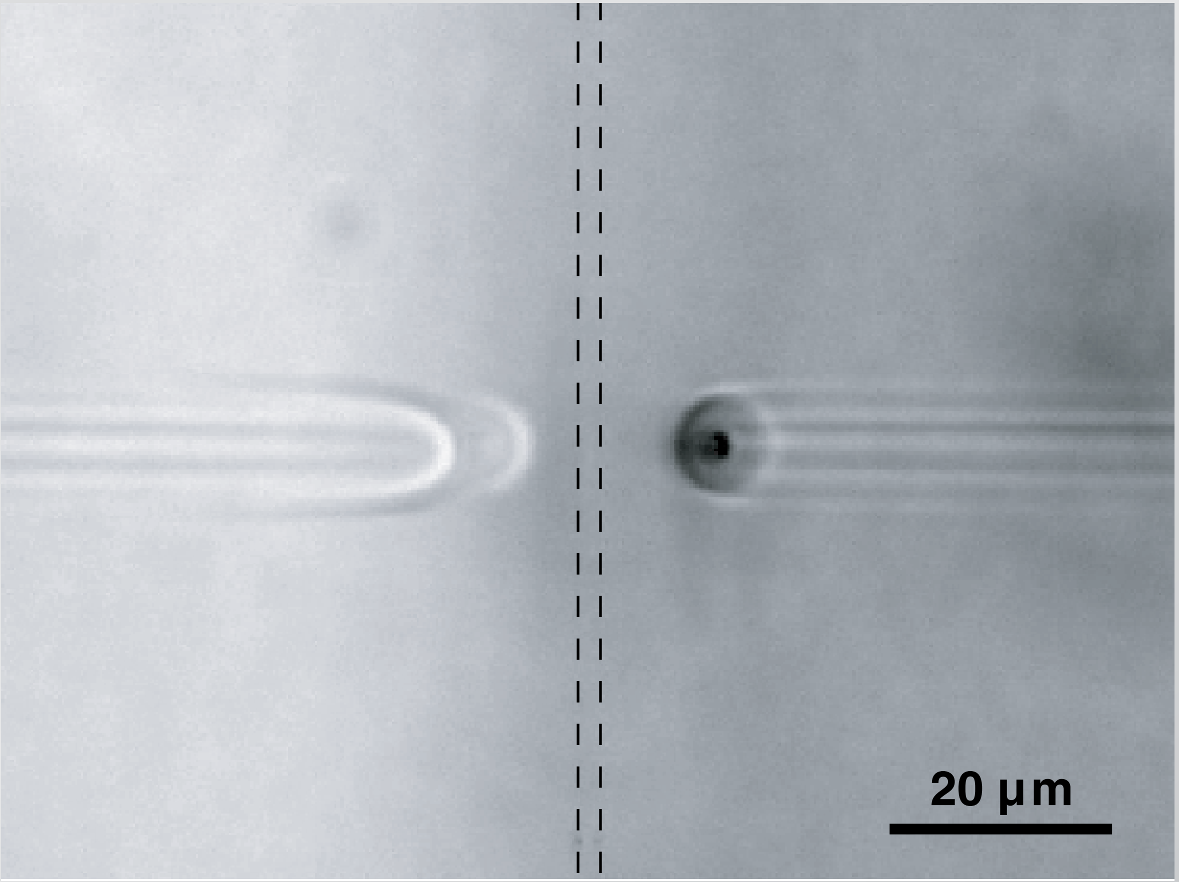
Appl. Phys. Lett. **87**, 051106 (2005)

Applications



Applications

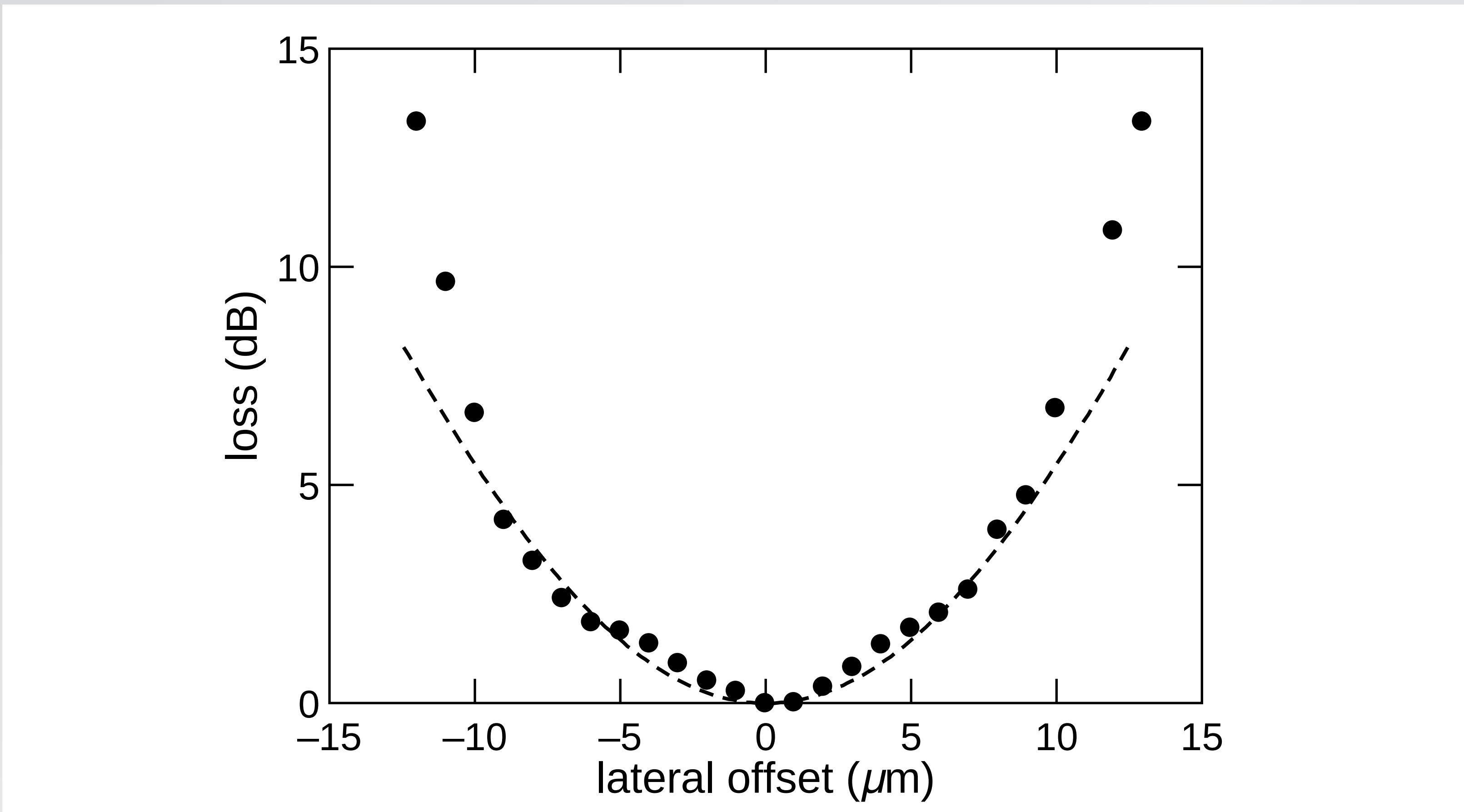
sensor gap



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

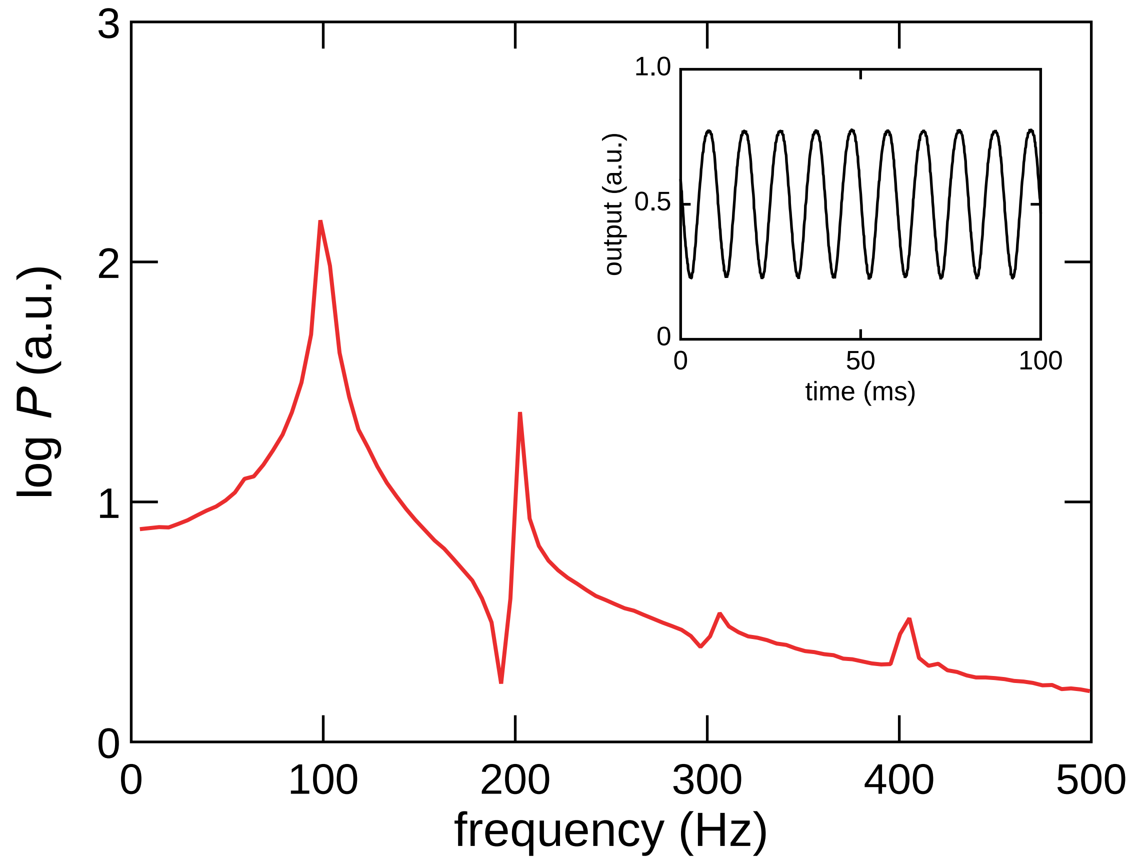
calibration



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

sensor response to 100 Hz acoustic wave



Appl. Phys. Lett. **87**, 051106 (2005)

Applications

ideal tool for ablating (living) tissue

Applications

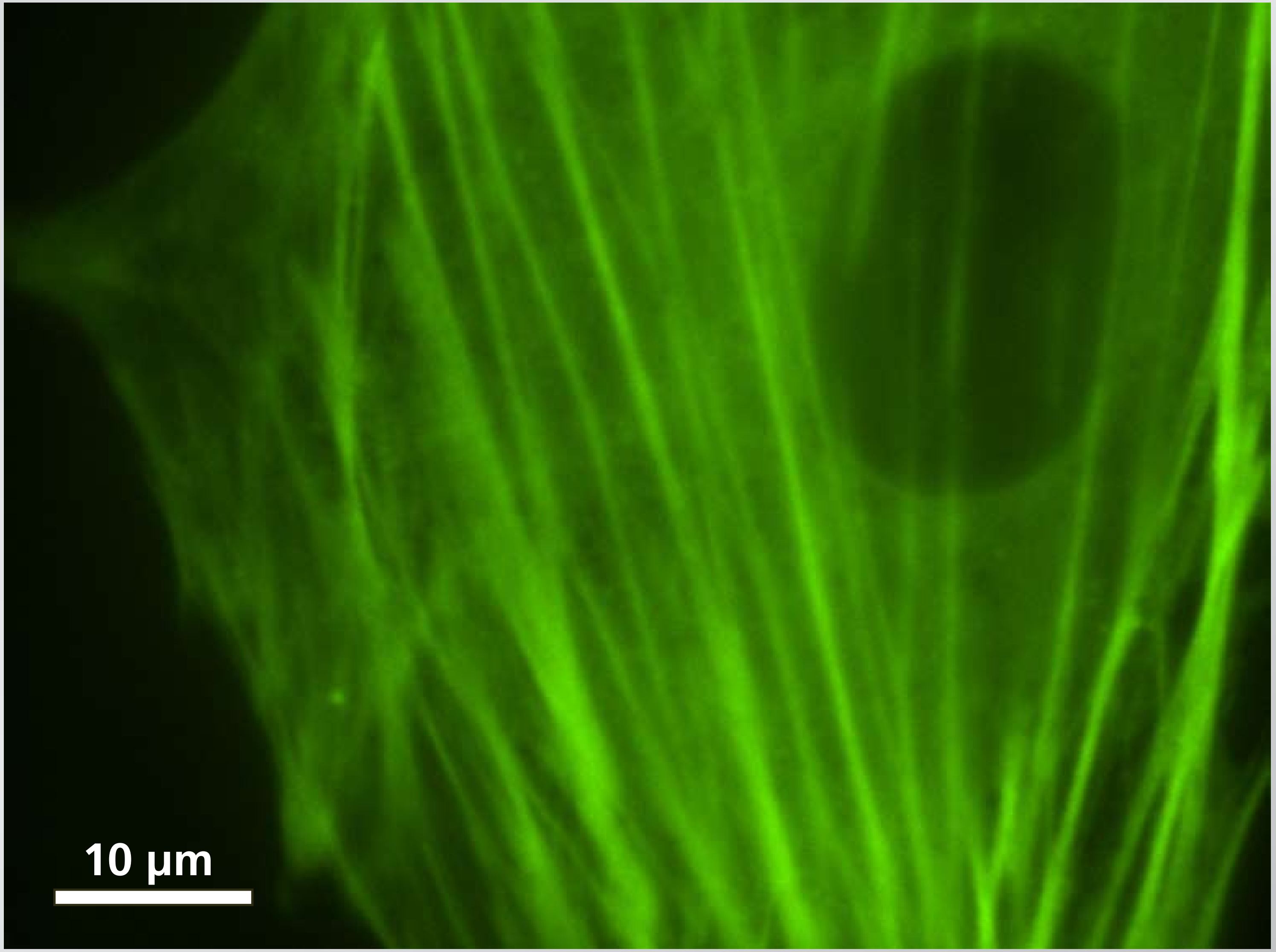
- standard biochemical tools: species selective
- fs laser “nanosurgery”: site specific

Applications

Q: can we probe the dynamics of the cytoskeleton?

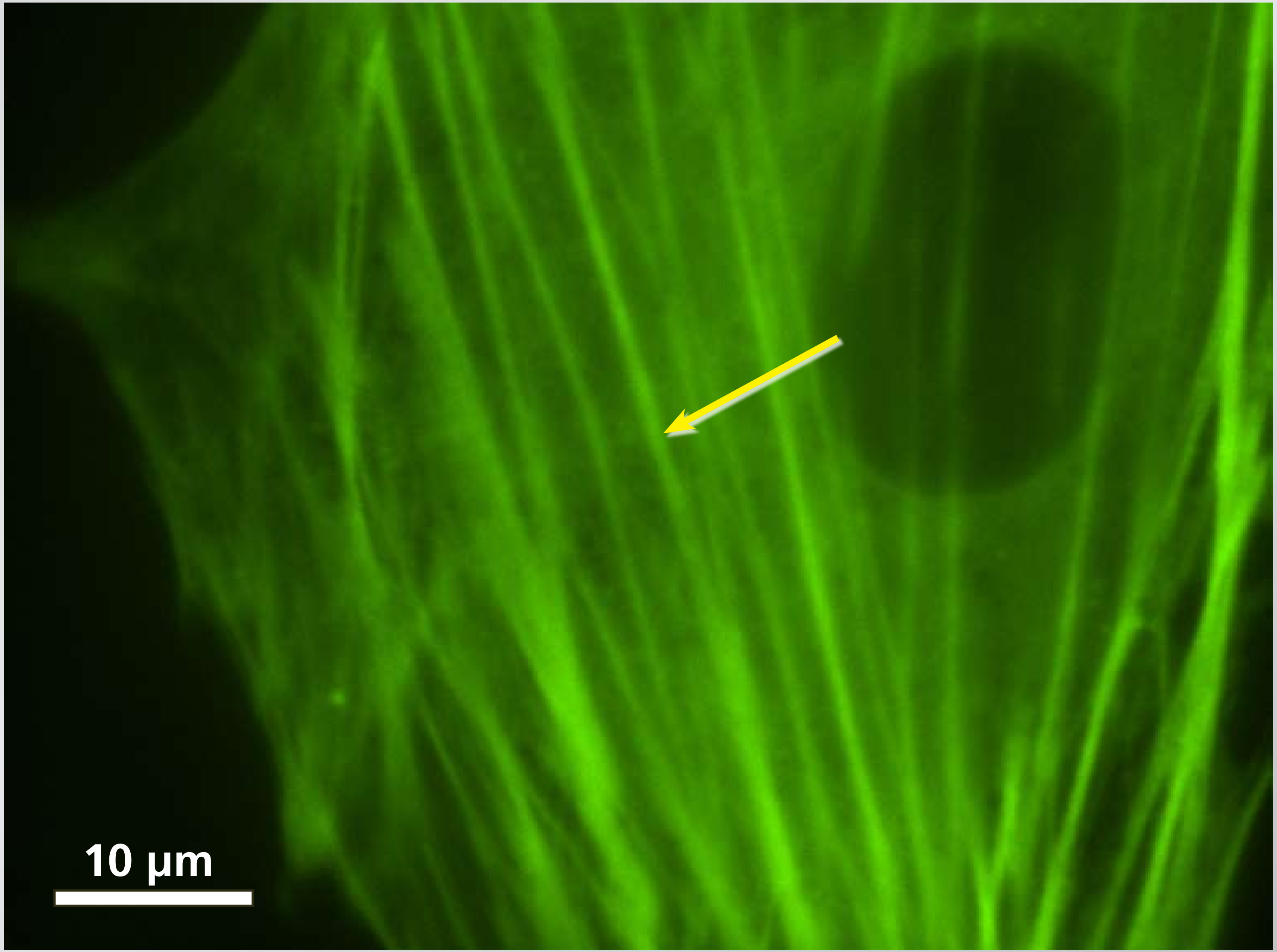
Applications

actin fiber network of a live cell



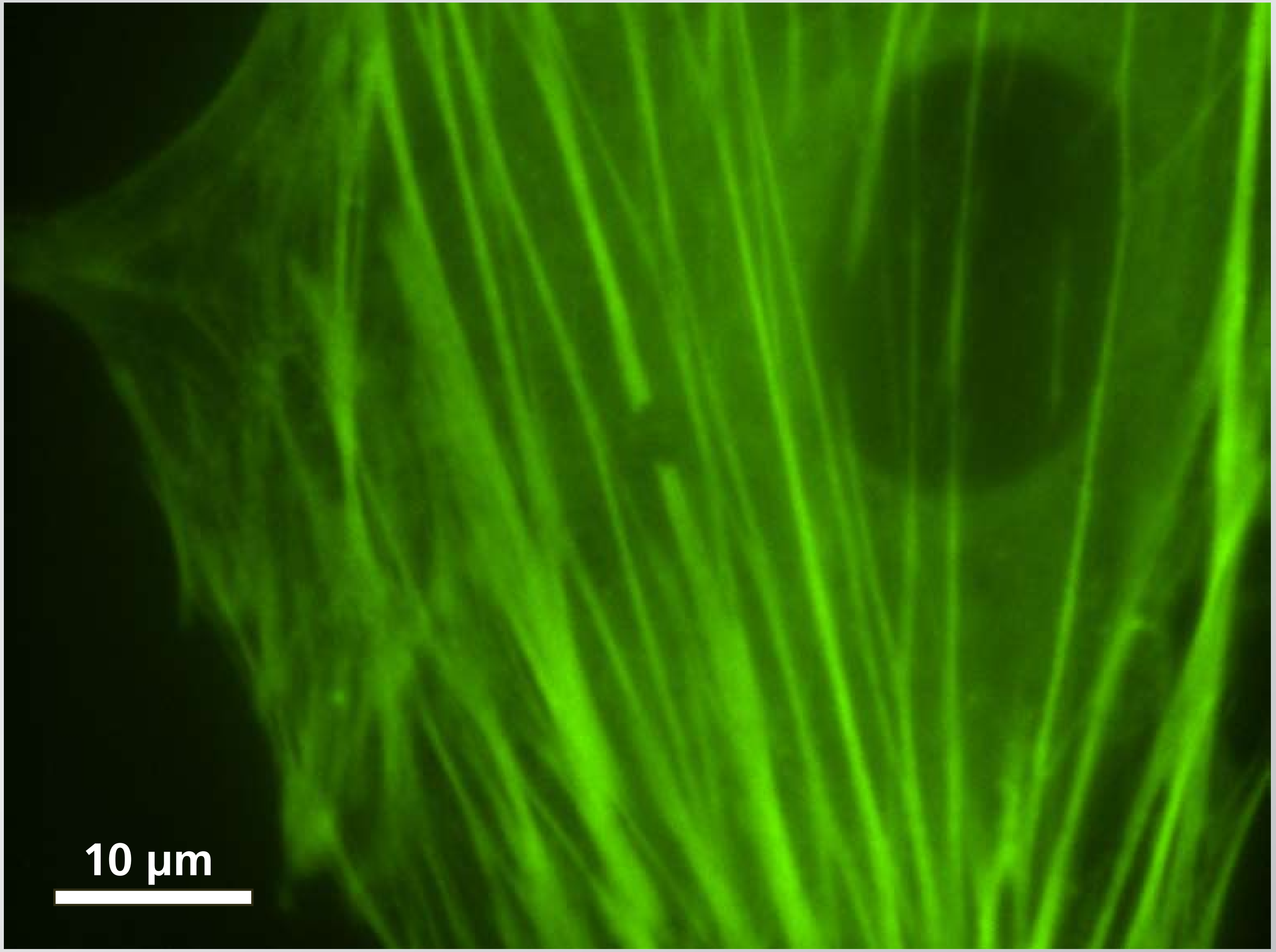
Applications

cut a single fiber bundle



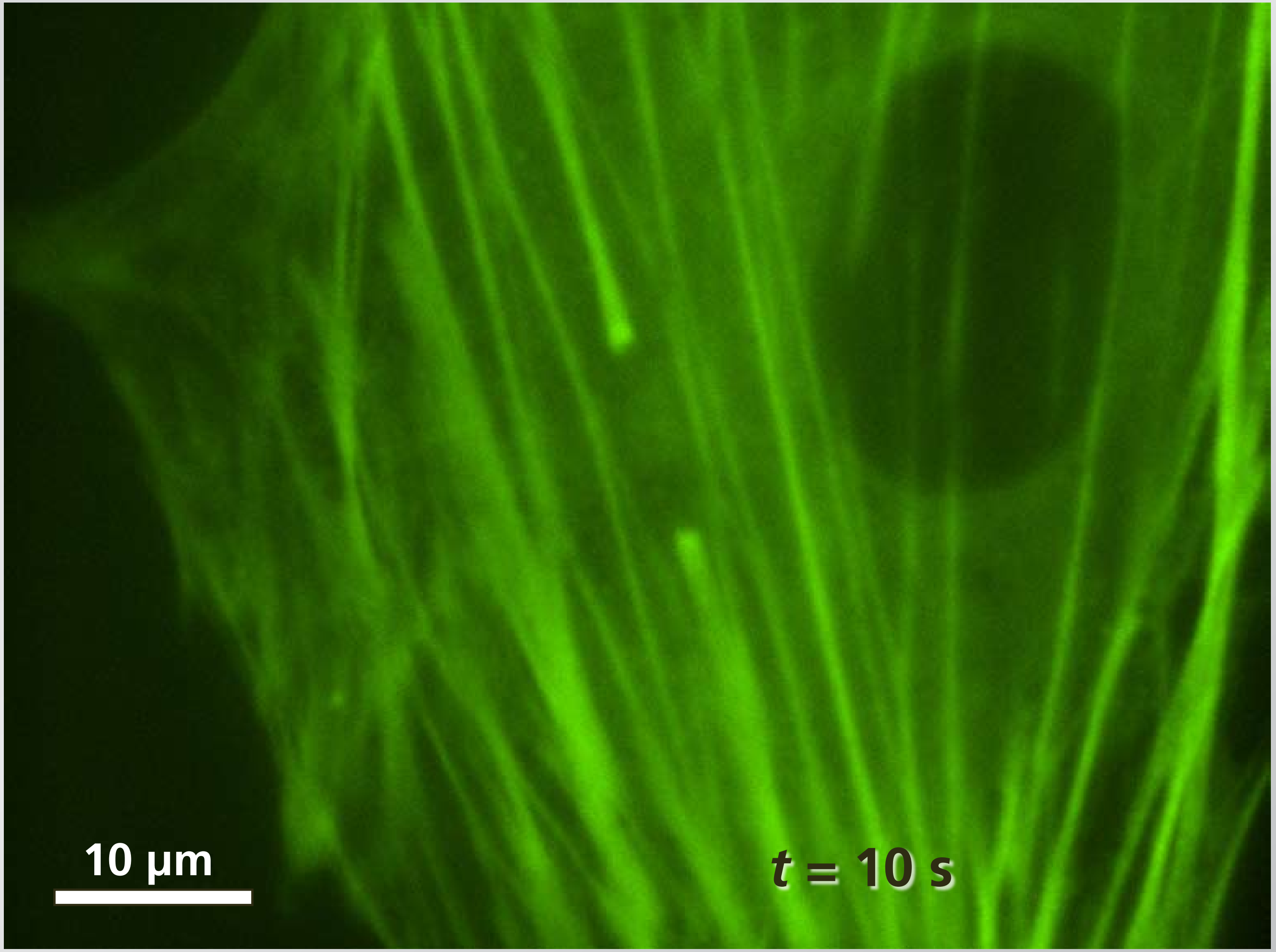
Applications

cut a single fiber bundle



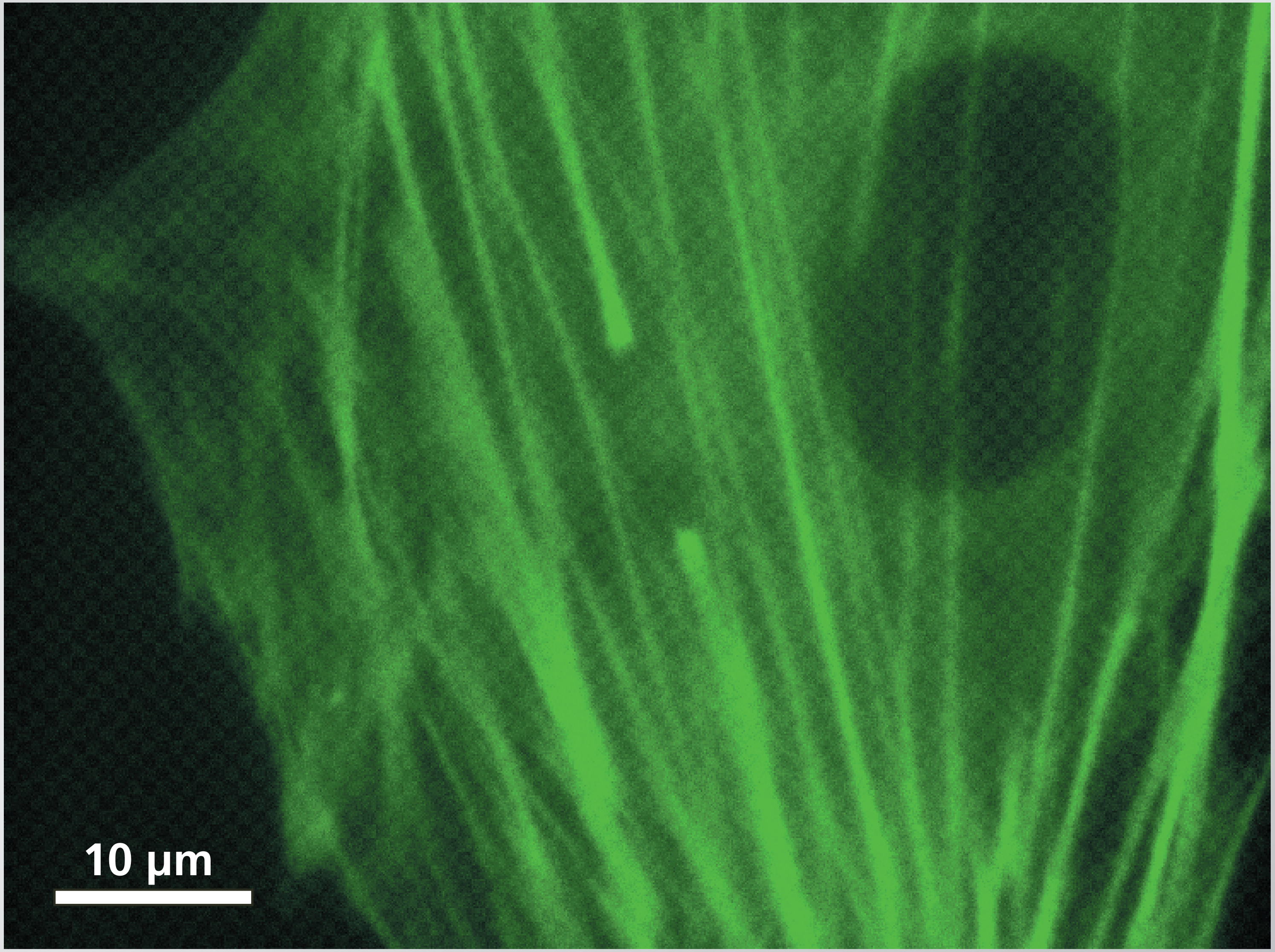
Applications

gap widens with time



Applications

dynamics provides information on *in vivo* mechanics



Applications

Q: can we probe the neurological origins of behavior?

Applications

Caenorhabditis Elegans

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

Applications

Caenorhabditis Elegans

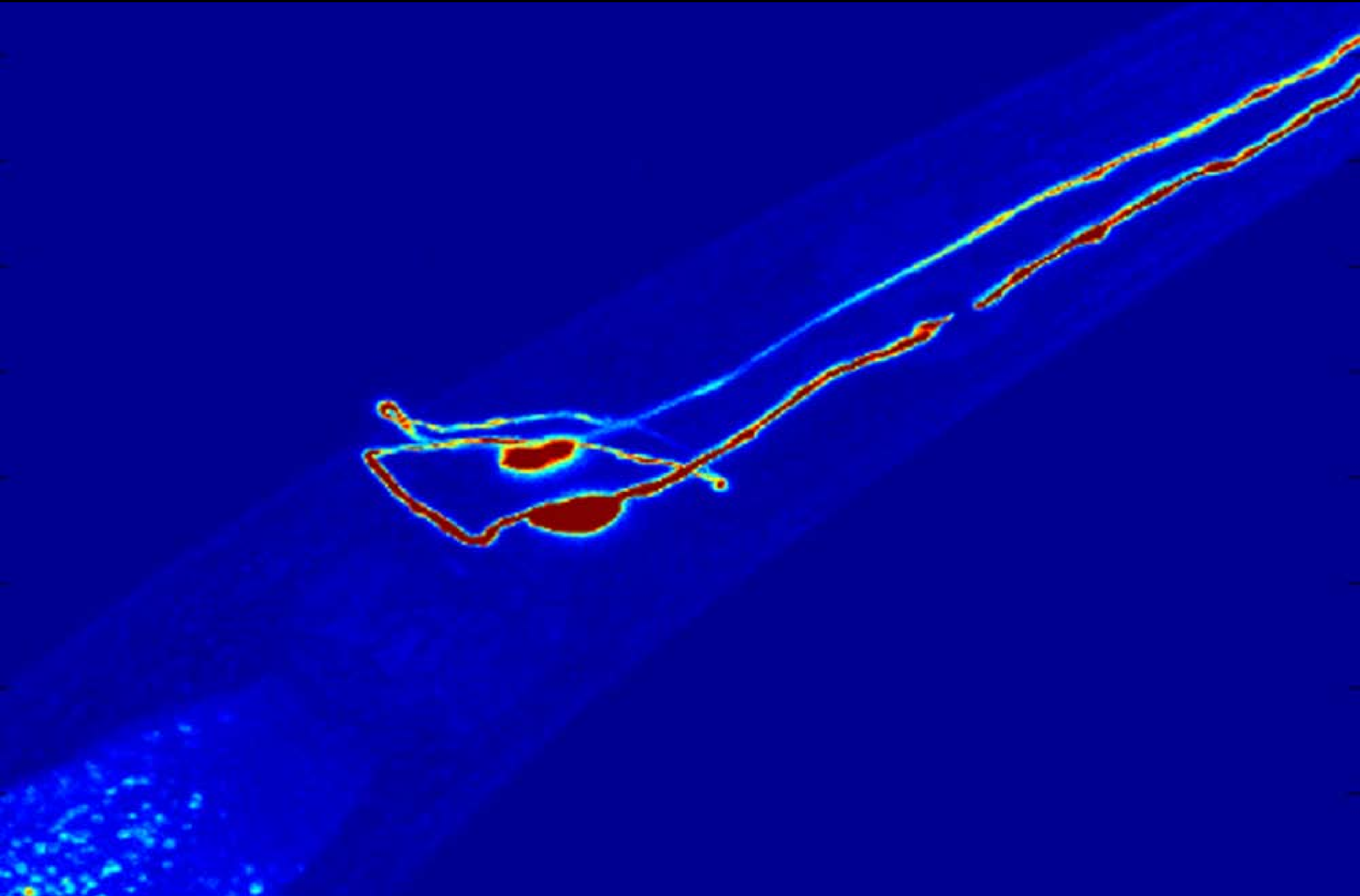
- simple model organism
- similarities to higher organisms
- genome fully sequenced
- easy to handle

Applications

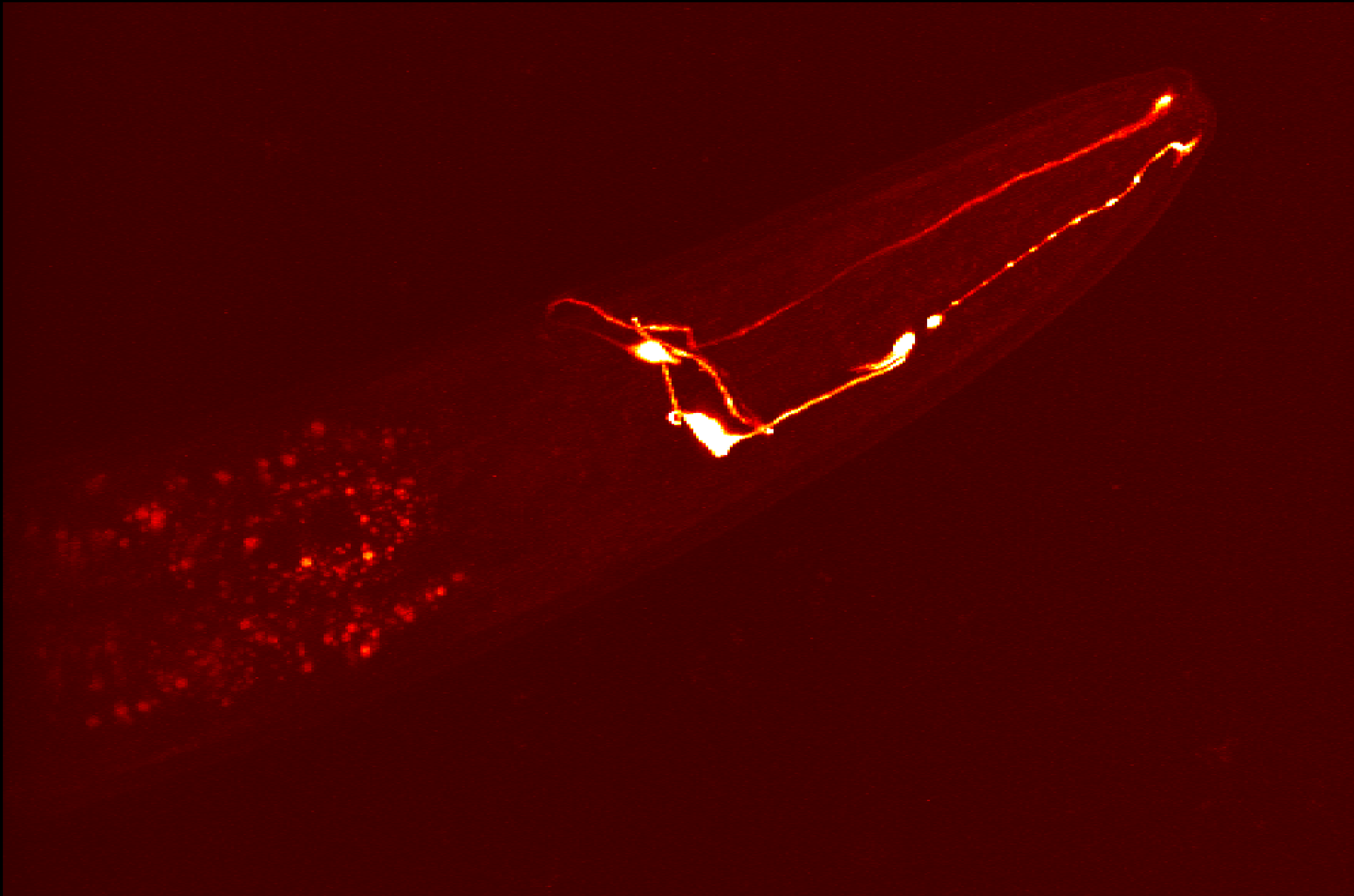
Caenorhabditis Elegans

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

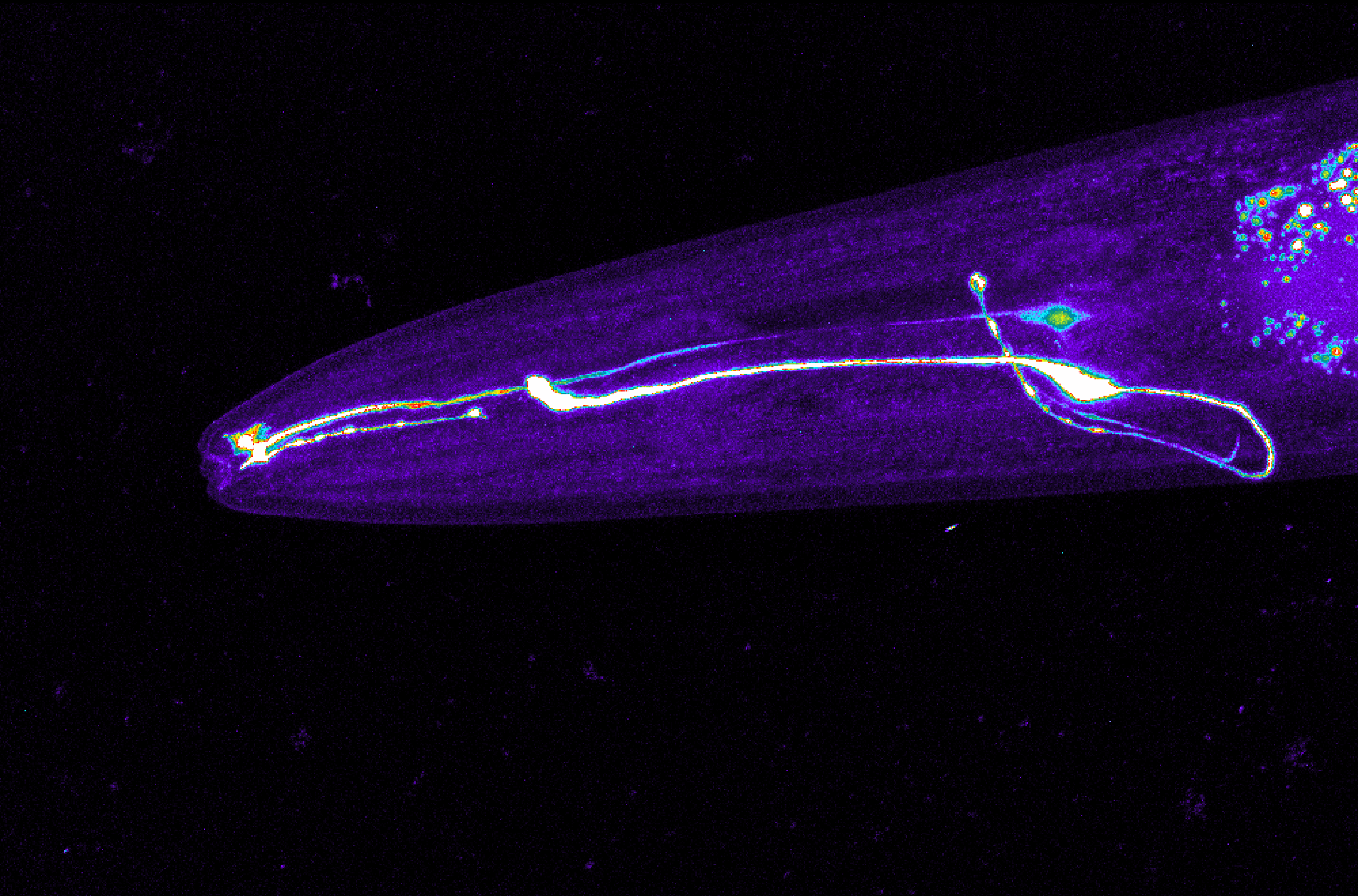
Applications



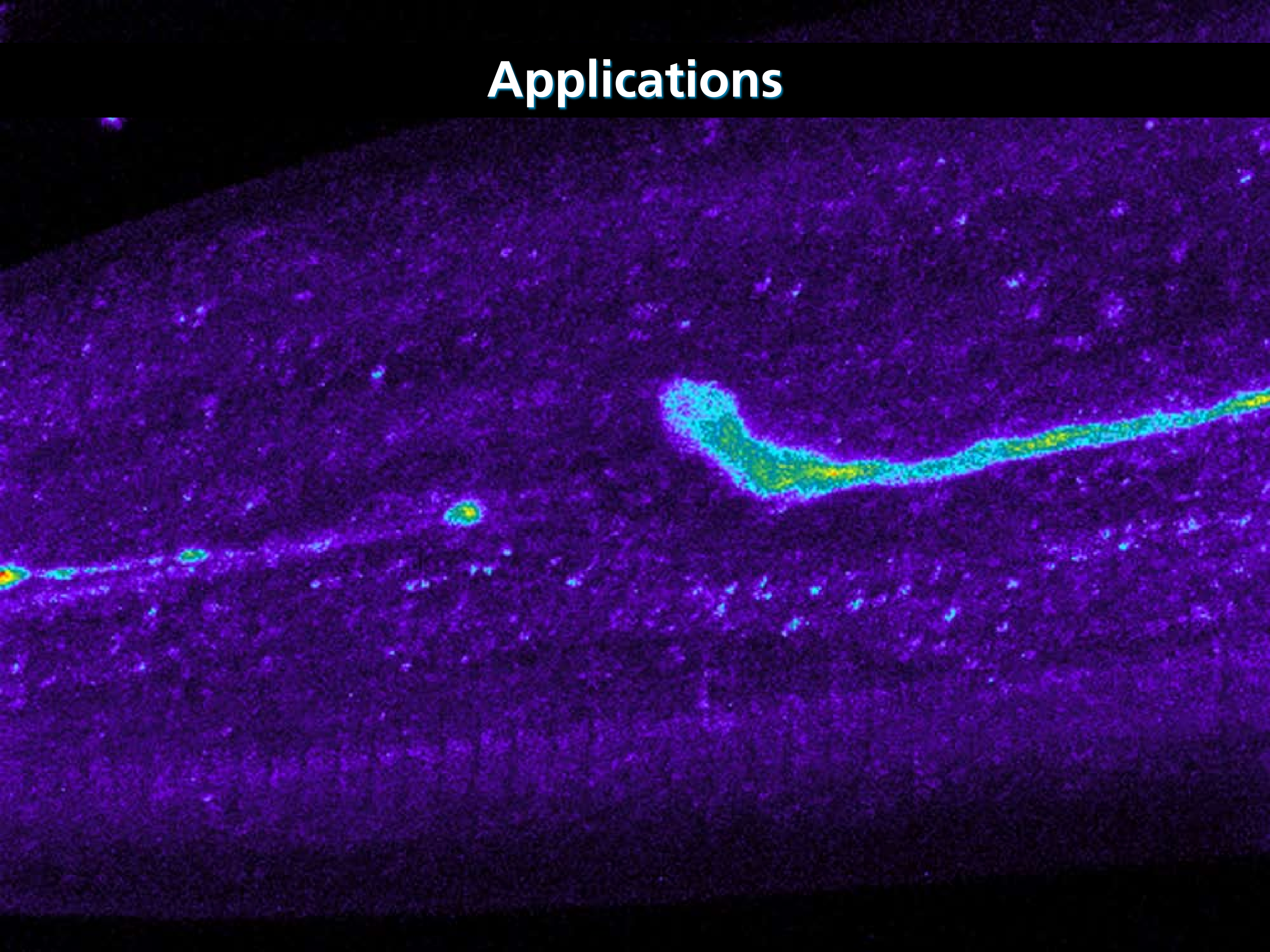
Applications



Applications

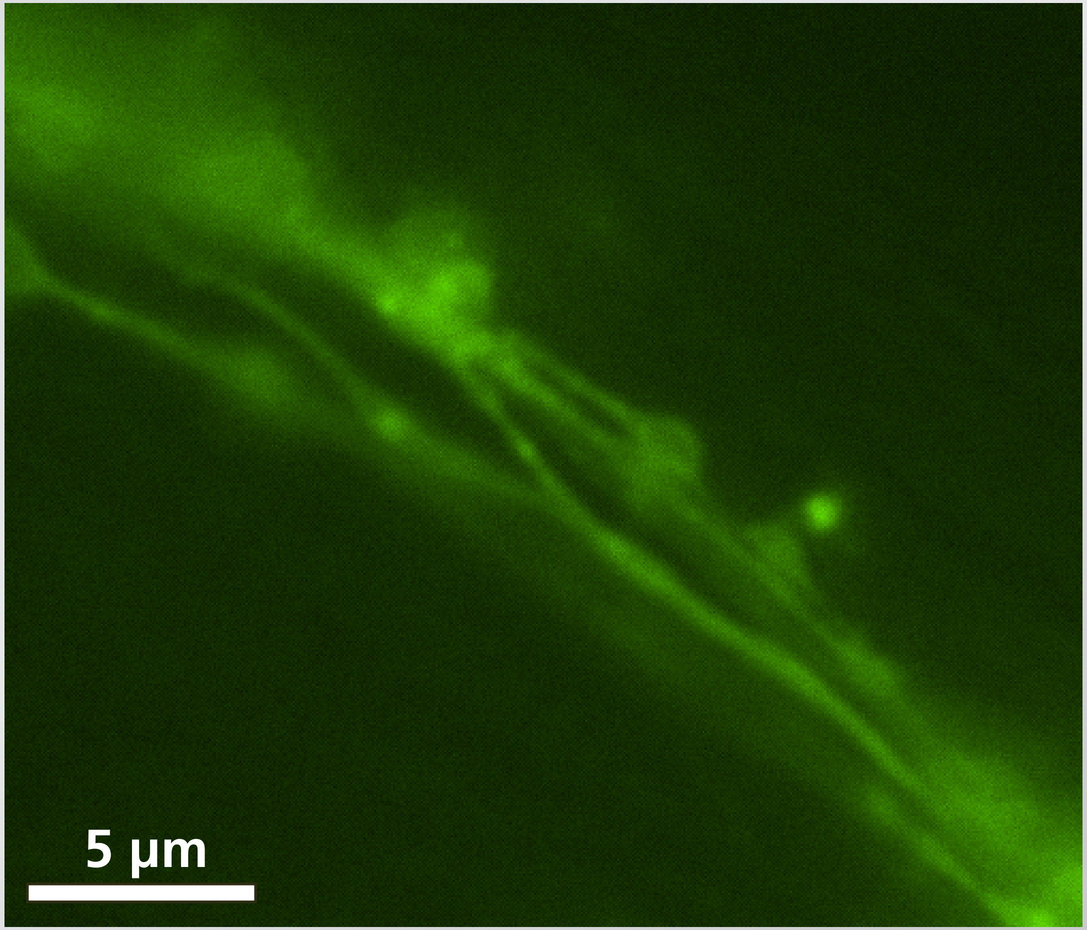


Applications



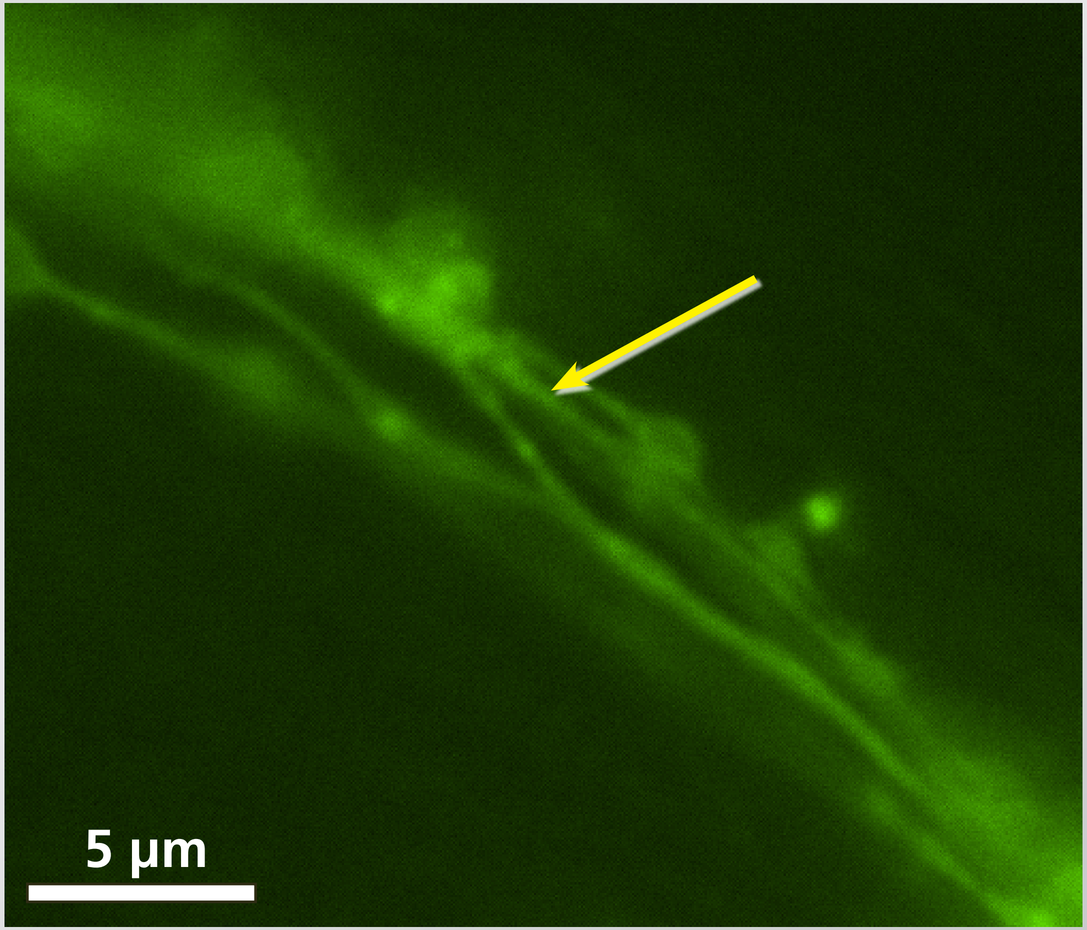
Applications

cut single dendrite in amphid bundle



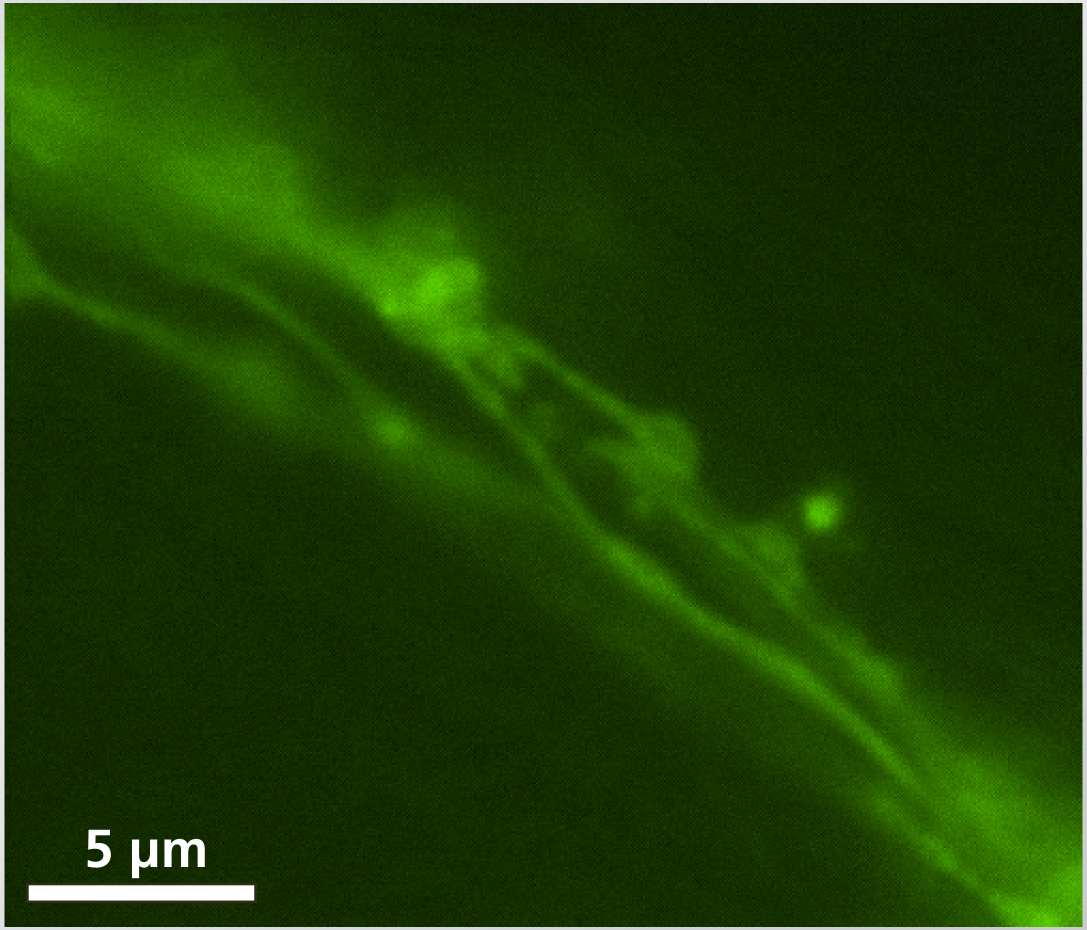
Applications

cut single dendrite in amphid bundle



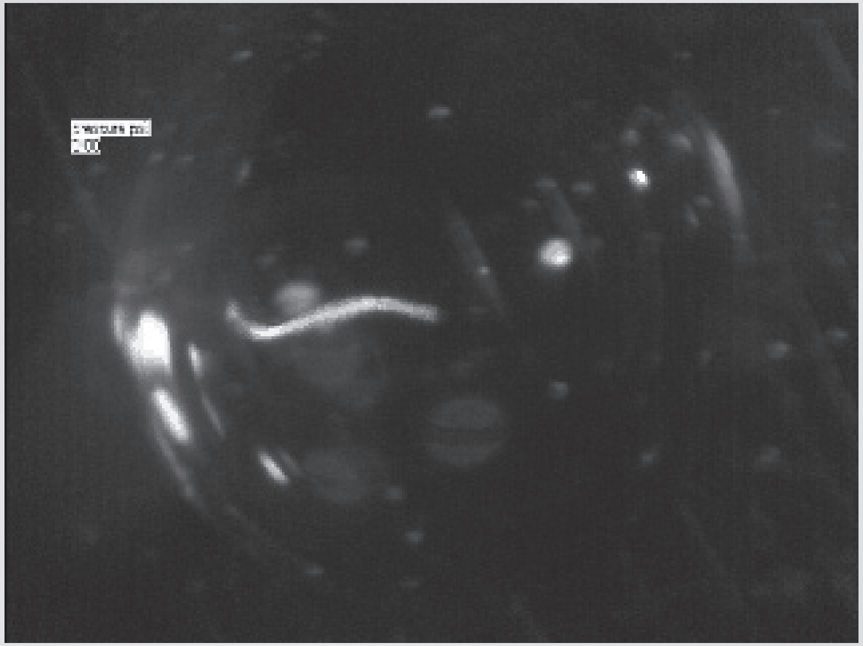
Applications

cut single dendrite in amphid bundle

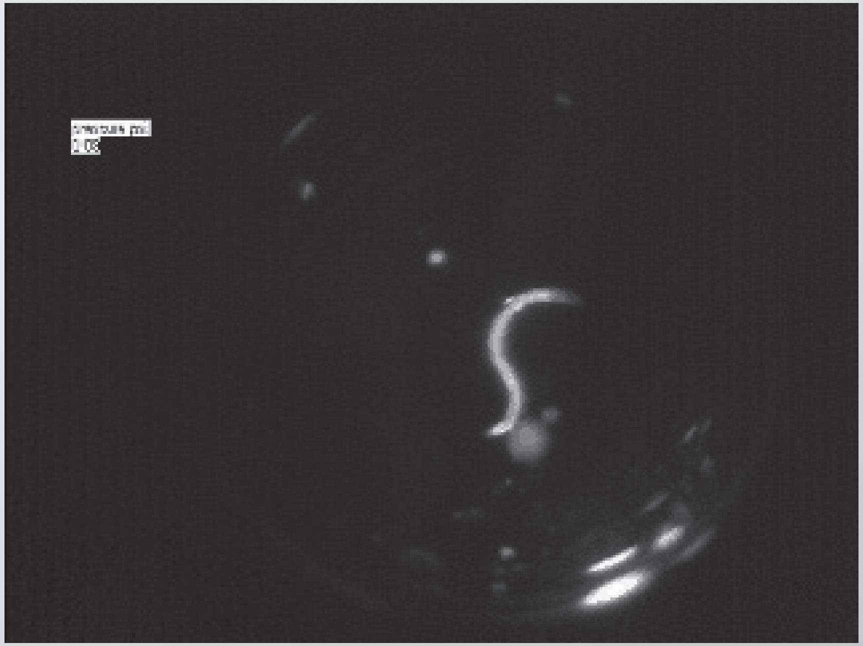


Applications

surgery results in quantifiable behavior changes



before



after

Summary

great tool for

- “wiring light”
- micromanipulating the machinery of life

Summary

- important parameters: focusing, energy, repetition rate
- nearly material independent
- two regimes: low and high repetition rate
- high-repetition rate (thermal) machining fast, convenient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APPLIED SCIENCE

Funding:

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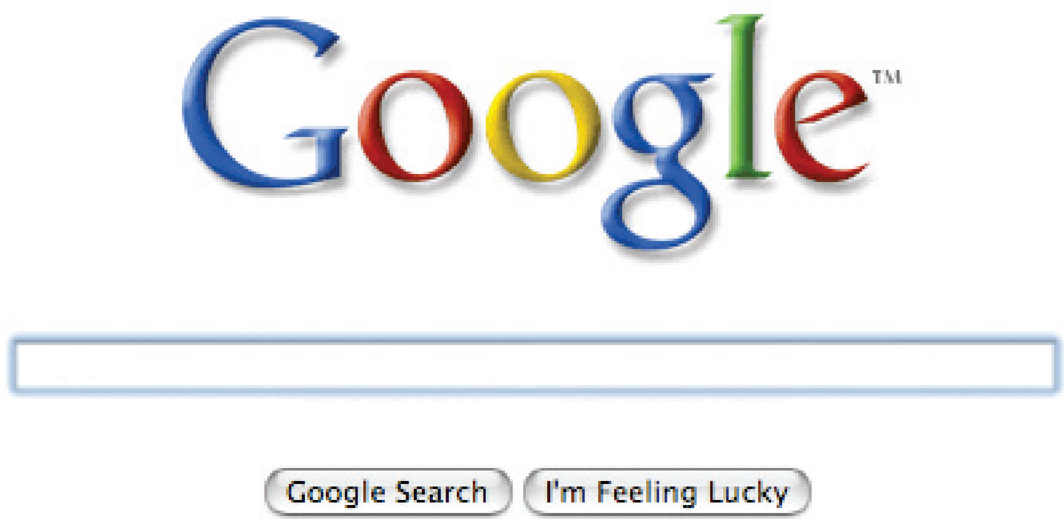
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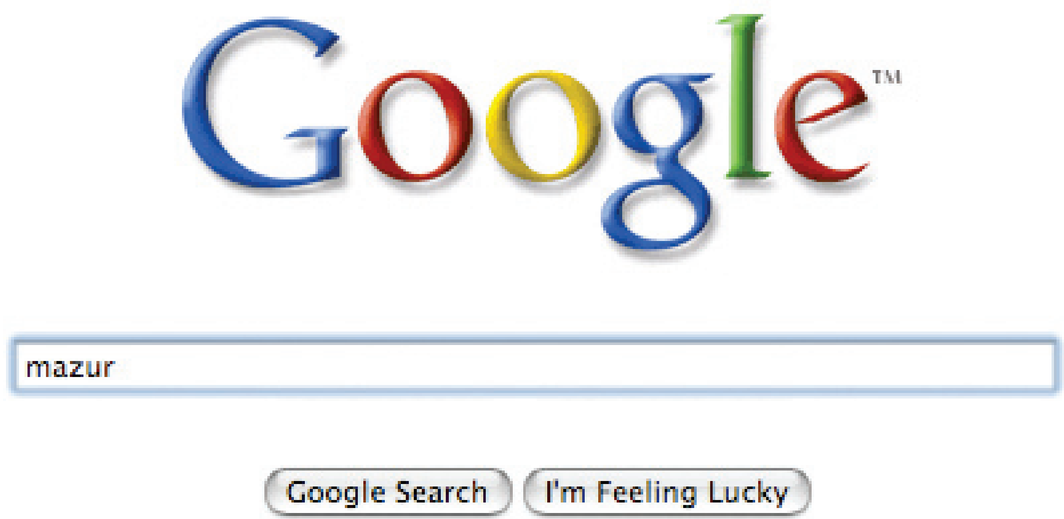
I'm Feeling Lucky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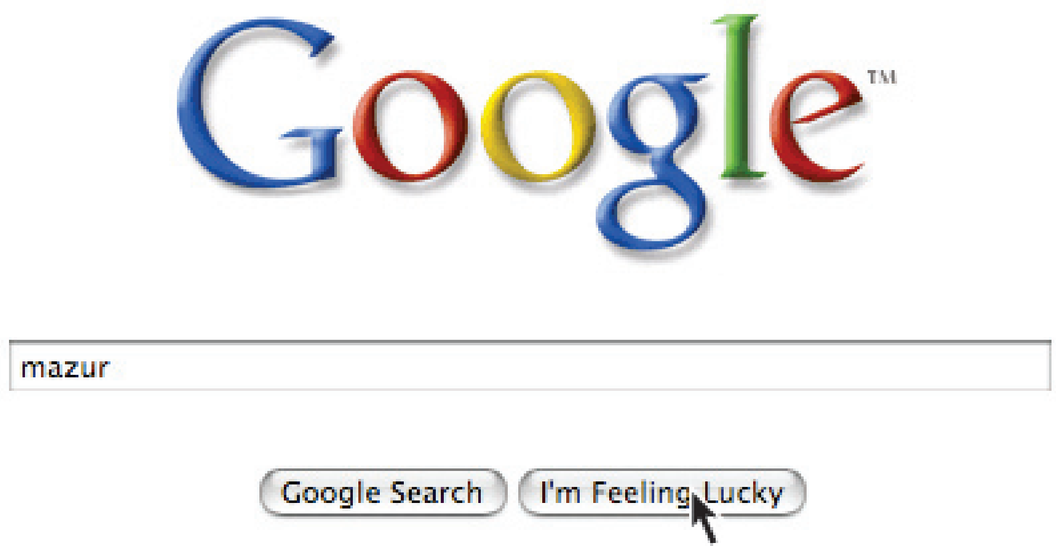
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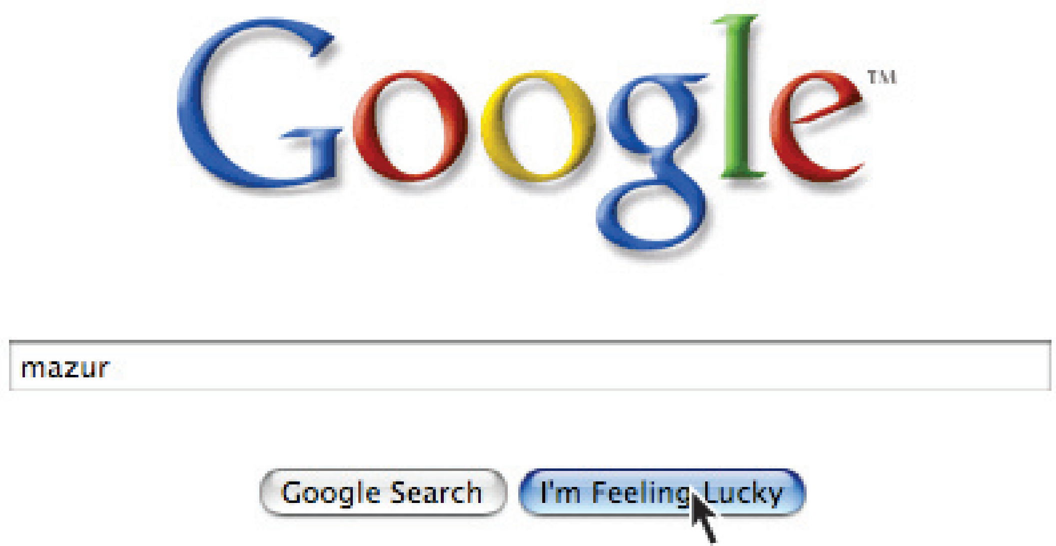
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