Femtosecond Laser Micromachining: Applications in Photonics and Biology

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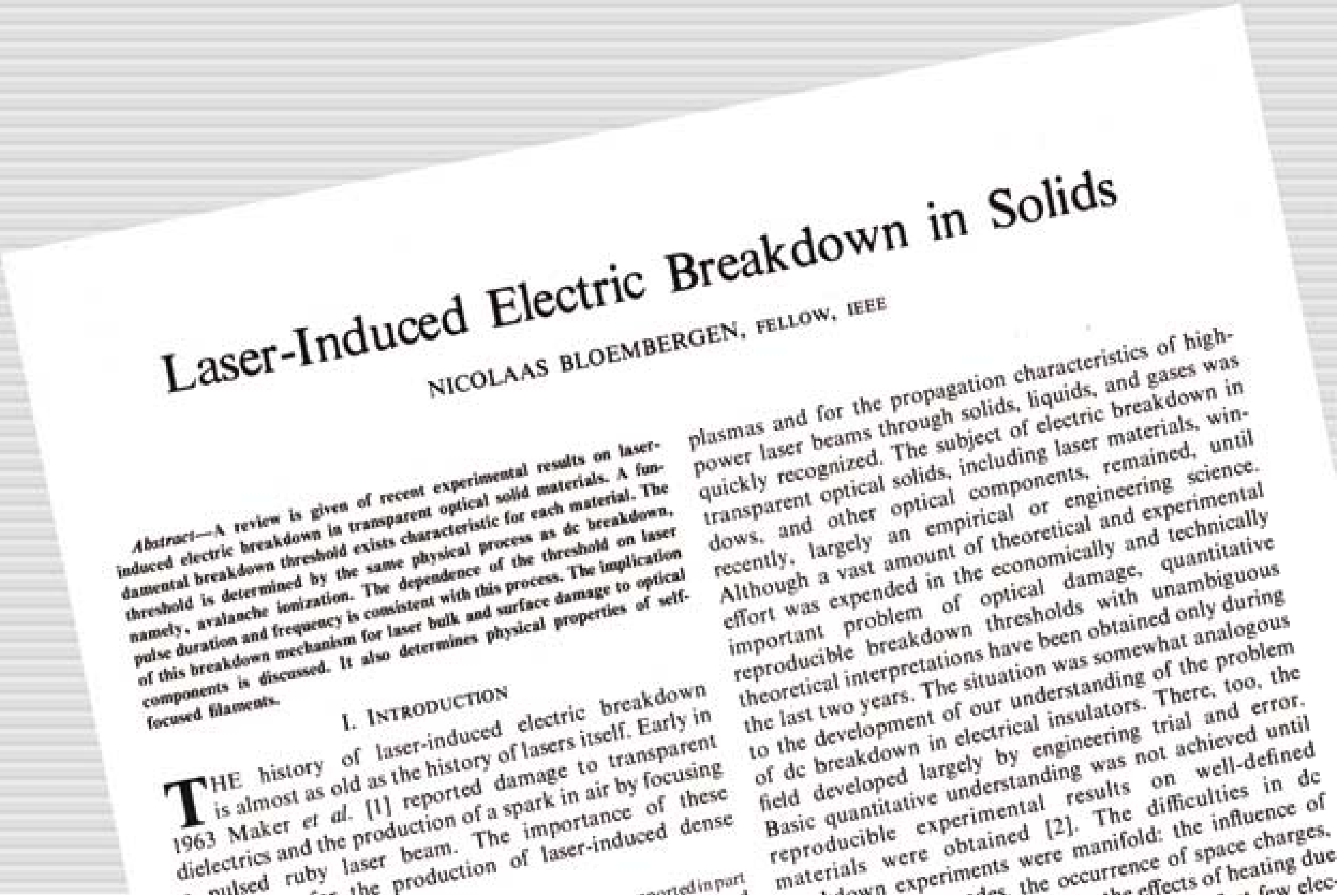


Laser-Induced Electric Breakdown in Solids

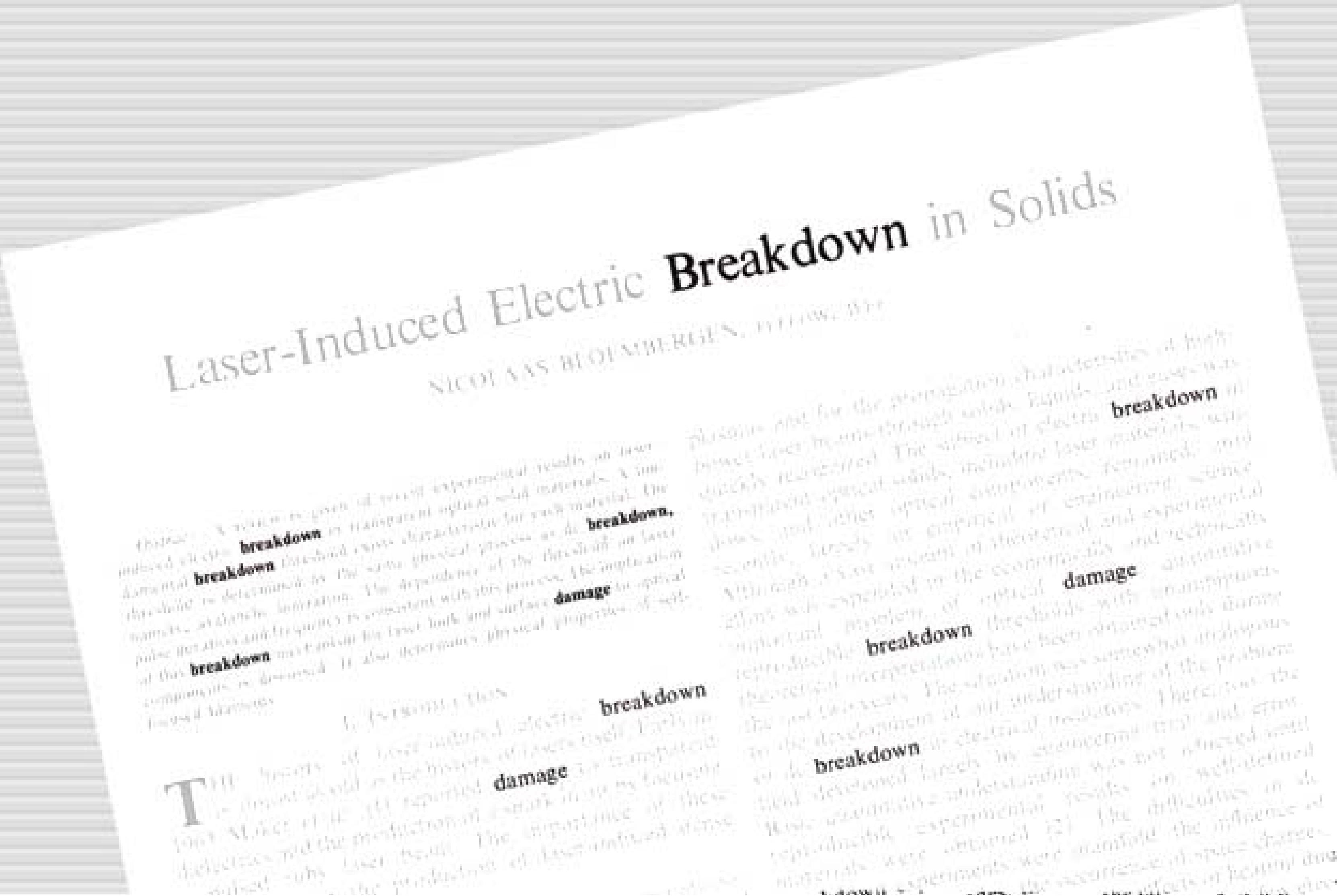
NICOLAAS BLOEMBERGEN, FELLOW, IEEE

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

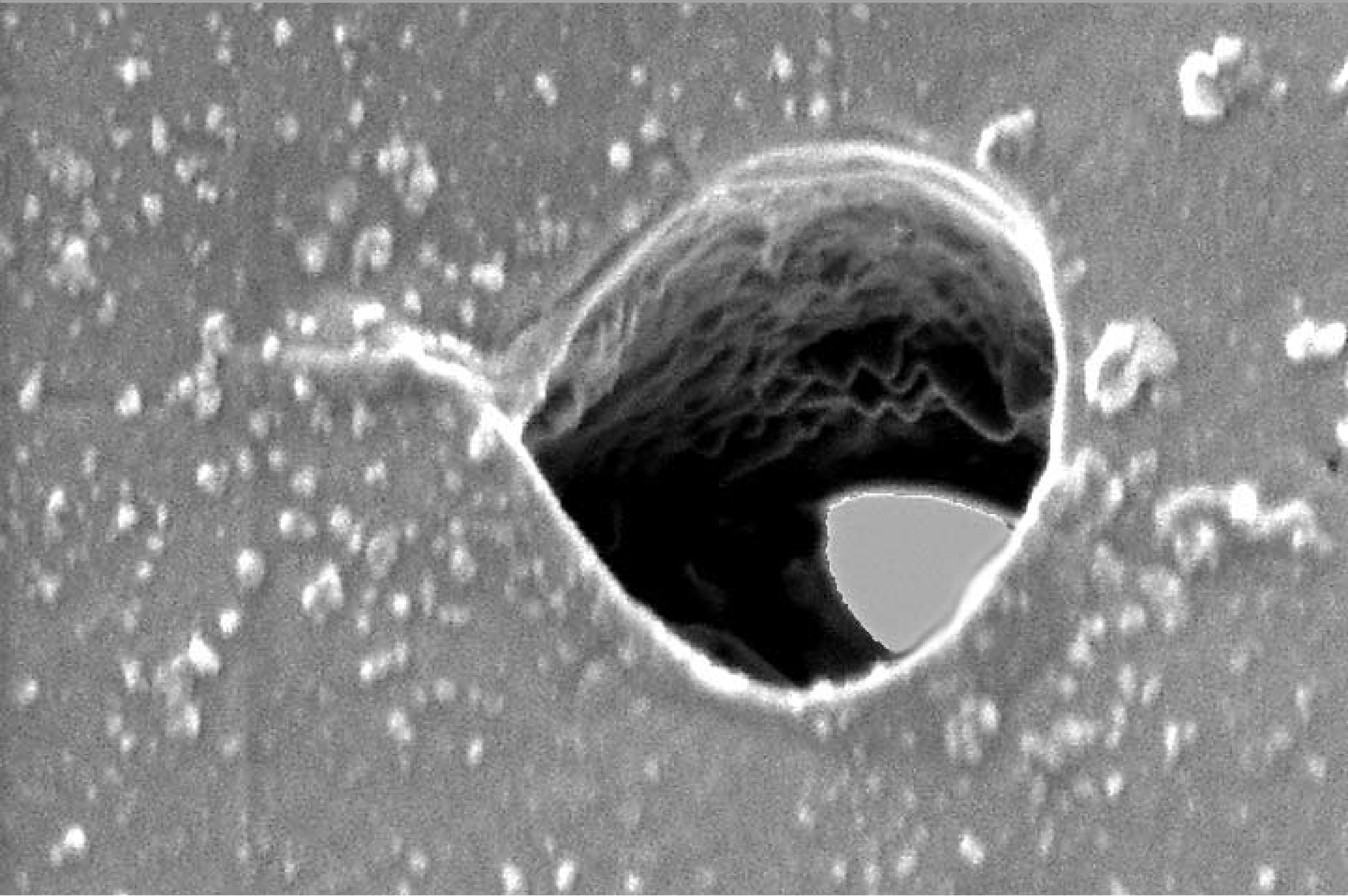
THE history of laser-induced electric breakdown is almost as old as the history of lasers itself. Early in 1963 Maker *et al.* [1] reported damage to transparent dielectrics and the production of a spark in air by focusing a pulsed ruby laser beam. The importance of these ... for the production of laser-induced 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 technically 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 ... the occurrence of space charges, ... the effects of heating due ... few elec-

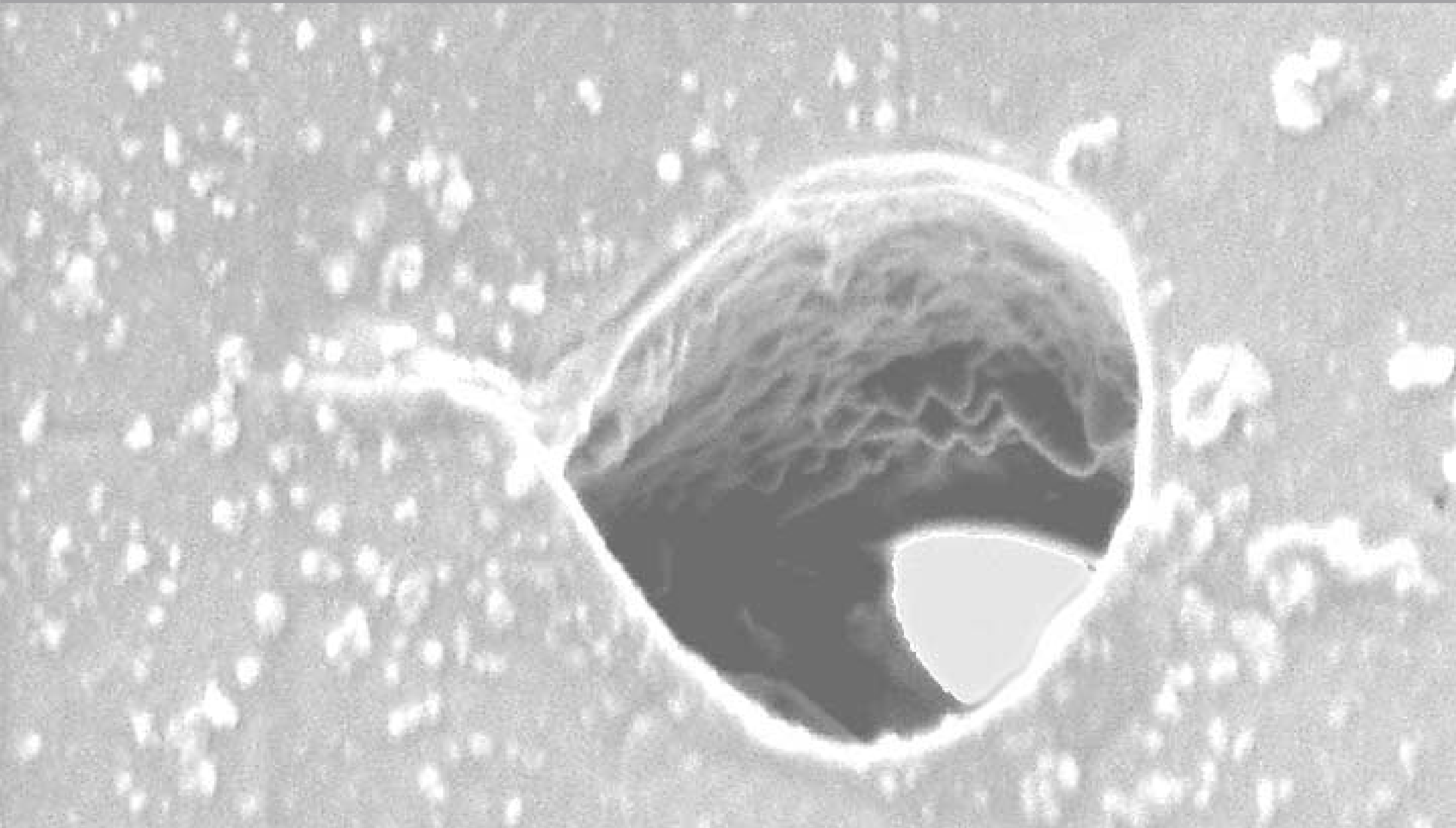
Introduction


Laser-Induced Electric Breakdown in Solids

Introduction

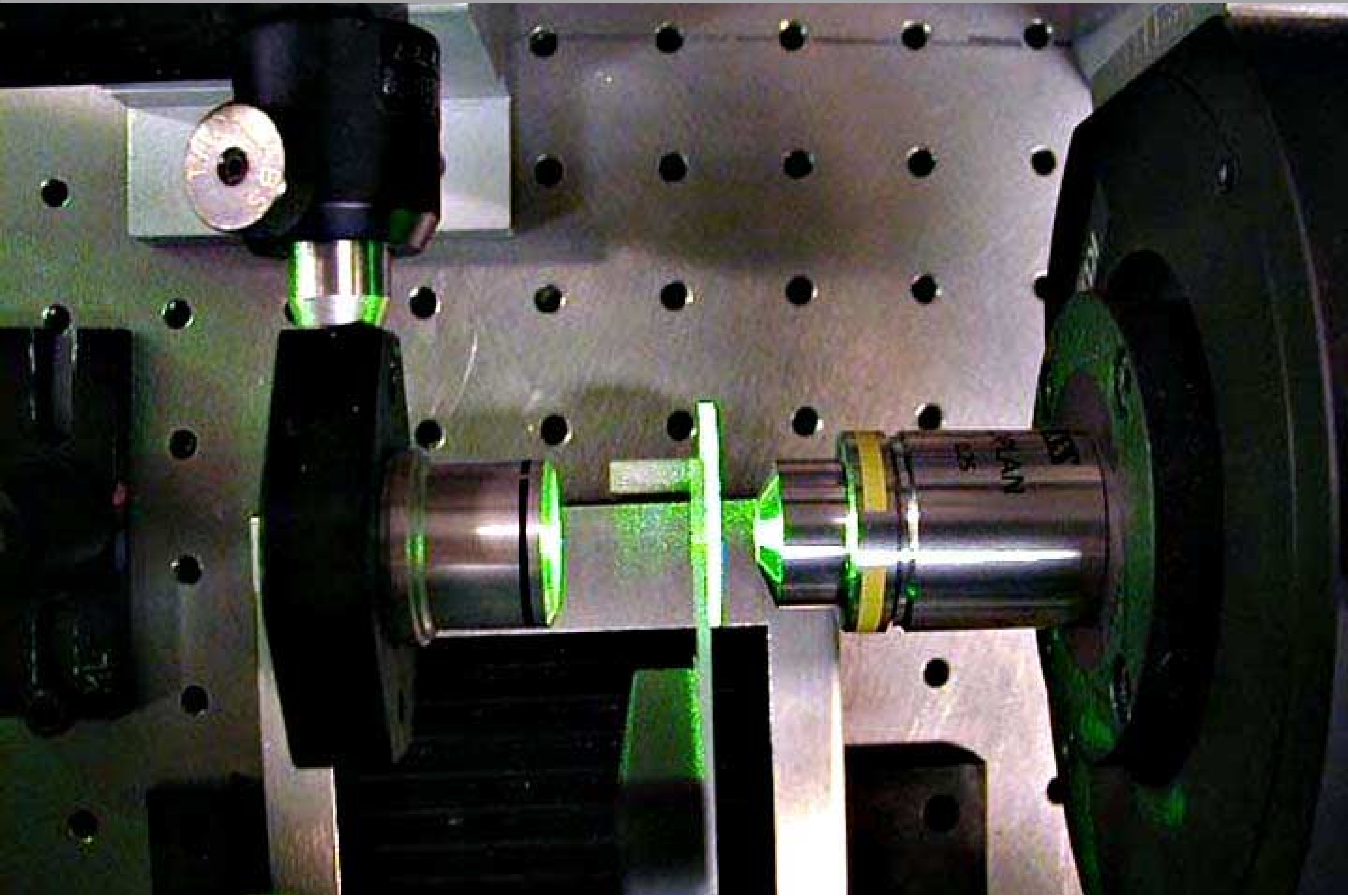
Introduction





use damage for processing!

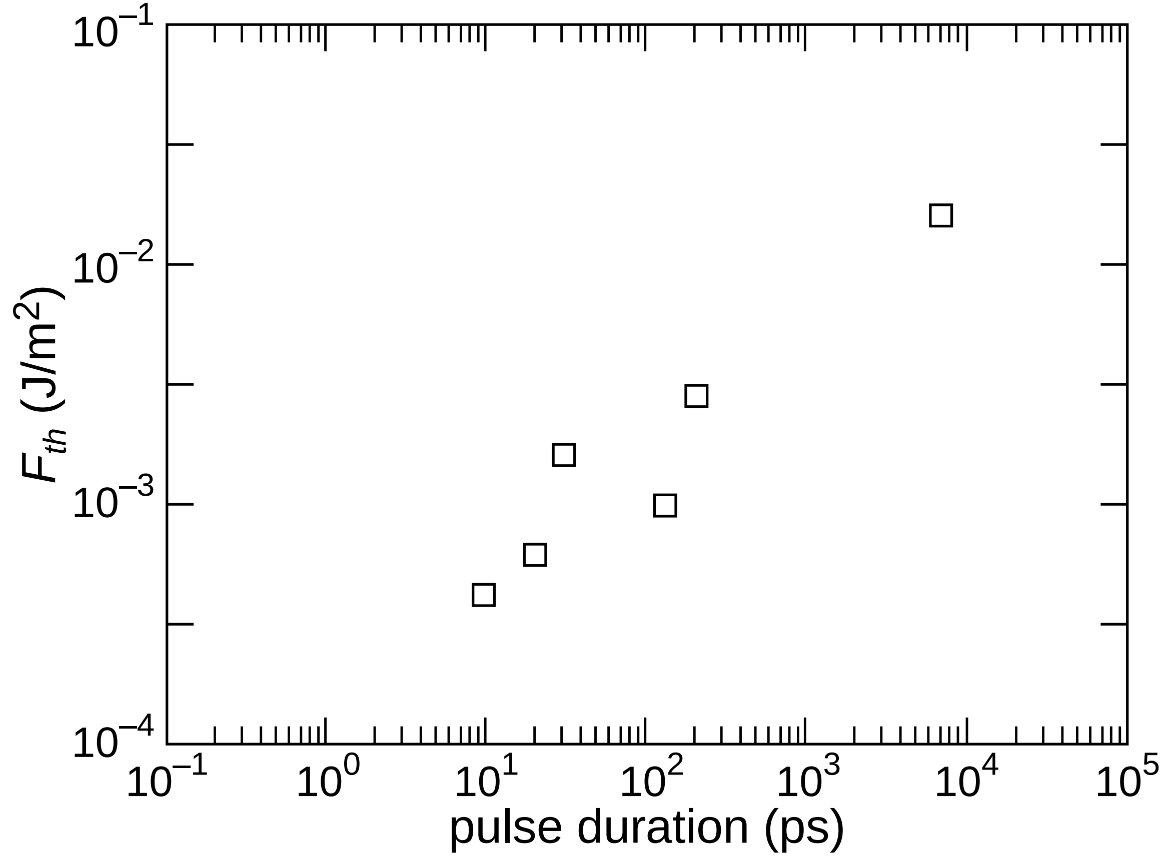
Outline



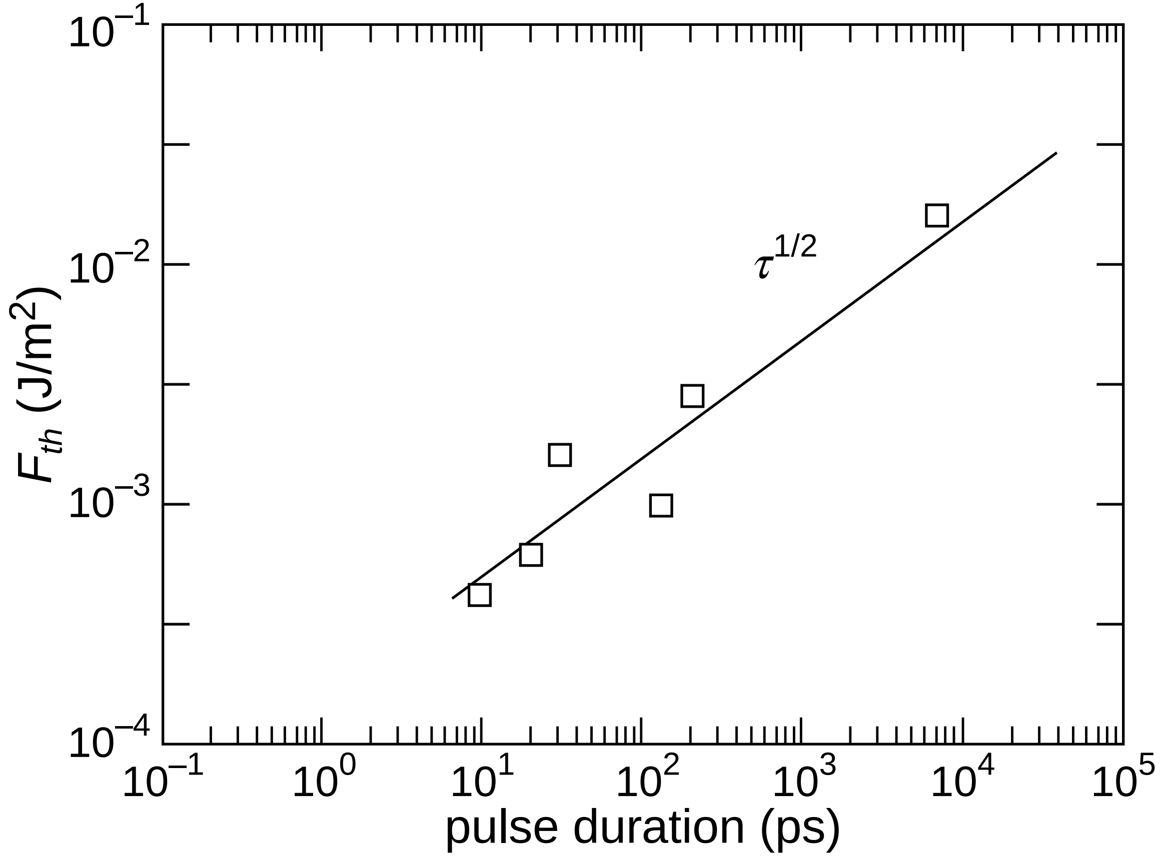
Outline

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

Processing with fs pulses



Processing with fs pulses



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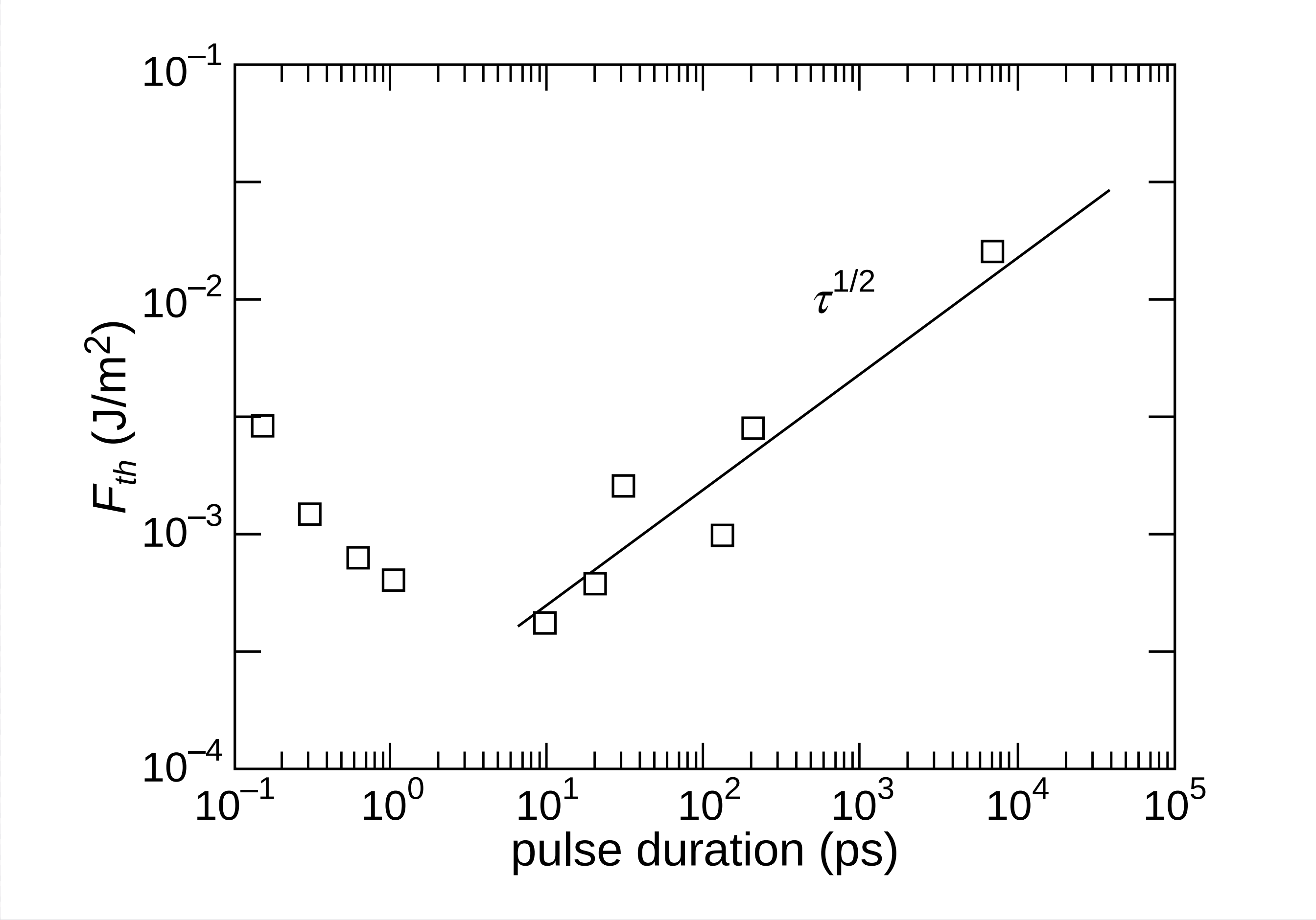
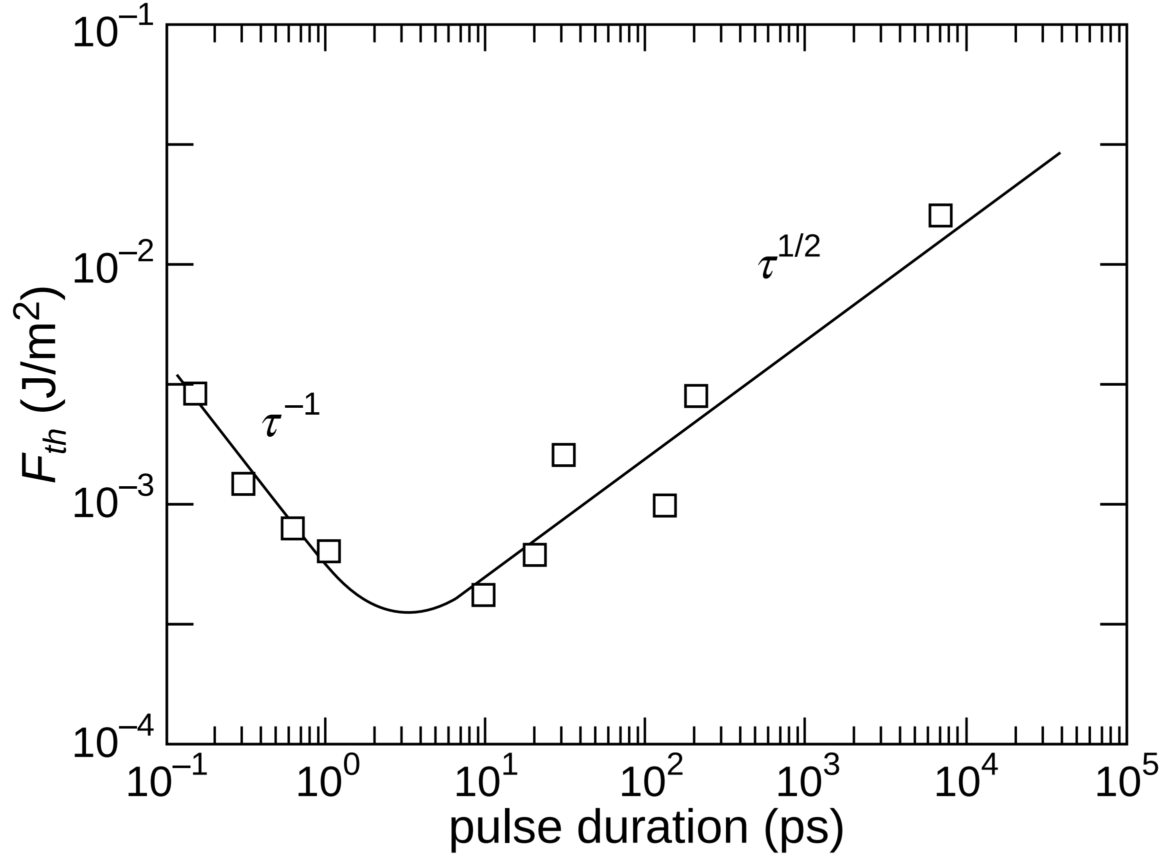


Du *et al.*, *Appl. Phys. Lett.* 64, 3071 (1994)

Processing with fs pulses



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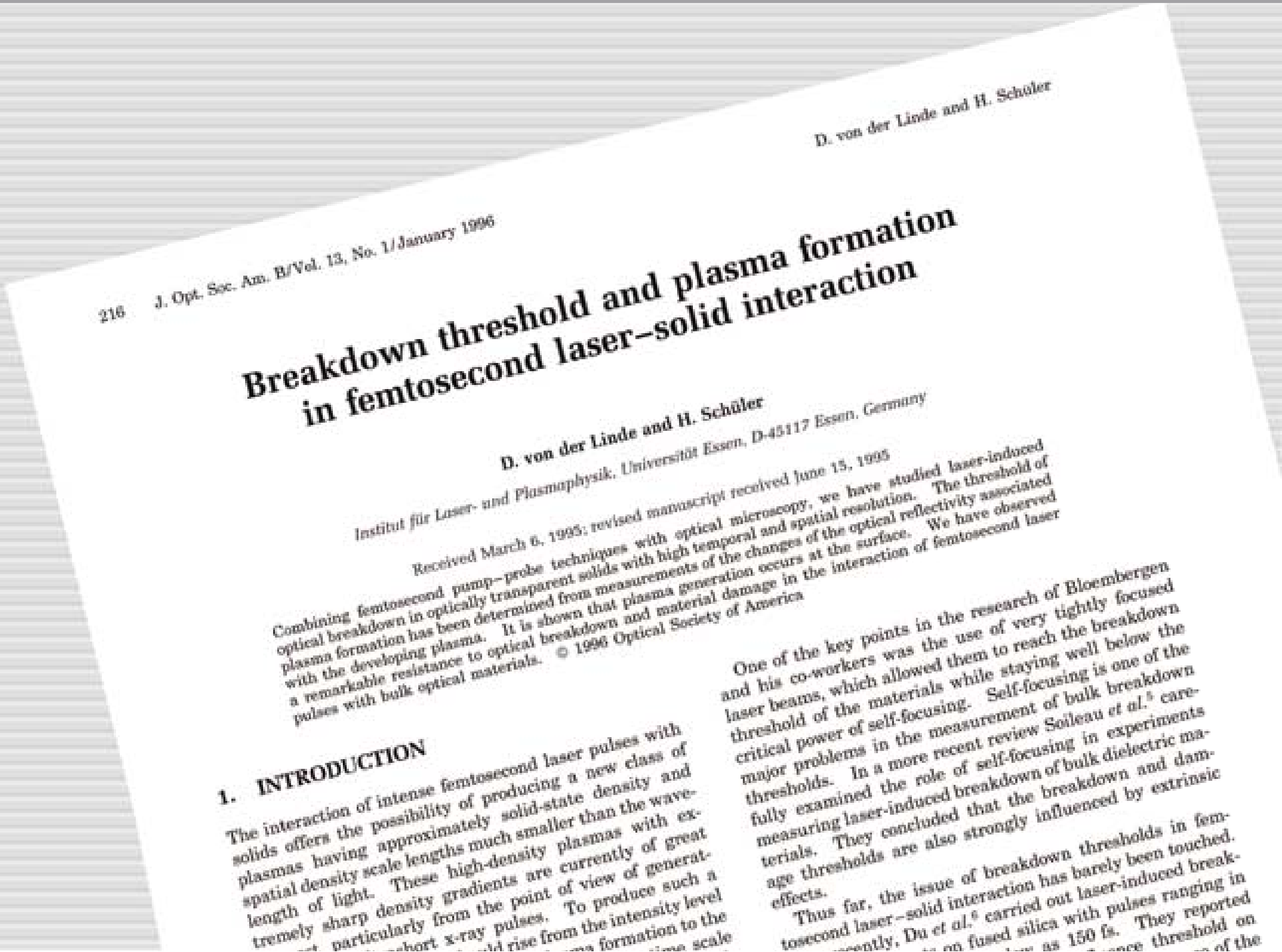
Processing with fs pulses



216 J. Opt. Soc. Am. B/Vol. 13, No. 1/January 1996

D. von der Linde and H. Schüler

Breakdown threshold and plasma formation in femtosecond laser–solid interaction

D. von der Linde and H. Schüler

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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 ... particularly from the point of view of generat... short x-ray pulses. To produce such a ... rise from the intensity level ... formation to the ... time scale

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. ...recently, Du *et al.*[6] carried out laser-induced break... on fused silica with pulses ranging in ... as 150 fs. They reported ... threshold on ... of the

Processing with fs pulses

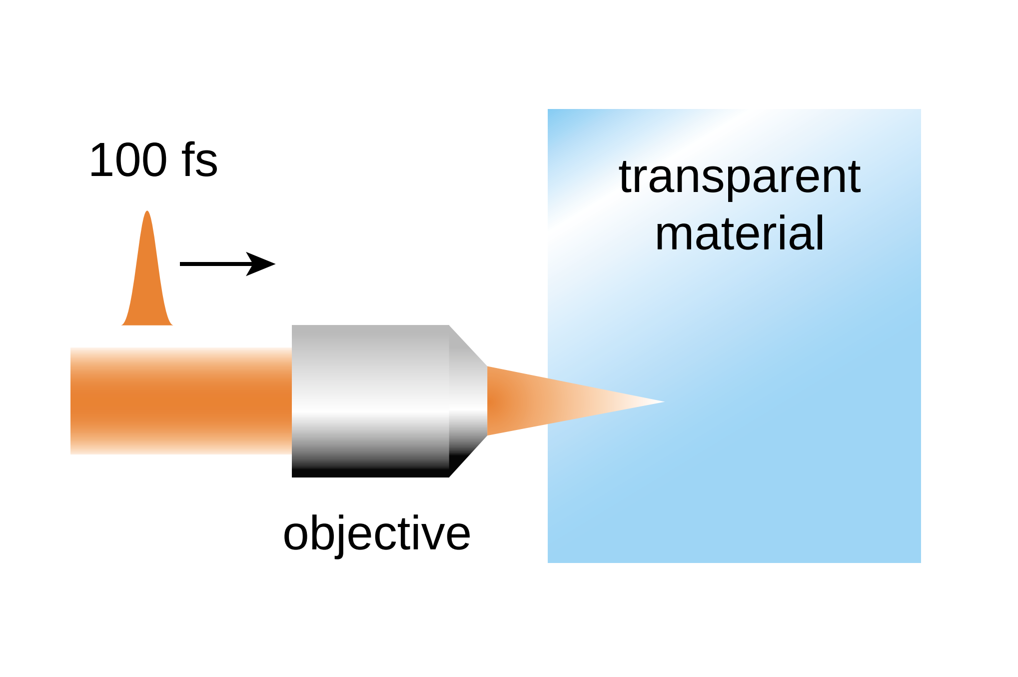
"… clear evidence that no bulk plasmas …

[and] … no bulk damage could be produced

with femtosecond laser pulses."

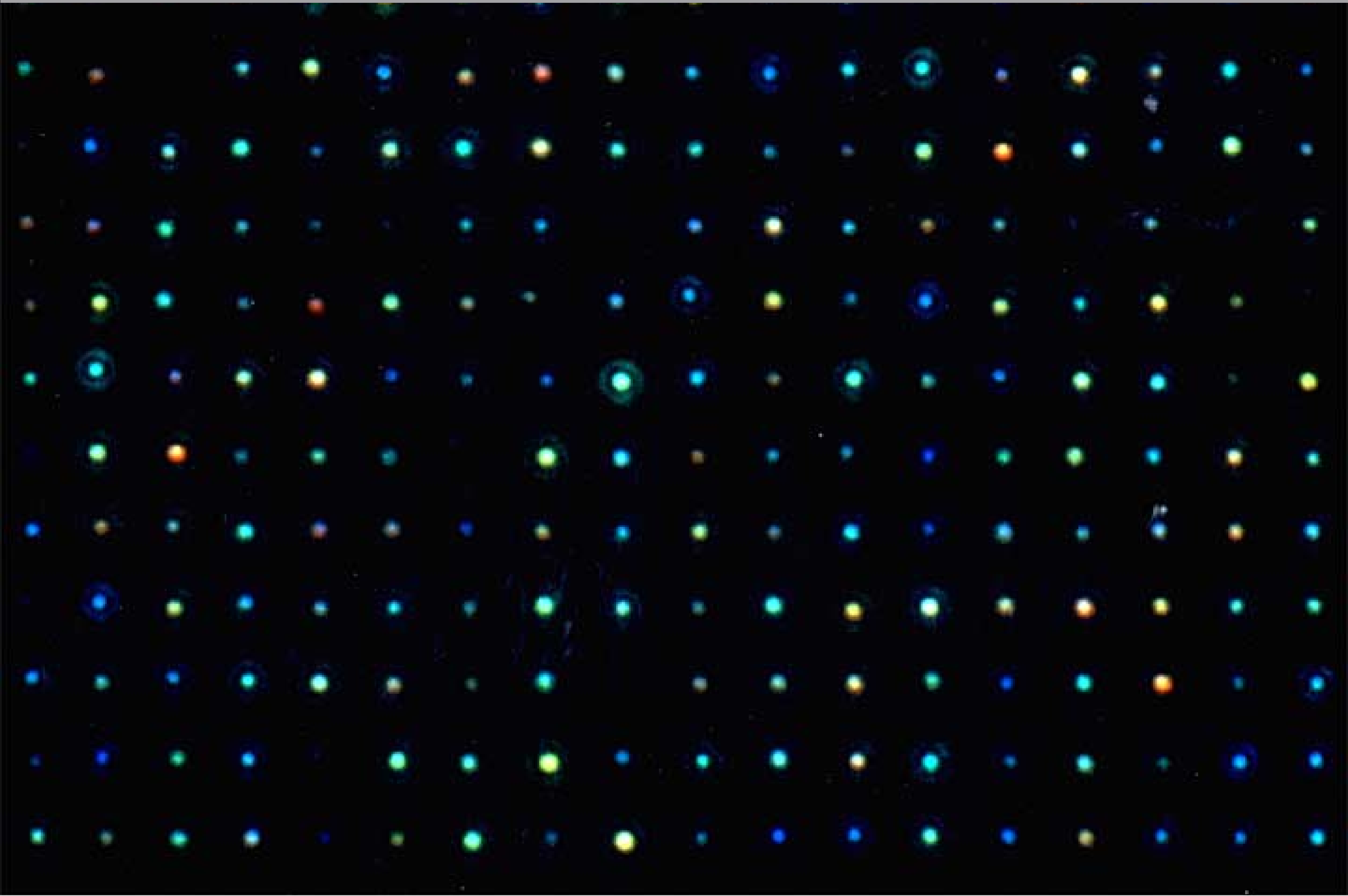
von der Linde, *et al.*, *J. Opt. Soc. Am.* 13, 216 (1996)

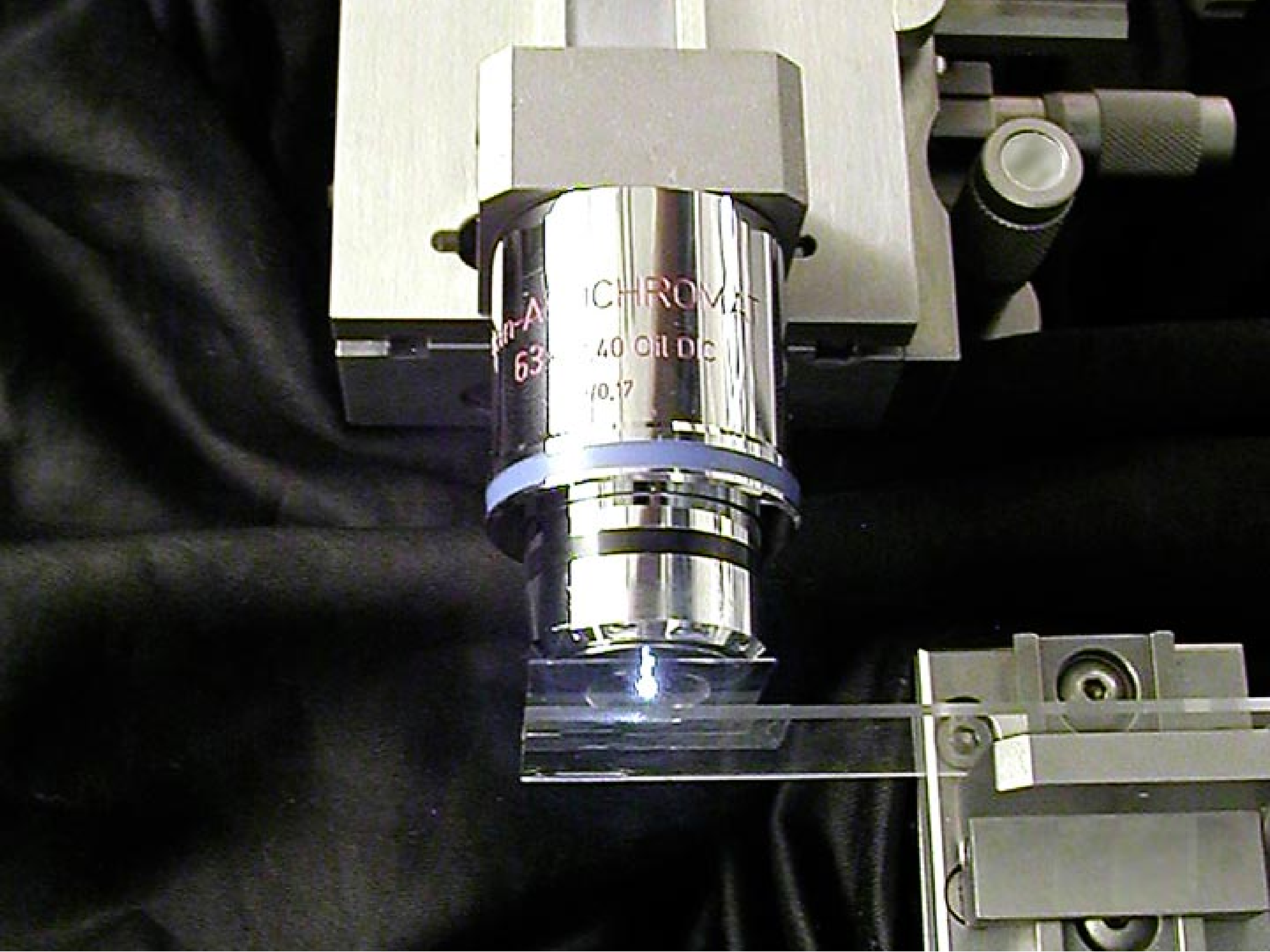
focus laser beam inside material

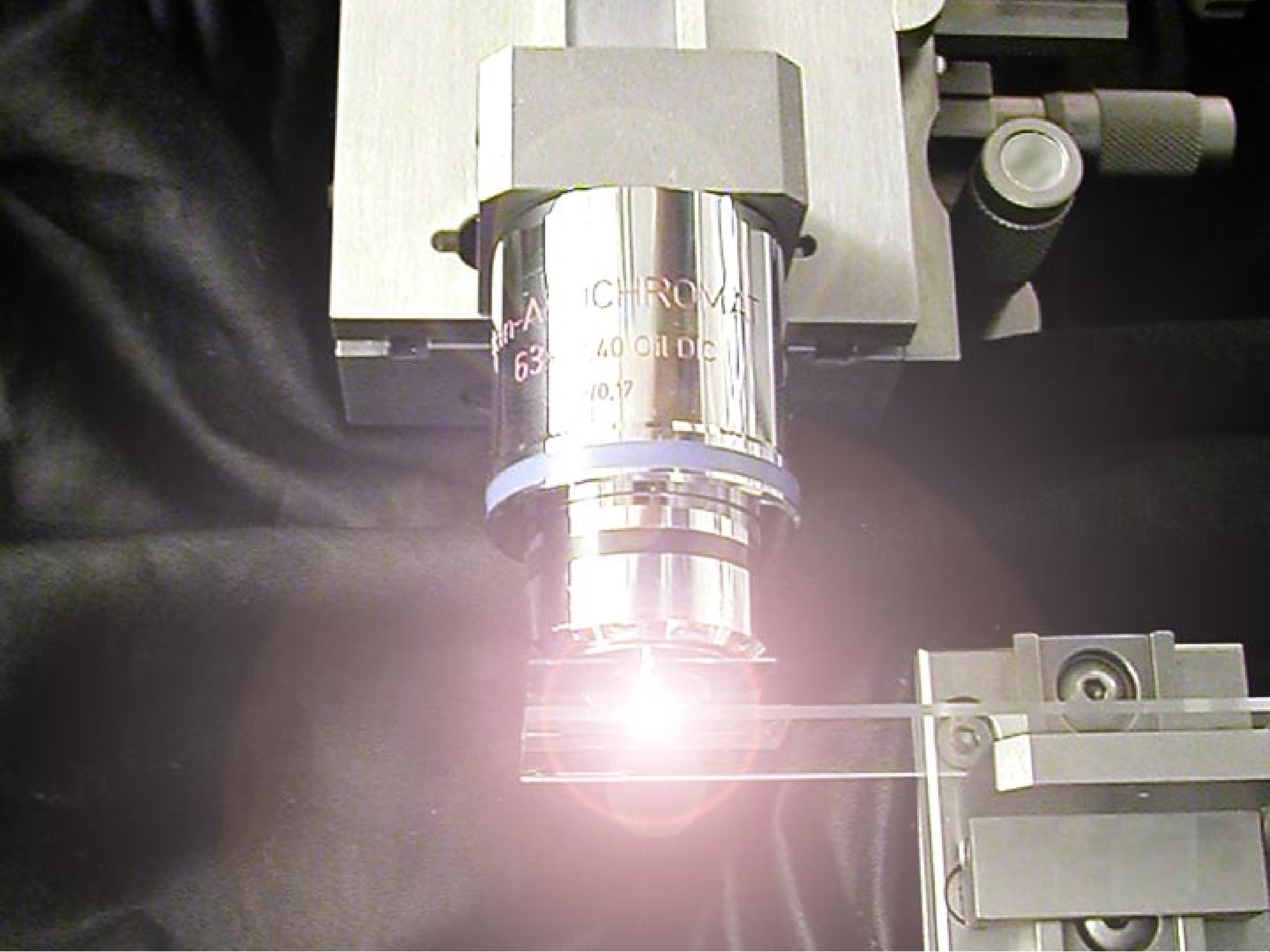


Glezer, *et al.*, *Opt. Lett.* 21, 2023 (1996)

Processing with fs pulses




ICHROMAT
40 Oil DIC
/0.17

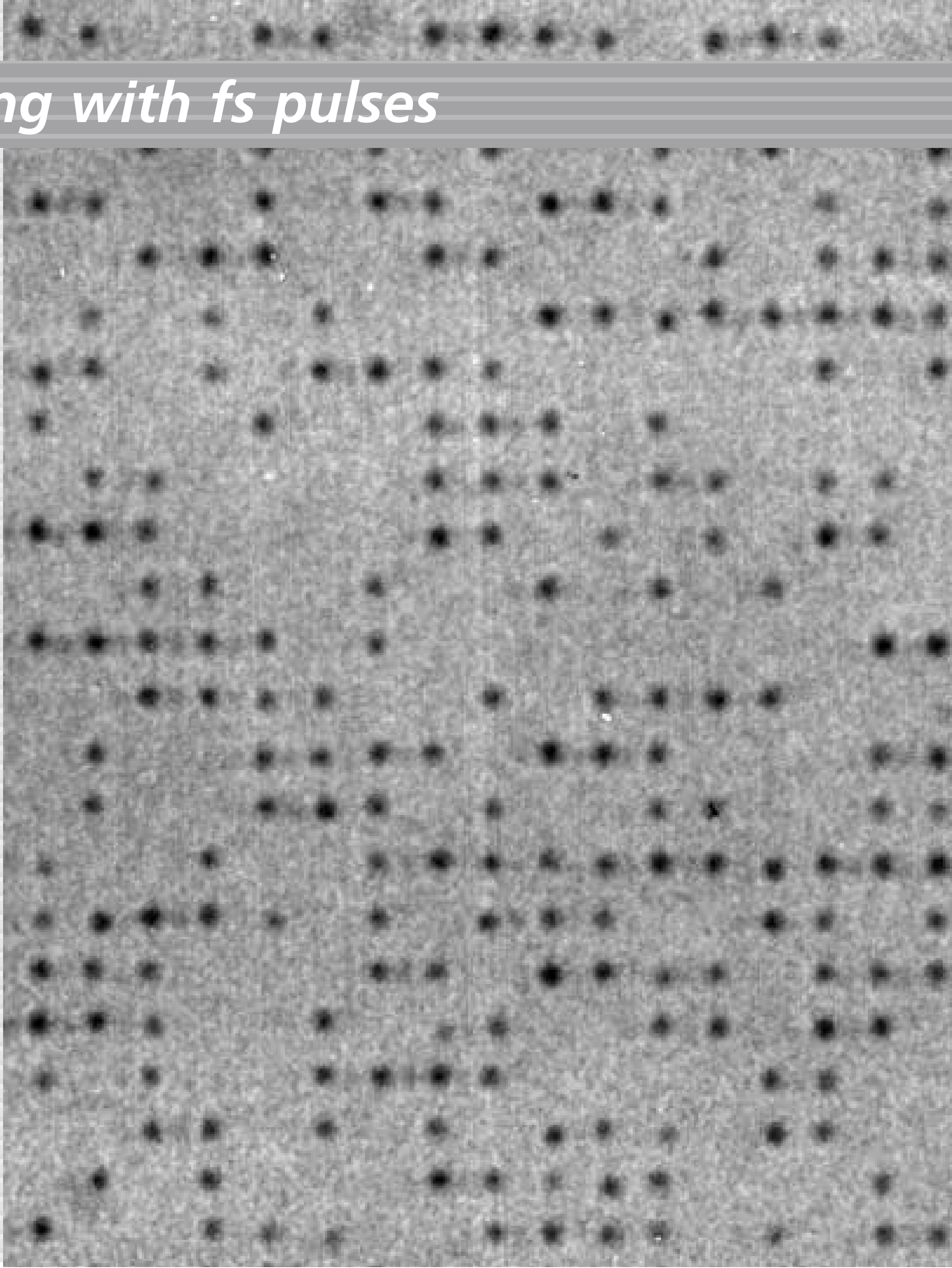

40 Oil DIC
/0.17

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)**

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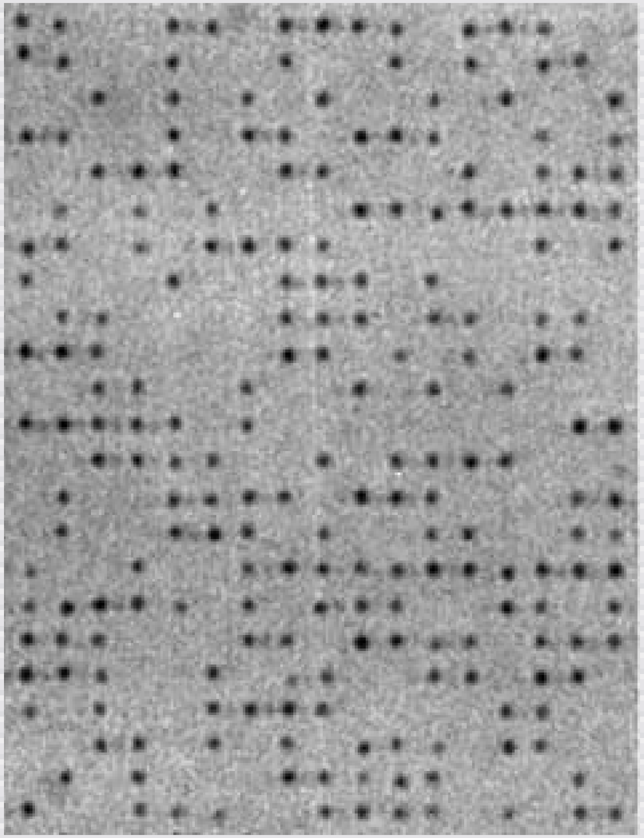

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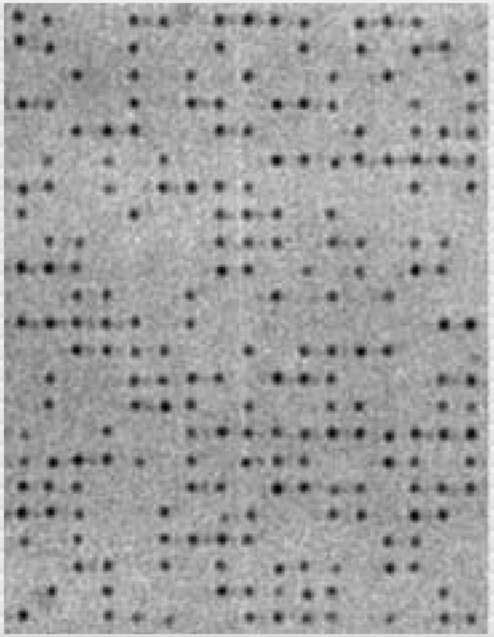

***Opt. Lett.* 21, 2023 (1996)**

Processing with fs pulses

2 x 2 µm array

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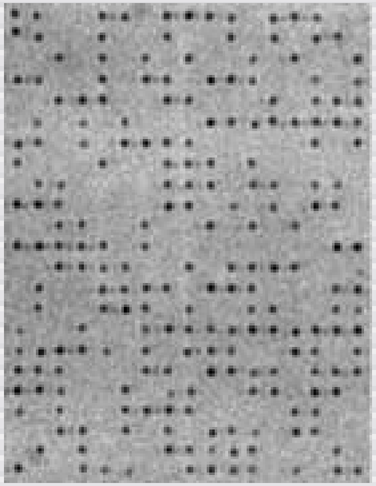

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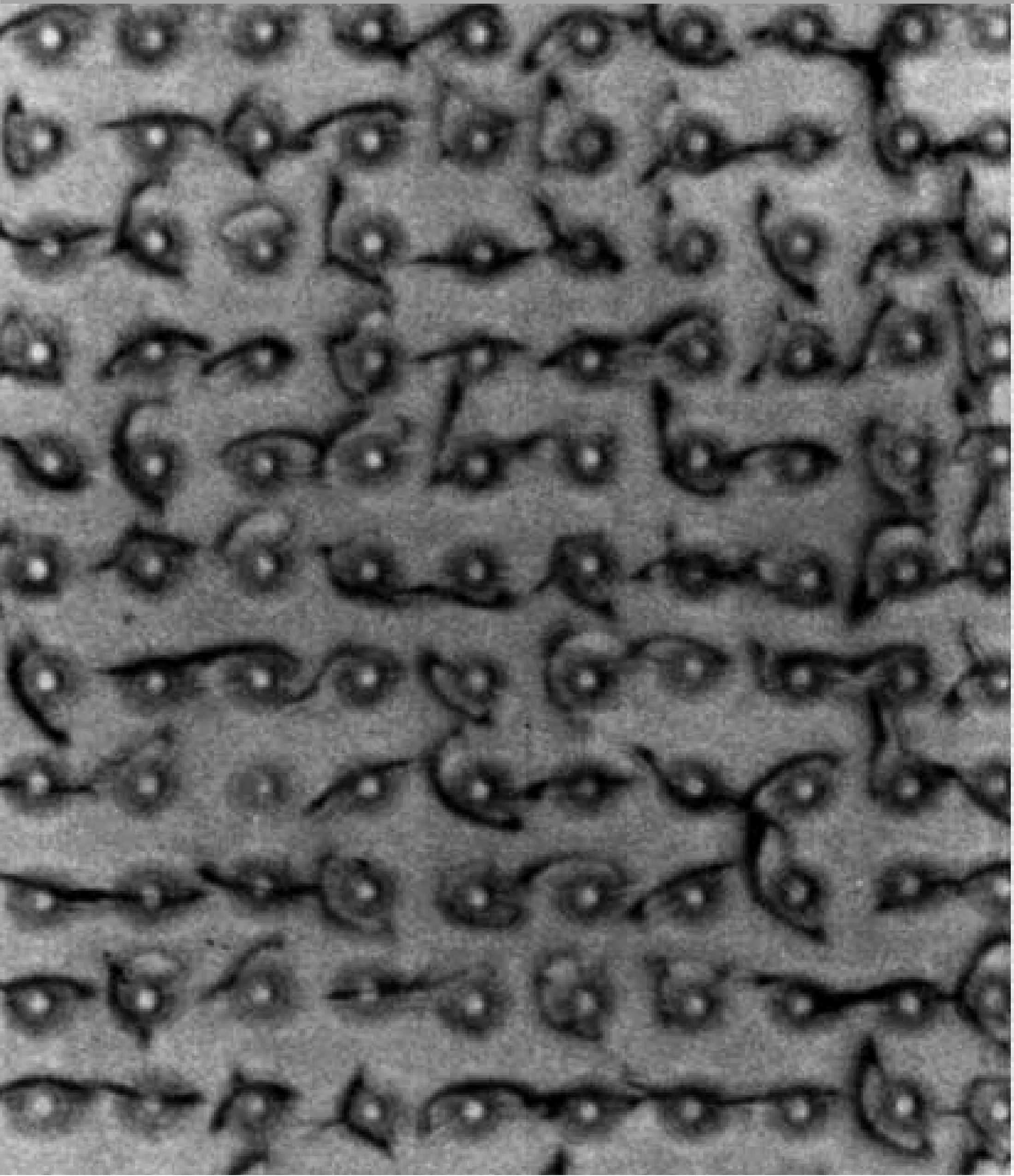
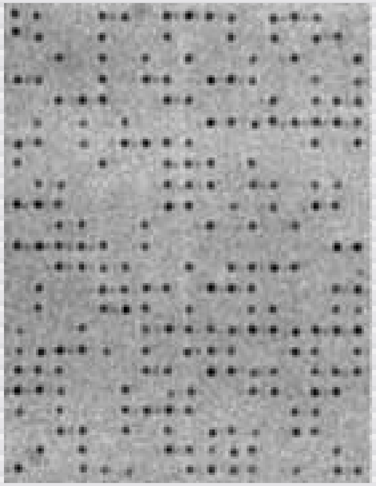
Processing with fs pulses

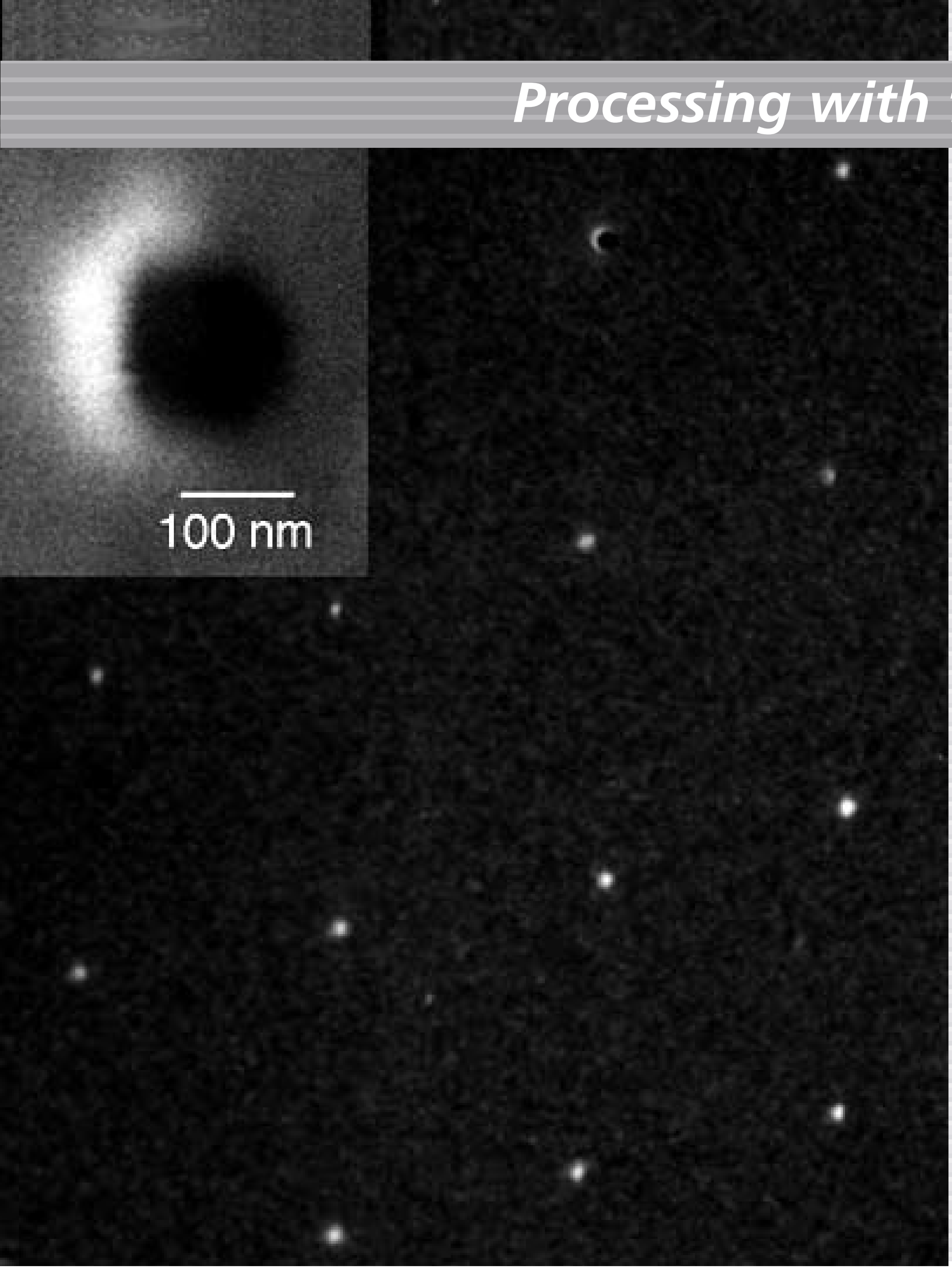


200 ps
9 µJ



100 fs
0.5 µJ

Processing with fs pulses



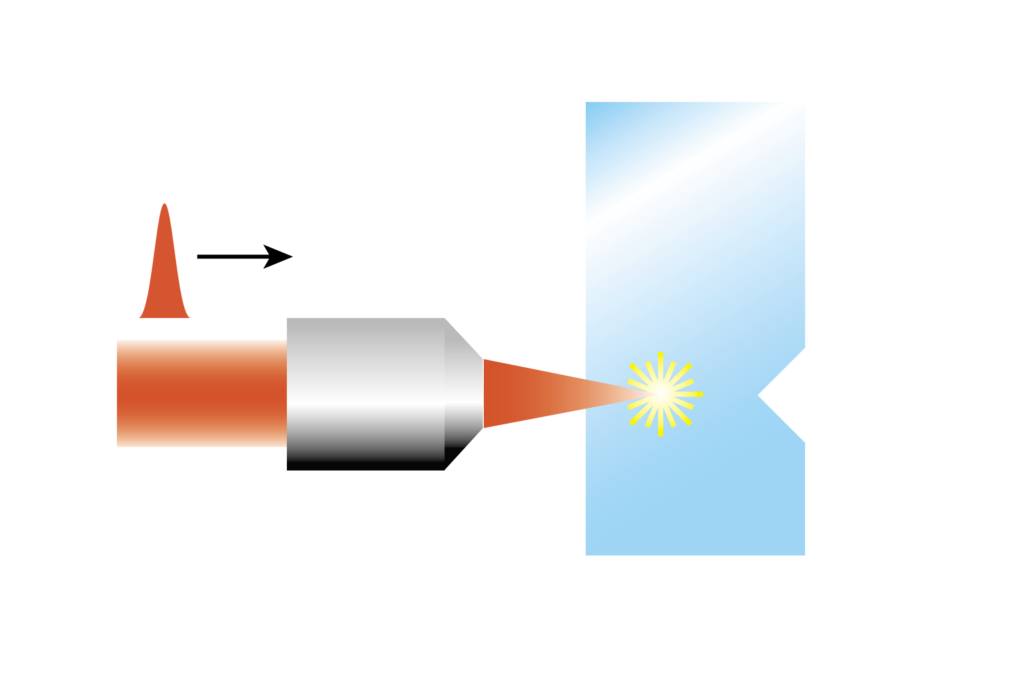
5 x 5 μm array

fused silica, 0.65 NA

0.5 μJ, 100 fs, 800 nm

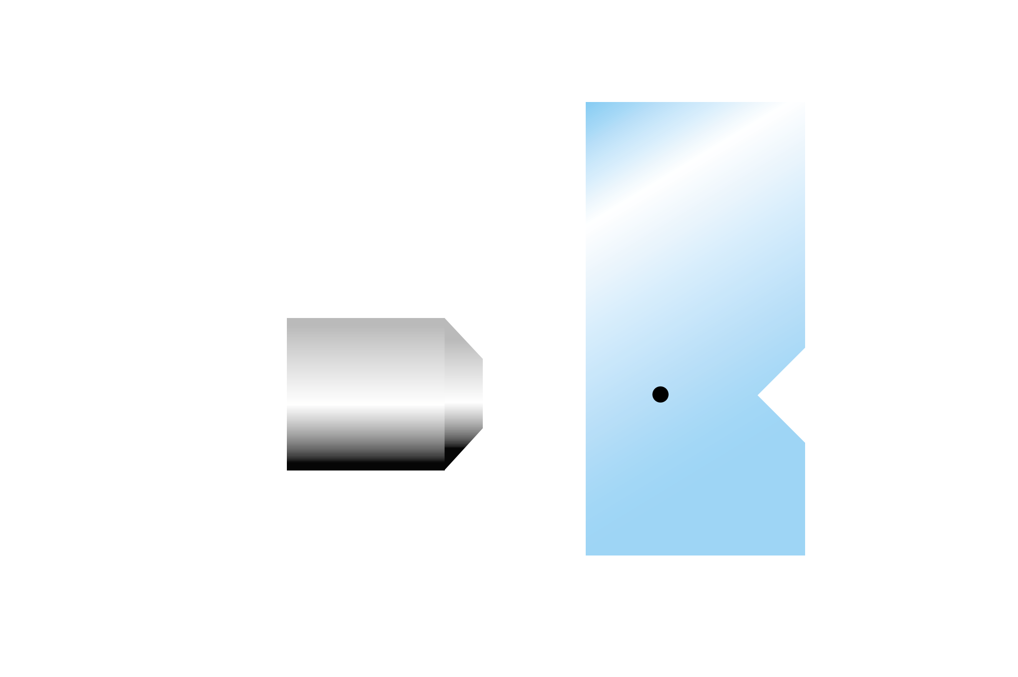
***Opt. Lett.* 21, 2023 (1996)**

Processing with fs pulses



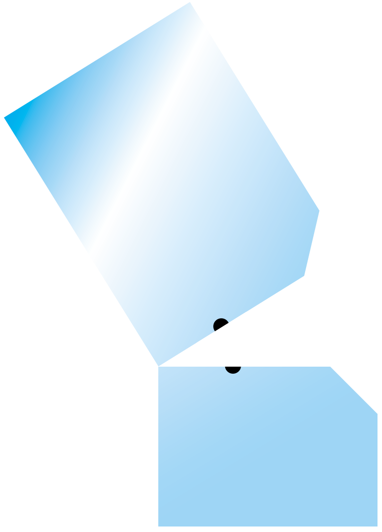
microstructure scribed sample

Processing with fs pulses



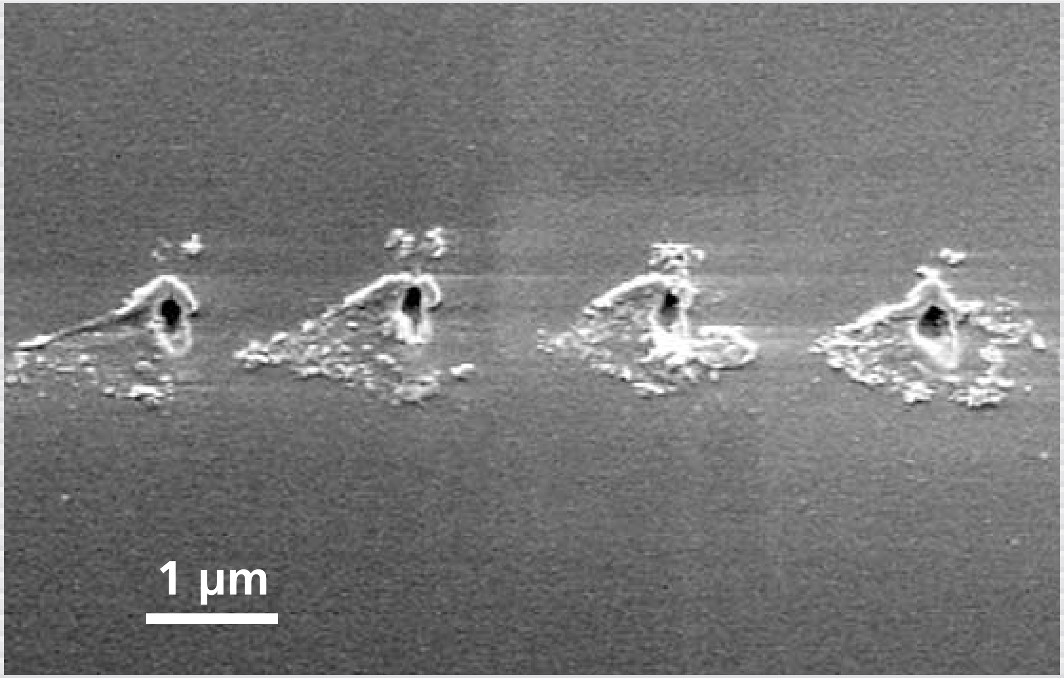
microstructure scribed sample

Processing with fs pulses



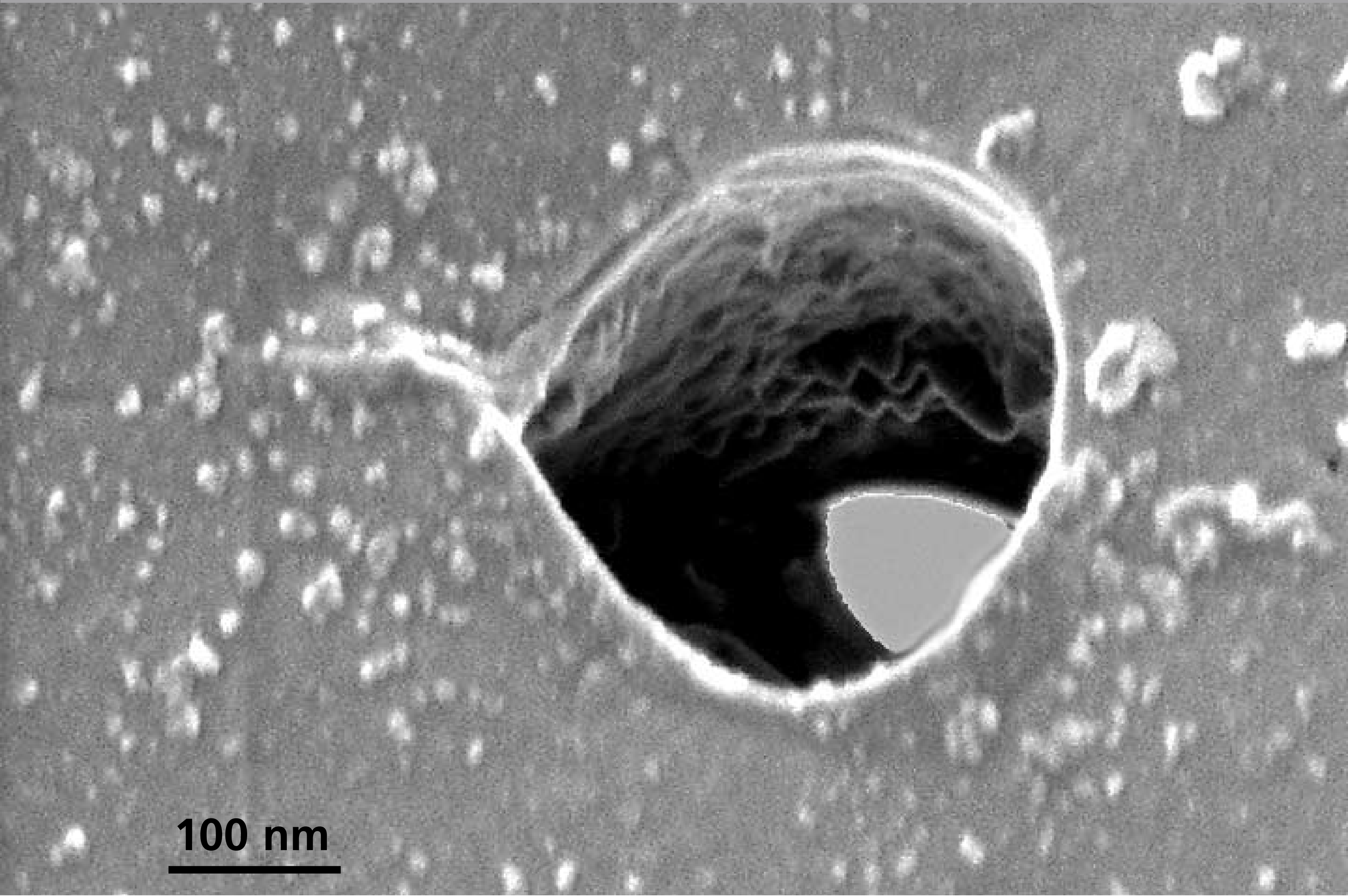
fracture along scribe line

Processing with fs pulses

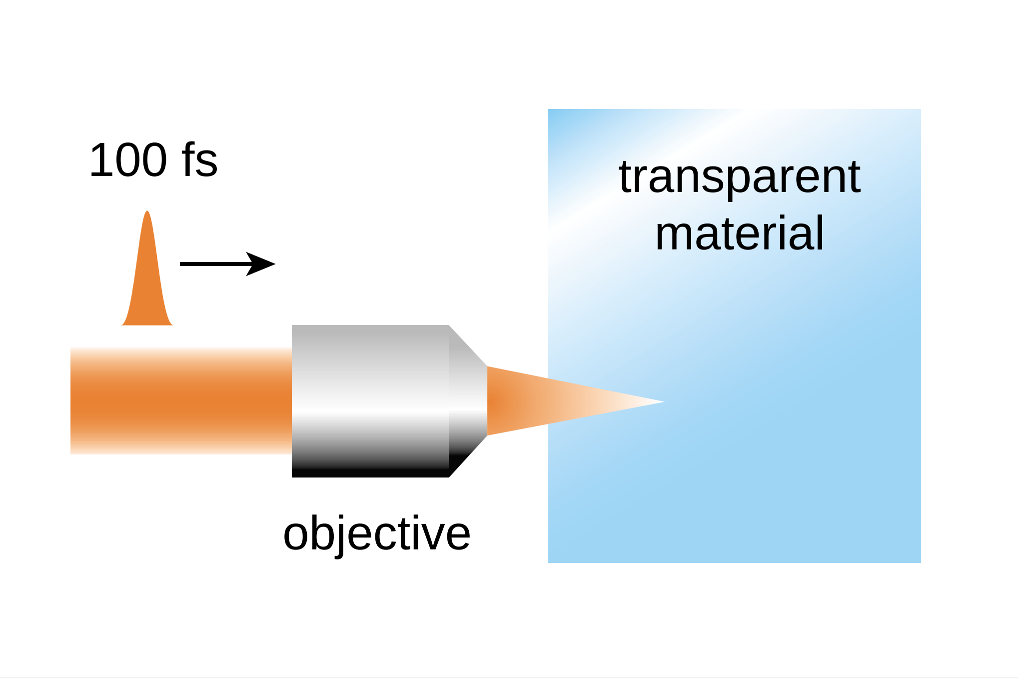


Corning 0211
1.4 NA, 140 nJ

Processing with fs pulses

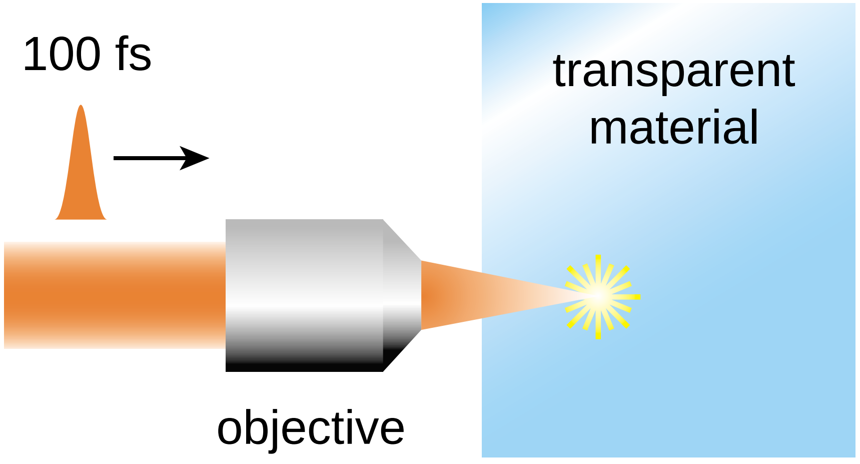


Processing with fs pulses



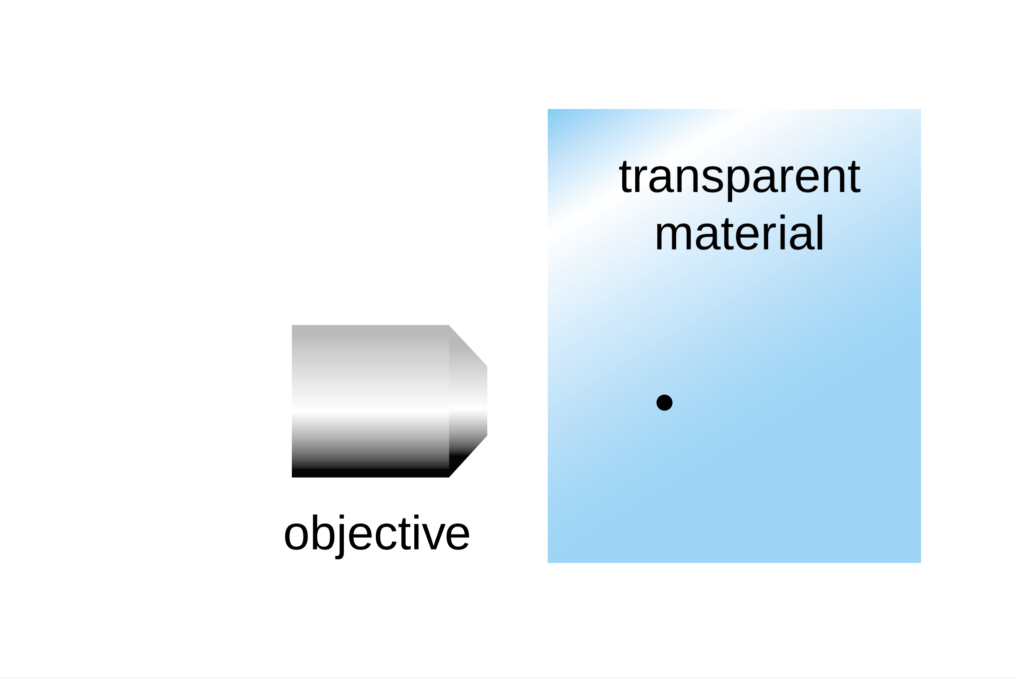
high intensity at focus…

Processing with fs pulses



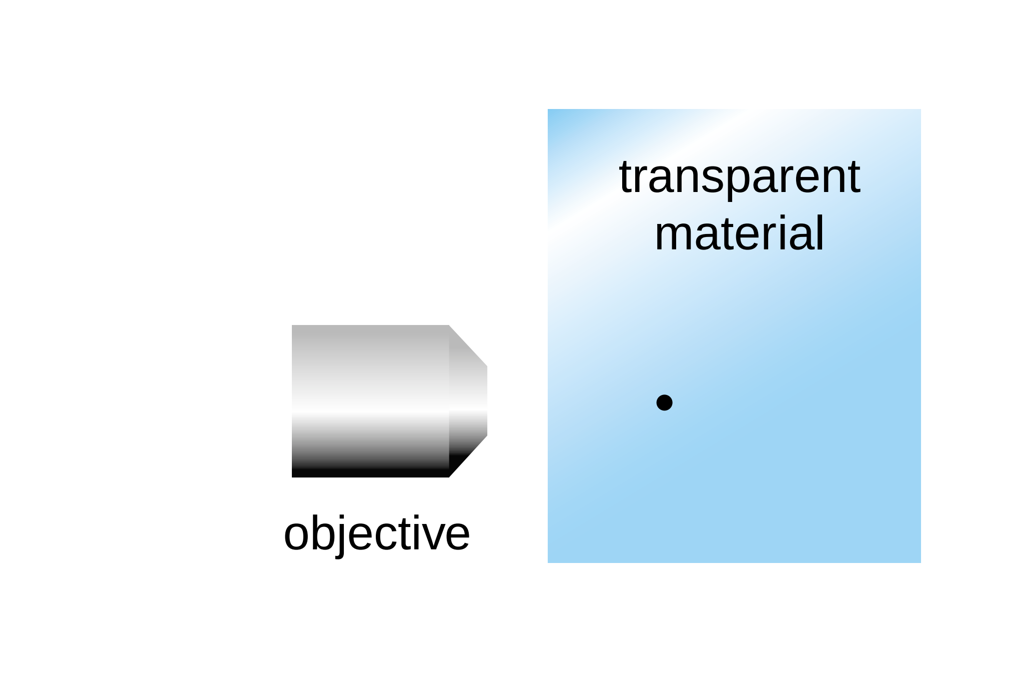
… causes nonlinear ionization…

Processing with fs pulses

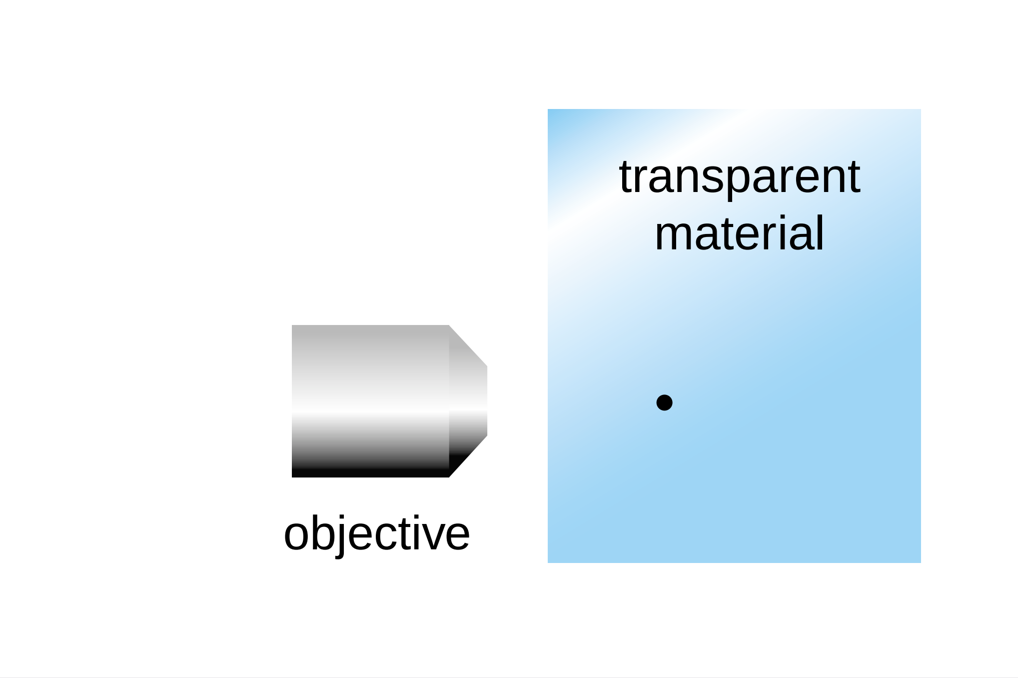


and 'microexplosion' causes microscopic damage

What are the conditions at focus?



What are the conditions at focus?



laser deposits energy in ~1 μm^3

What temperature?

What temperature?

$$\Delta E = C_V \rho V \Delta T$$

What temperature?

$$\Delta E = C_V \rho V \Delta T$$

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

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

Processing with fs pulses

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 μJ in 1 μm^3 gives

~1,000,000 K!

What pressure?

Processing with fs pulses

What pressure?

Treat ionized material as an ideal gas:

$$pV = nRT$$

Processing with fs pulses

What pressure?

Treat ionized material as an ideal gas:

$$pV = nRT$$

Gives

$$p = 10\,\mathrm{MBar!}$$

So:

	microexplosion
T	≈ 1 MK
p	≈ 10 MBar
ρ	2.2×10^3 kg/m^3

So:

	microexplosion	sun
T	$\approx$1 MK	2 − 5 MK
p	$\approx$10 MBar	
ρ	2.2×10^3 kg/m^3	$0.15 - 150 \times 10^3$ kg/m^3

So:

	microexplosion	**sun**
T	≈ 1 MK	$2-5$ MK
p	≈ 10 MBar	
ρ	2.2×10^3 kg/m^3	$0.15-150 \times 10^3$ kg/m^3

creating stellar conditions in lab!

Processing with fs pulses

Points to keep in mind:

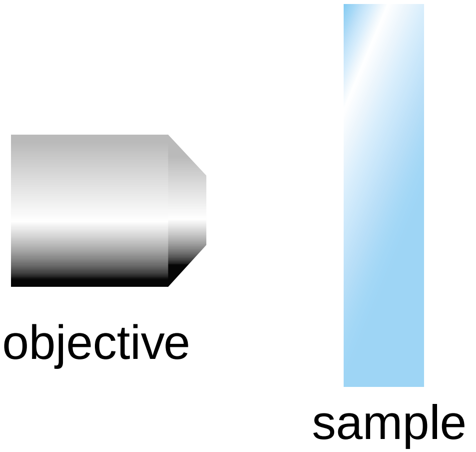
- **fs laser processing works**
- **focusing very important**
- **no collateral damage**

Outline

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

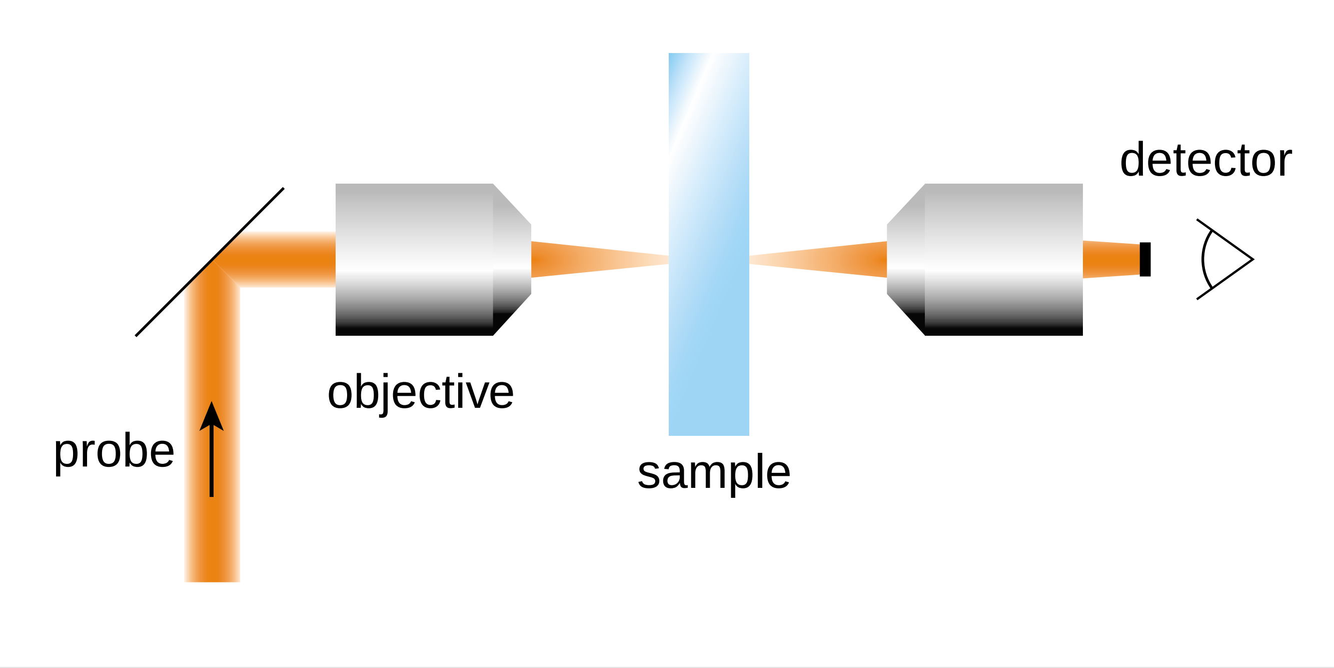
Role of focusing

Dark-field scattering



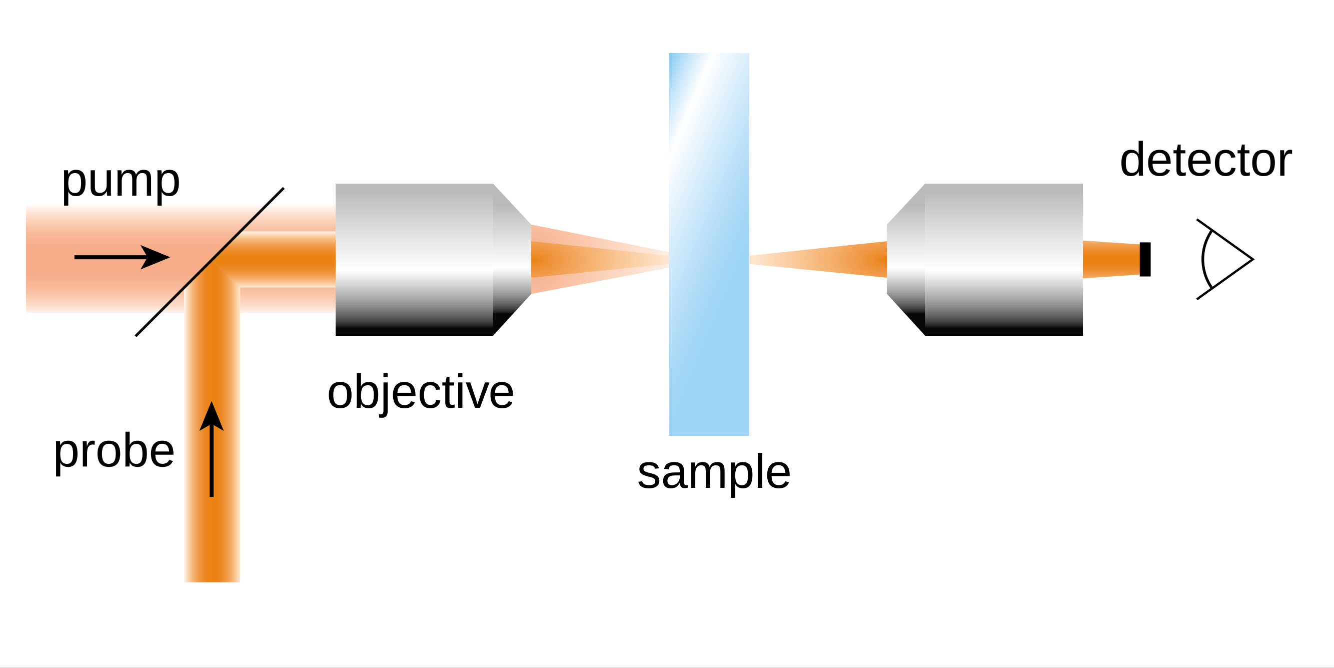
Role of focusing

block probe beam…



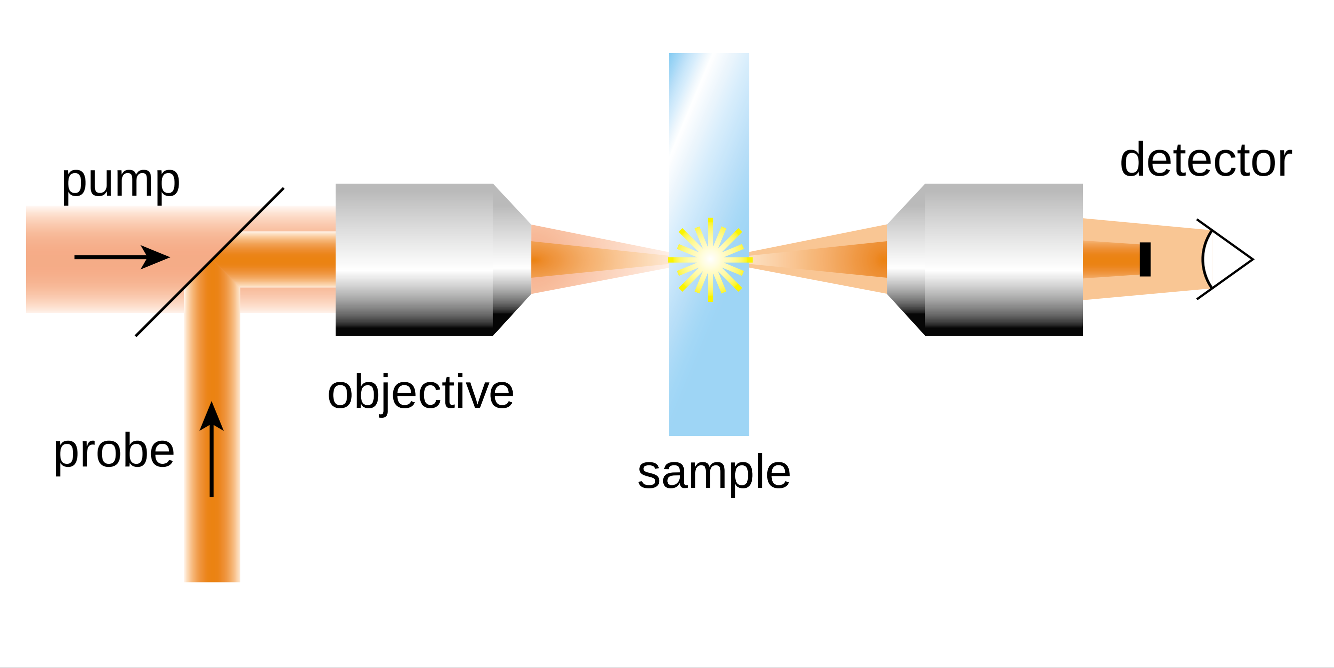
Role of focusing

… bring in pump beam…

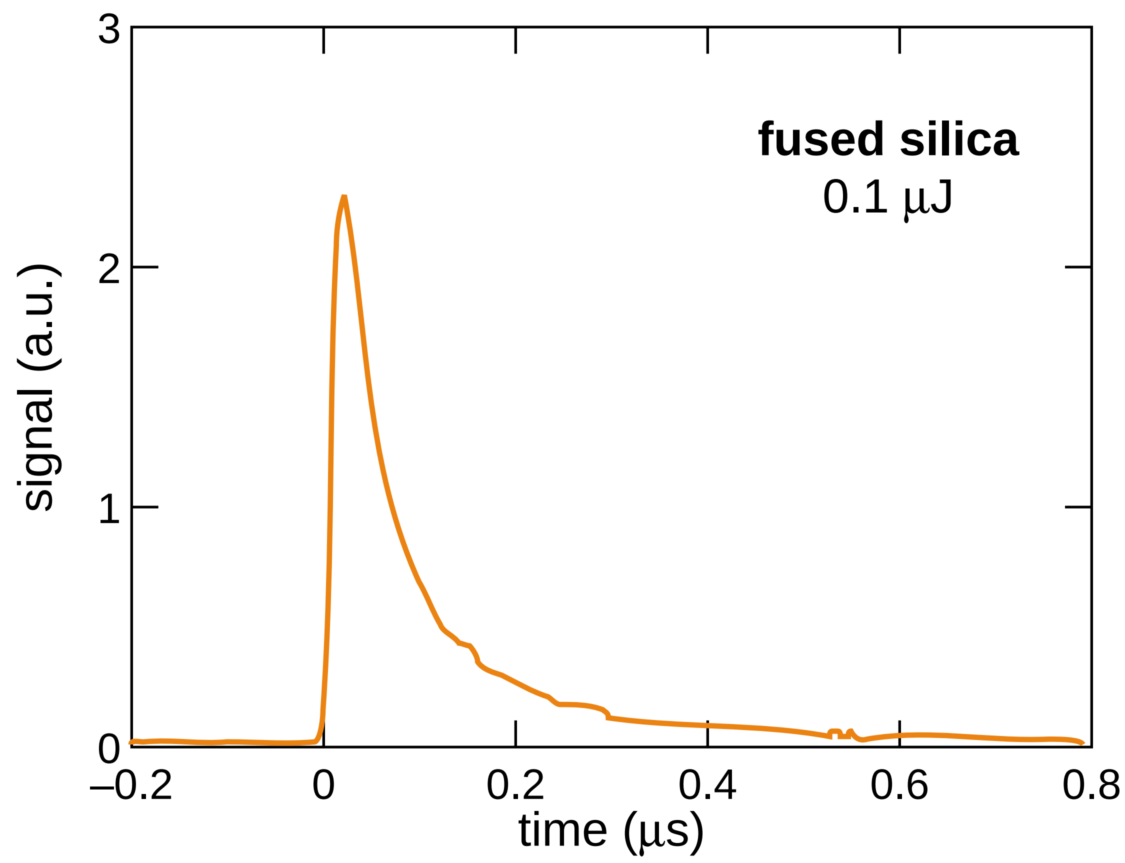


Role of focusing

… damage scatters probe beam



Role of focusing



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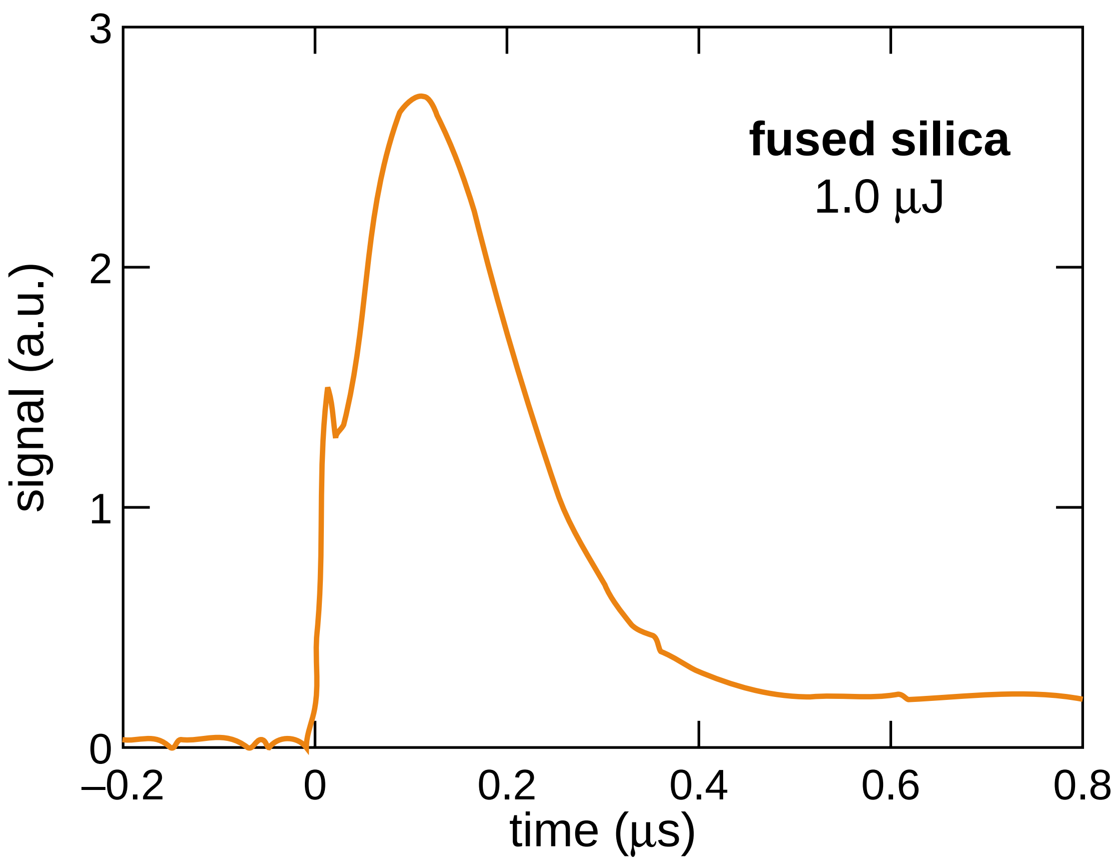
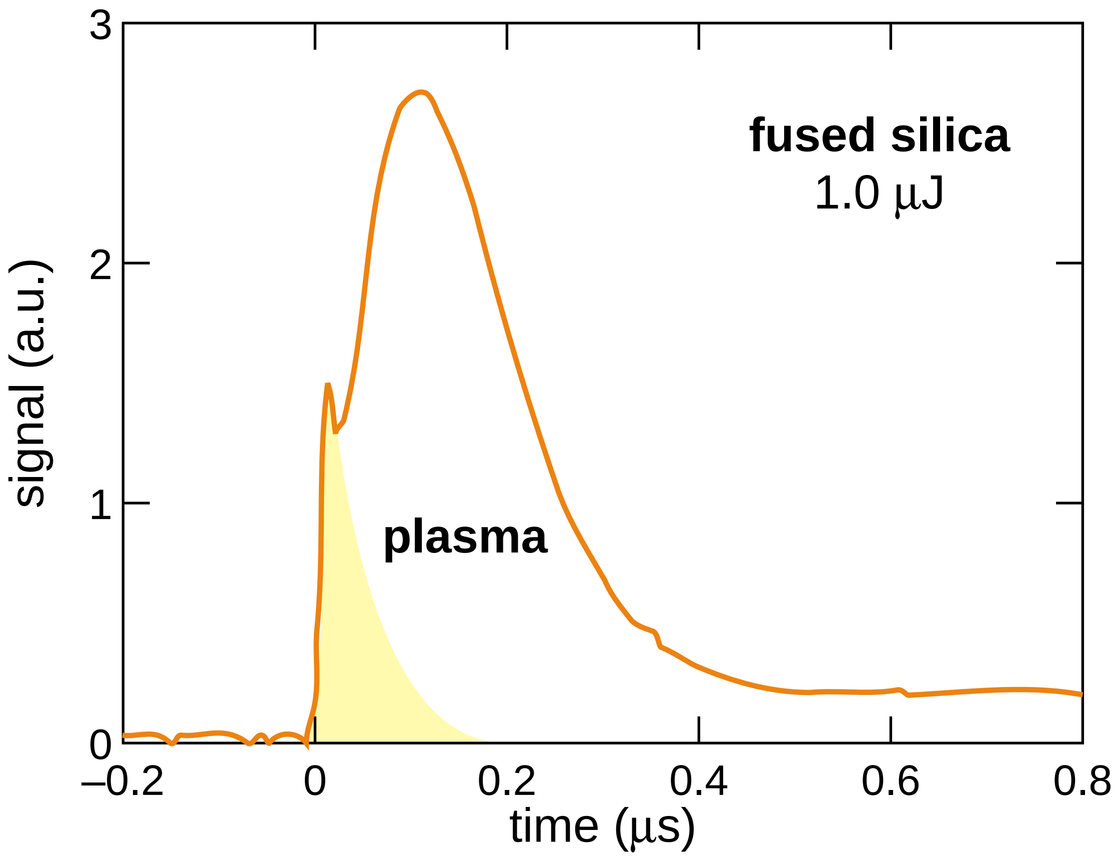


Role of focusing



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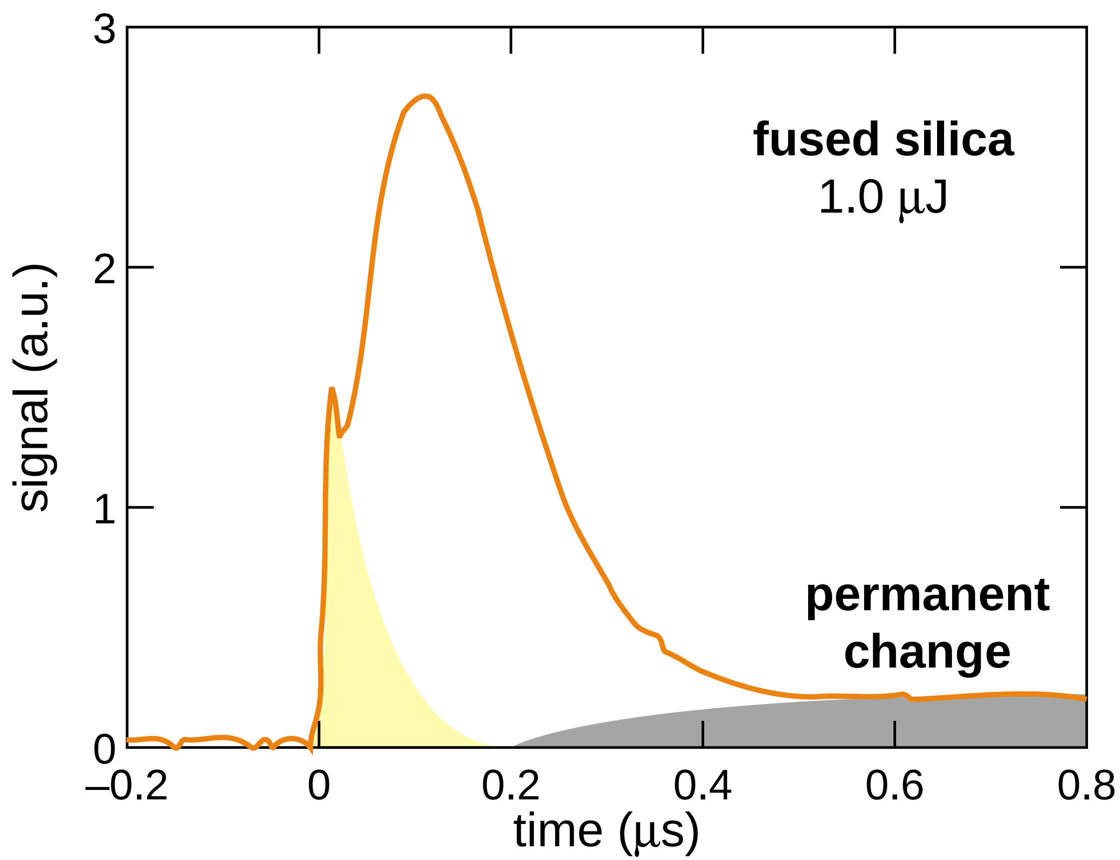
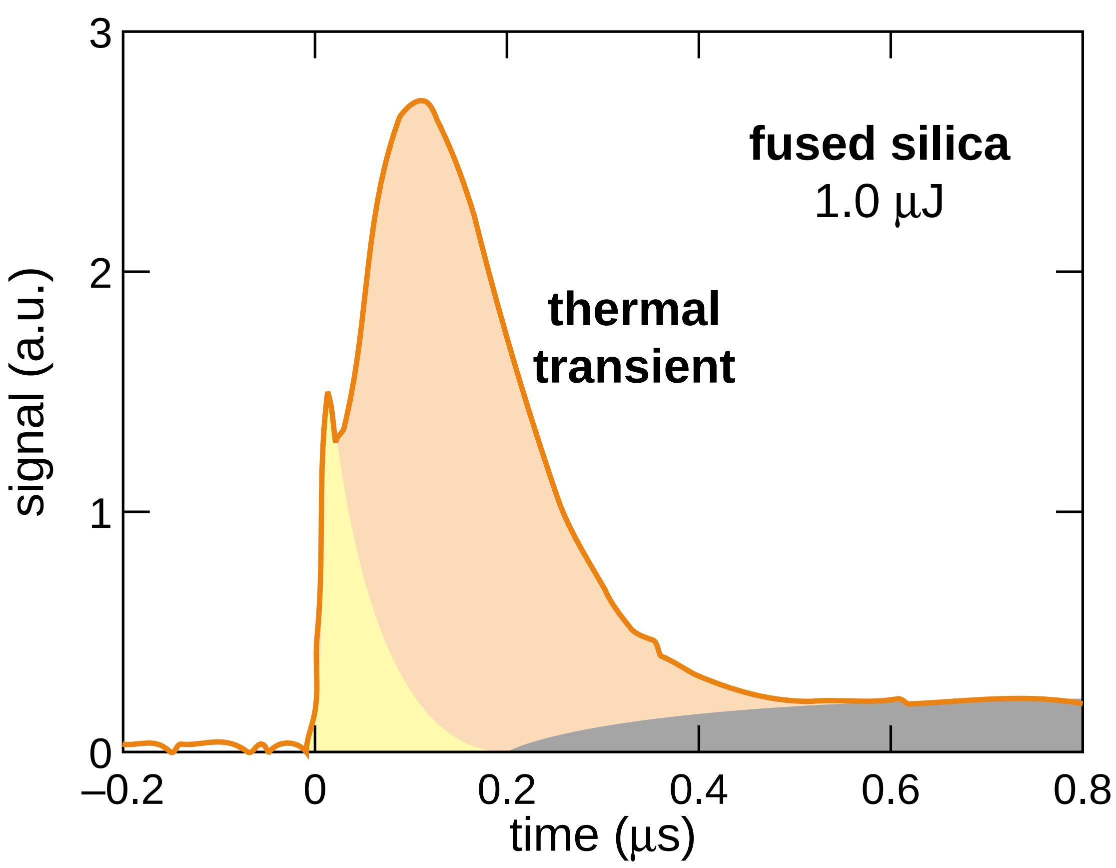
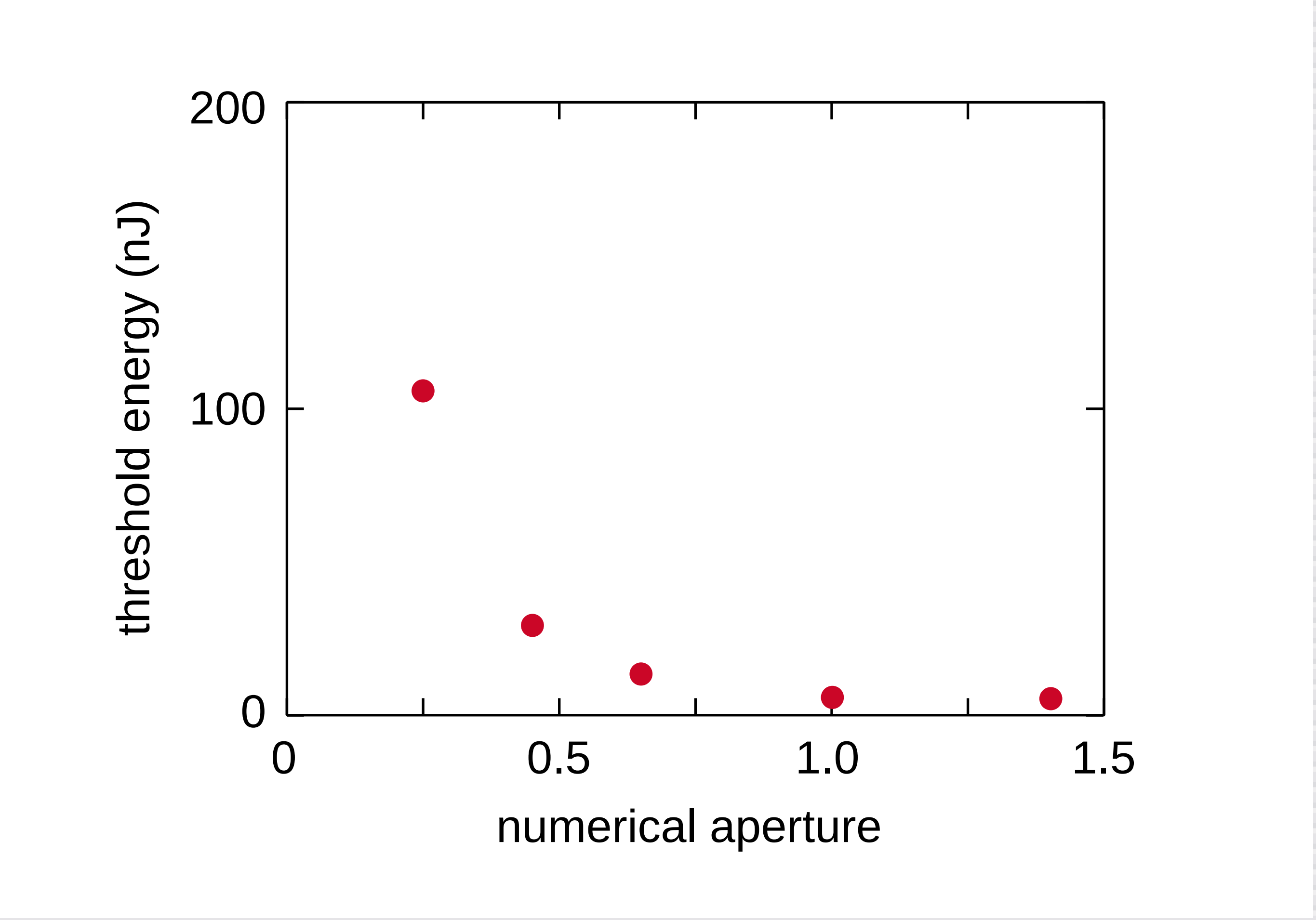


Role of focusing

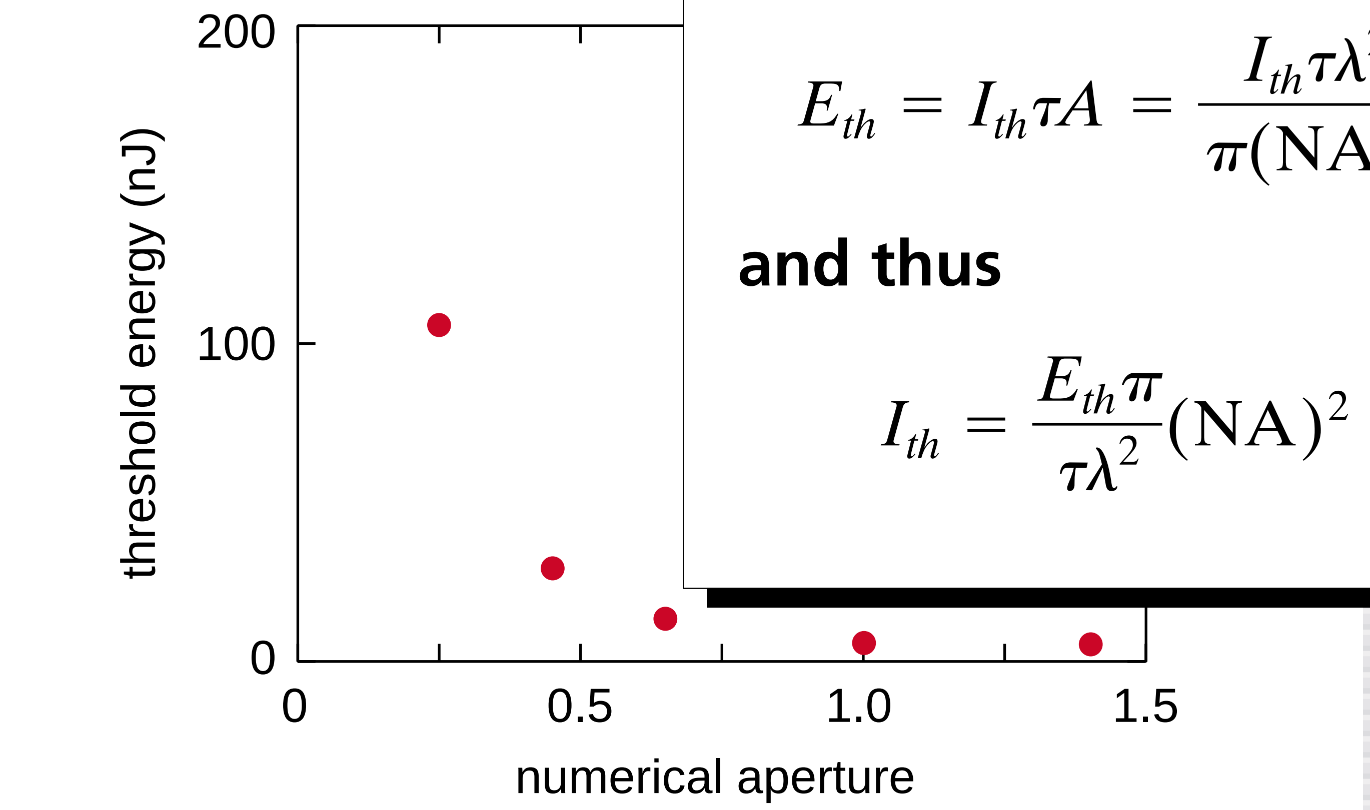


Role of focusing

vary numerical aperture in Corning 0211



Role of focusing



spot size determined by numerical aperture:

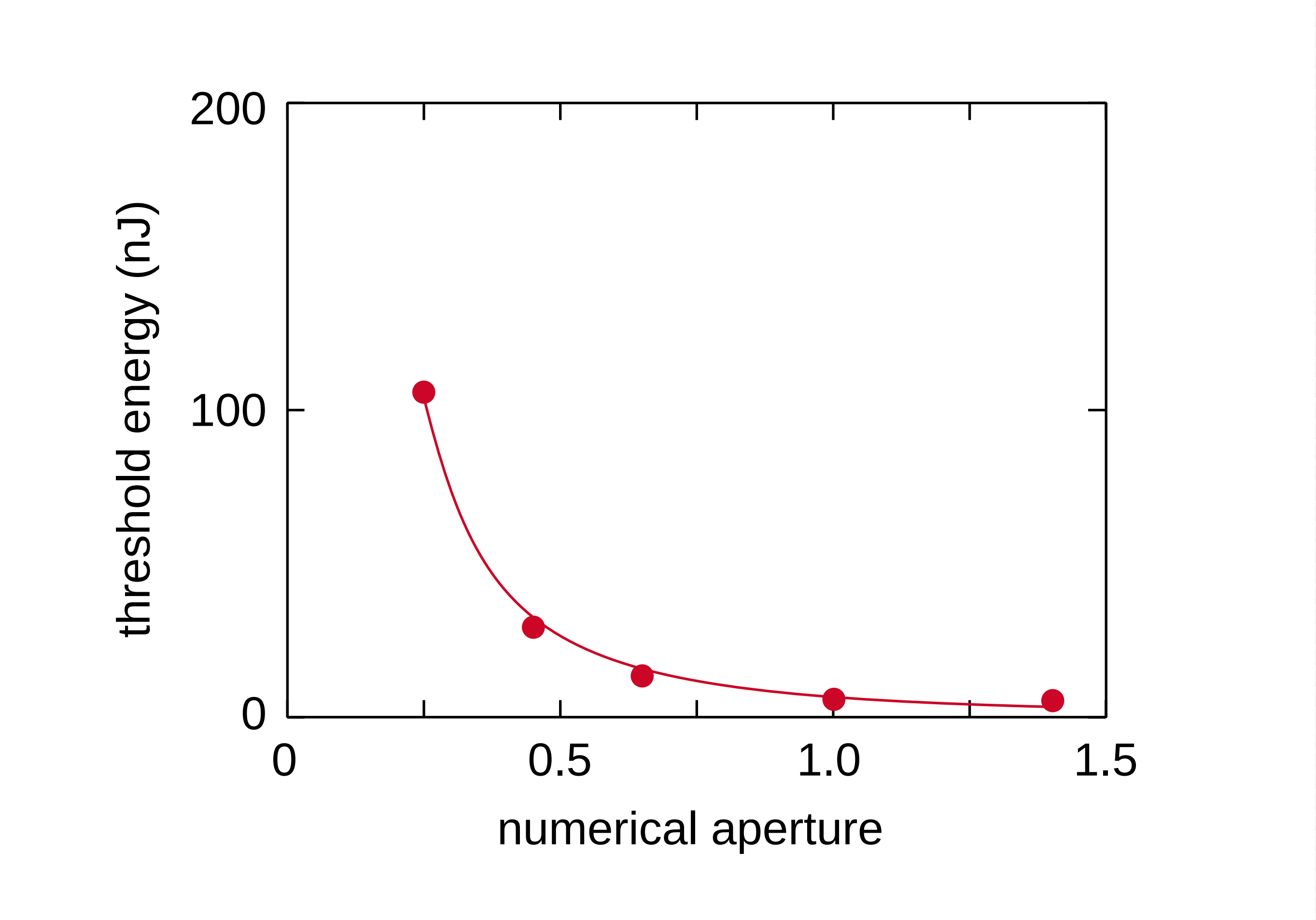
$$E_{th} = I_{th}\tau A = \frac{I_{th}\tau\lambda^2}{\pi(\mathrm{NA})^2}$$

and thus

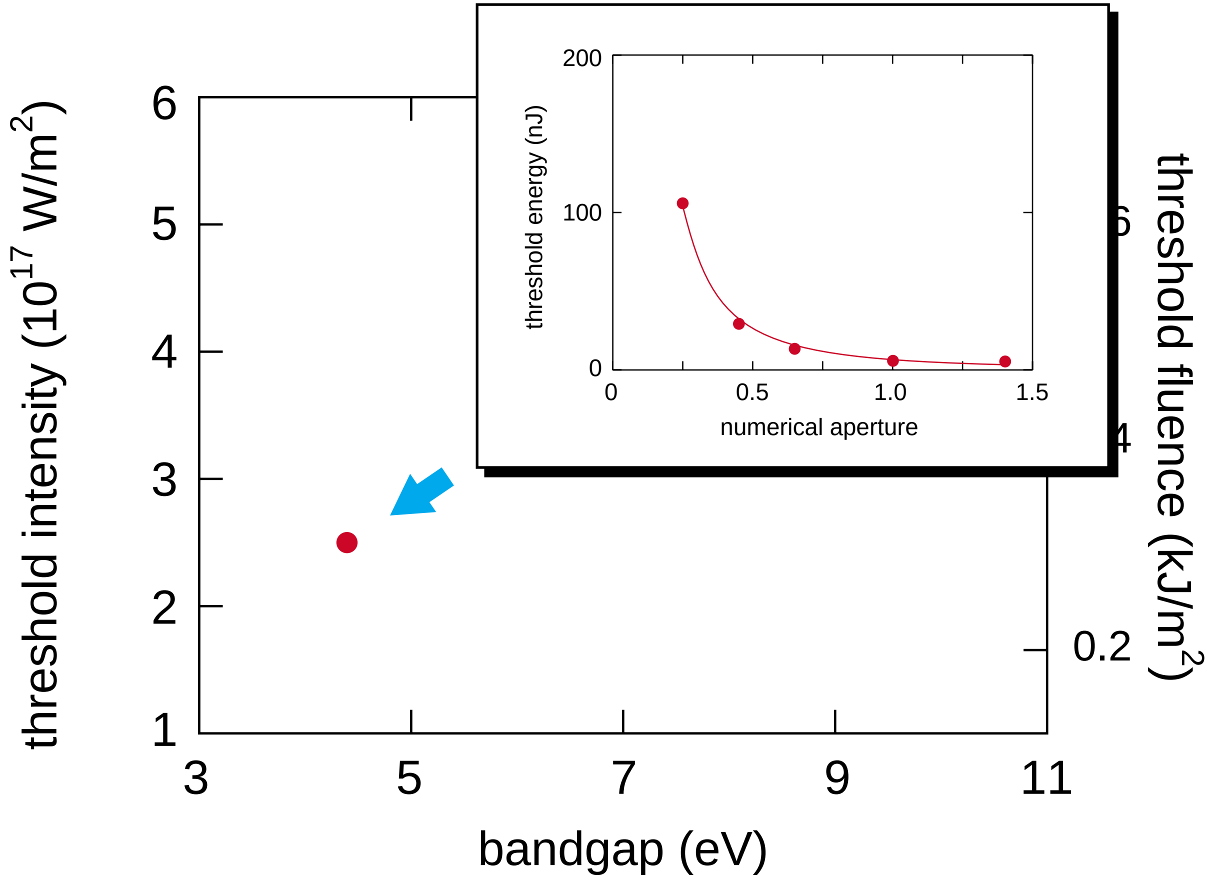
$$I_{th} = \frac{E_{th}\pi}{\tau\lambda^2}(\mathrm{NA})^2$$

Role of focusing

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

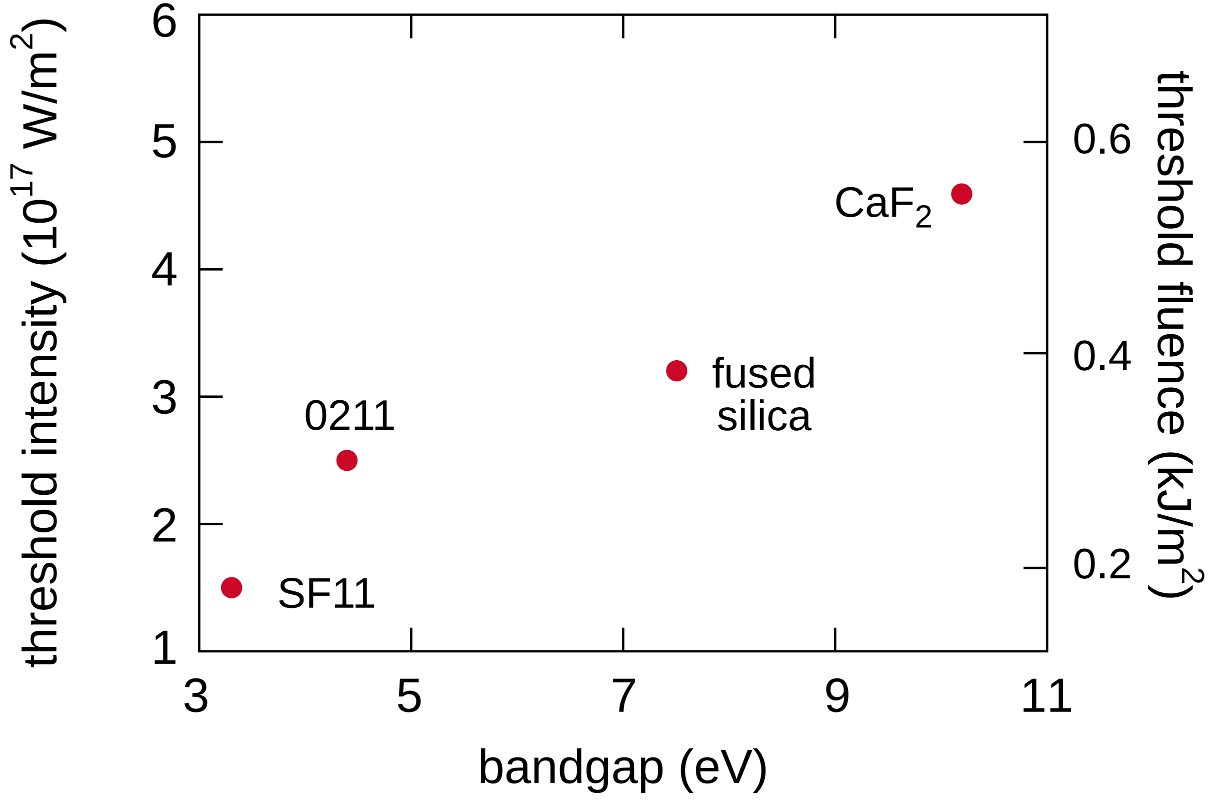


Role of focusing

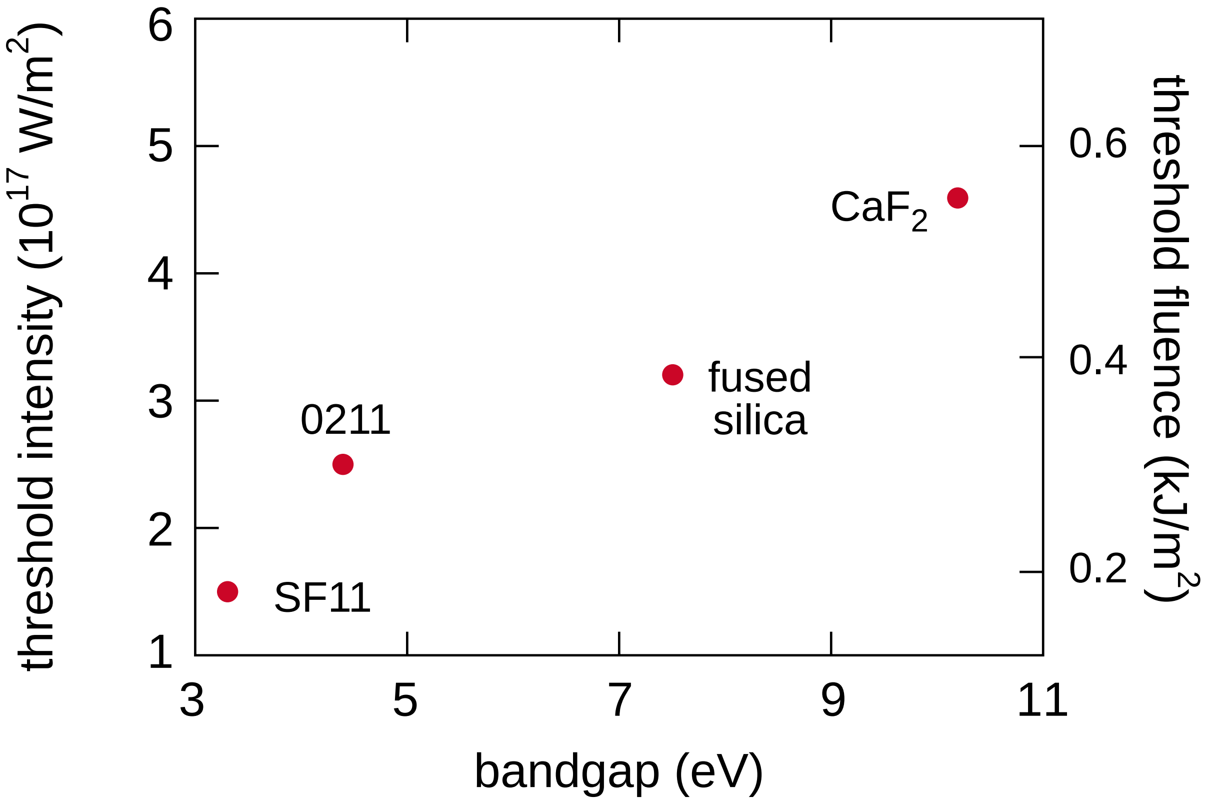


Role of focusing

vary material…



threshold varies with bandgap



Role of focusing

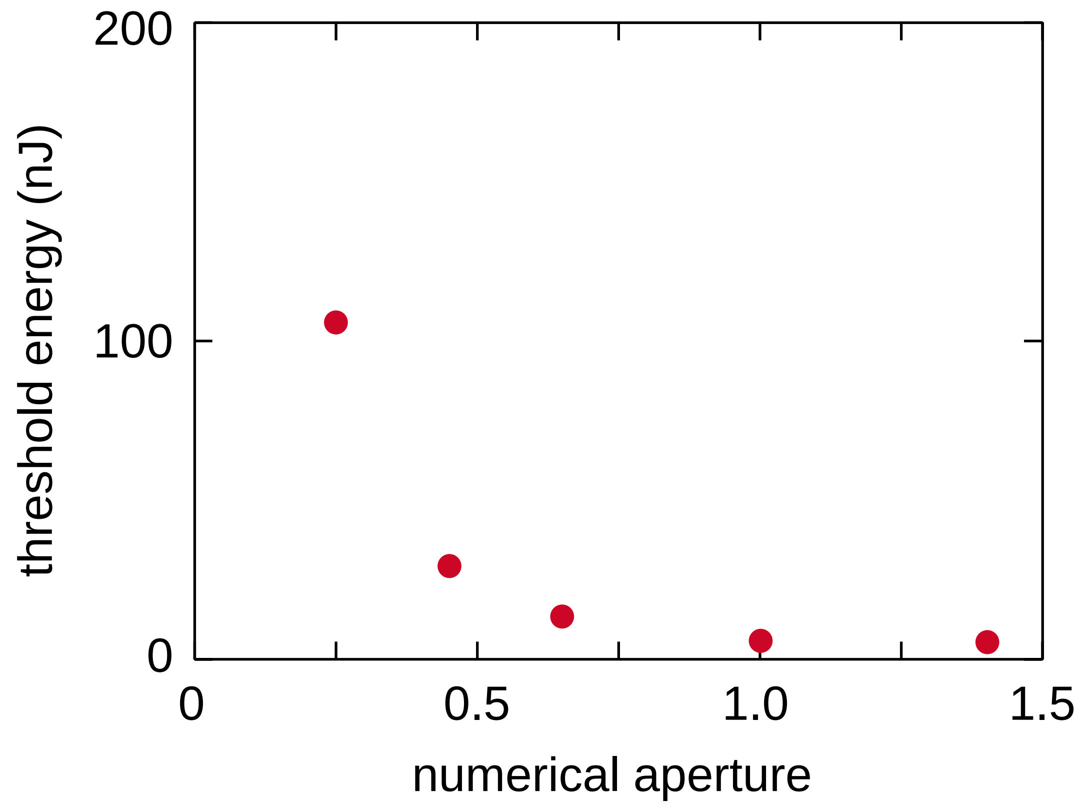
Points to keep in mind:

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

Outline

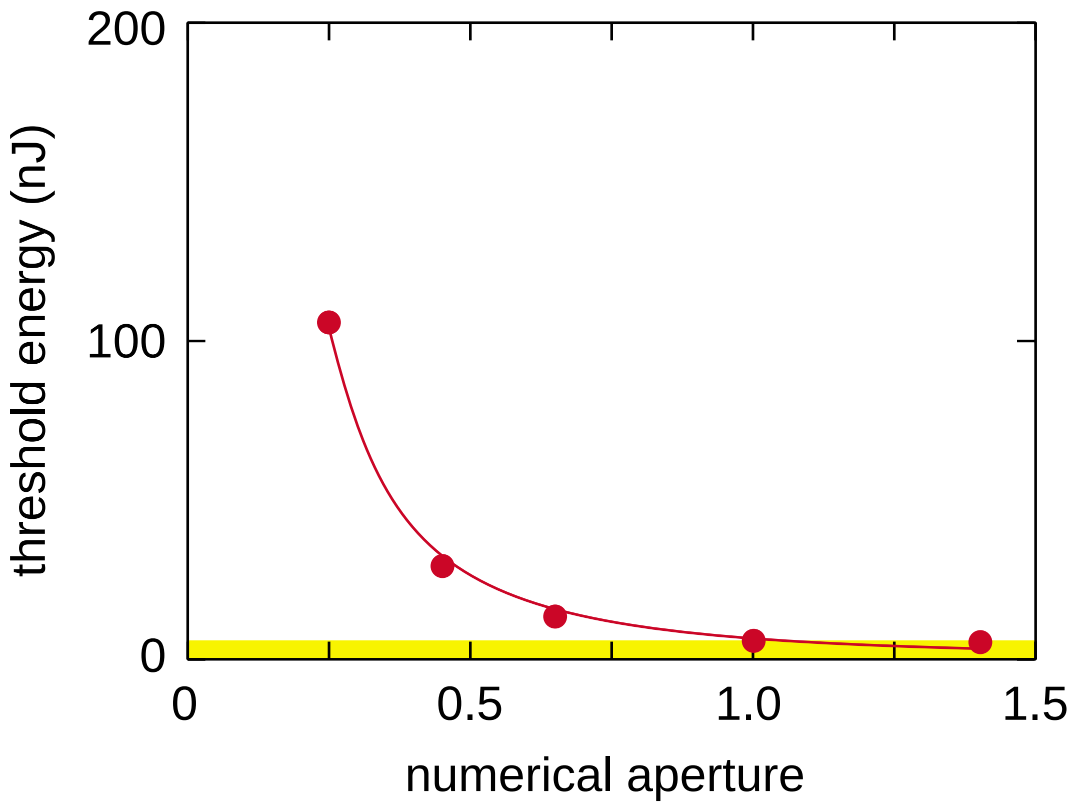
- Processing with fs pulses
- Role of focusing
- **Low-energy processing**

threshold decreases with increasing numerical aperture



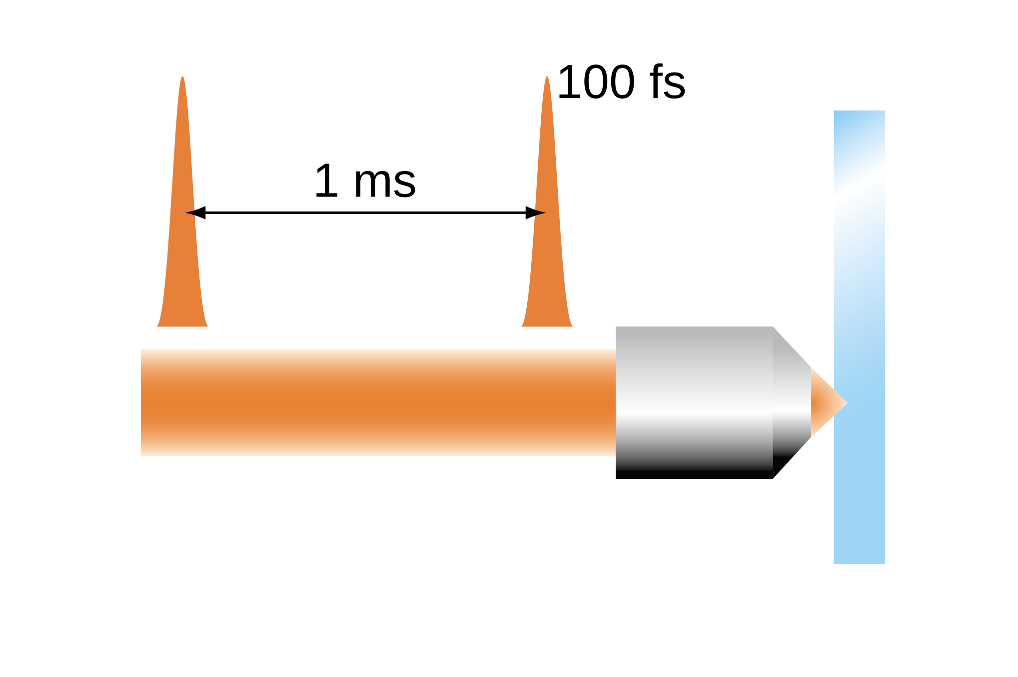
Low-energy processing

less than 10 nJ at high numerical aperture!



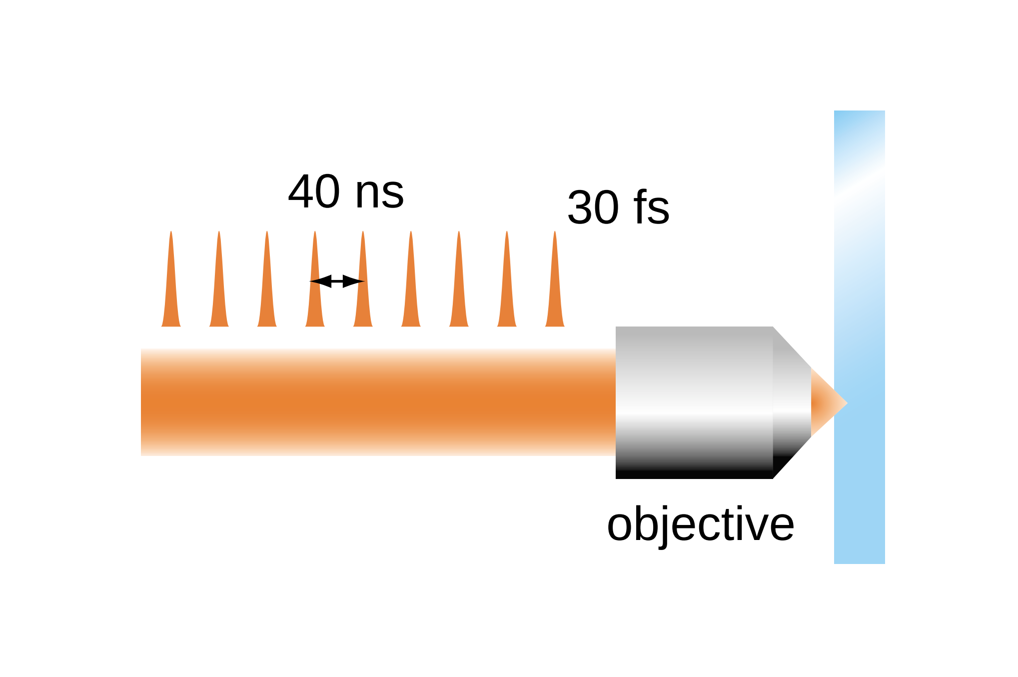
Low-energy processing

amplified laser



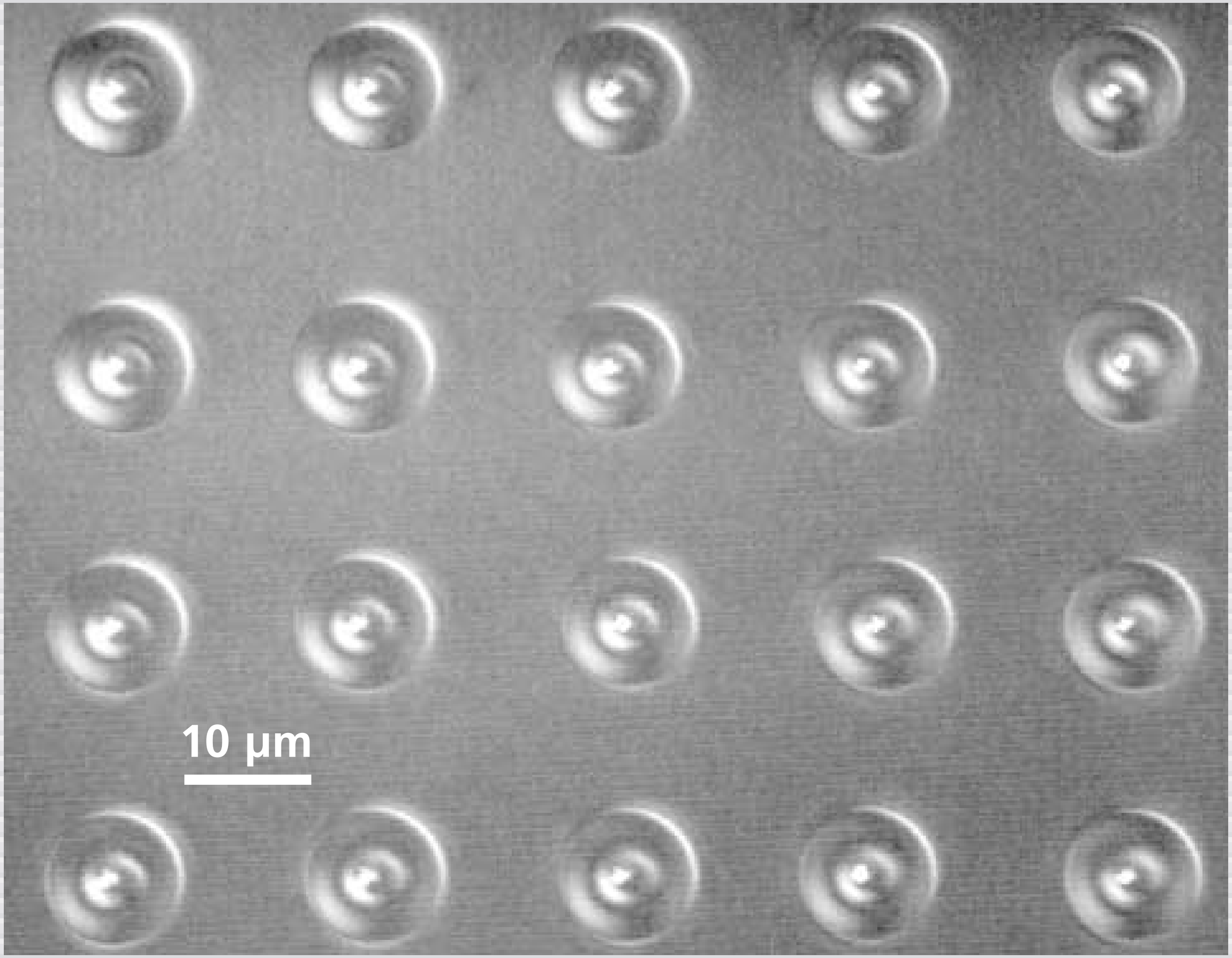
heat-diffusion time: $\tau_{diff} \approx 1\ \mu s$

long-cavity Ti:sapphire oscillator

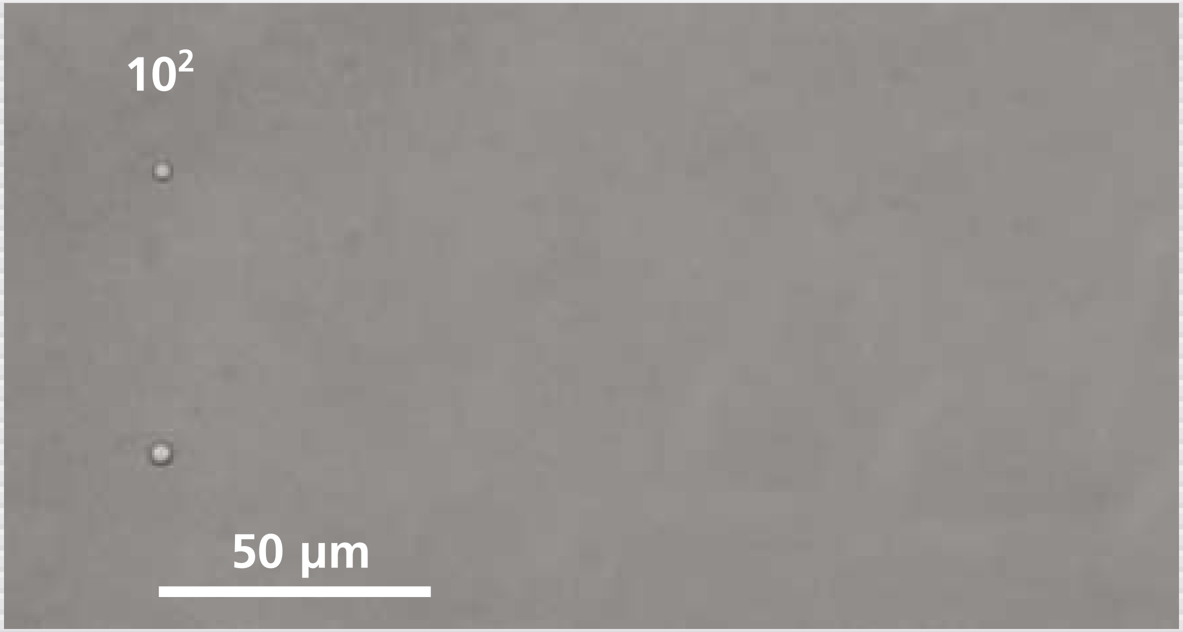


heat-diffusion time: $\tau_{diff} \approx 1\ \mu s$

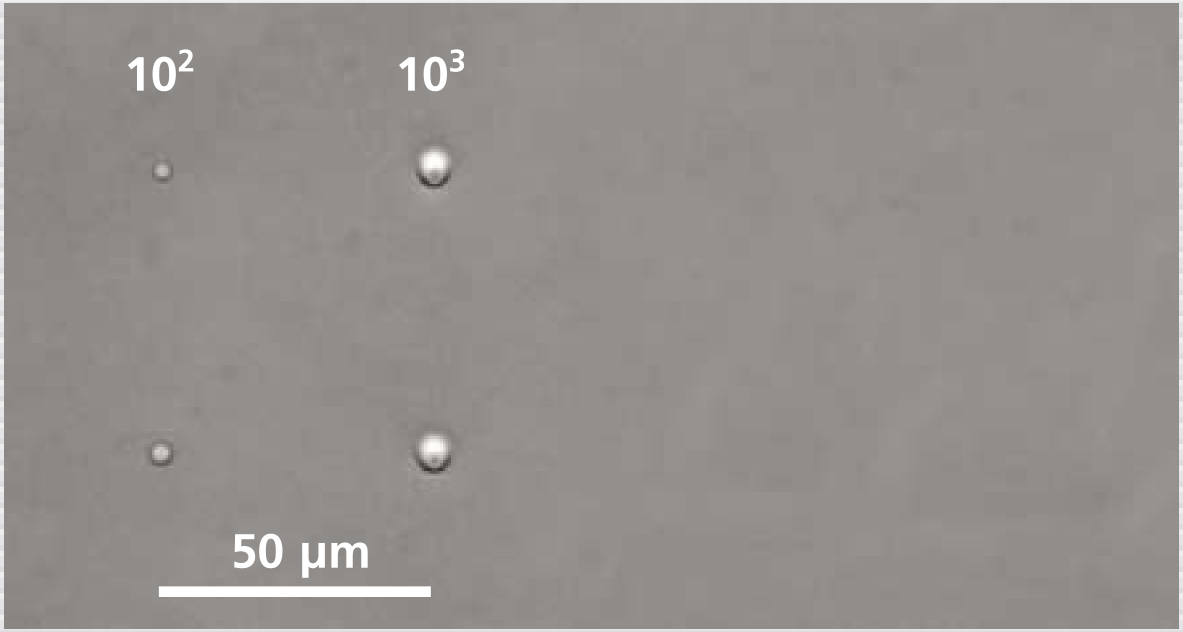
Low-energy processing



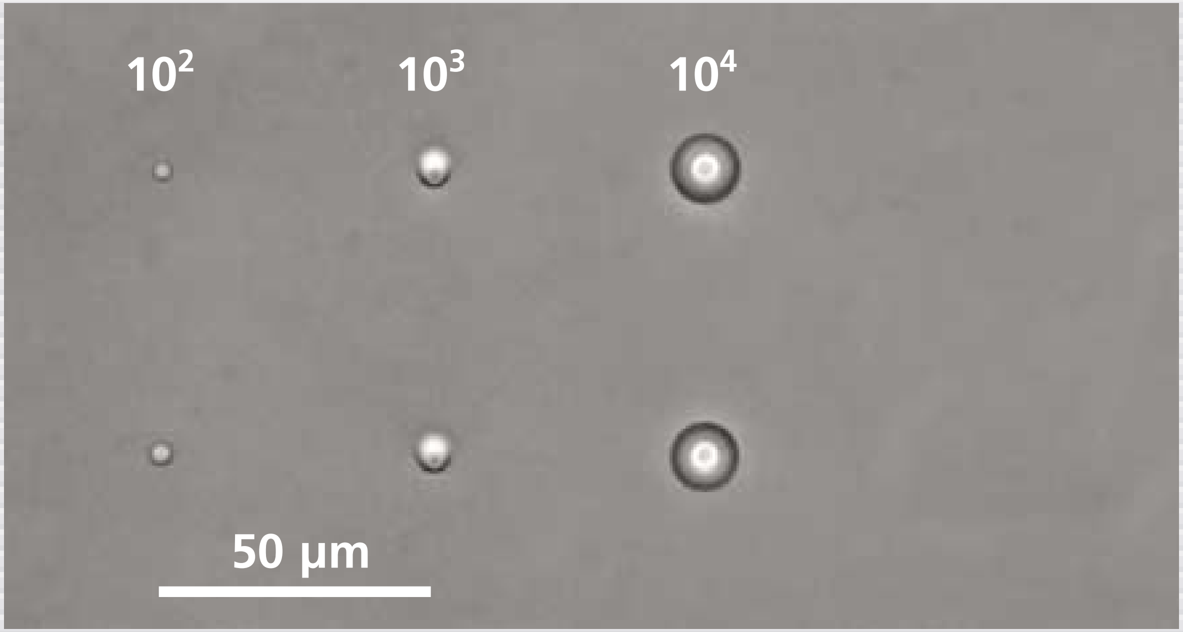
Low-energy processing



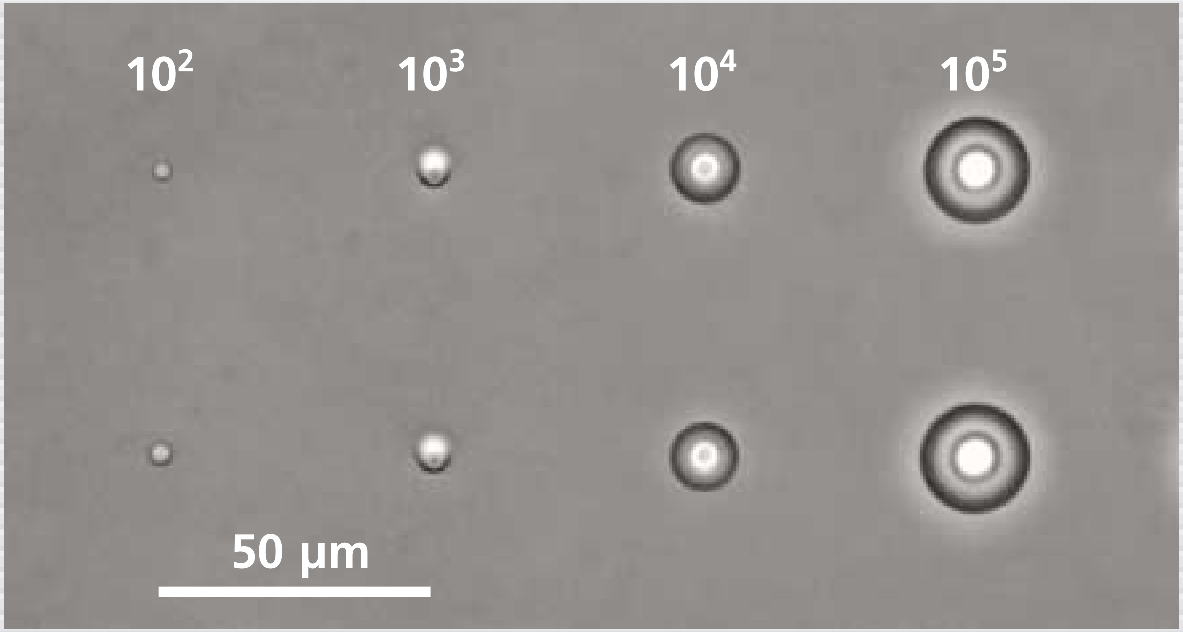
Low-energy processing



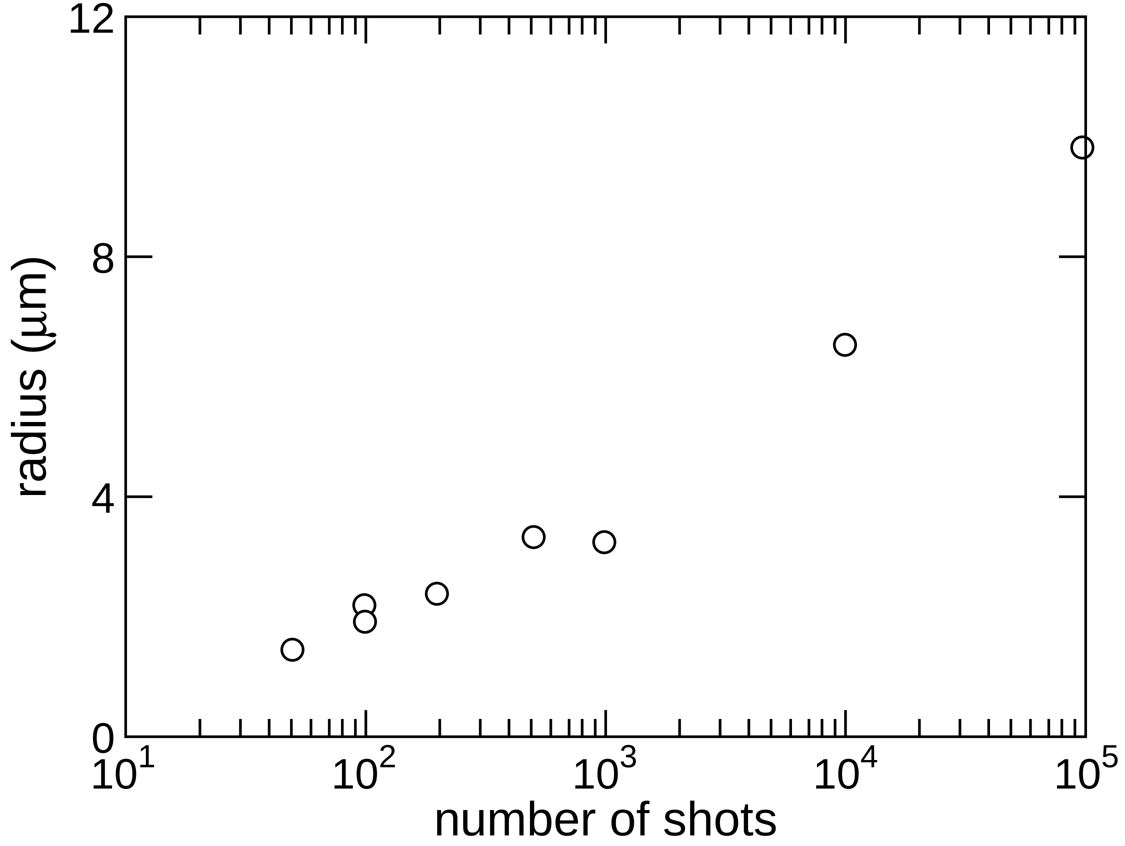
Low-energy processing



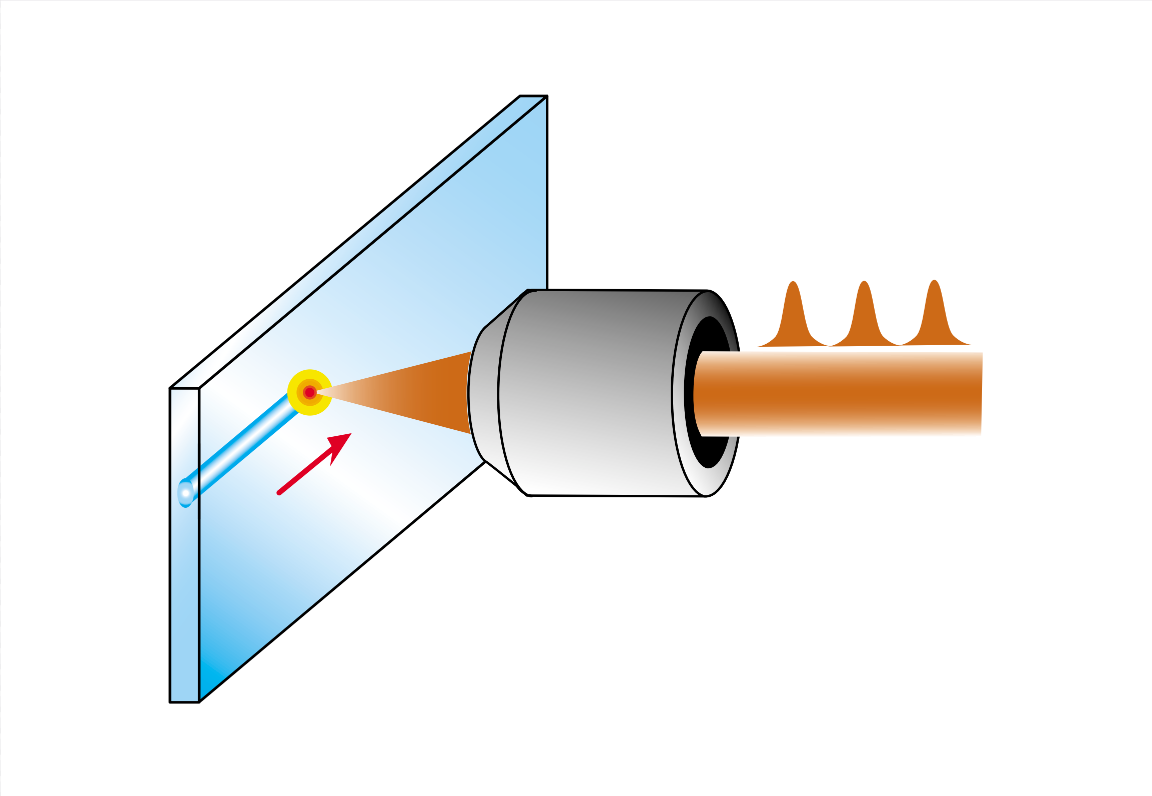
Low-energy processing



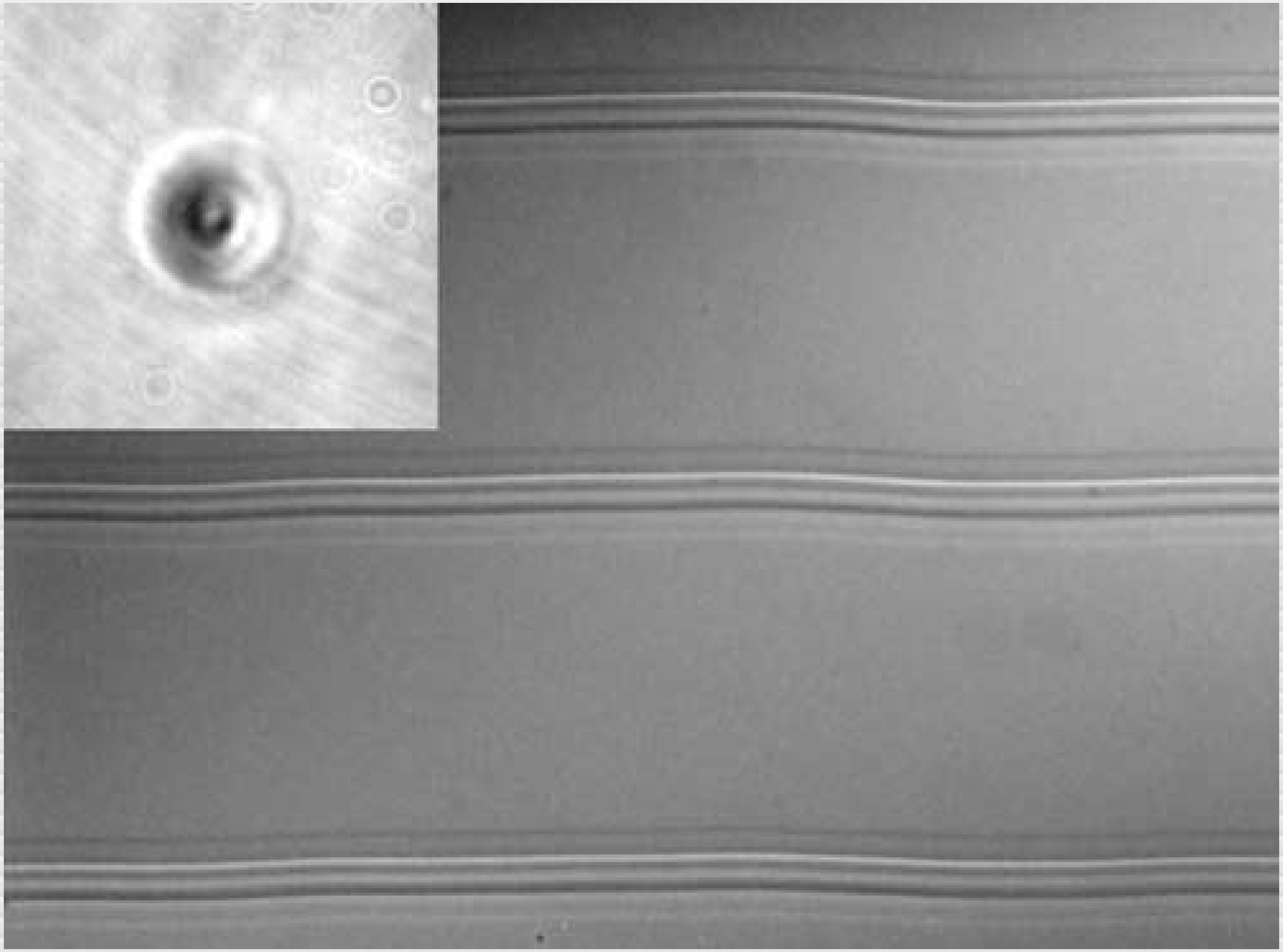
Low-energy processing



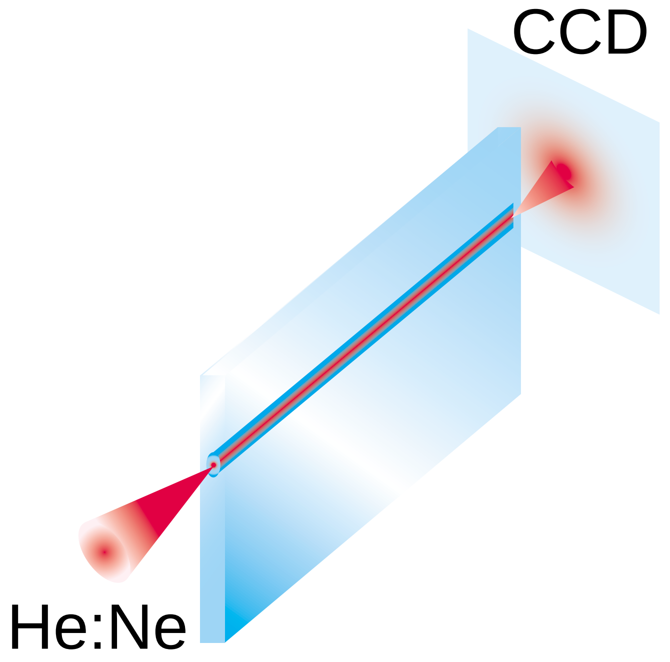
waveguide machining



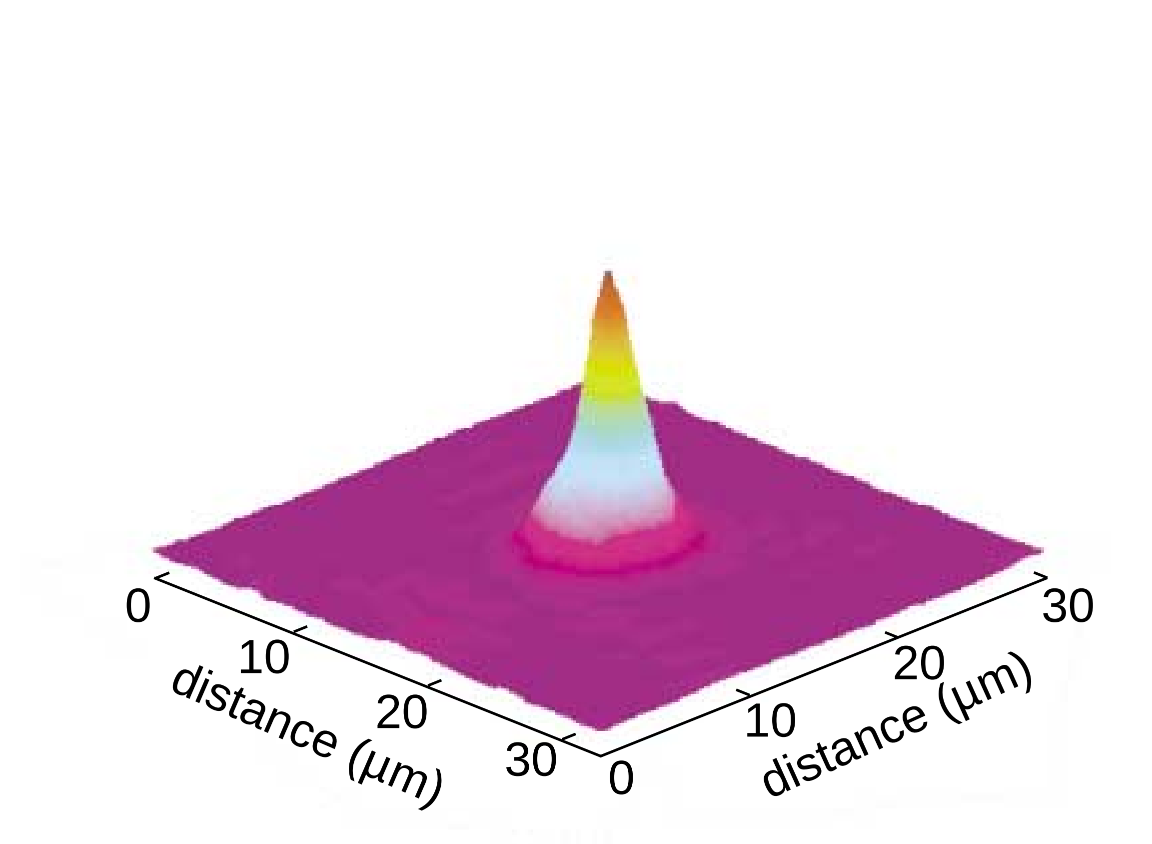
waveguide machining



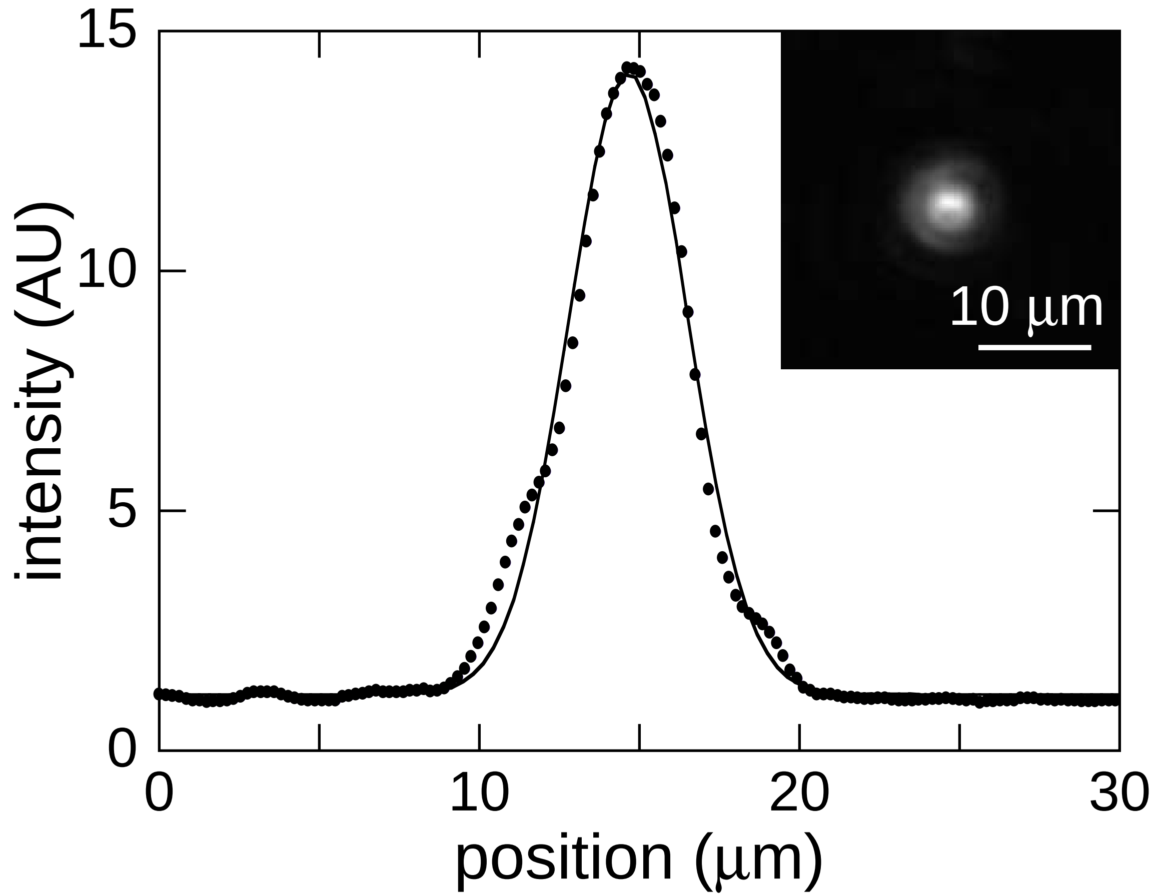
waveguide mode analysis



near field mode

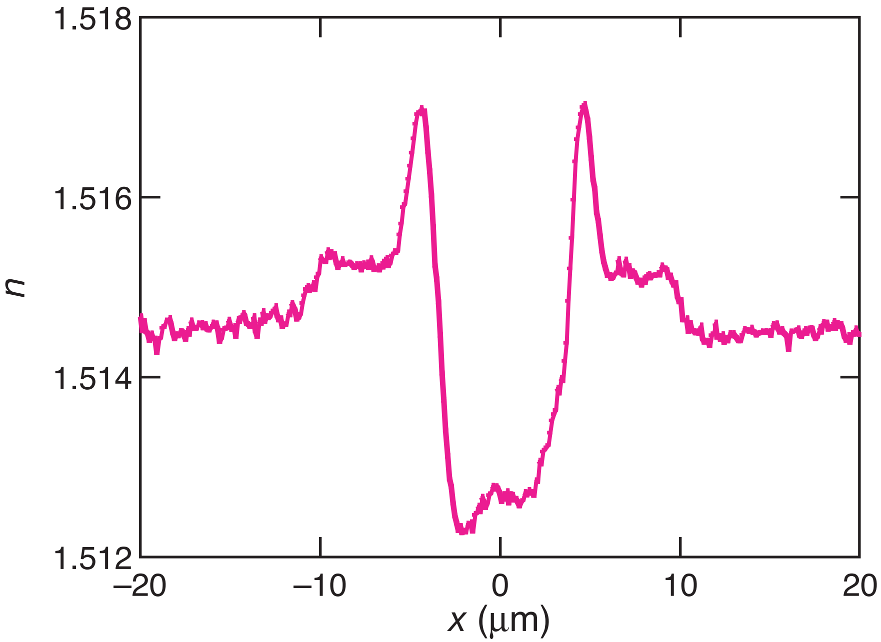


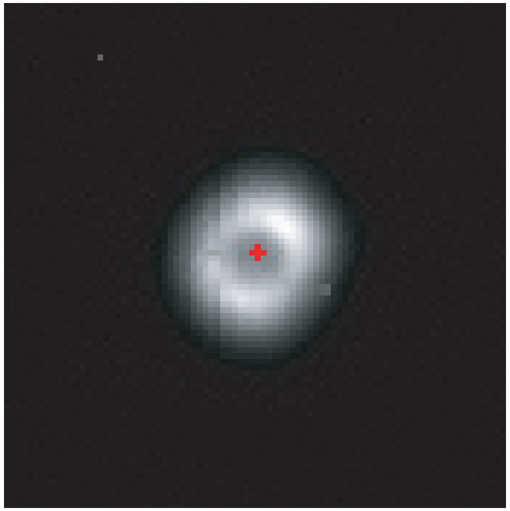
near field mode



refractive index profiles and near field mode at 633 nm

5 mm/s





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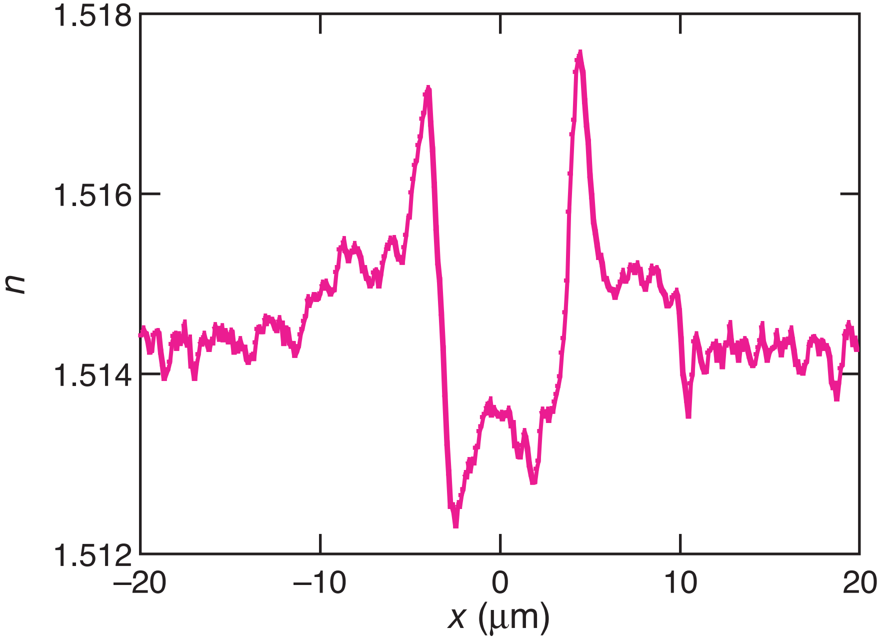
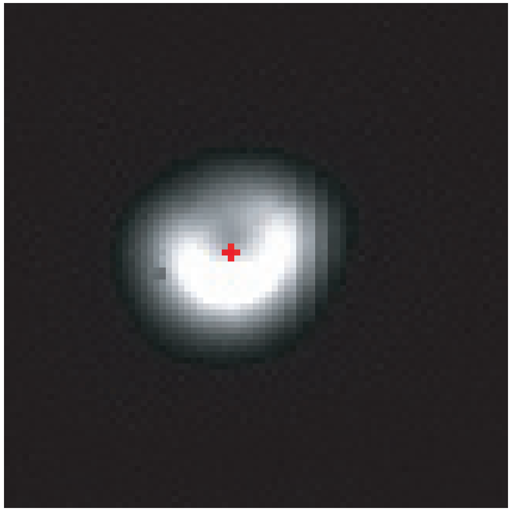
refractive index profiles and near field mode at 633 nm

10 mm/s

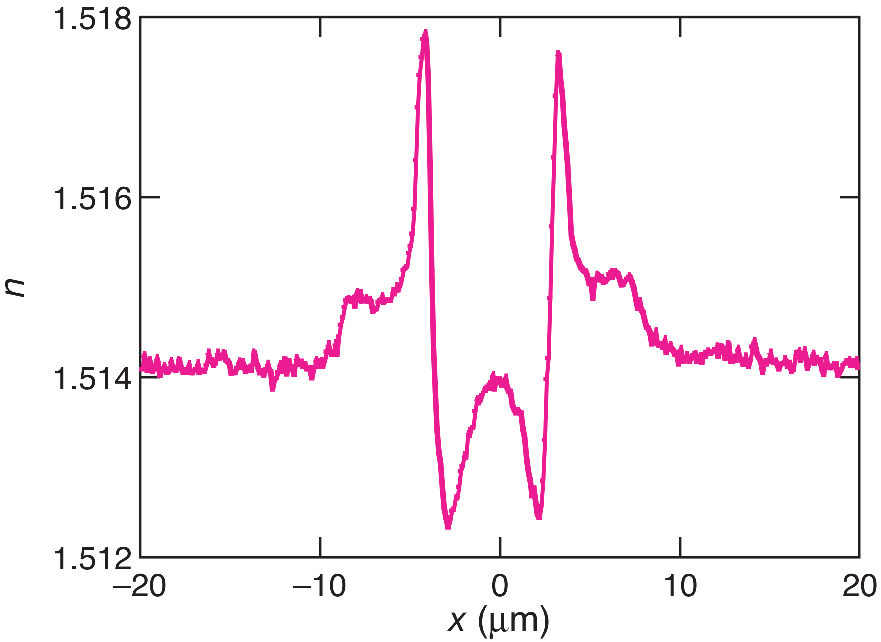


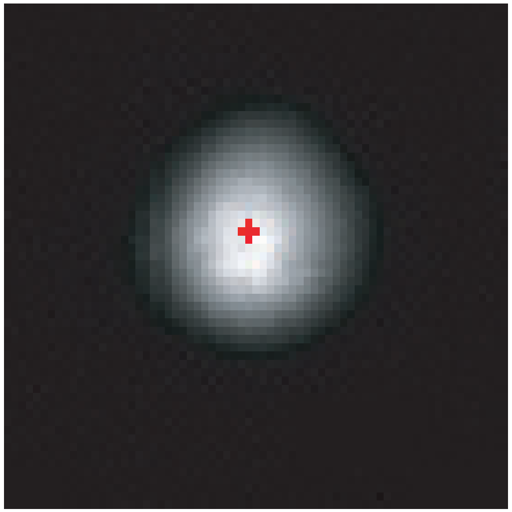


Sagitta, Inc.

refractive index profiles and near field mode at 633 nm

20 mm/s





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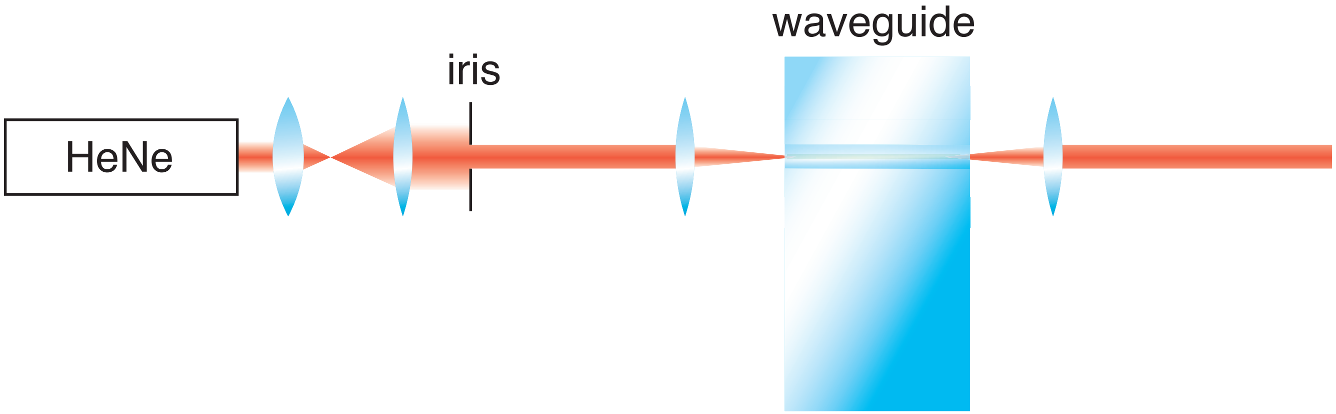
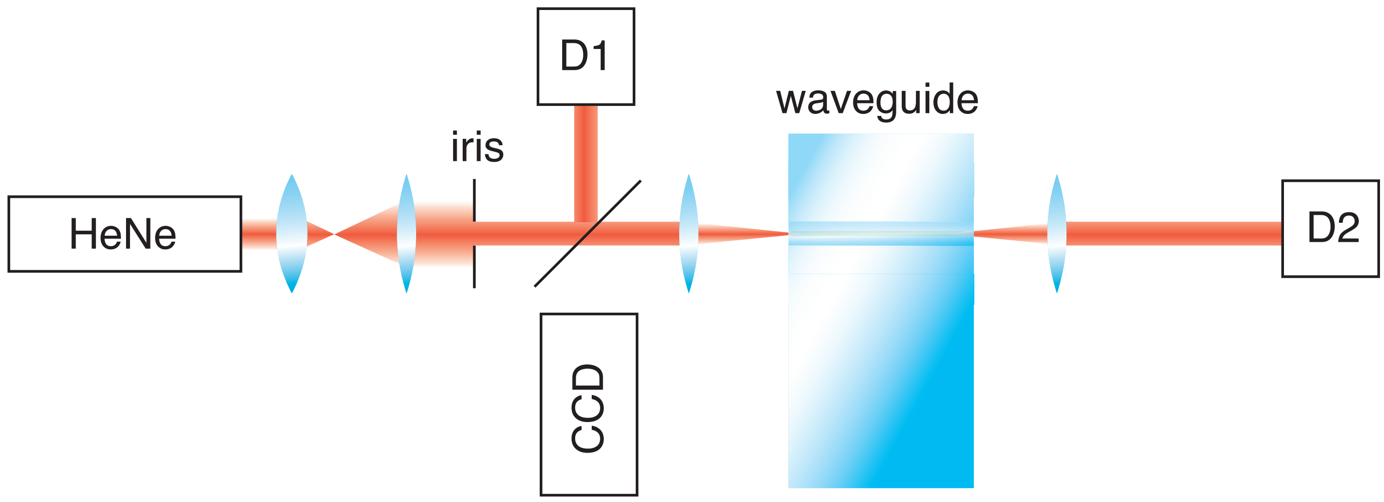
waveguide loss measurement

waveguide loss measurement

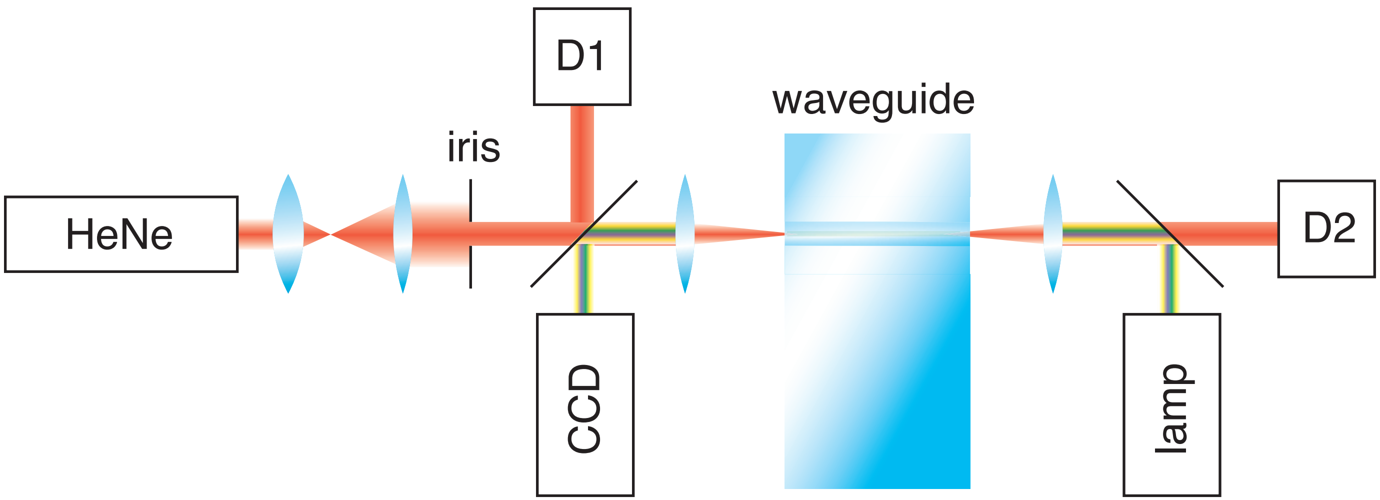
waveguide loss measurement



waveguide loss measurement



waveguide loss measurement



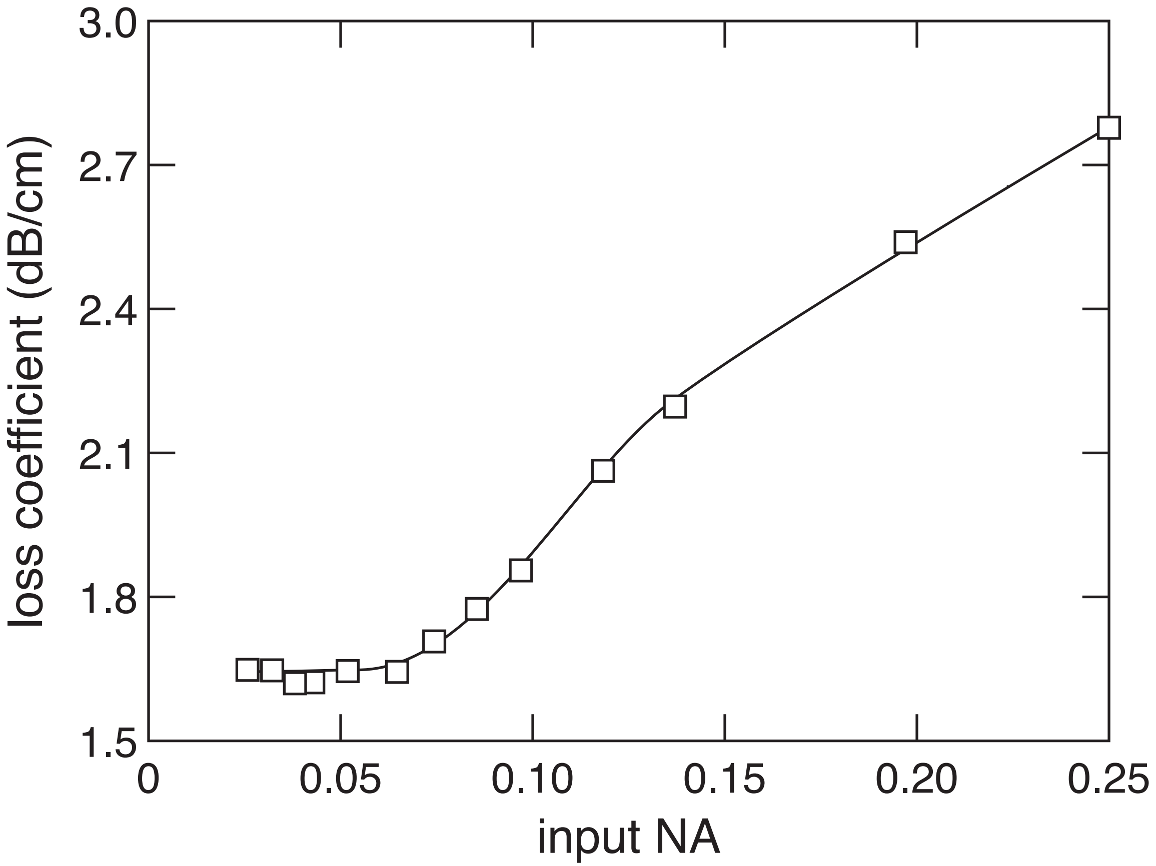
Low-energy processing

- **at low NA: 1.6 dB/cm < loss < 3.2 dB/cm**

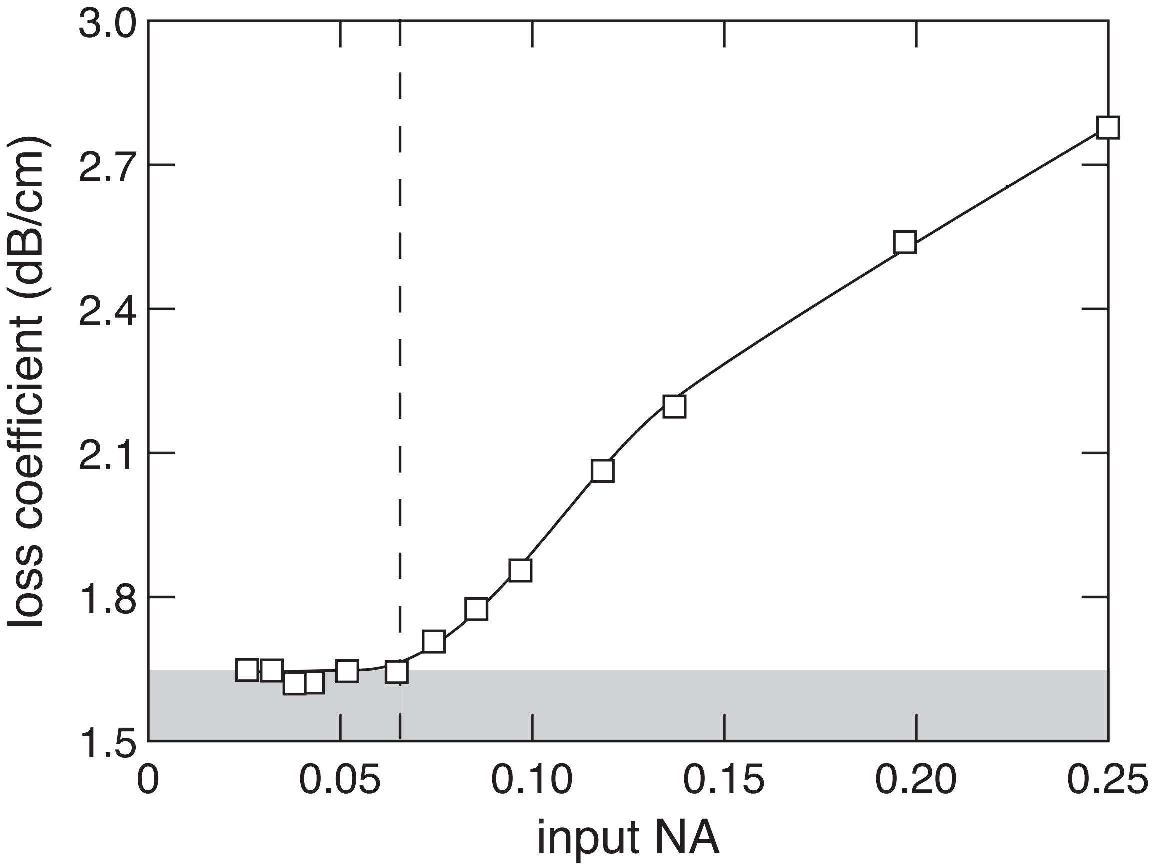
Low-energy processing

- at low NA: 1.6 dB/cm < loss < 3.2 dB/cm
- losses mostly due to scattering

numerical aperture of waveguide



numerical aperture of waveguide



numerical aperture of waveguide

$$NA = \sqrt{n_1^2 - n_2^2} = 0.065$$

numerical aperture of waveguide

$$NA = \sqrt{n_1^2 - n_2^2} = 0.065$$

$$n_2 = 1.52$$

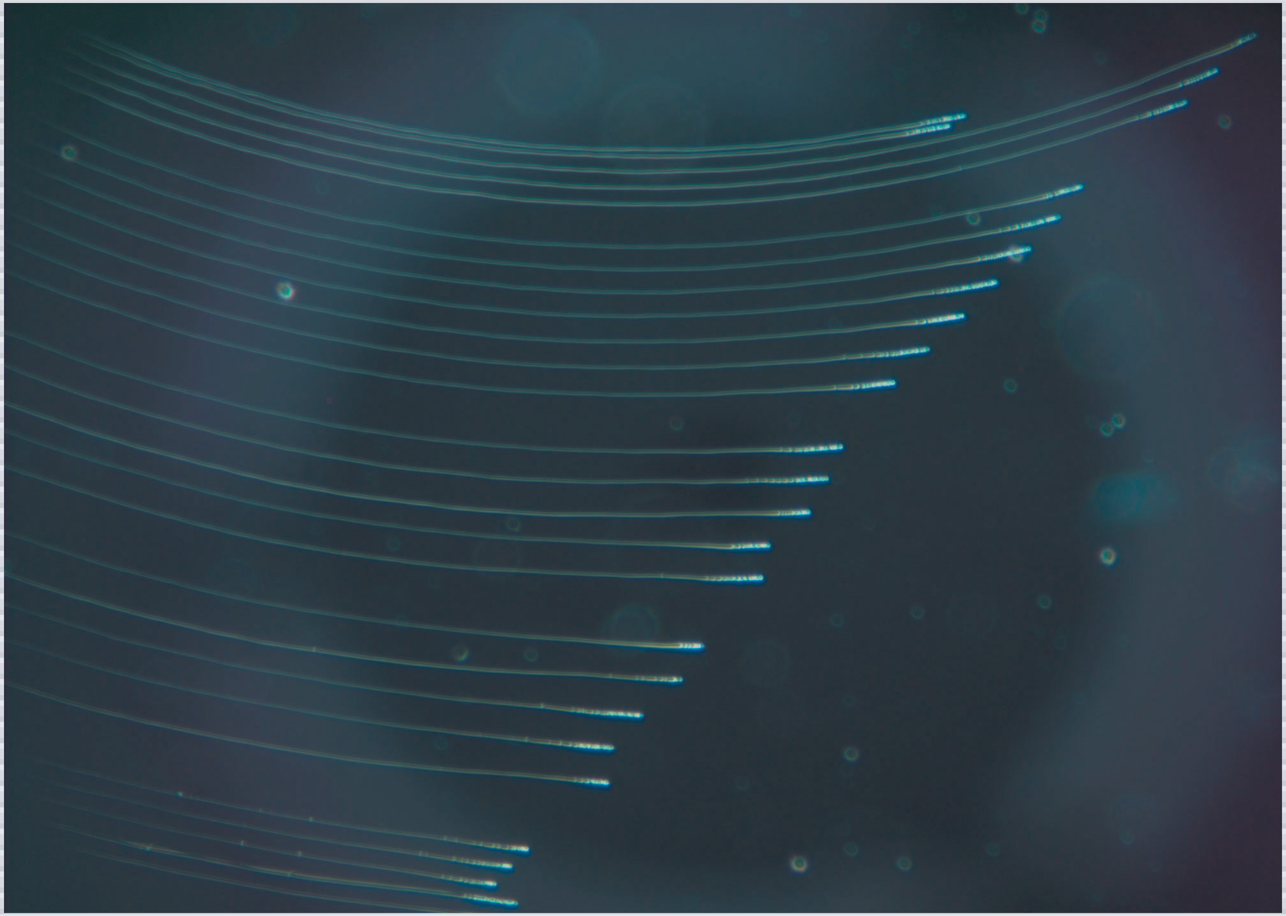
numerical aperture of waveguide

$$NA = \sqrt{n_1^2 - n_2^2} = 0.065$$

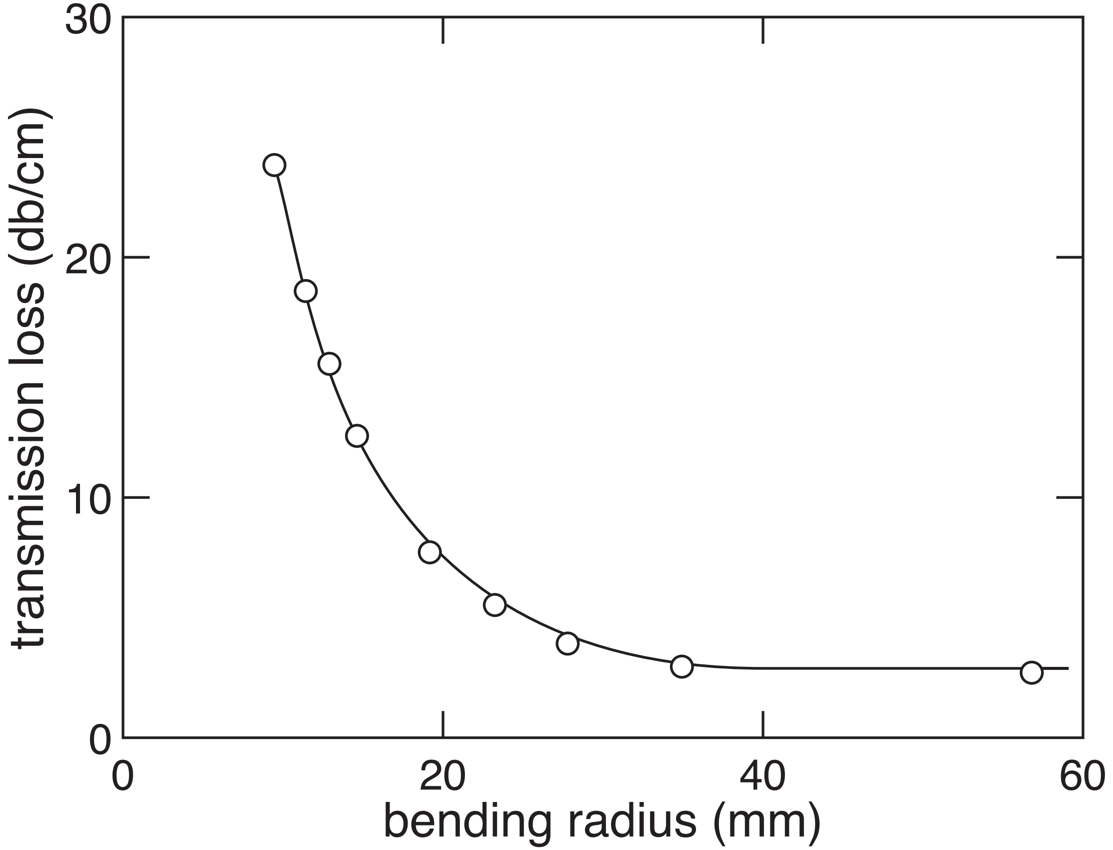
$$n_2 = 1.52$$

$$\Delta n = 1.4 \times 10^{-3}$$

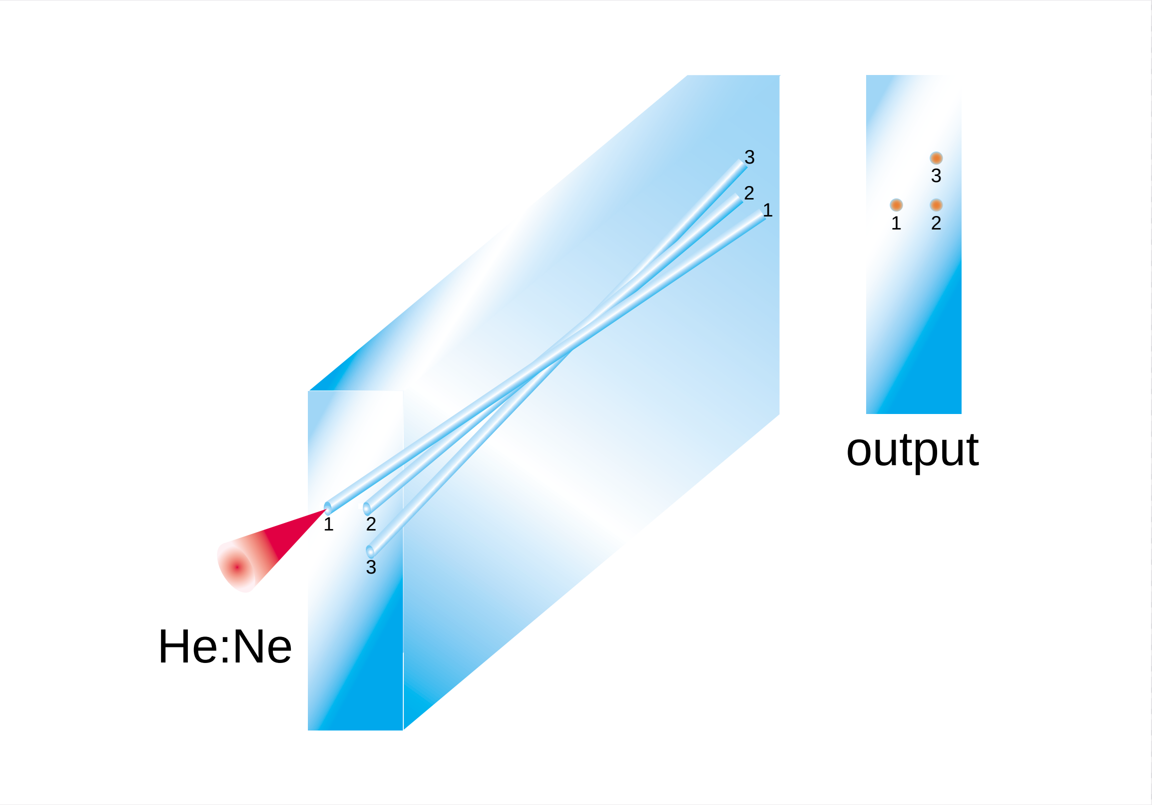
curved waveguides



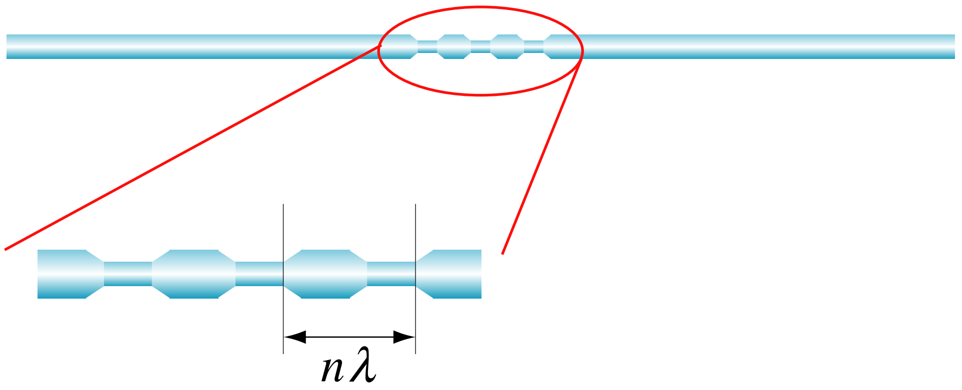
curved waveguides



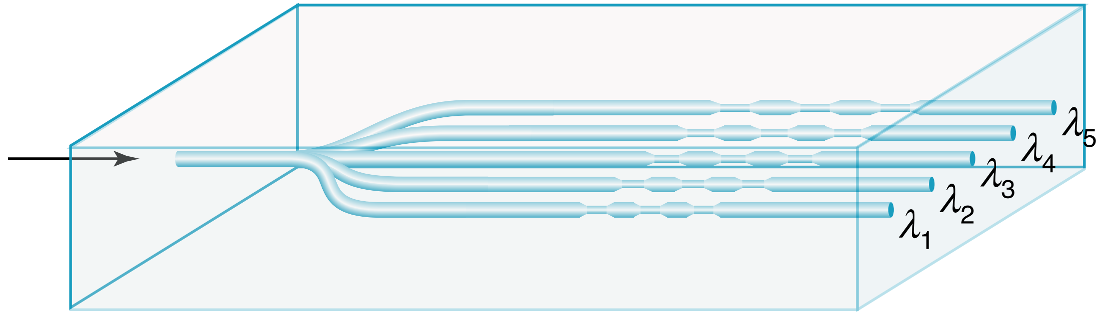
3D wave splitter



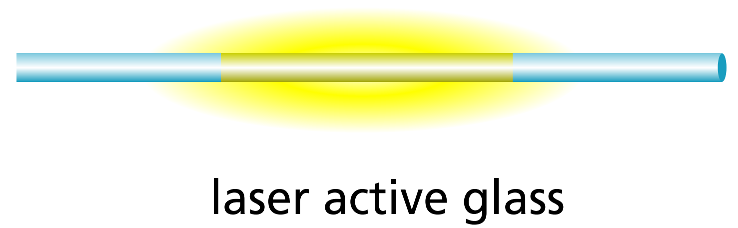
Bragg grating



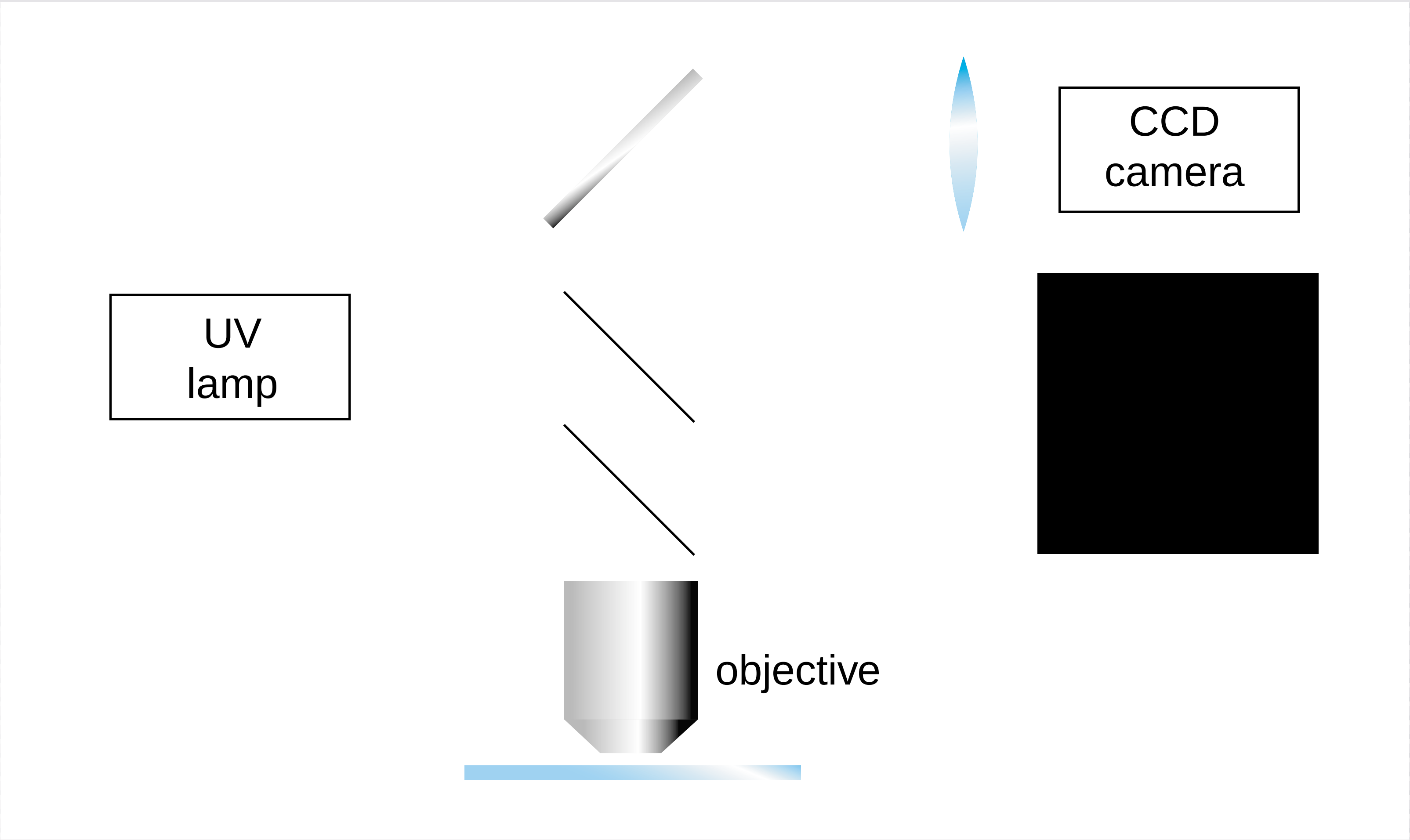
Bragg grating



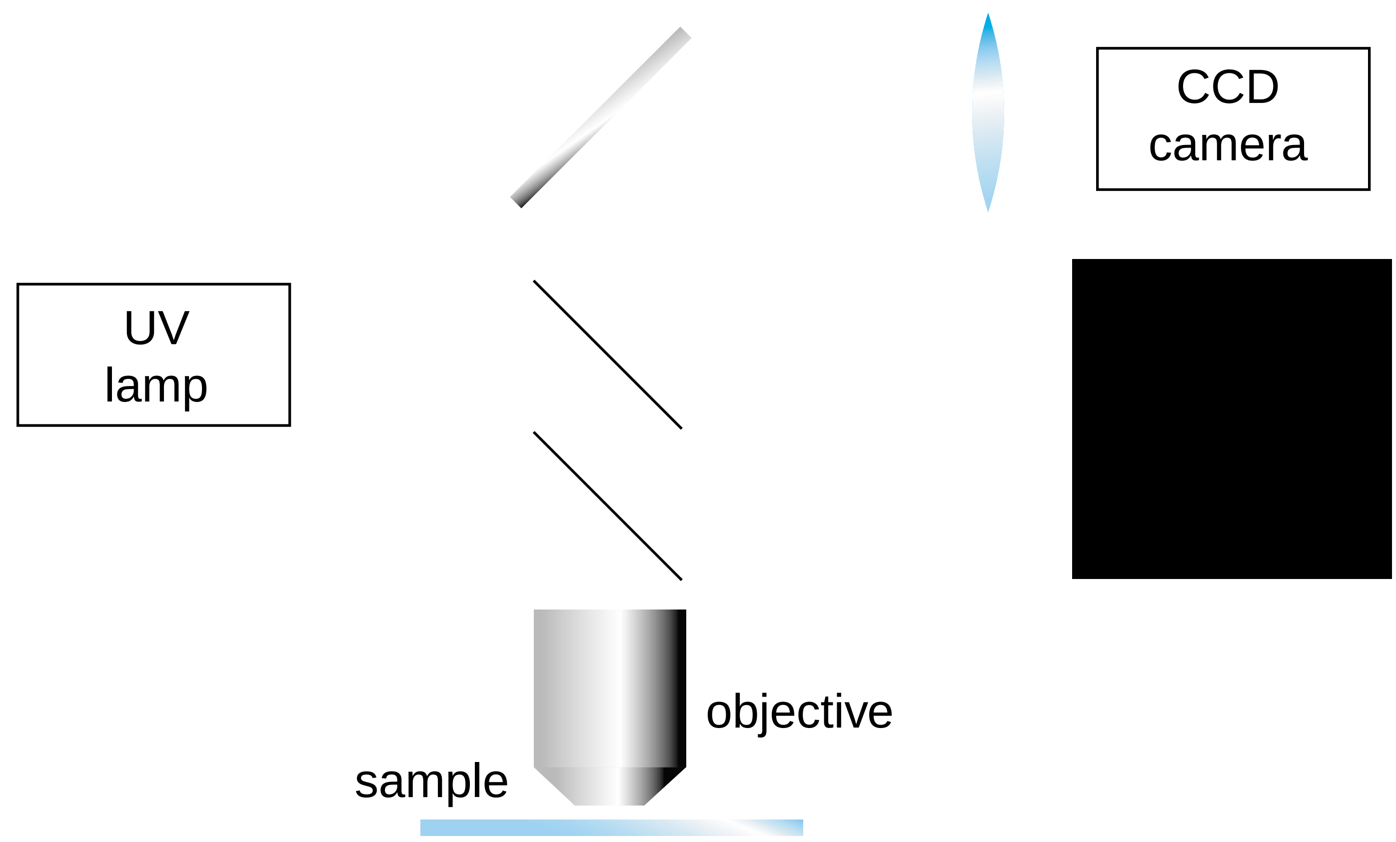
monolithic amplifier



epi-fluorescence microscope

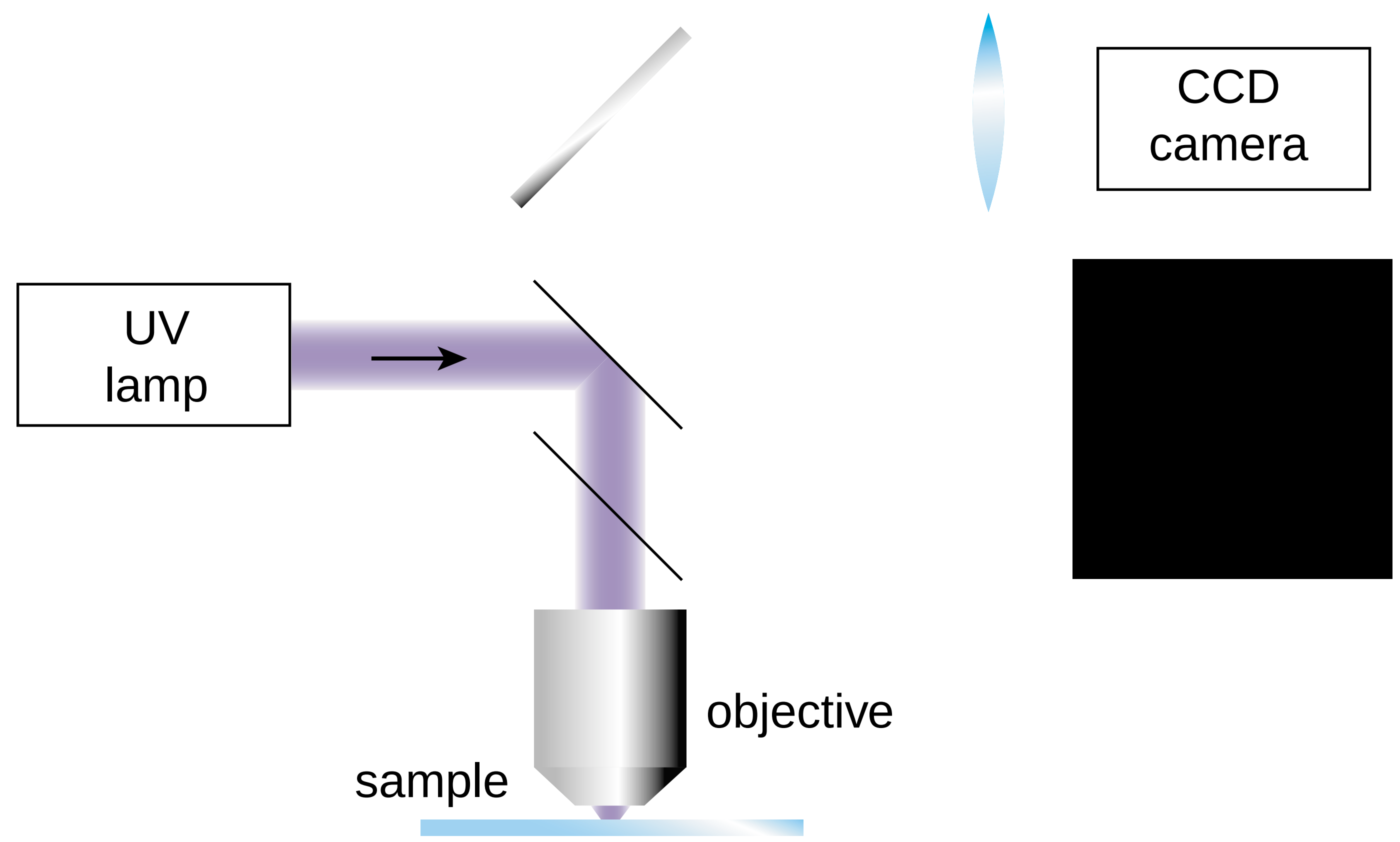


mount fluorescently tagged sample

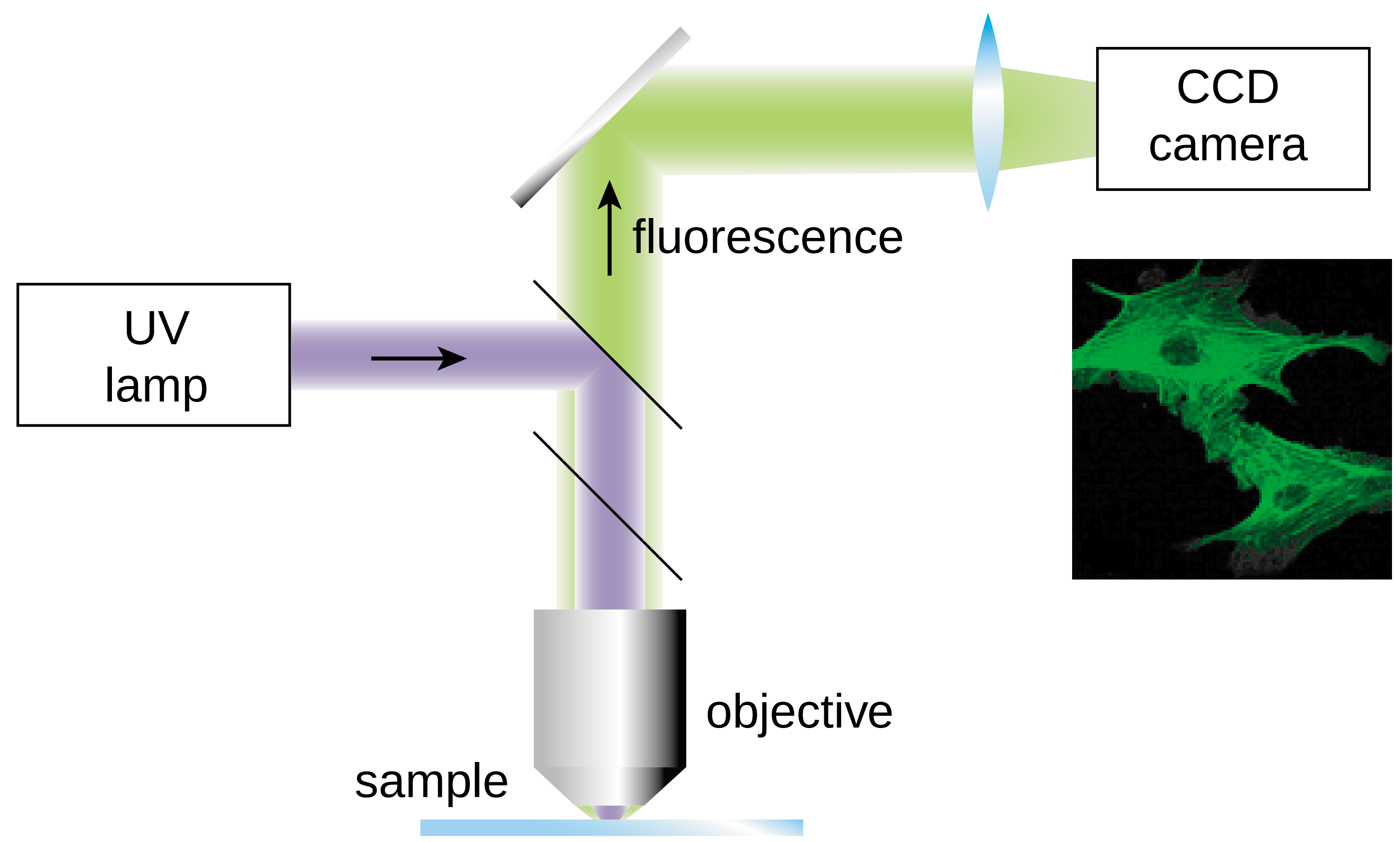


Low-energy processing

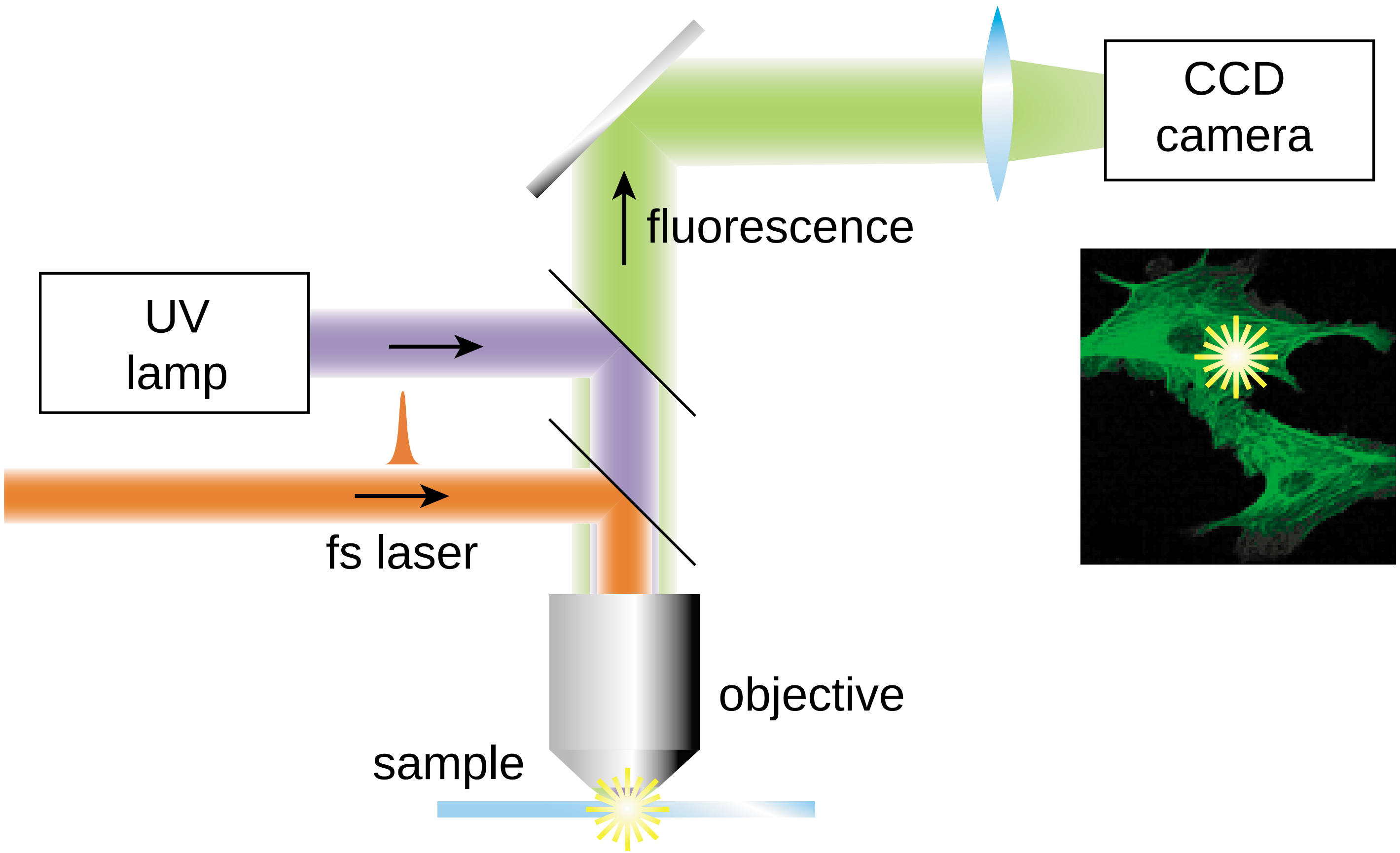
UV illumination…



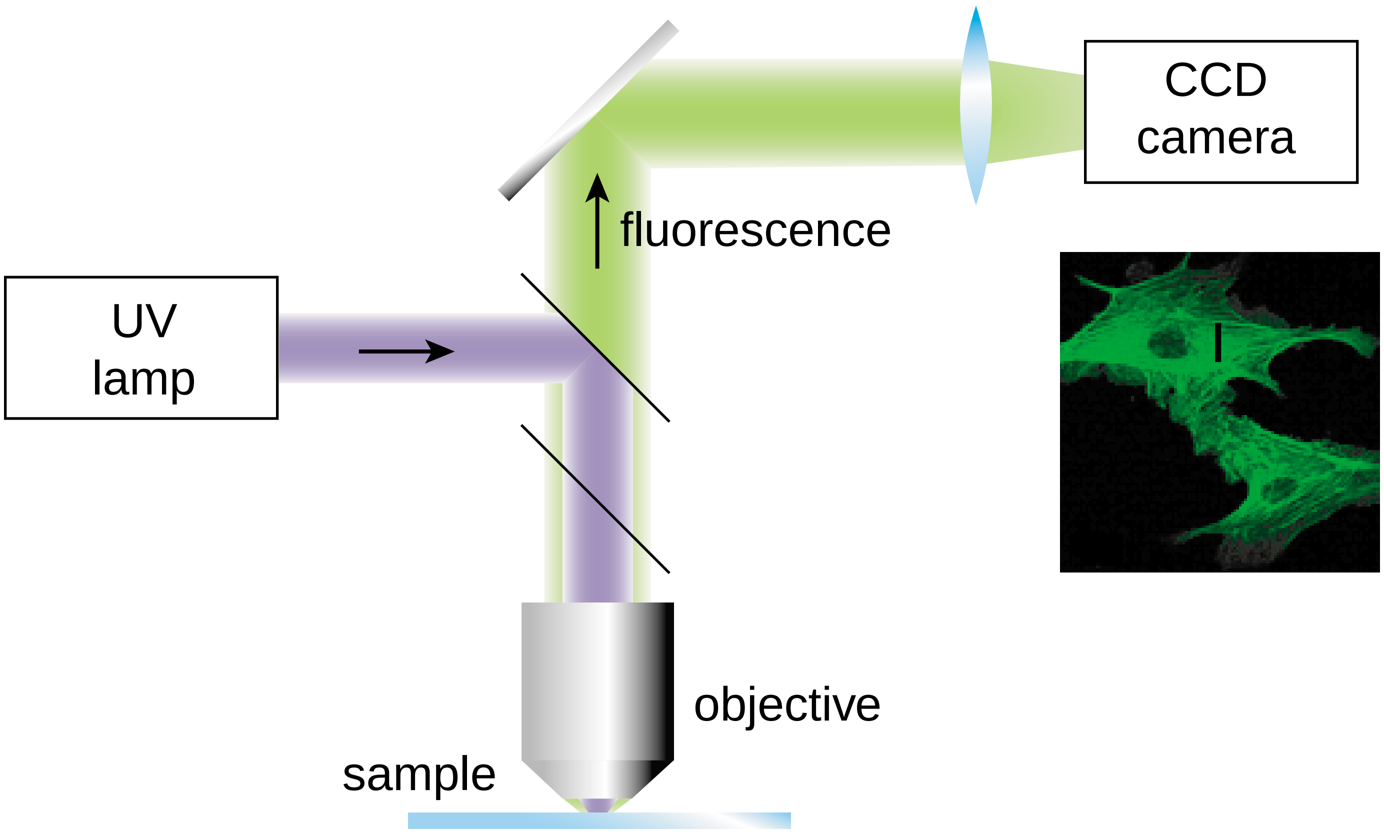
… causes fluorescence



process with fs laser beam

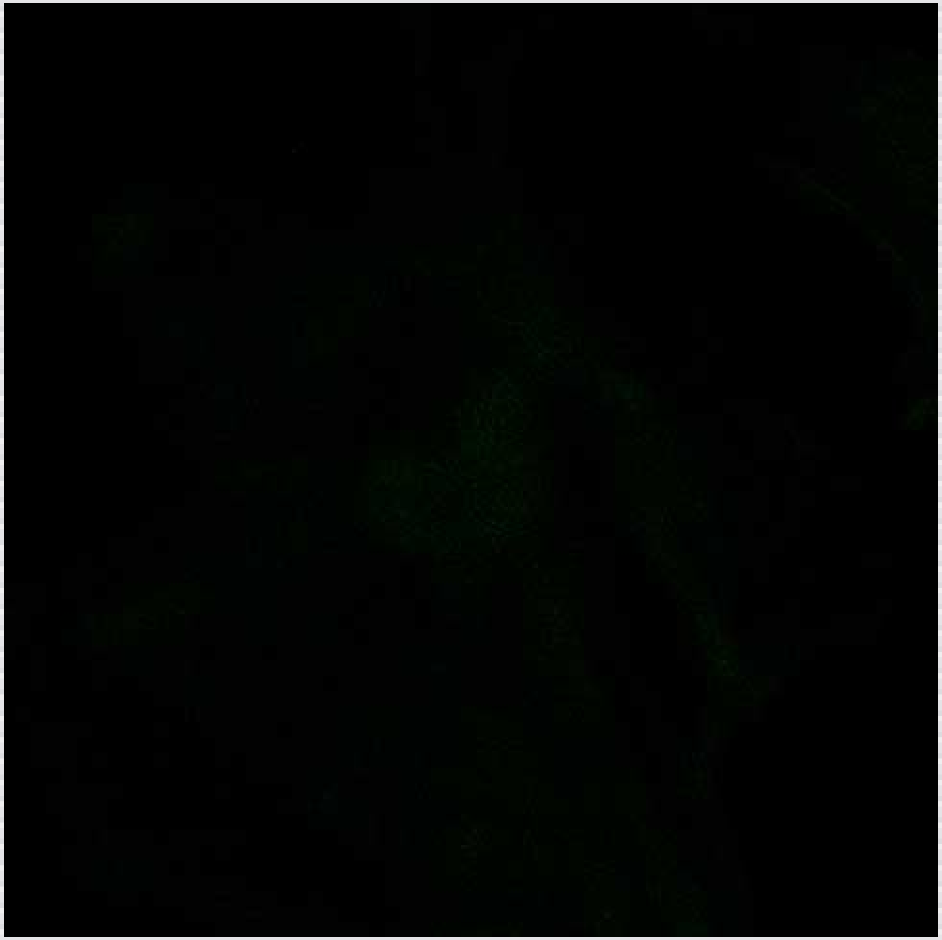


Low-energy processing

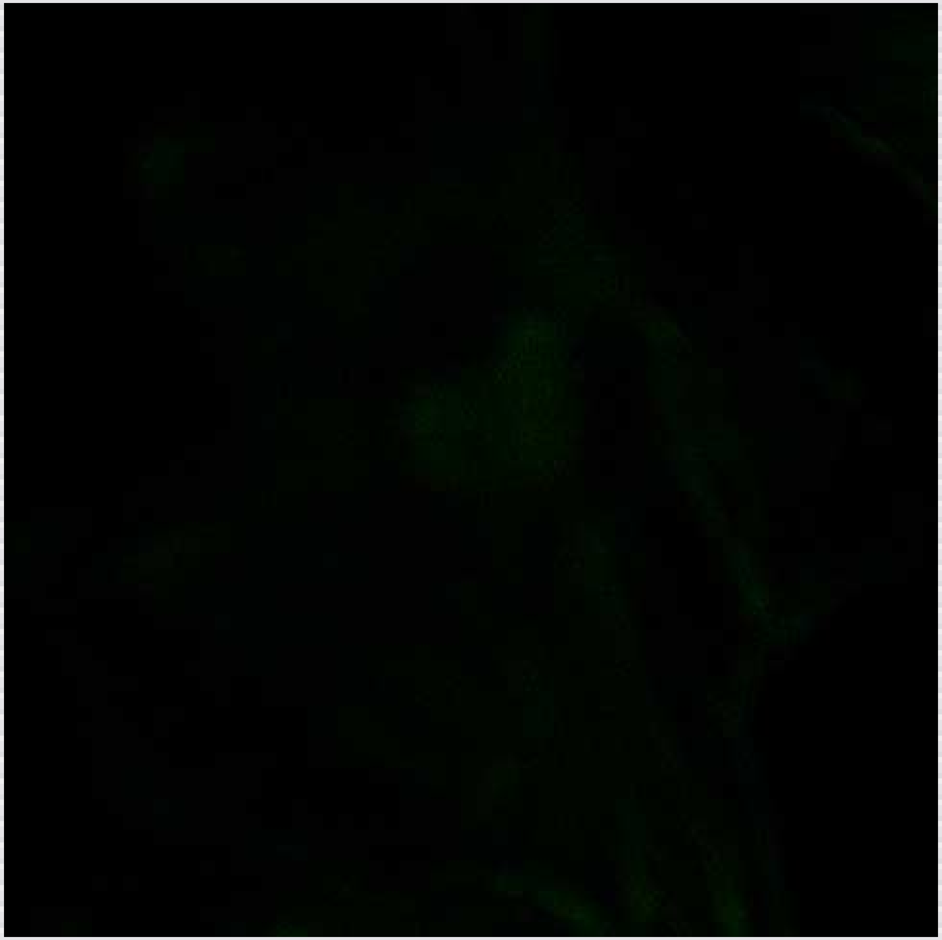


Low-energy processing

before



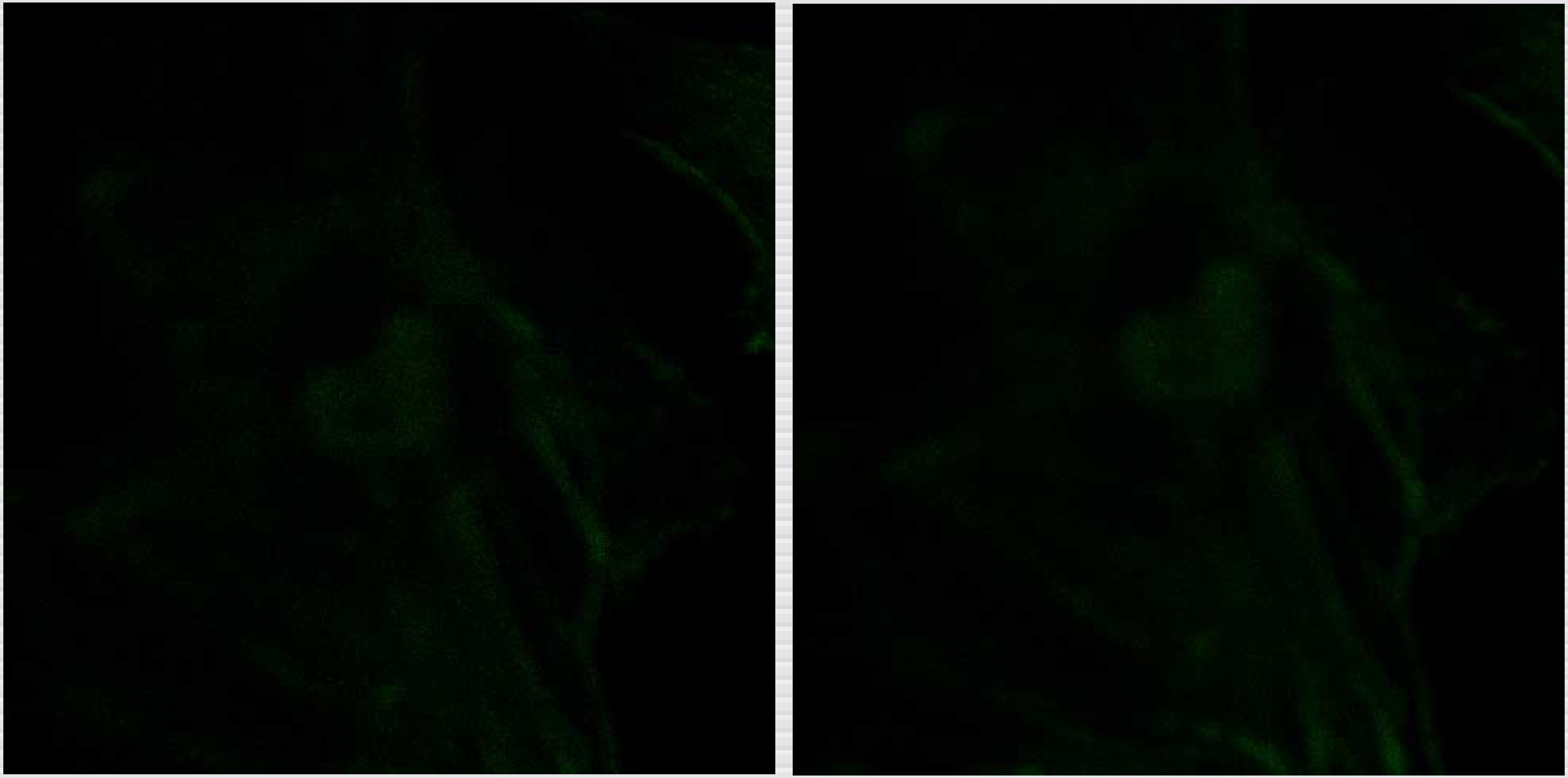
after



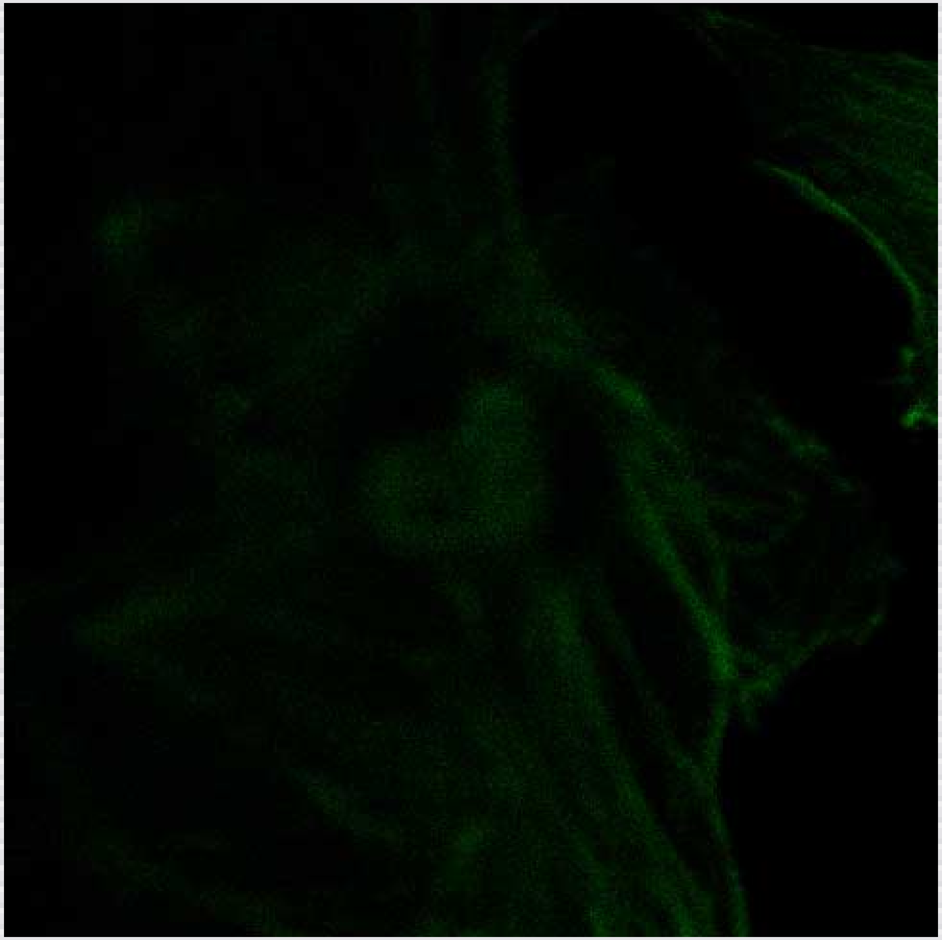
examine in confocal microscope

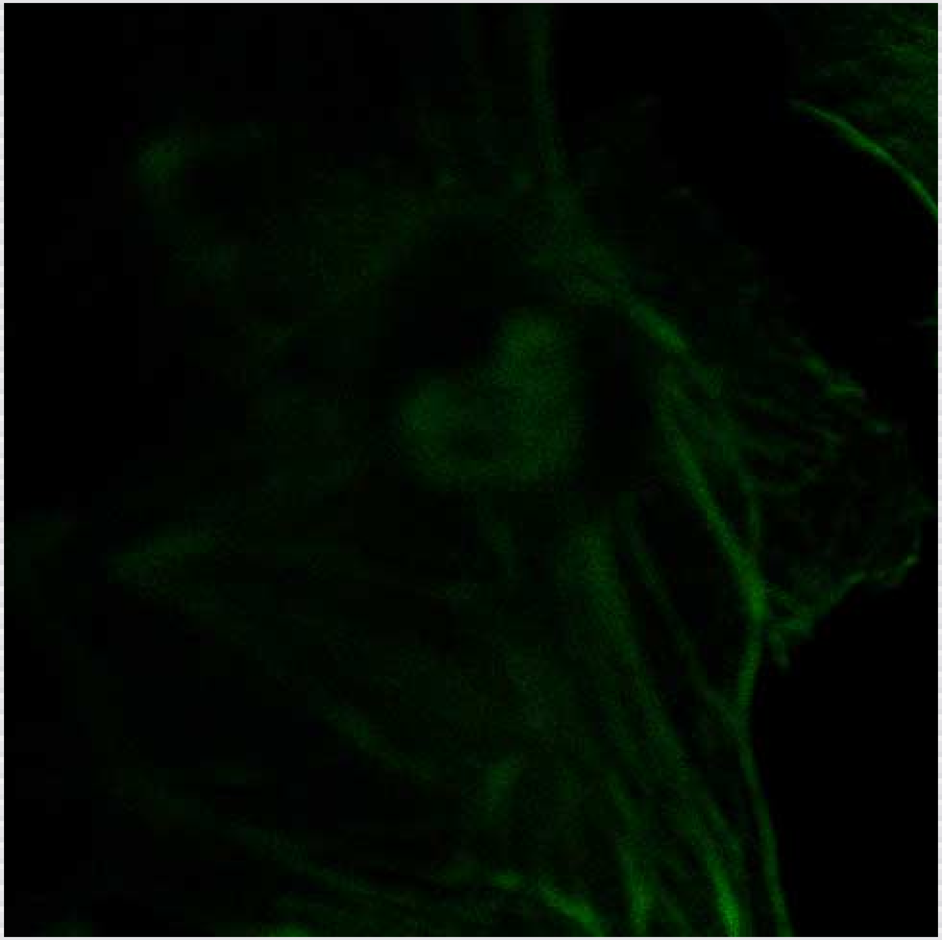
Low-energy processing

before **after**



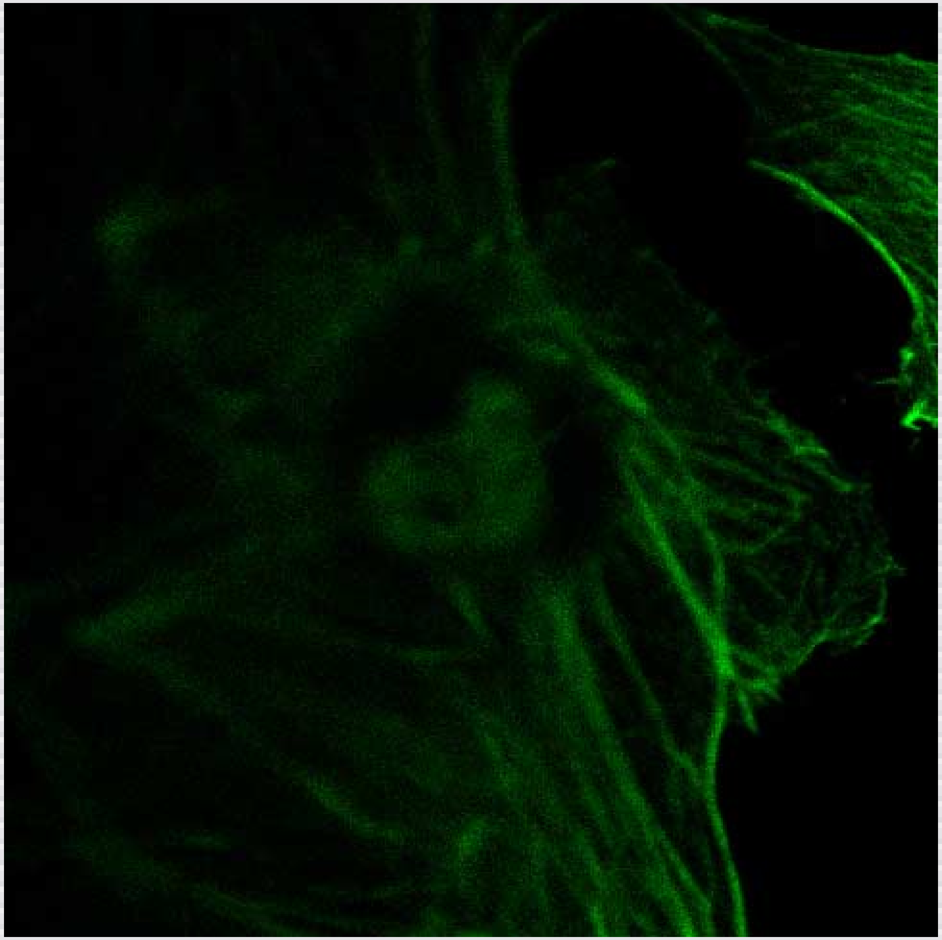
Low-energy processing



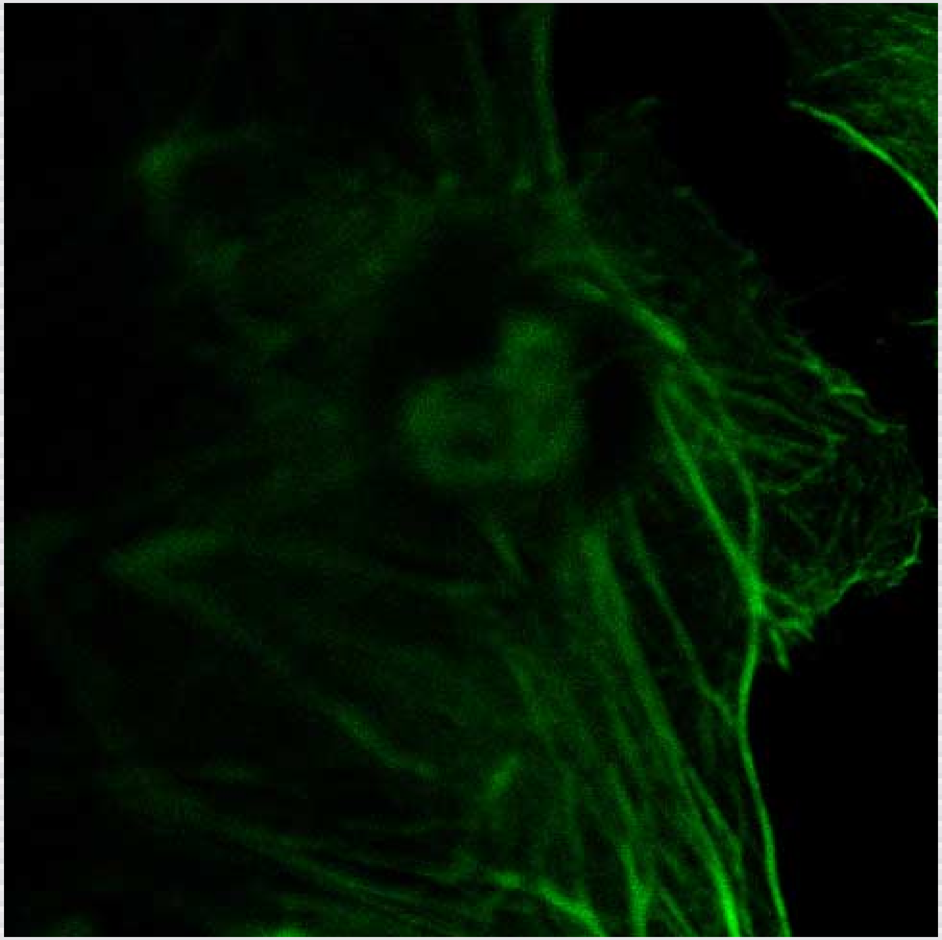


Low-energy processing

before

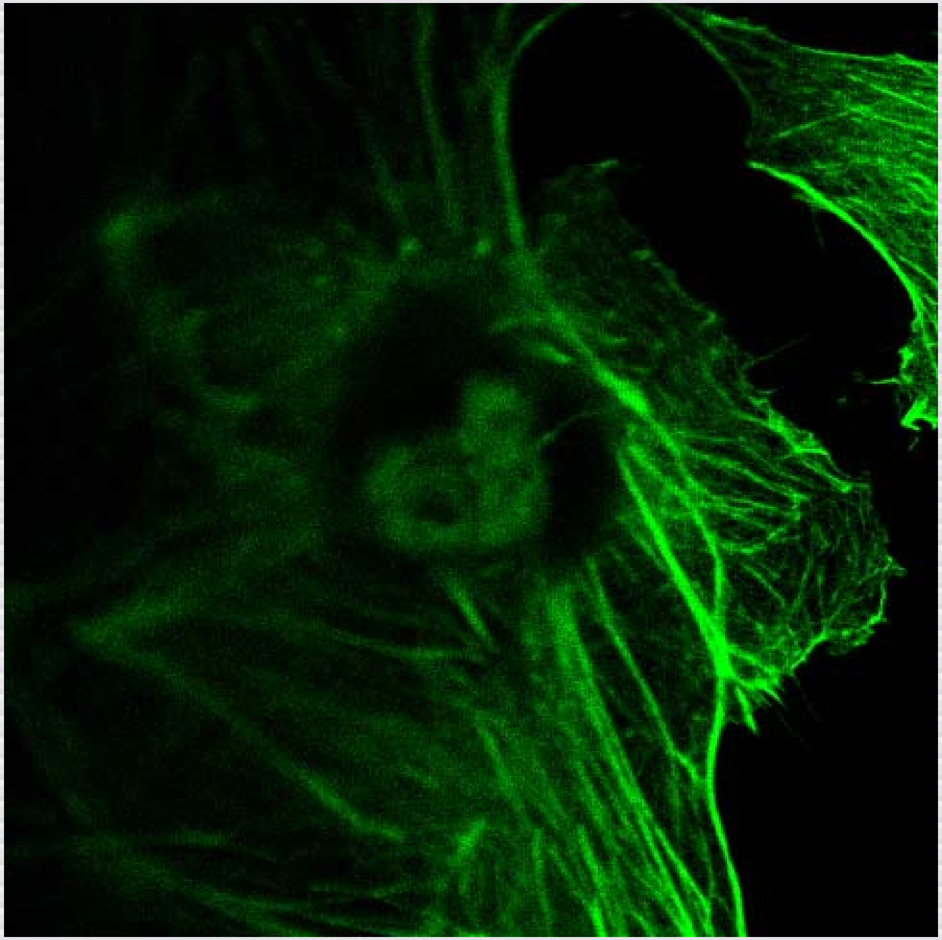


after

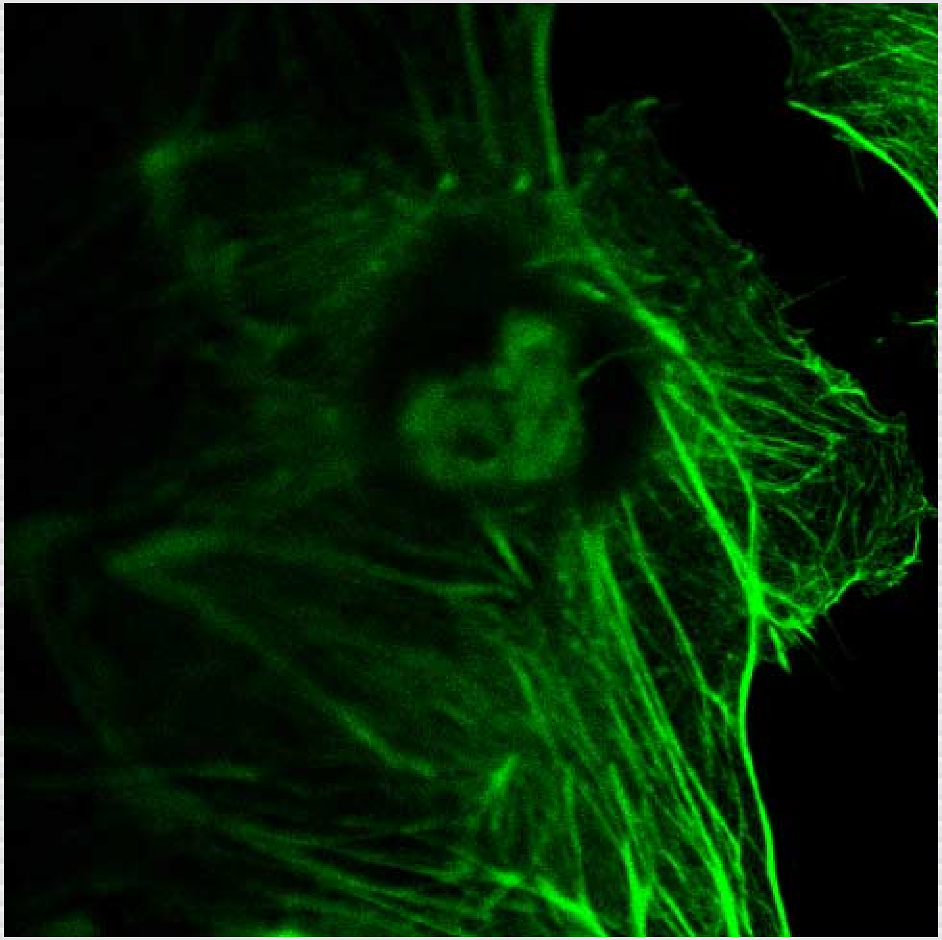


Low-energy processing

before

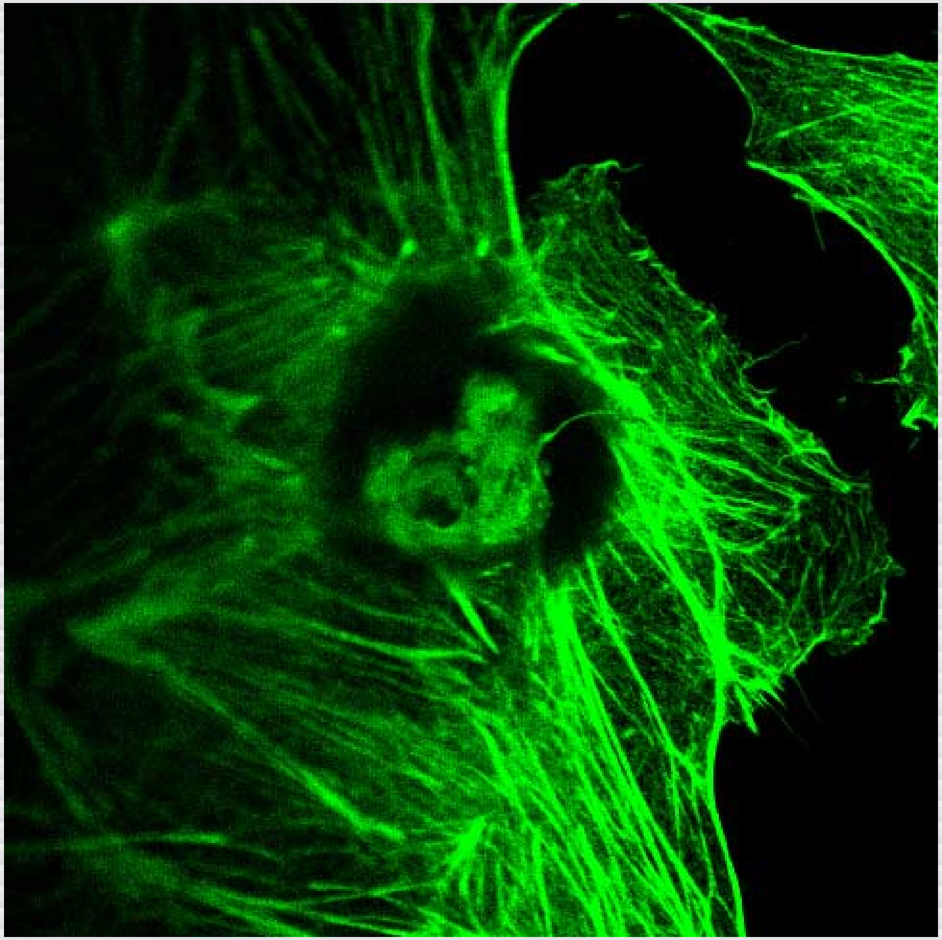


after

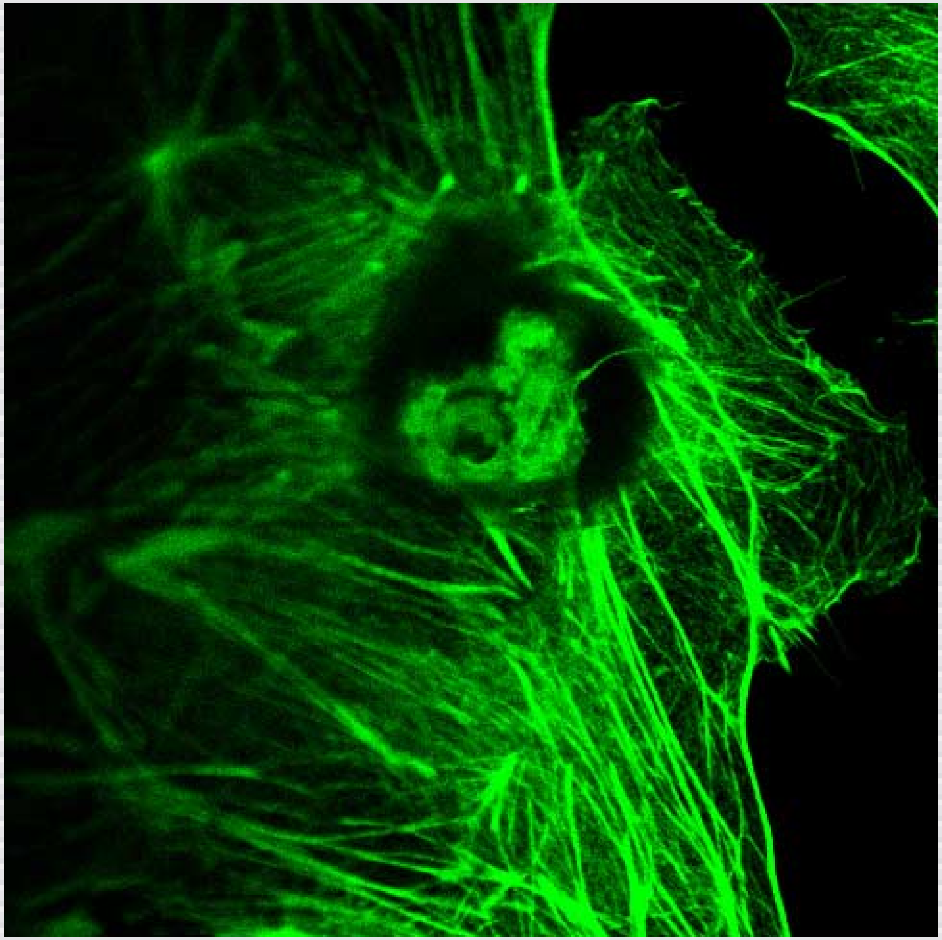


Low-energy processing

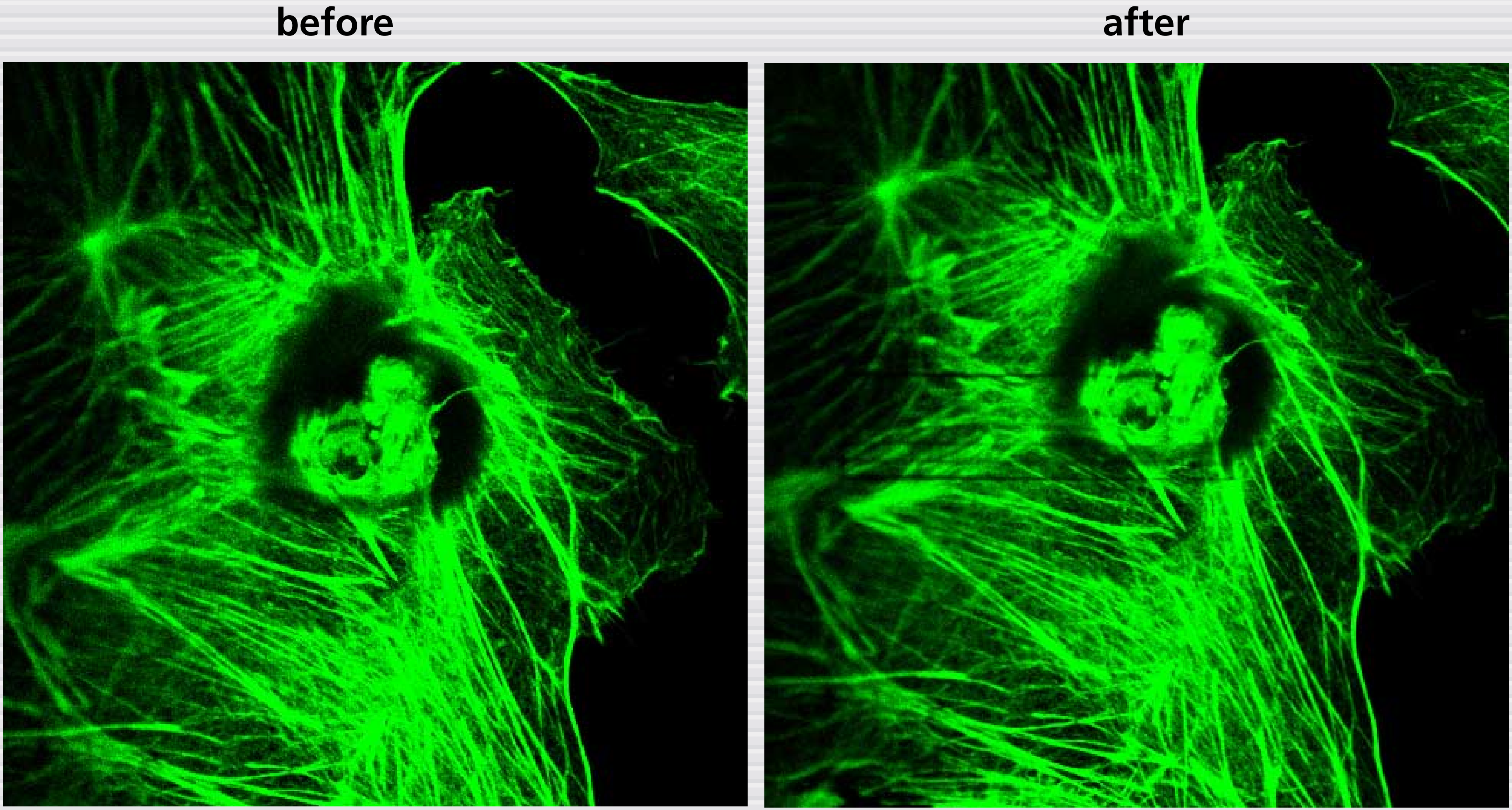
before



after

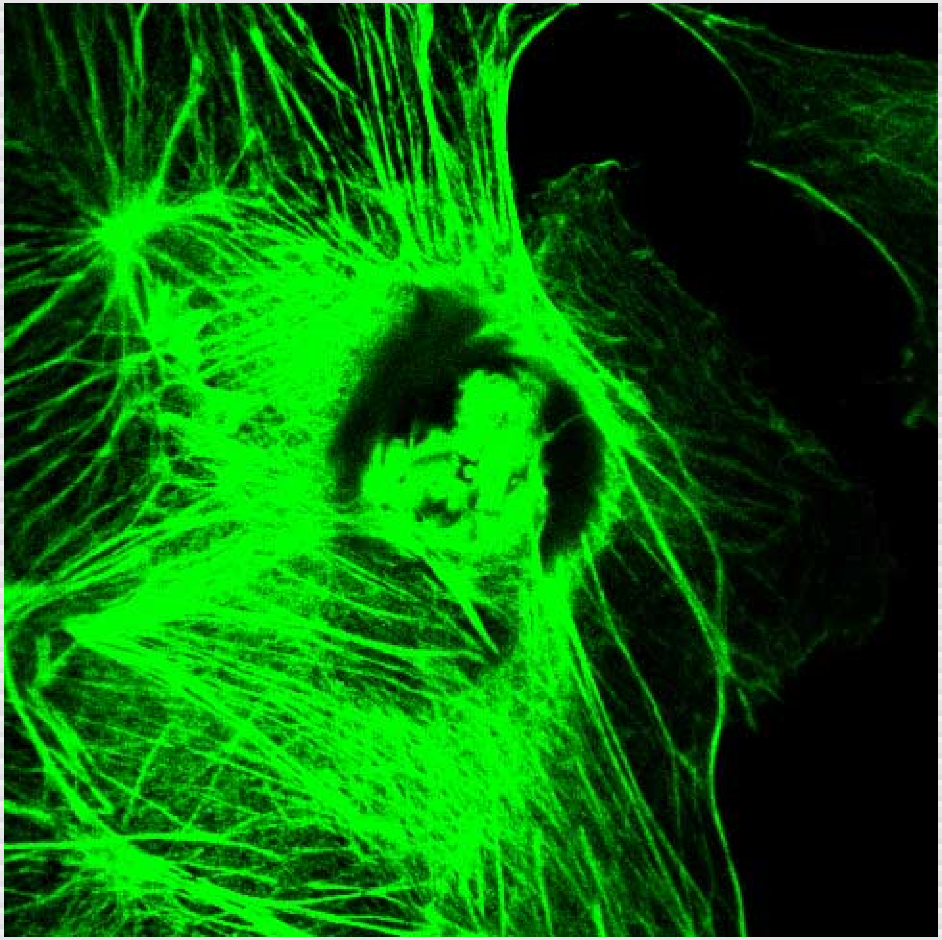


Low-energy processing

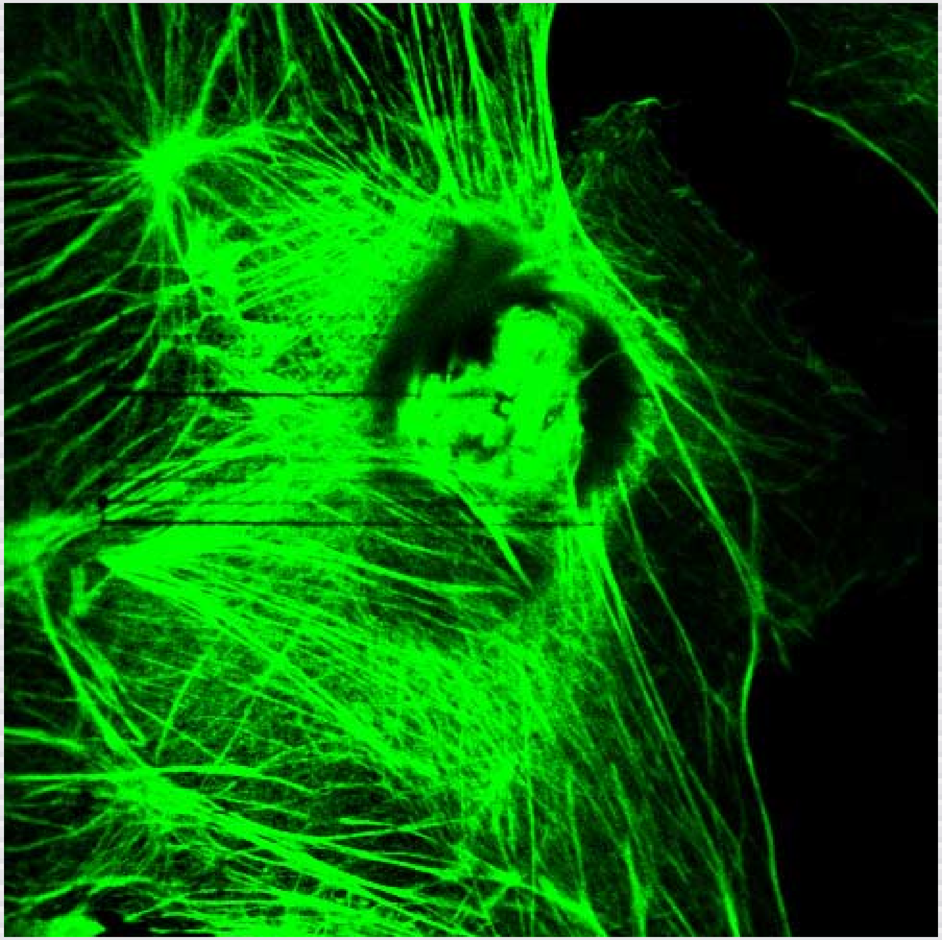


Low-energy processing

before

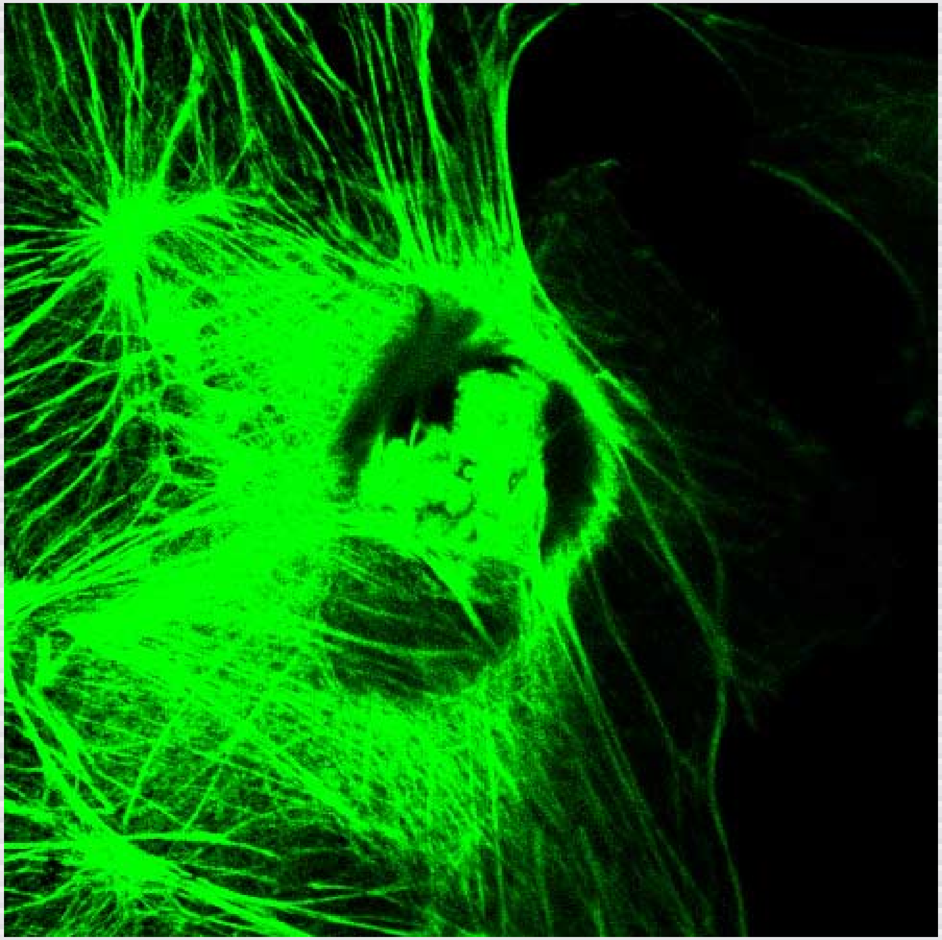


after

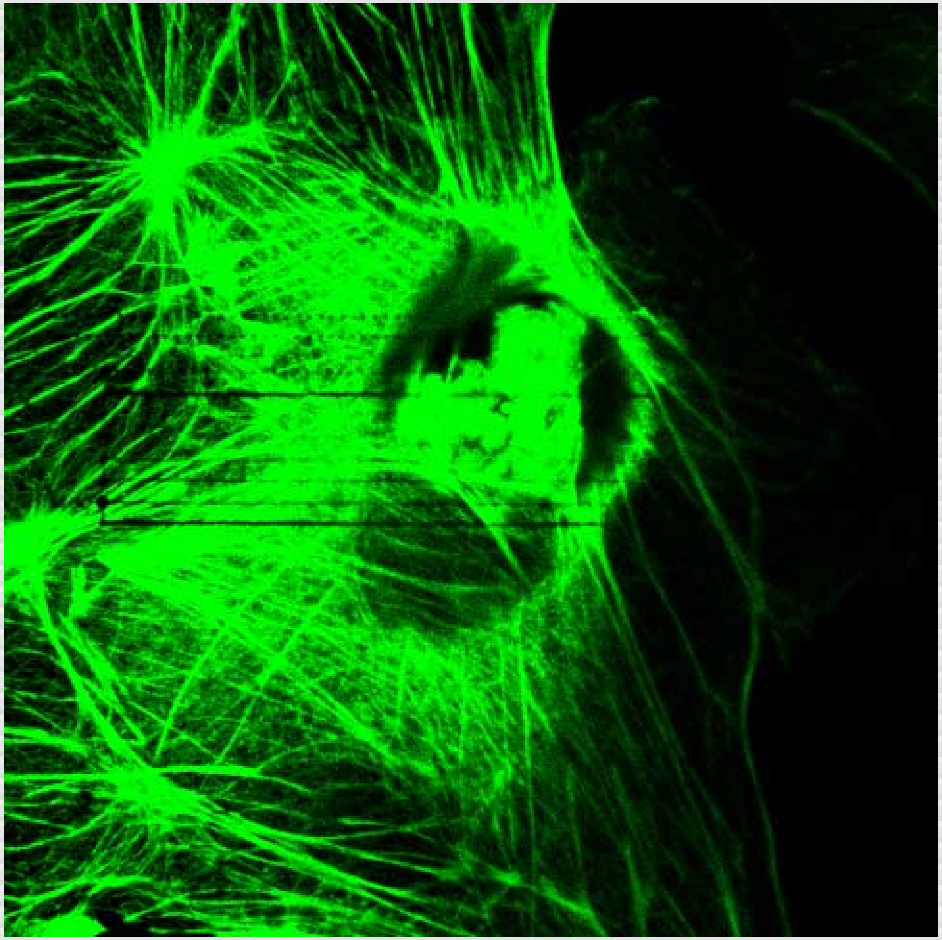


Low-energy processing

before

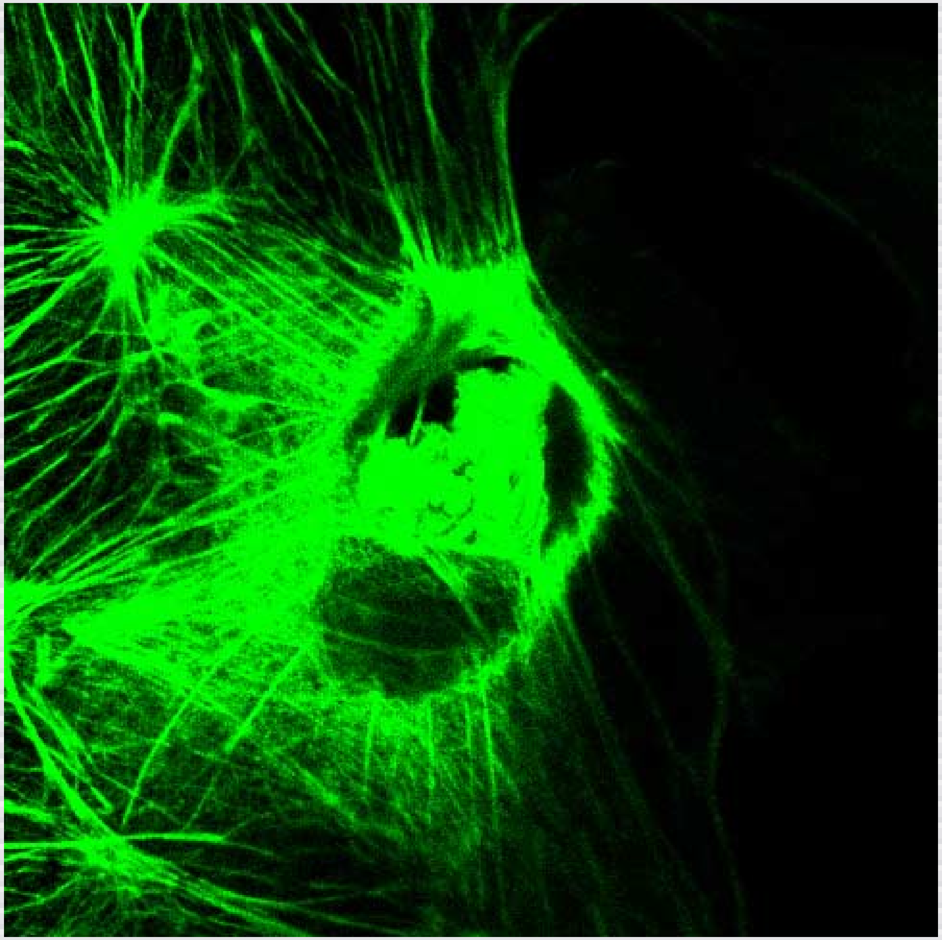


after

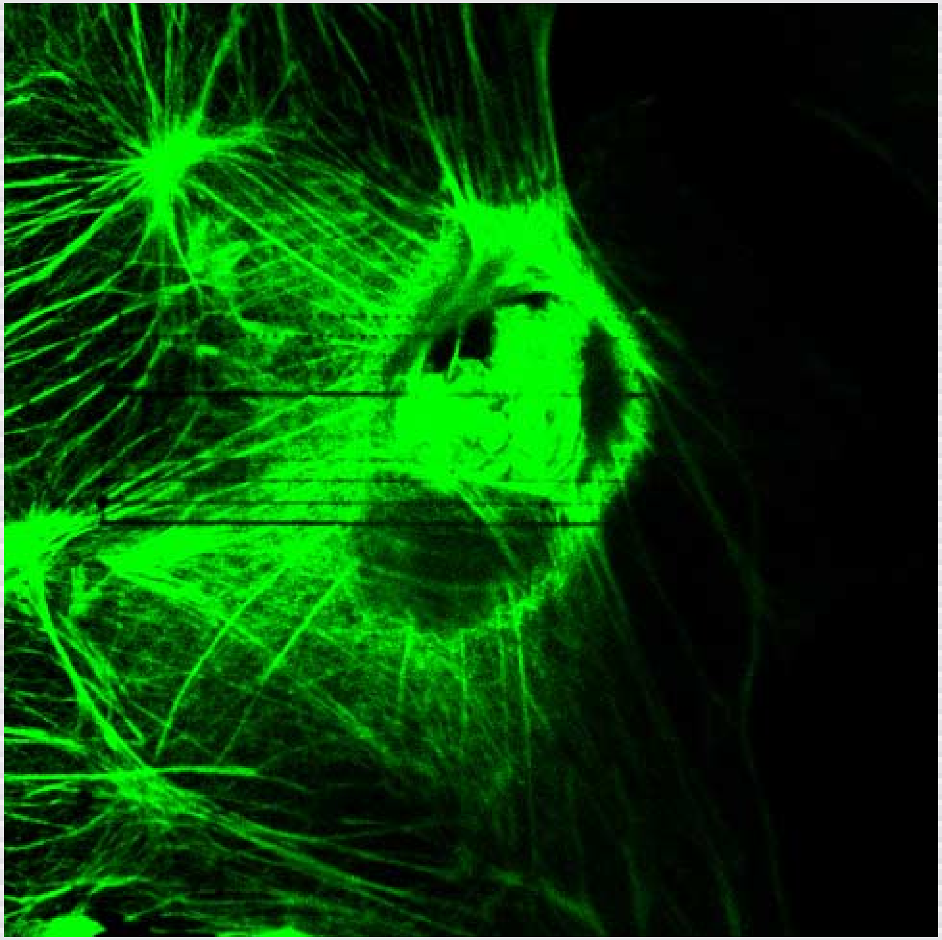


Low-energy processing

before

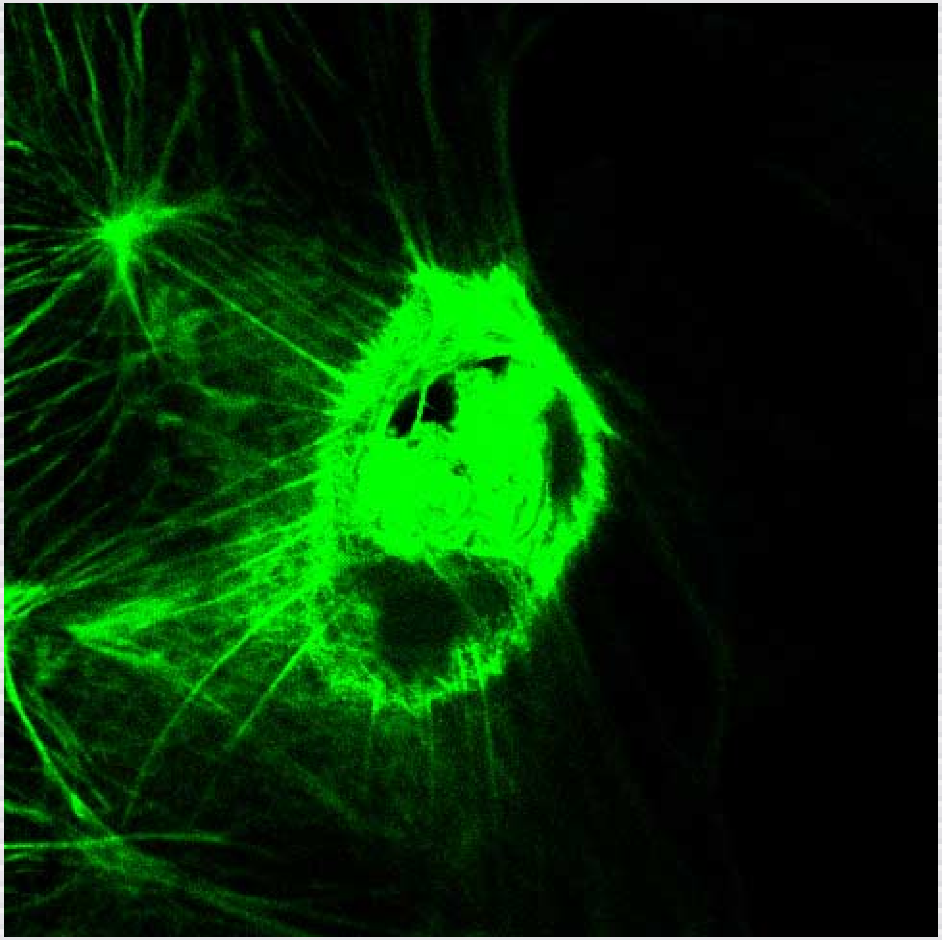


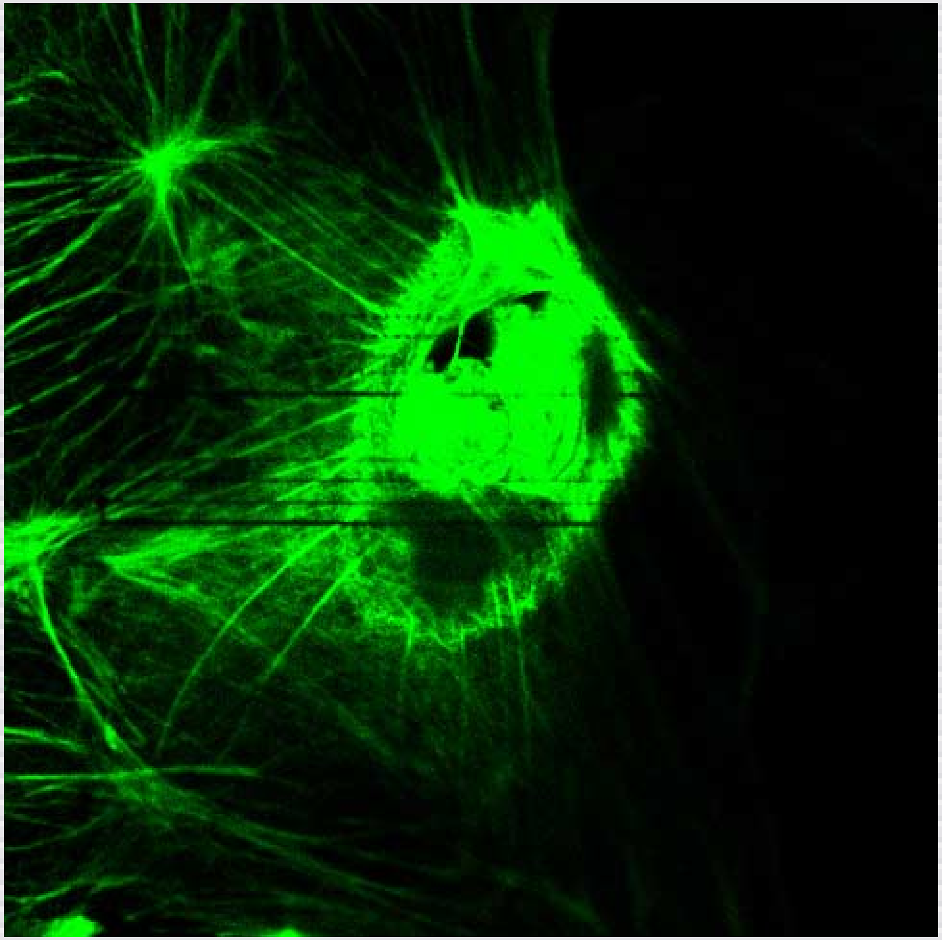
after



Low-energy processing

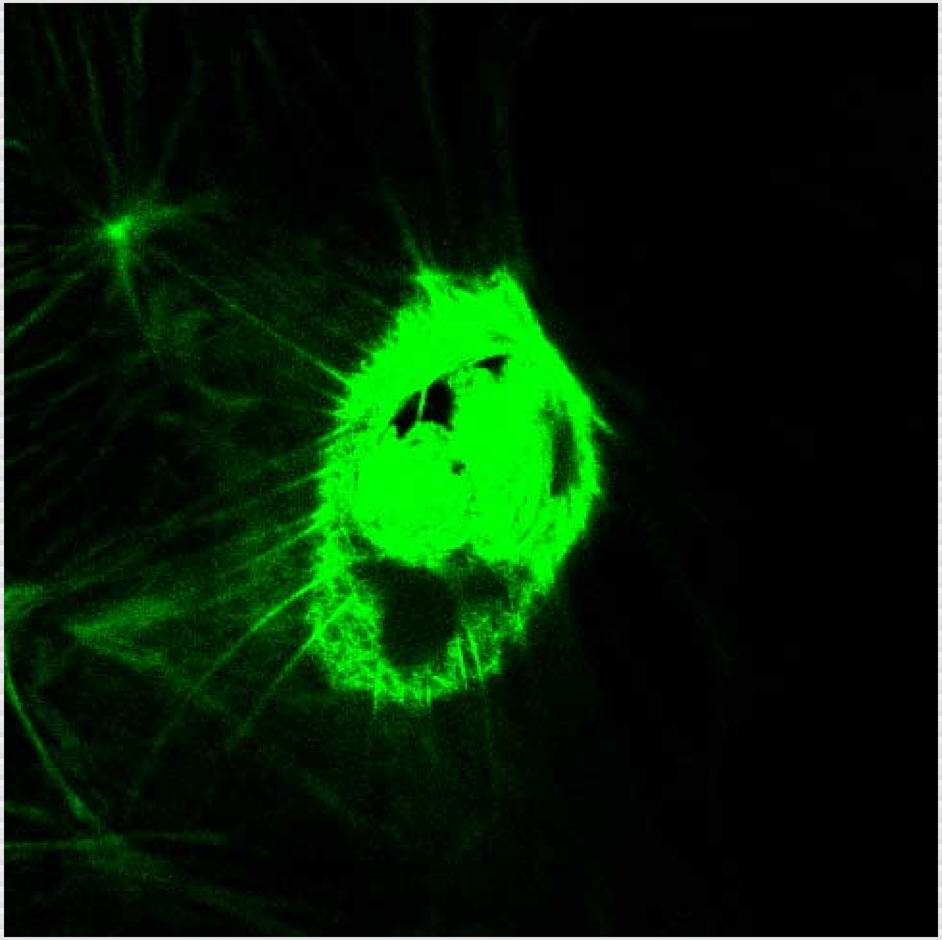
before | **after**



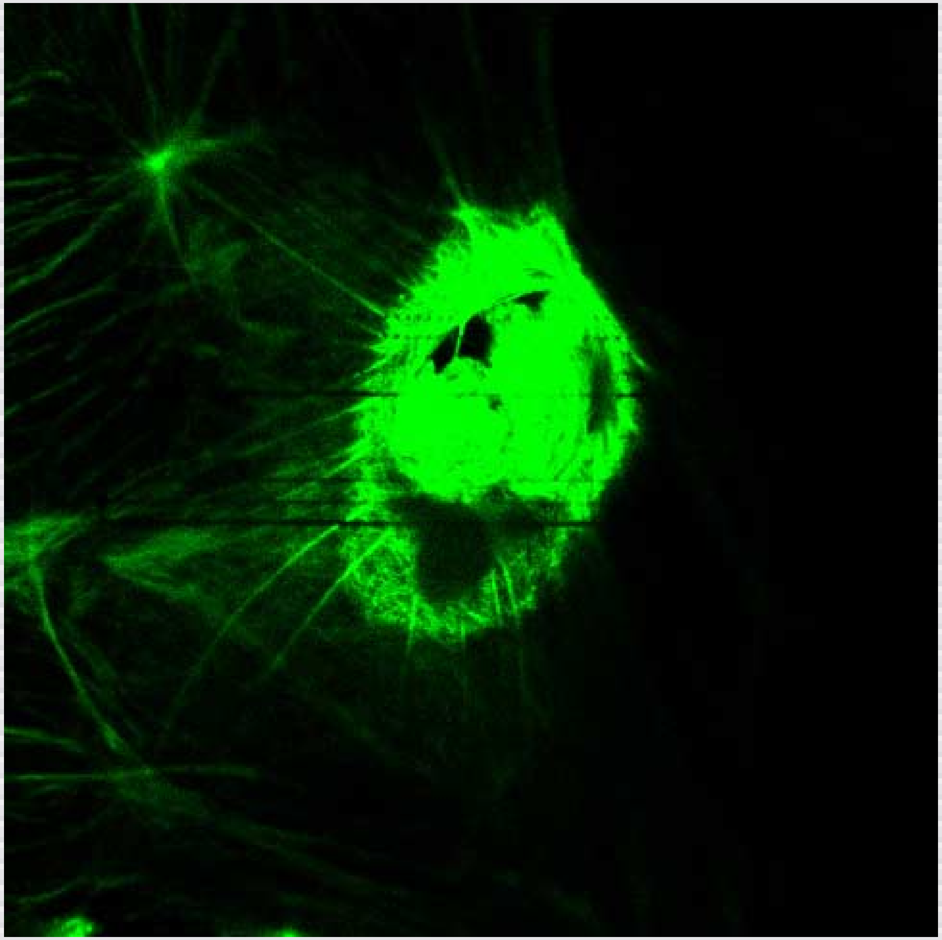


Low-energy processing

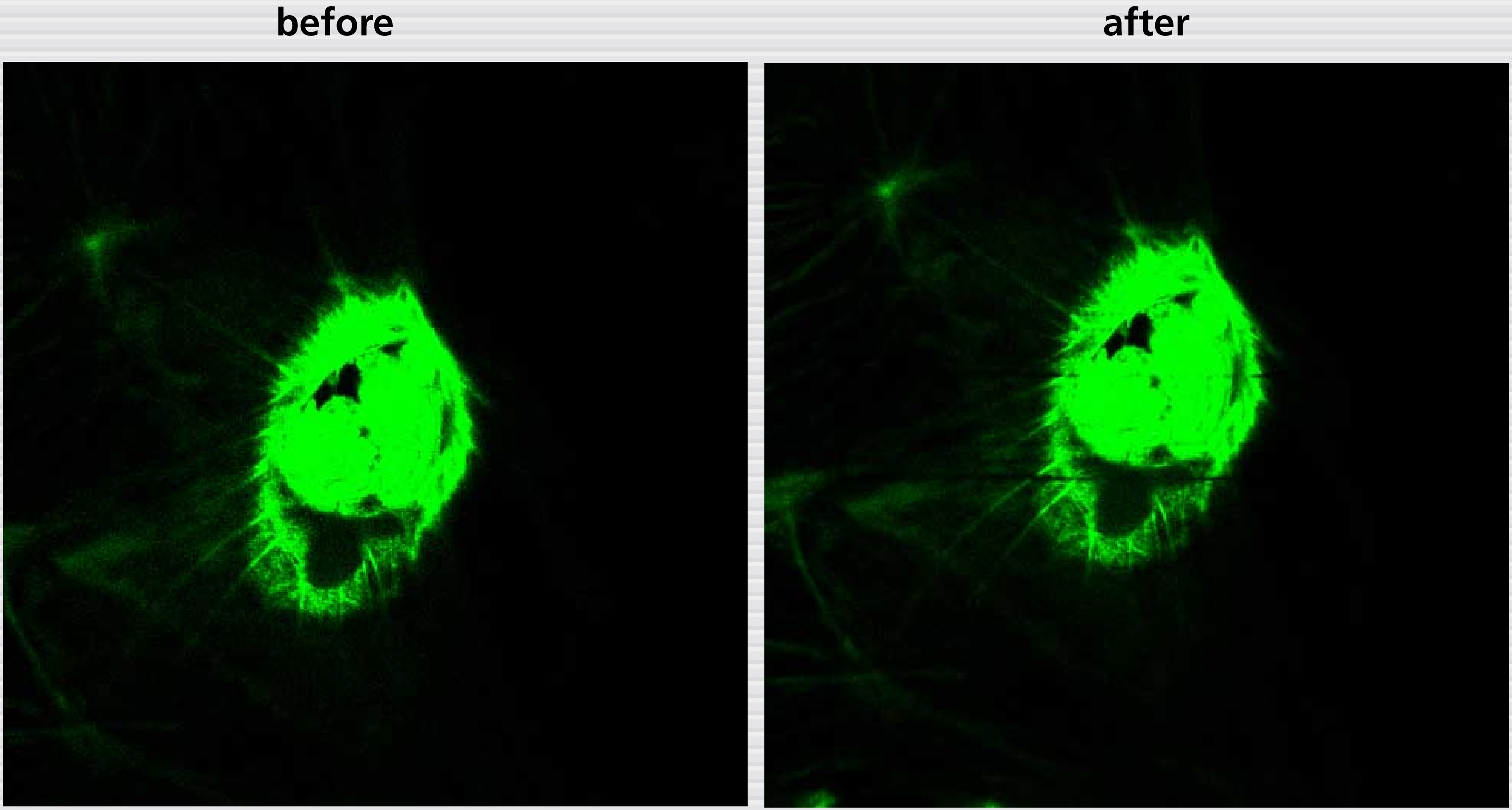
before



after

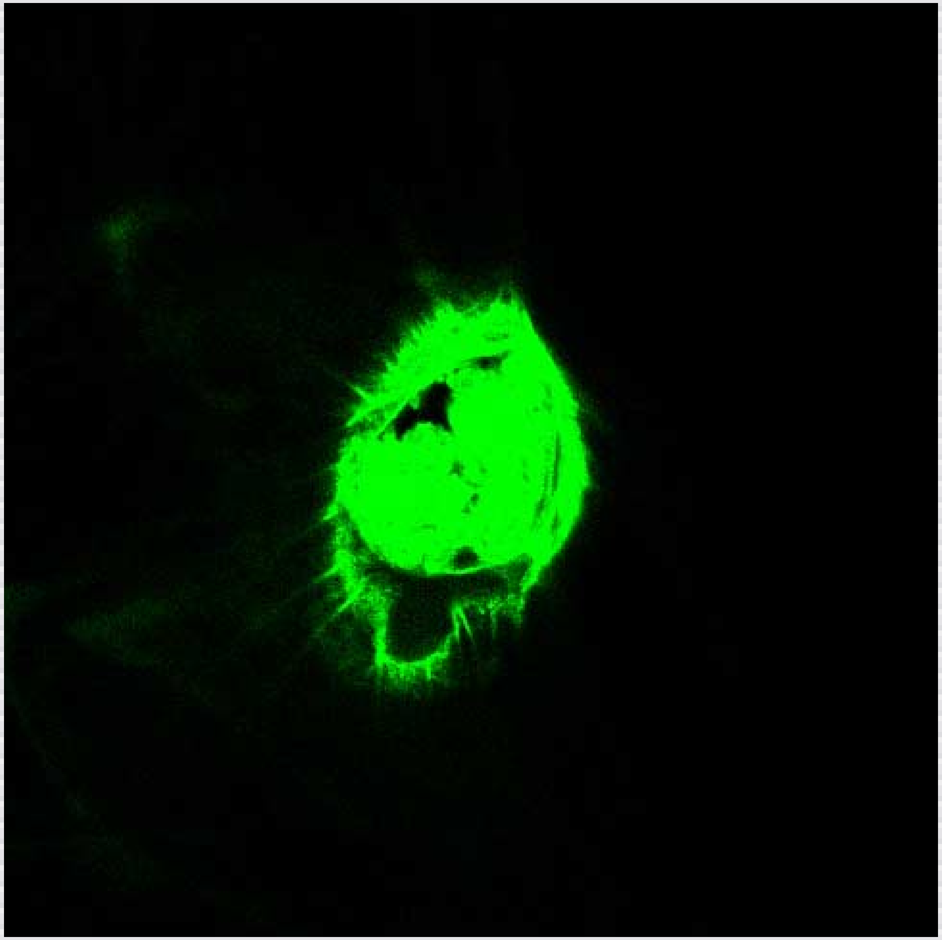


Low-energy processing

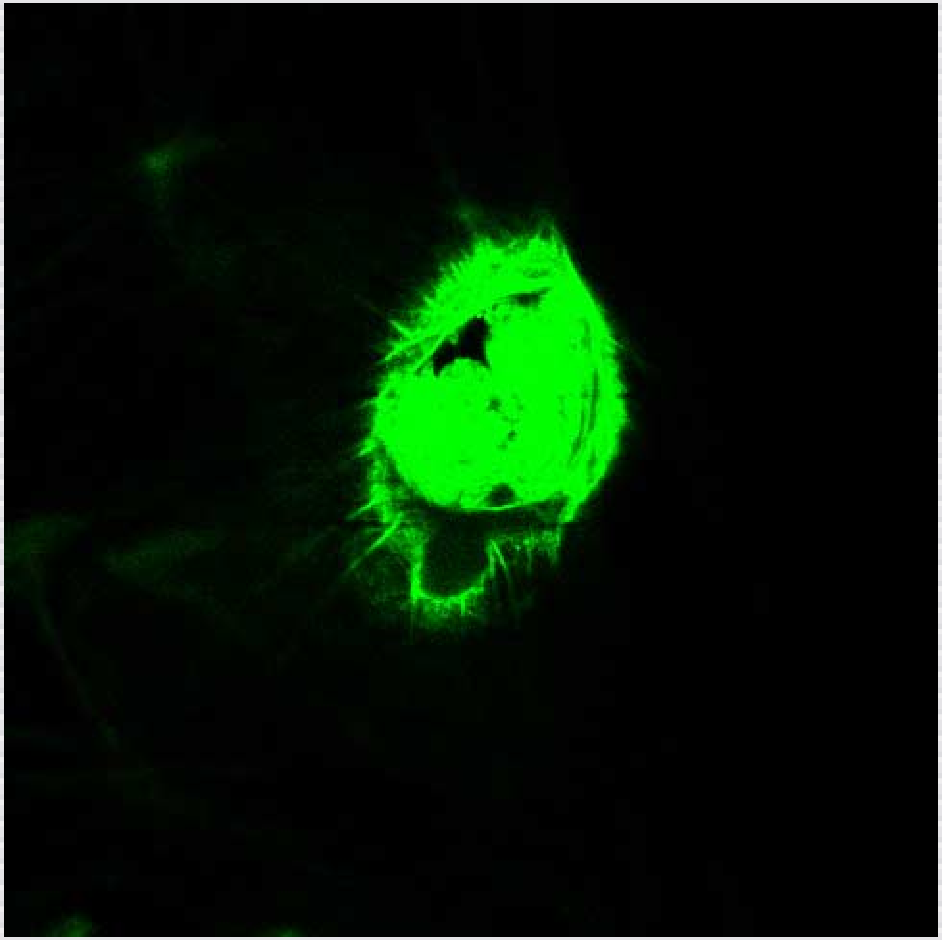


Low-energy processing

before

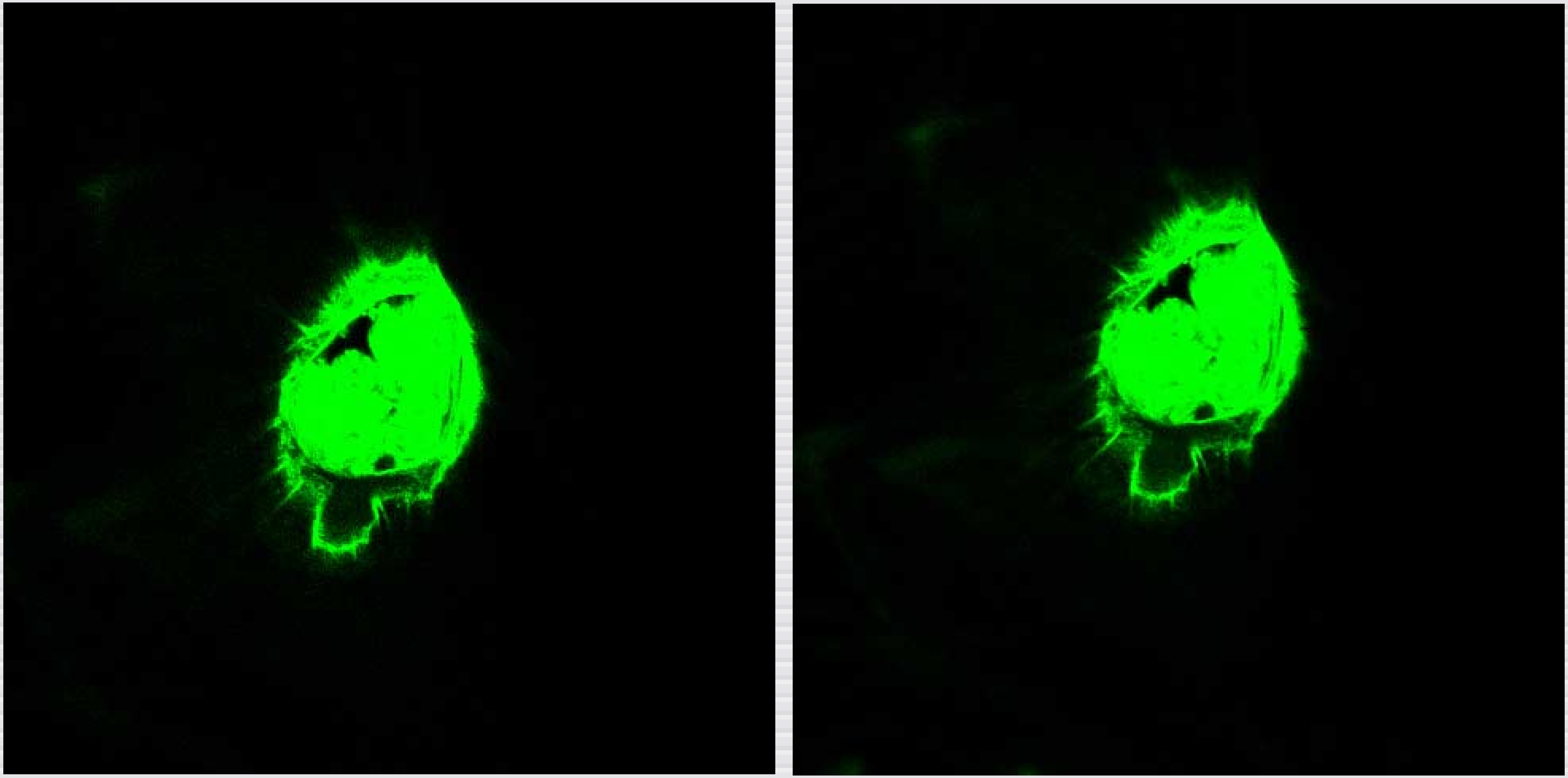


after



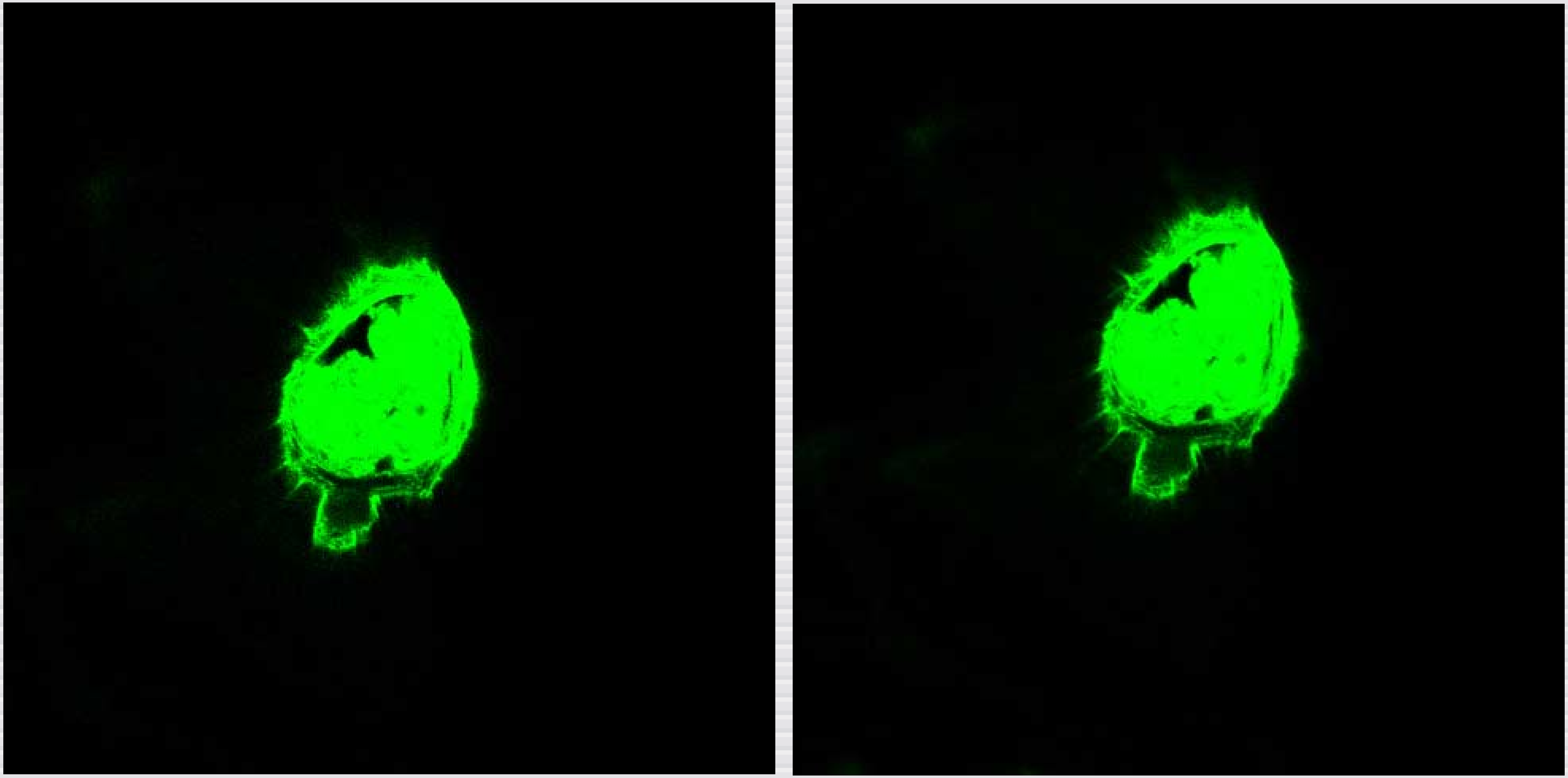
Low-energy processing

before after



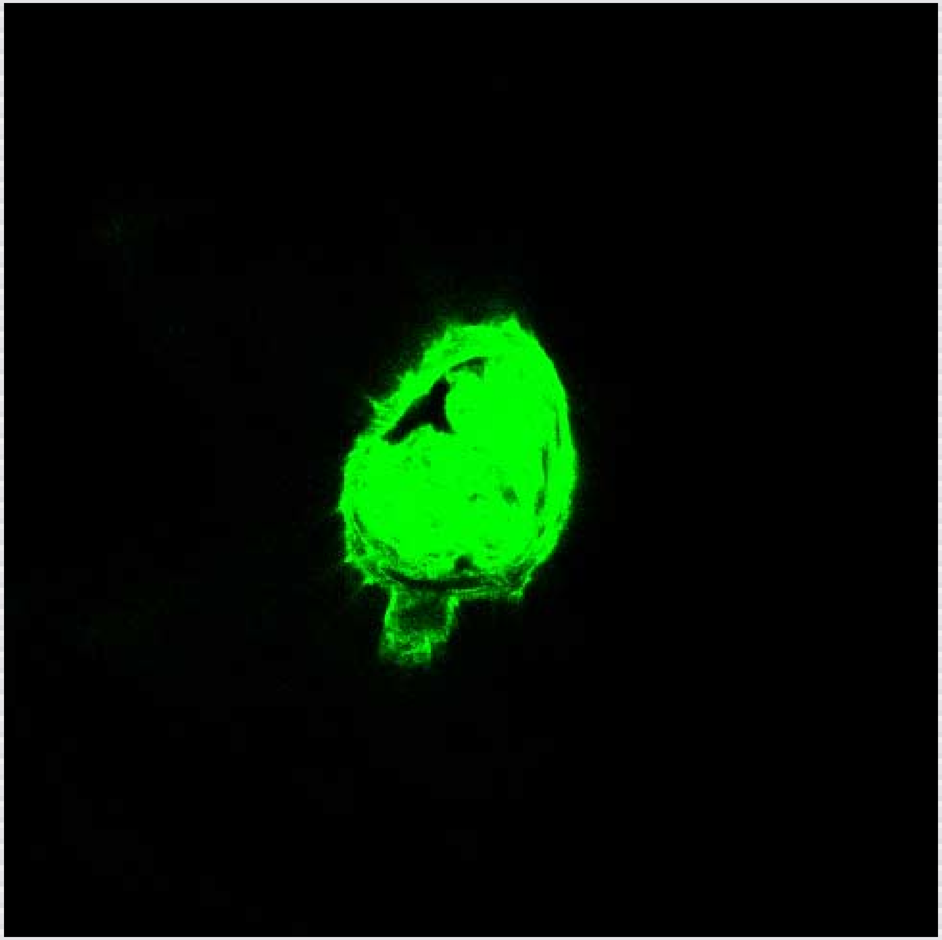
Low-energy processing

before | after

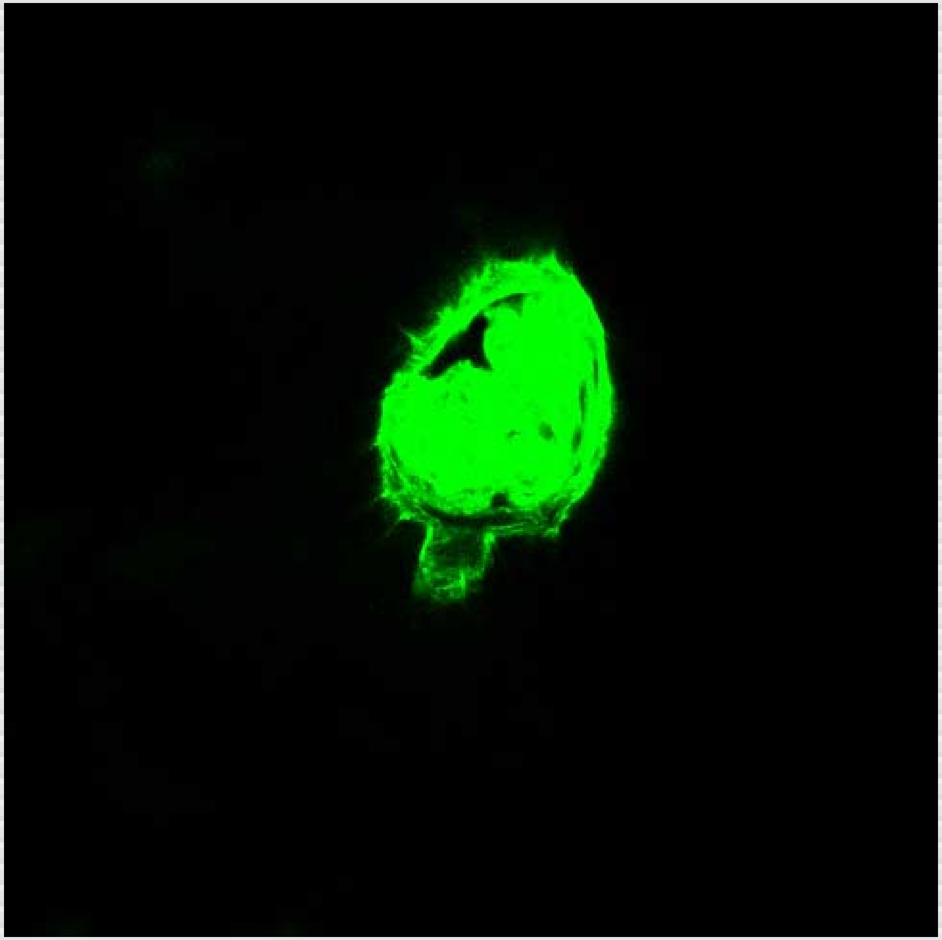


Low-energy processing

before

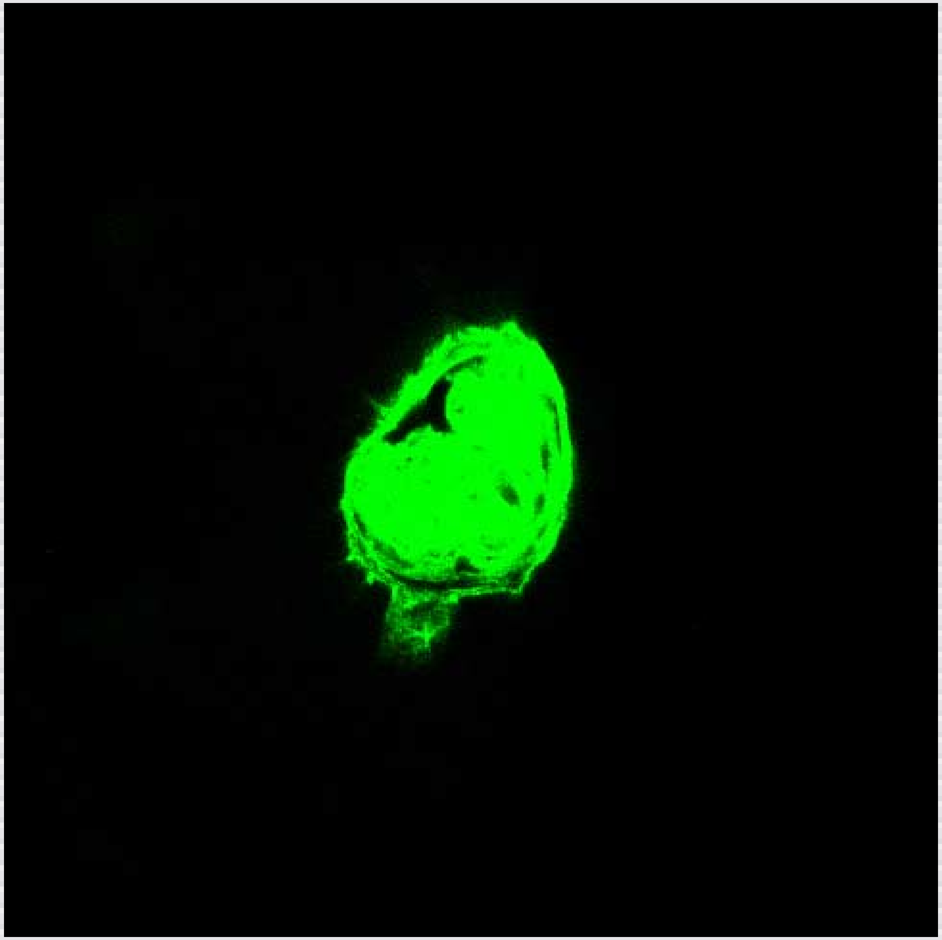


after

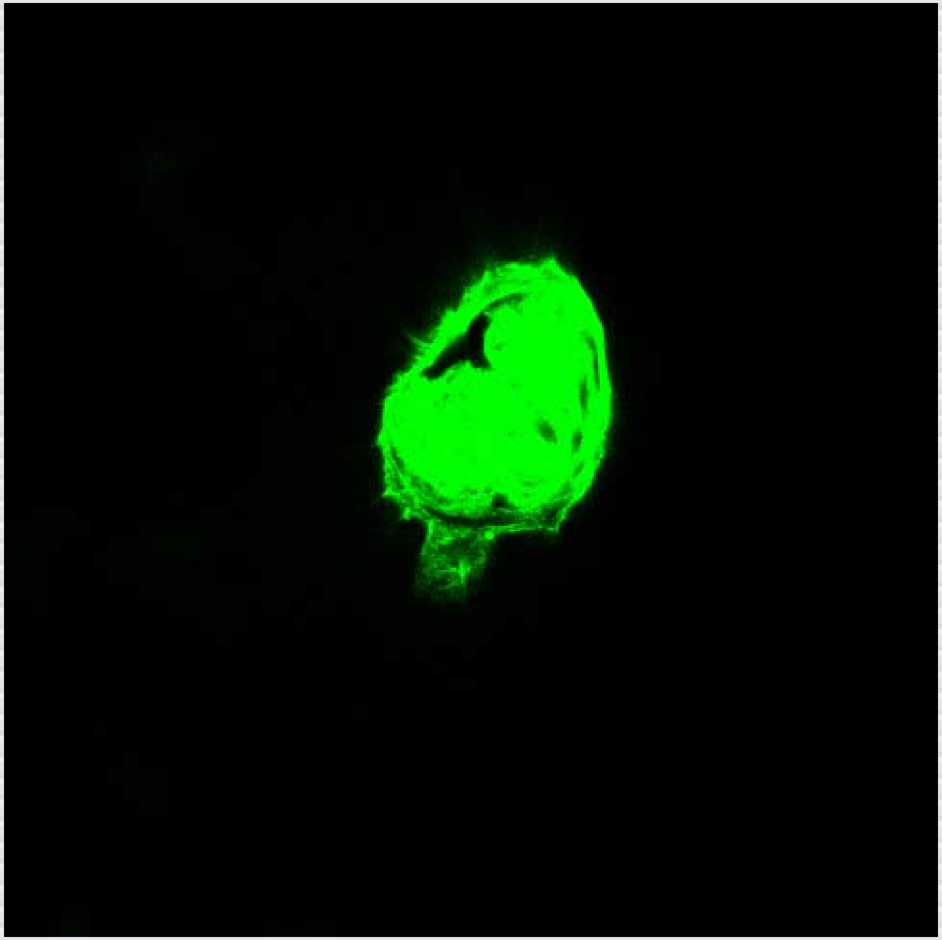


Low-energy processing

before

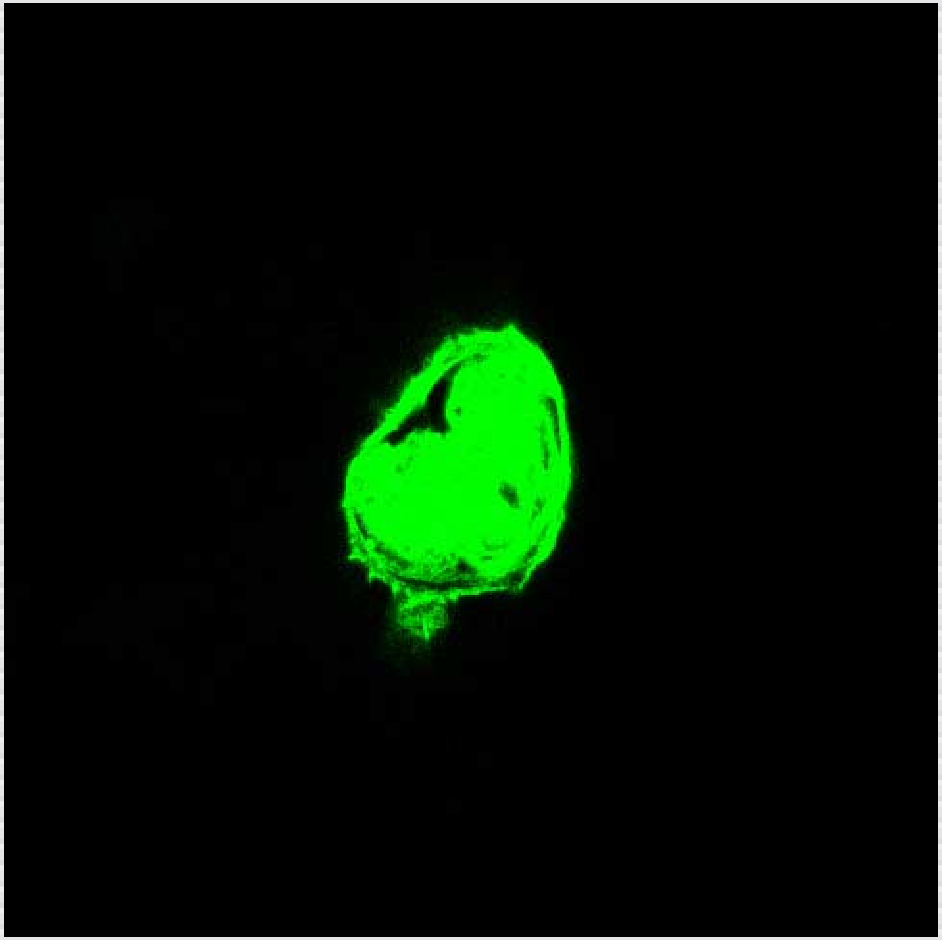


after

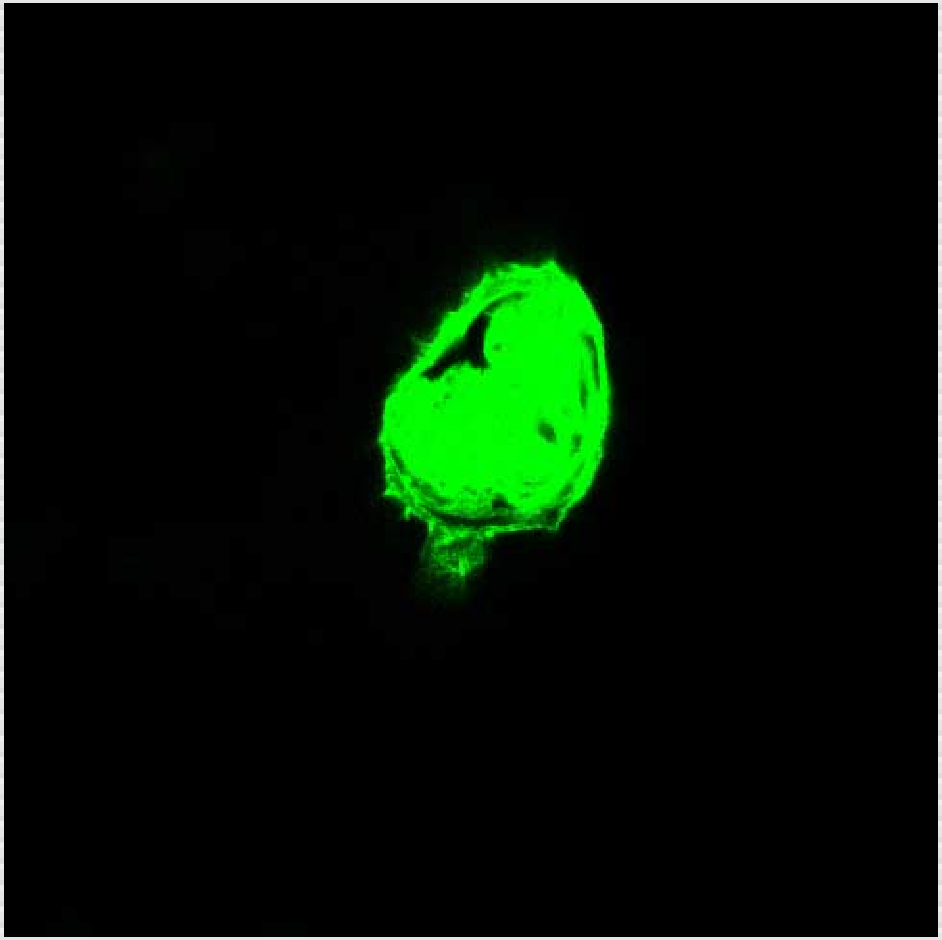


Low-energy processing

before

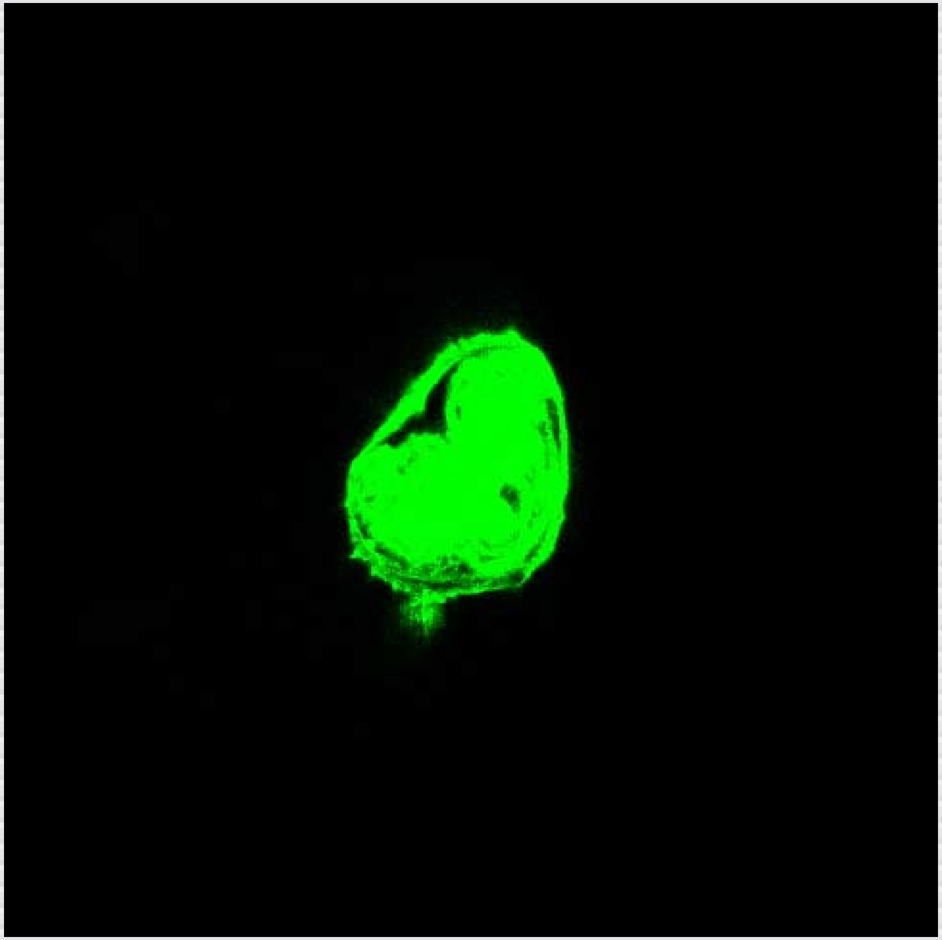


after

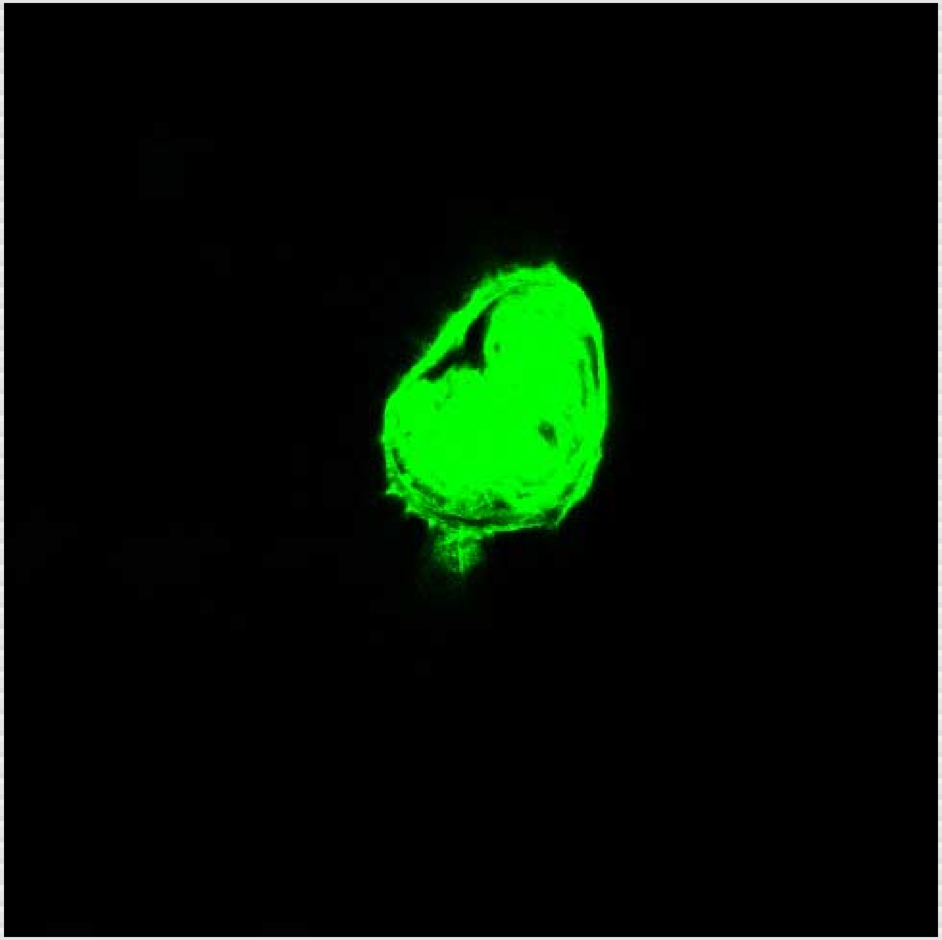


Low-energy processing

before



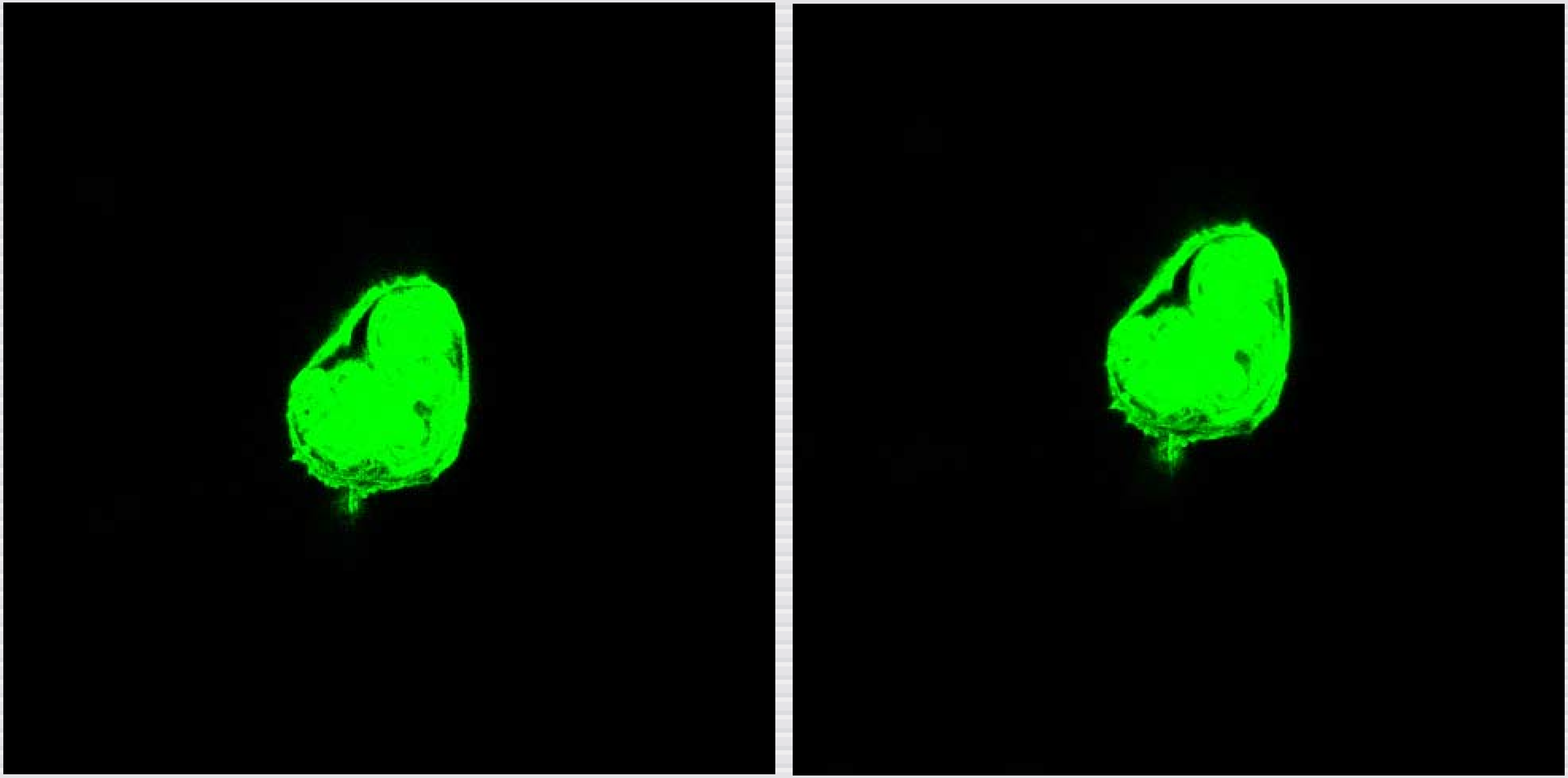
after



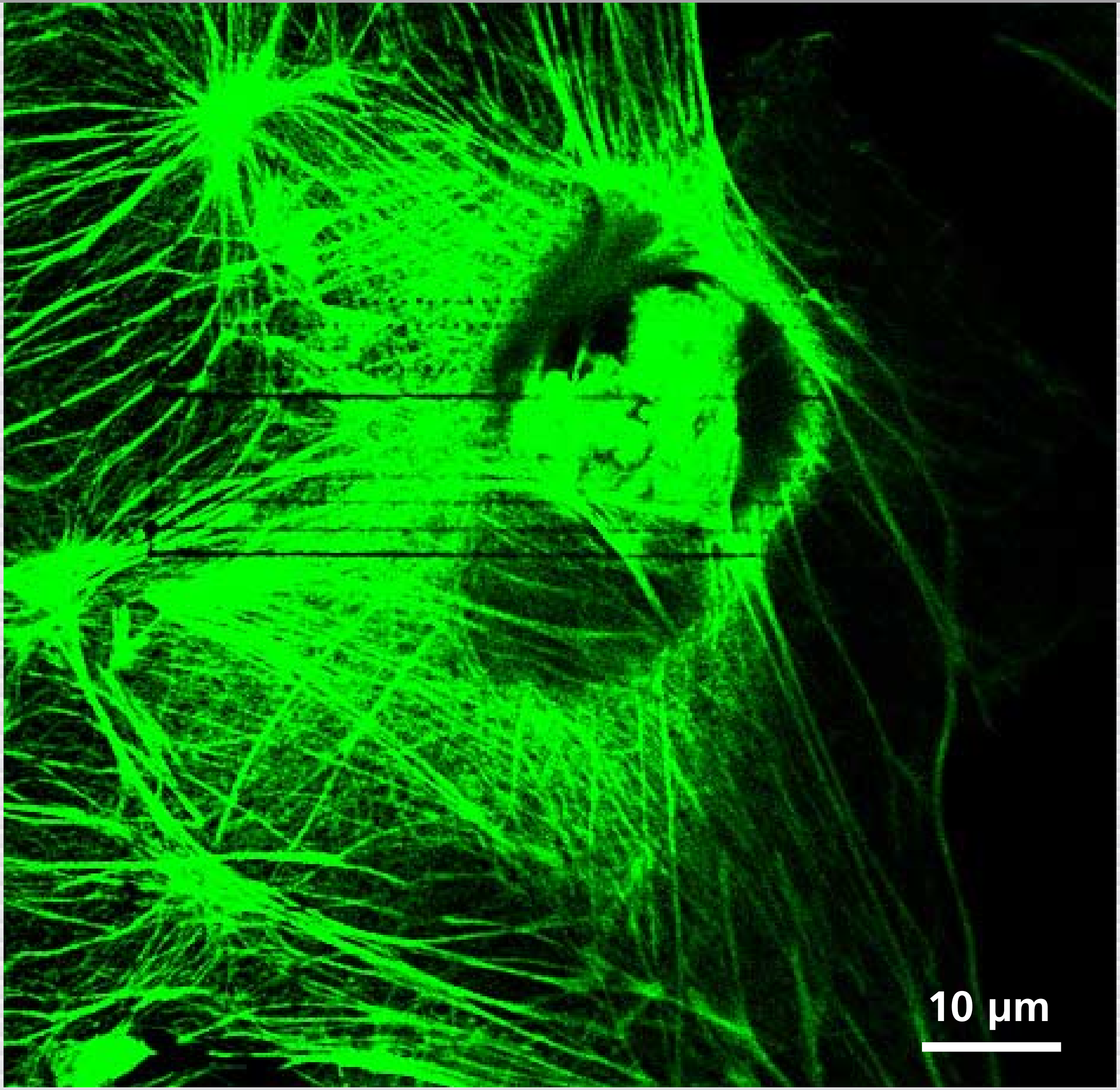
Low-energy processing

before

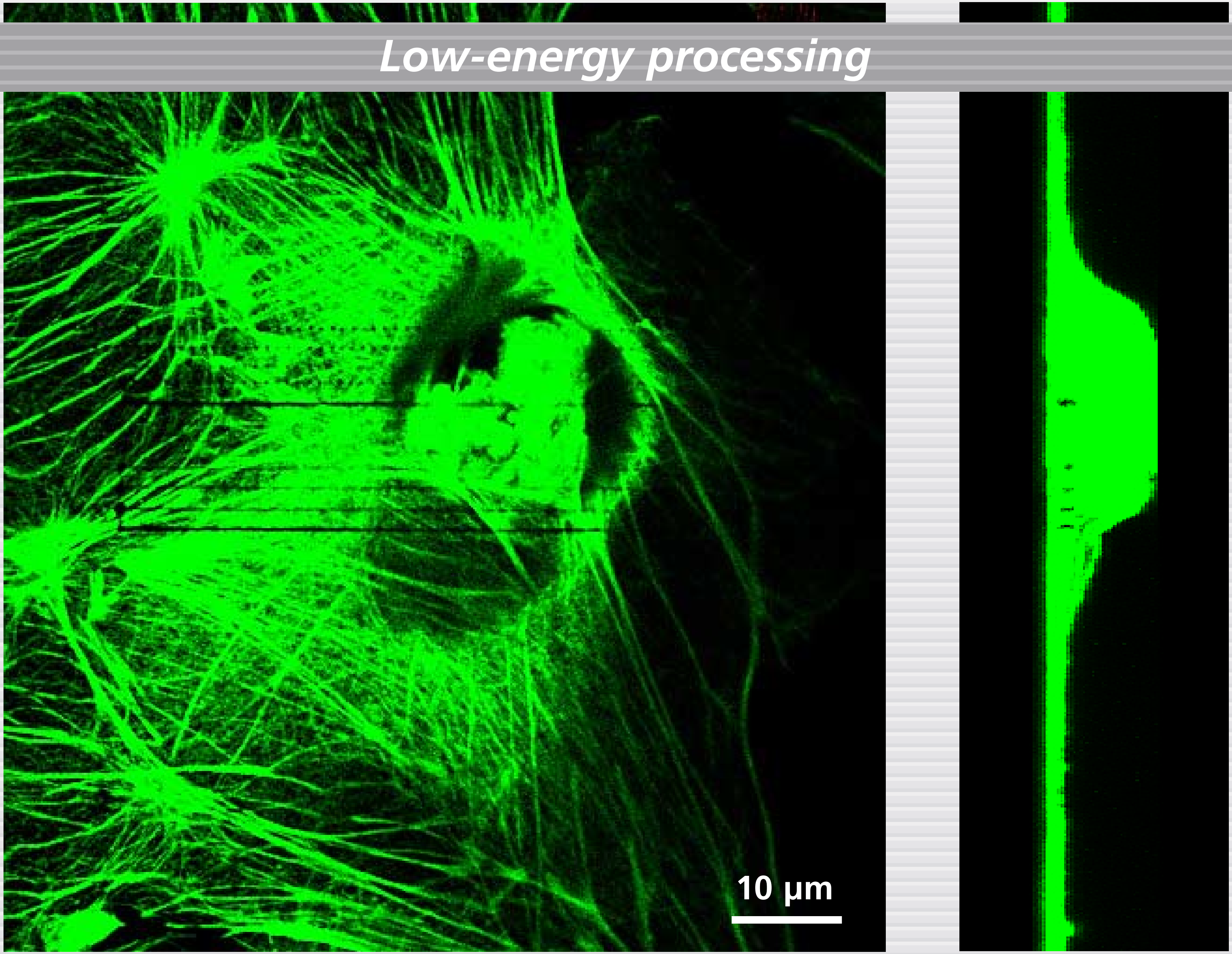
after



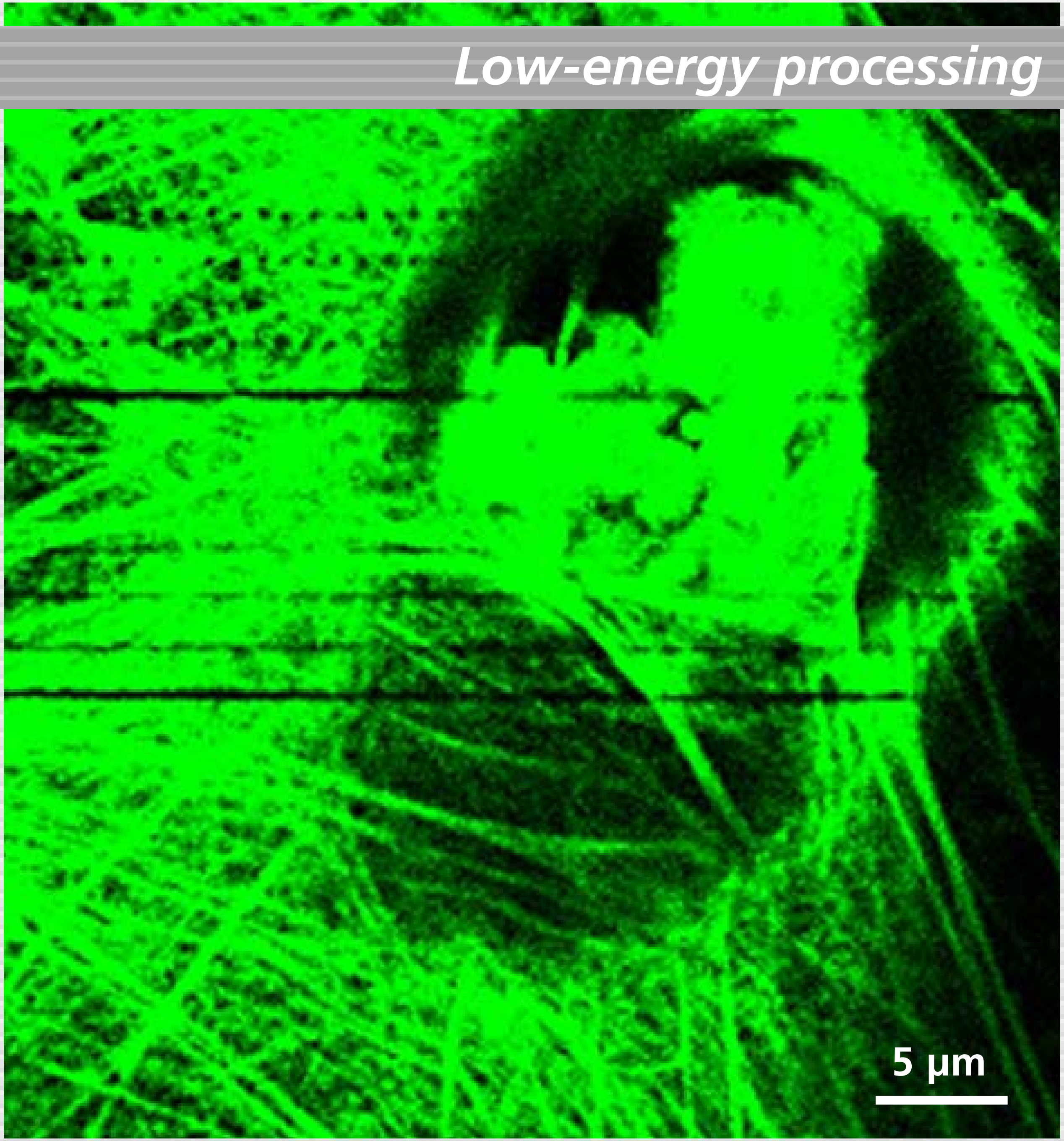
Low-energy processing

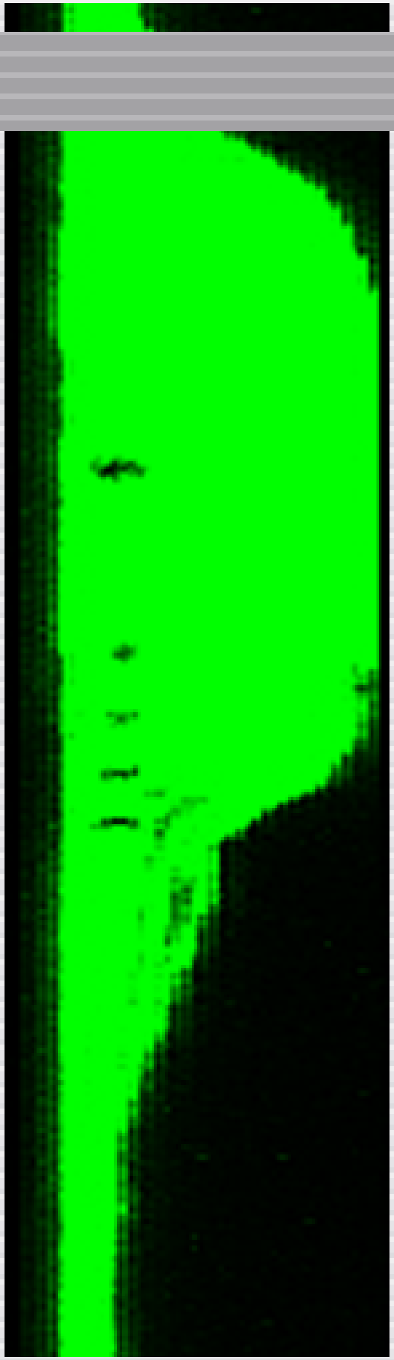


Low-energy processing

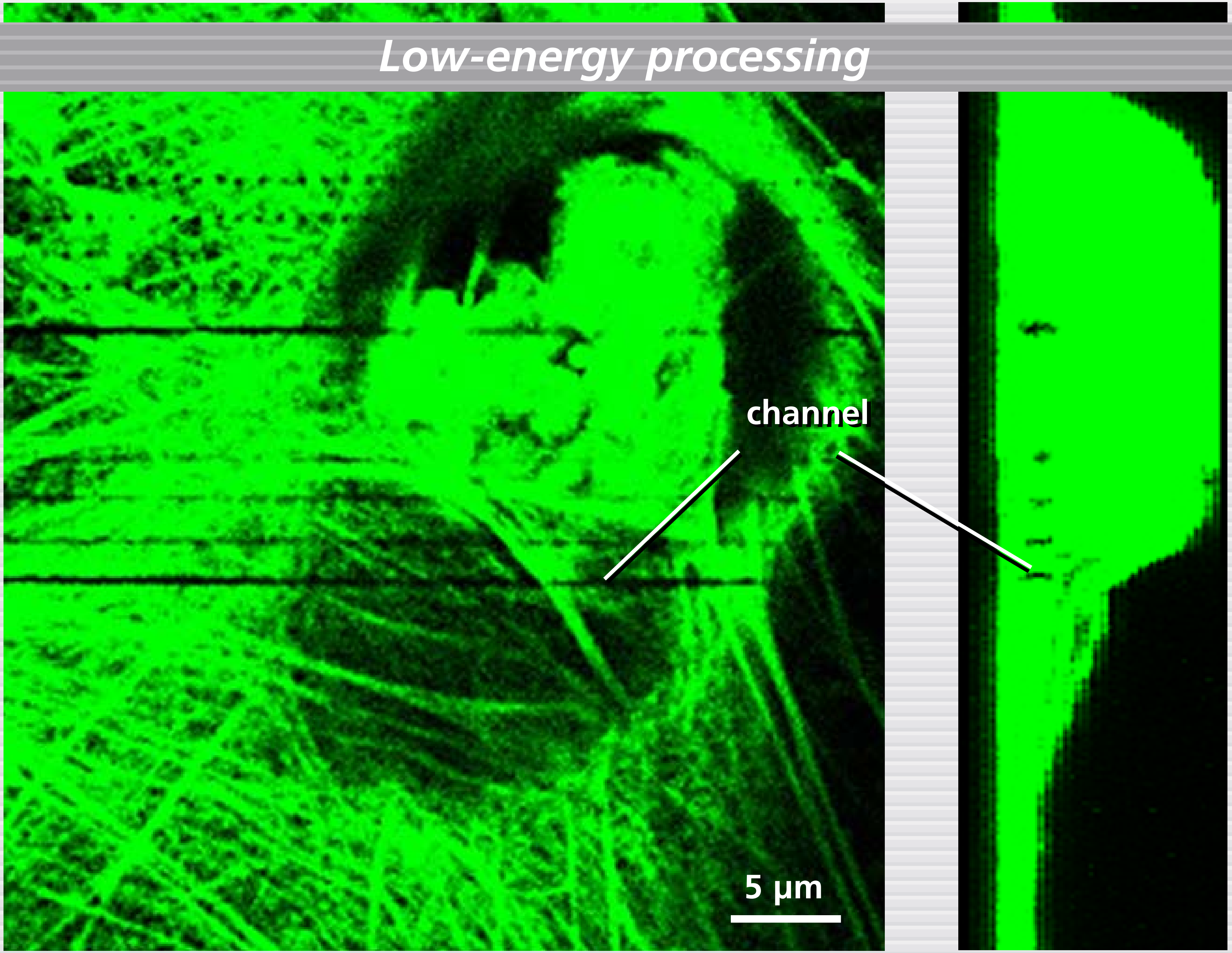


Low-energy processing





Low-energy processing



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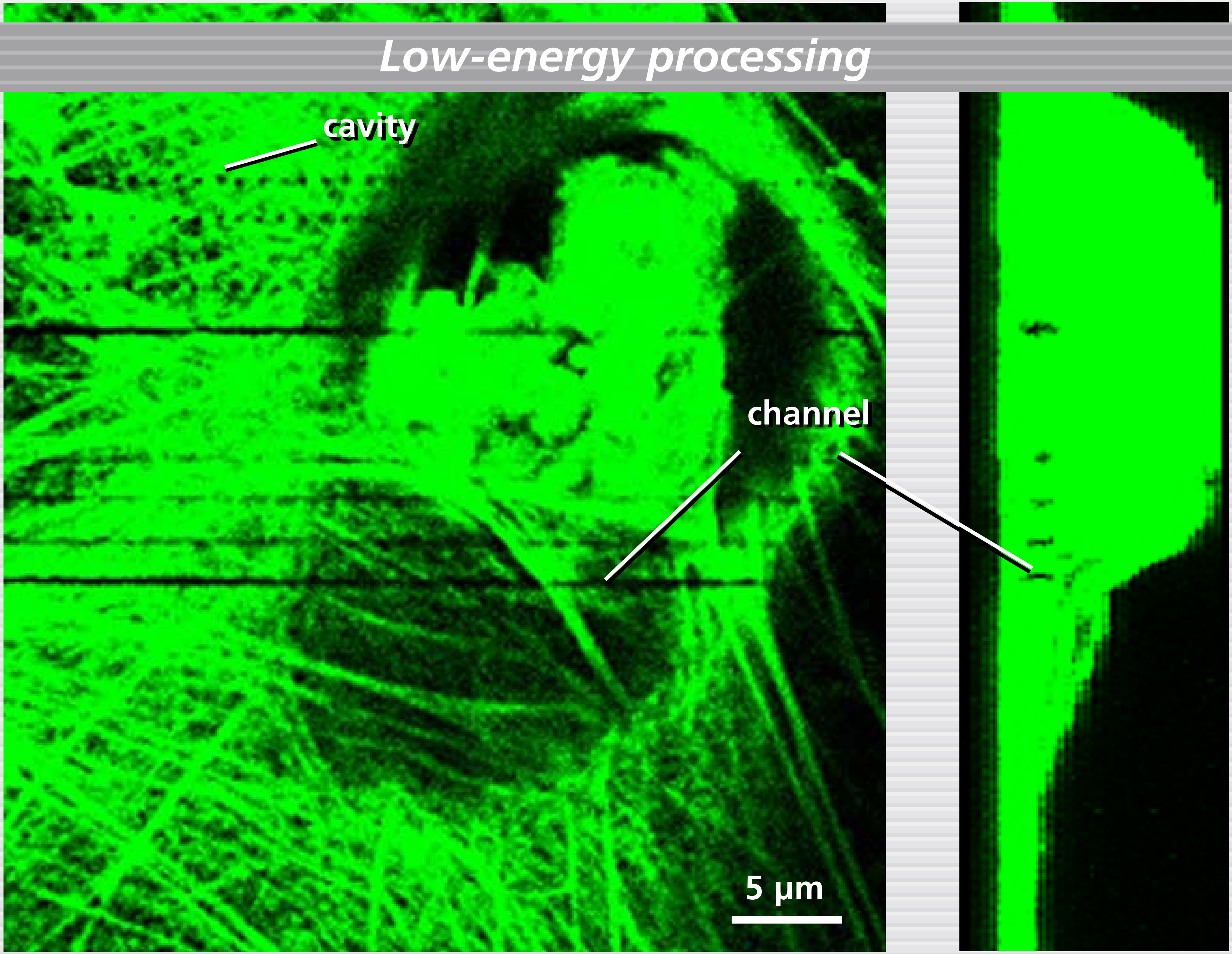
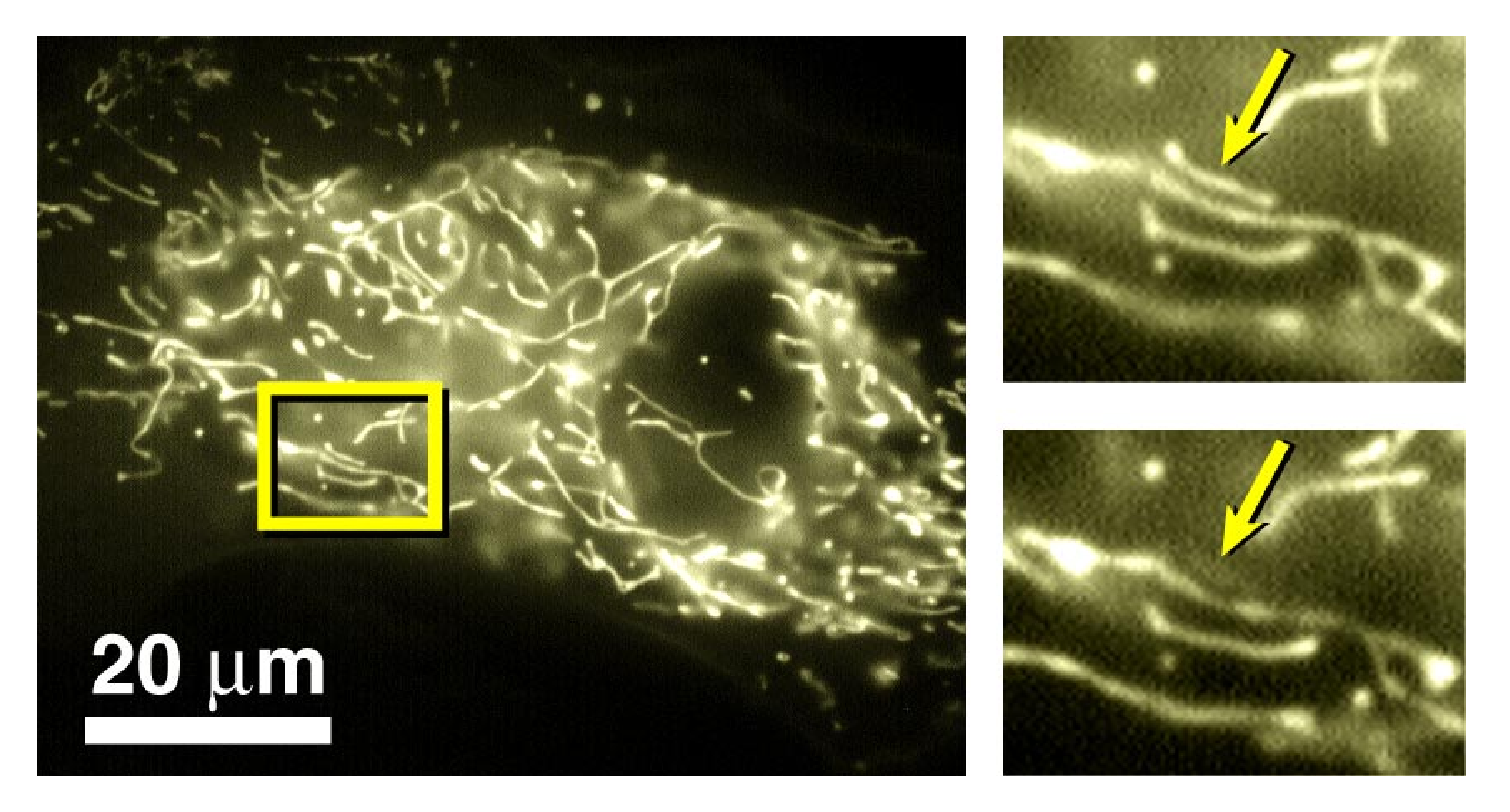
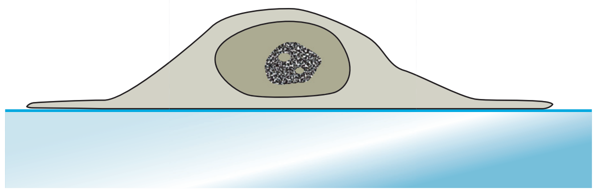
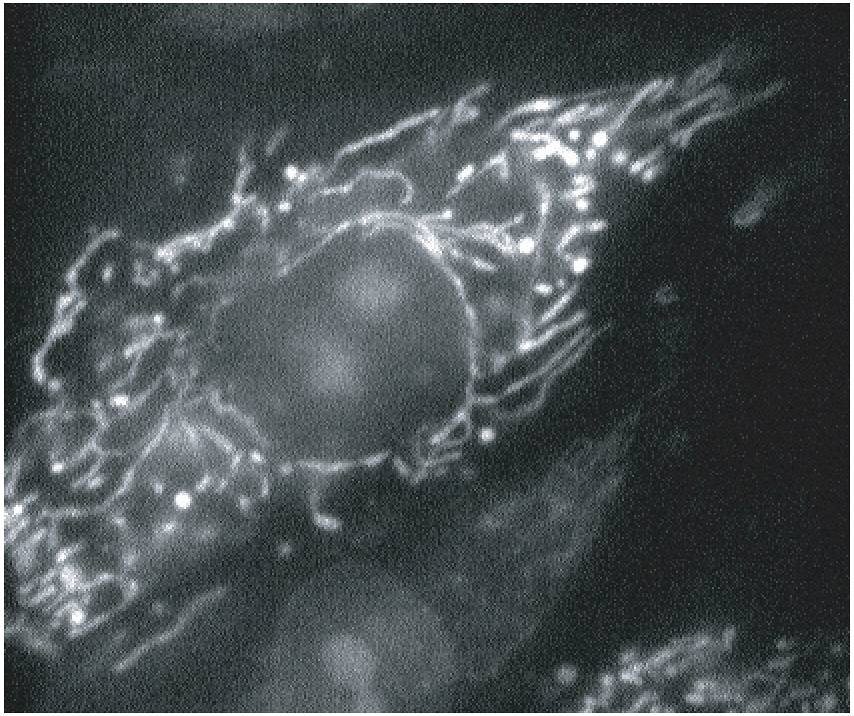


Low-energy processing

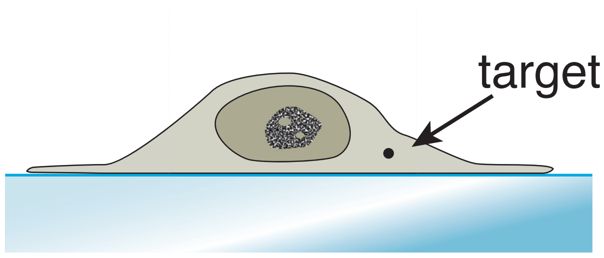


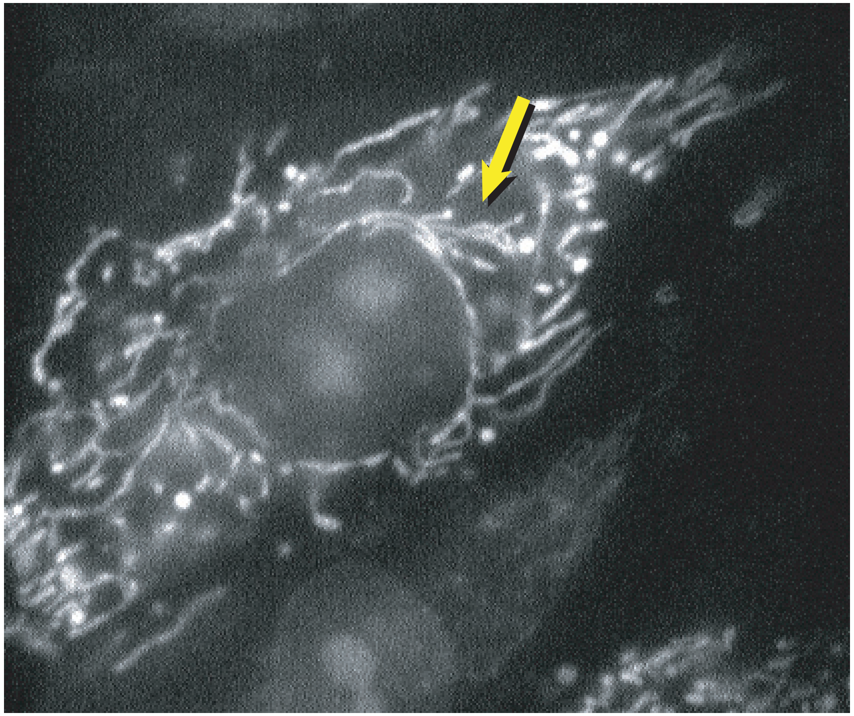
Ethydium bromide test





Ethydium bromide test





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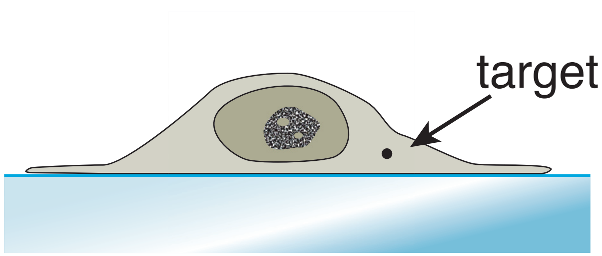
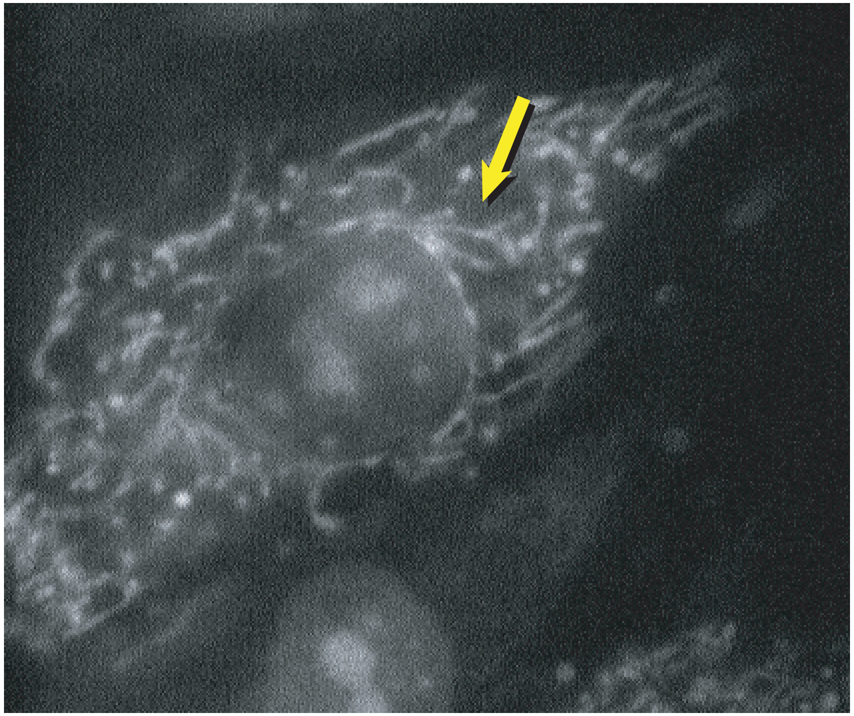
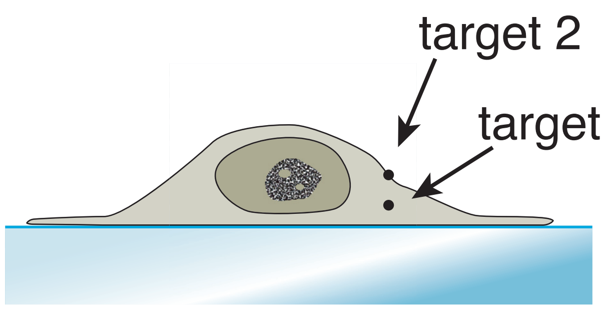
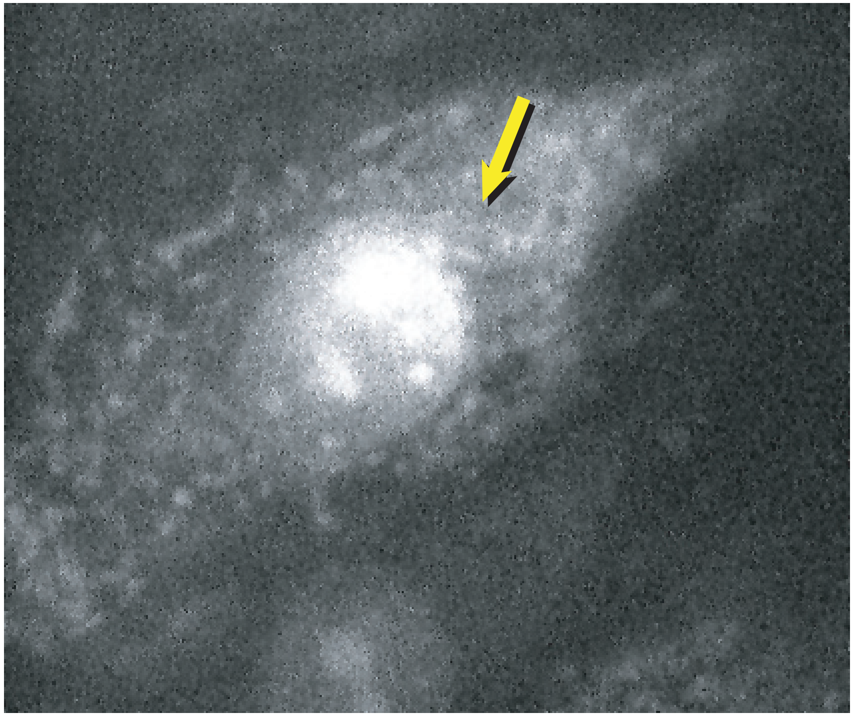


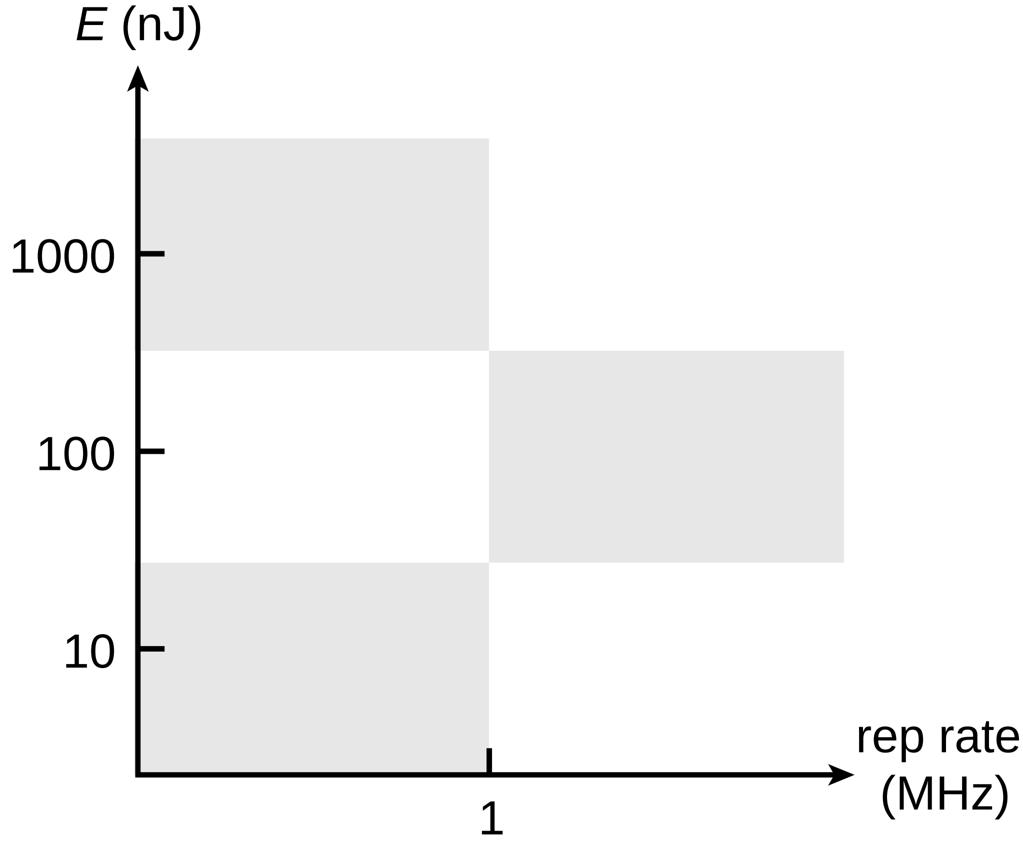


Ethydium bromide test

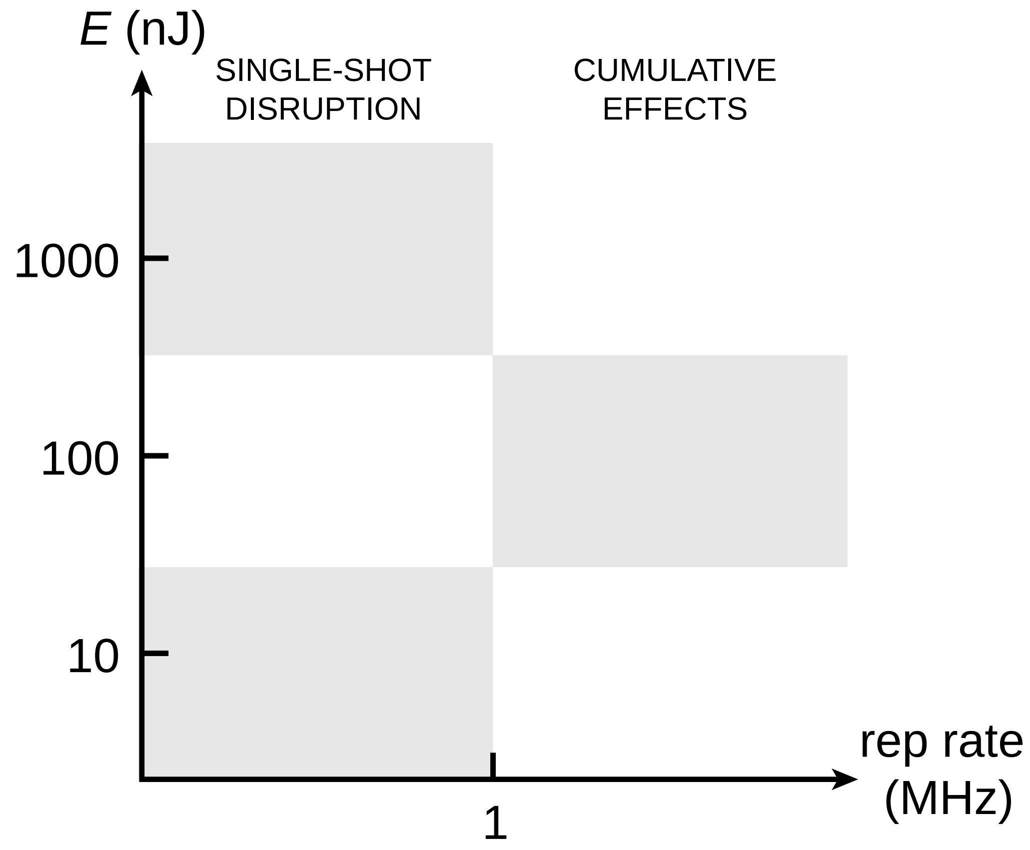




Summary

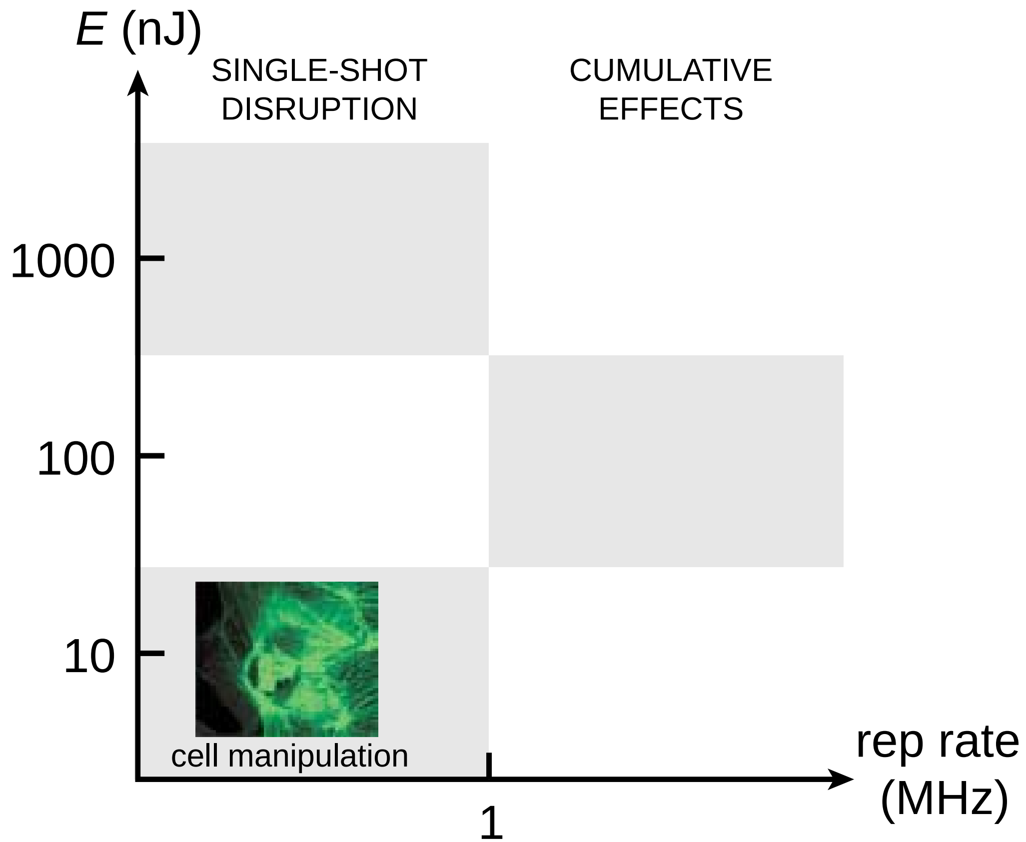


Summary

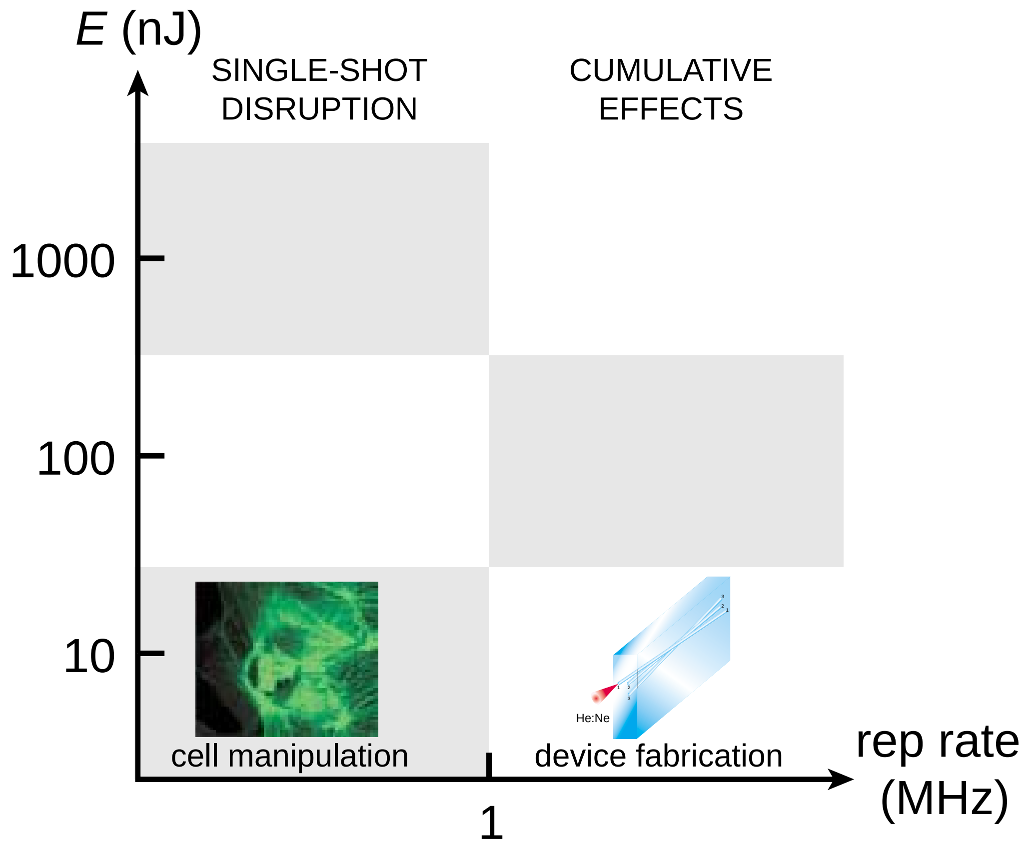


E (nJ)
SINGLE-SHOT
DISRUPTION
CUMULATIVE
EFFECTS
1000
100
10
rep rate
(MHz)
1

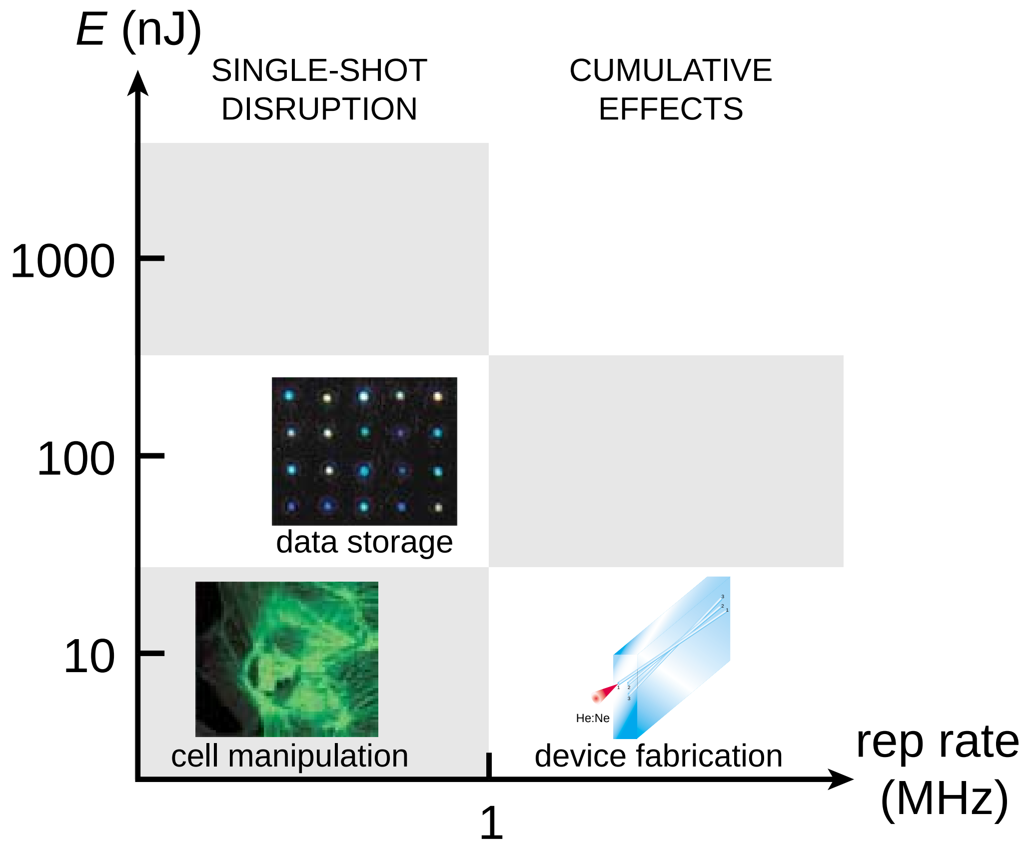
Summary


E (nJ)
SINGLE-SHOT DISRUPTION
CUMULATIVE EFFECTS
1000
100
10
cell manipulation
1
rep rate (MHz)

Summary

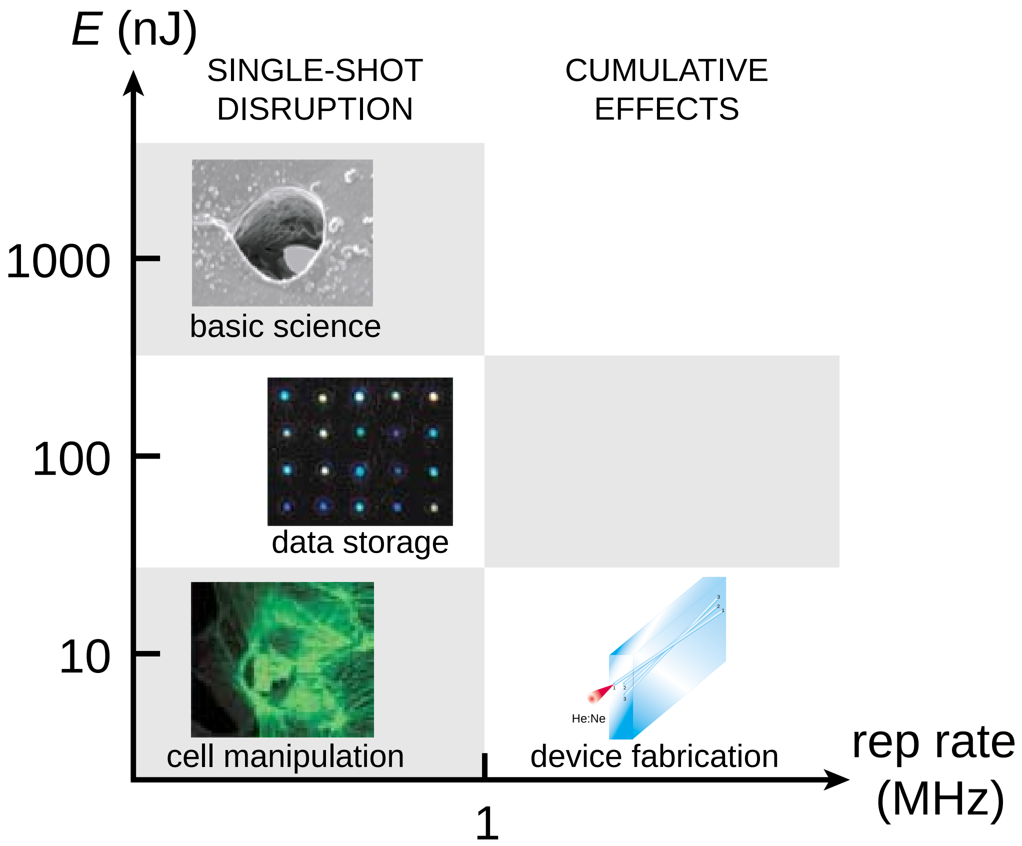

E (nJ)
SINGLE-SHOT
DISRUPTION
CUMULATIVE
EFFECTS
1000
100
10
He:Ne
cell manipulation
device fabrication
rep rate
(MHz)
1

Summary



E (nJ)
SINGLE-SHOT DISRUPTION
CUMULATIVE EFFECTS
1000
100
10
data storage
cell manipulation
He:Ne
device fabrication
rep rate (MHz)
1

Summary


E (nJ)
SINGLE-SHOT DISRUPTION
CUMULATIVE EFFECTS
1000
100
10
basic science
data storage
cell manipulation
He:Ne
device fabrication
1
rep rate (MHz)

Conclusion

- wiring optoelectronics circuits of the future
- manipulating the machinery of life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LABORATORY OF
APPLIED SCIENCE

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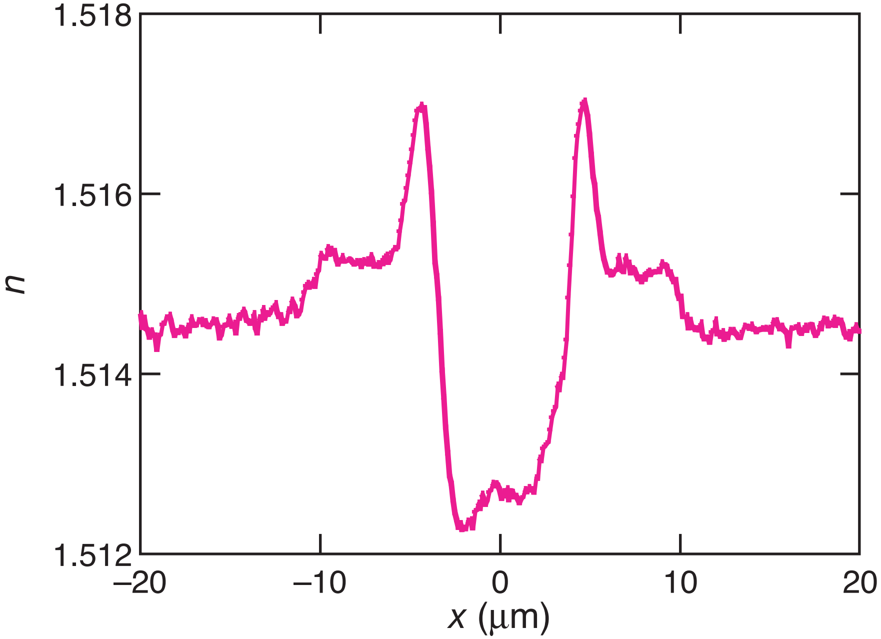
Yossi Chai (Sagitta, Inc.)

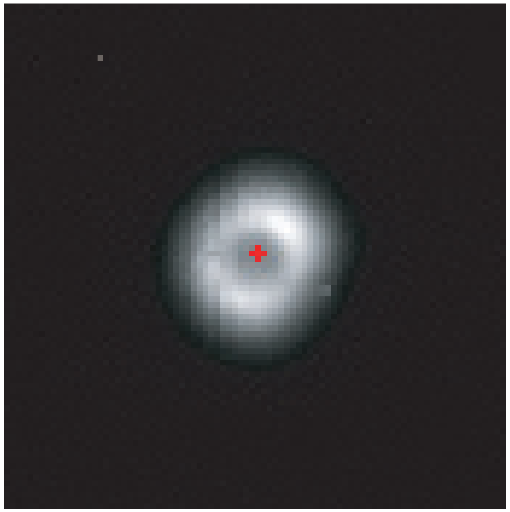
For a copy of this talk and additional information, see:

http://mazur-www.harvard.edu

refractive index profiles and near field mode at 633 nm

5 mm/s

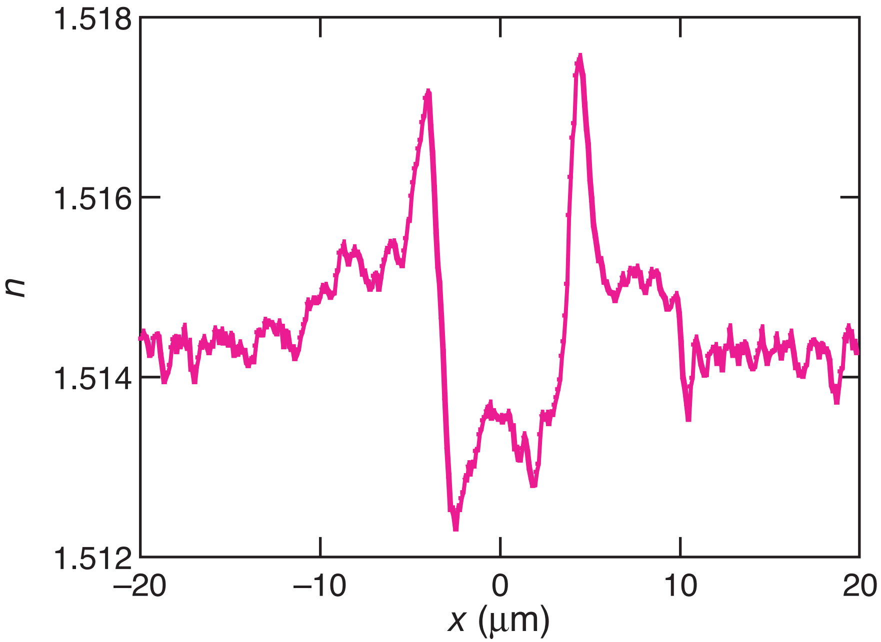


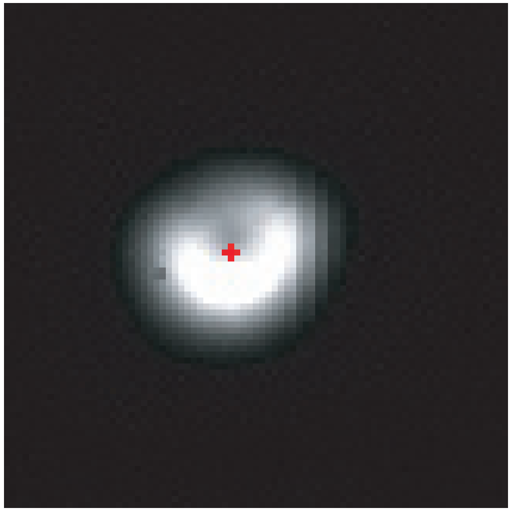


Sagitta, Inc.

refractive index profiles and near field mode at 633 nm

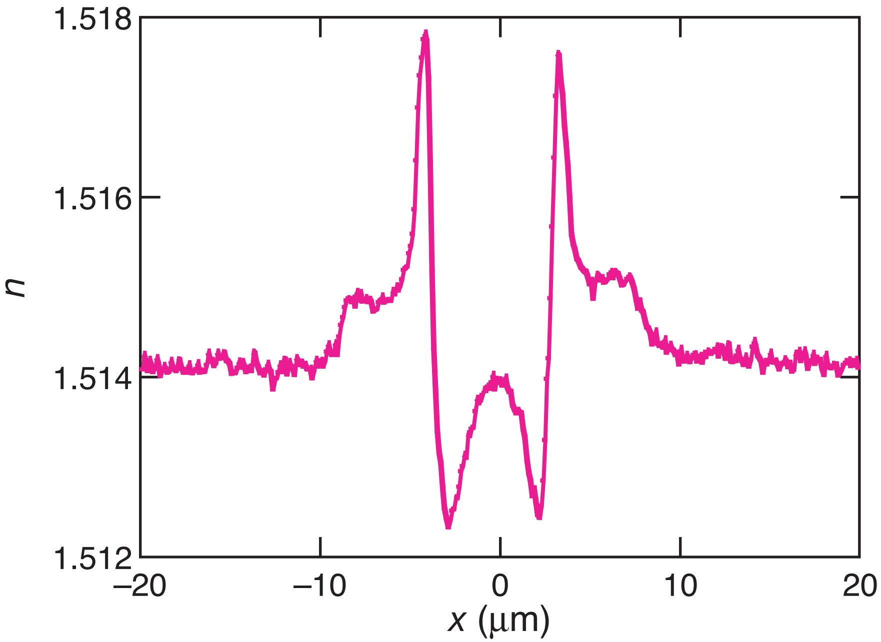
10 mm/s

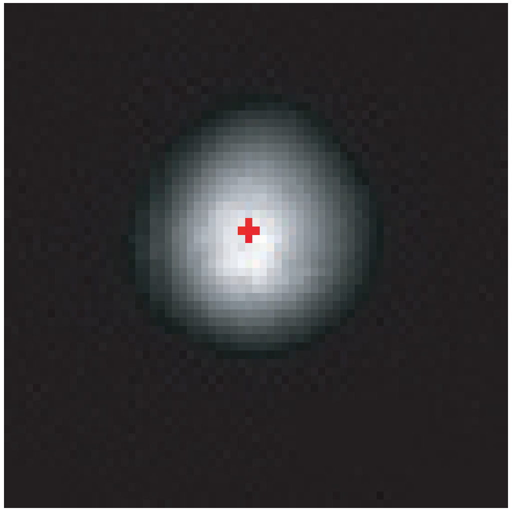




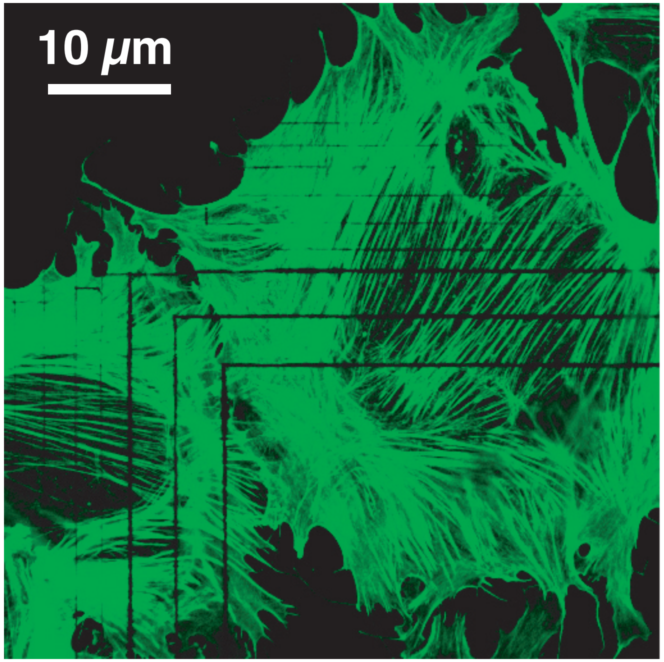
refractive index profiles and near field mode at 633 nm

20 mm/s





bleaching or disruption?



bleaching or disruption?