# Femtosecond micromaching of transparent materials

Iva Maxwell, Rafael Gattass, Jonathan Ashcom,
Limin Tong and Eric Mazur

Department of Physics
Division of Engineering and Applied Sciences
Harvard University

Erice, May 2003

# Outline

1. Our group & Cambridge
2. Nonlinear absorption in transparent materials
3. Focusing effects
4. Repetitive vs. thermal regime
5. Applications

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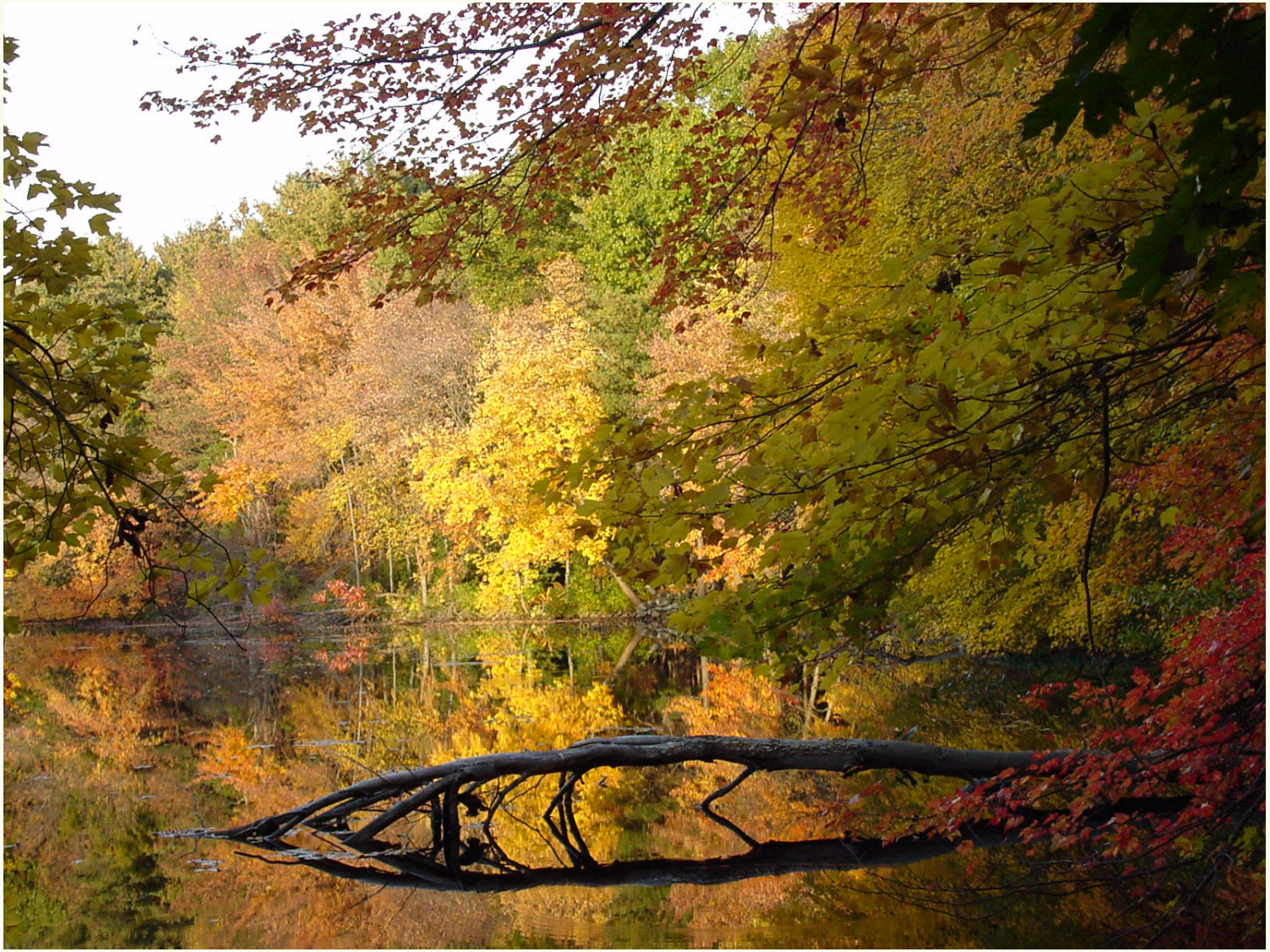
# Massachusetts

# Massachusetts

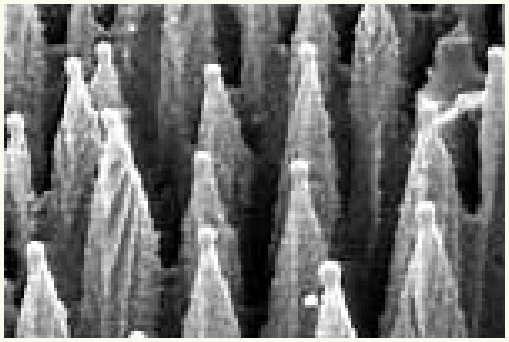


# The Mazur Group

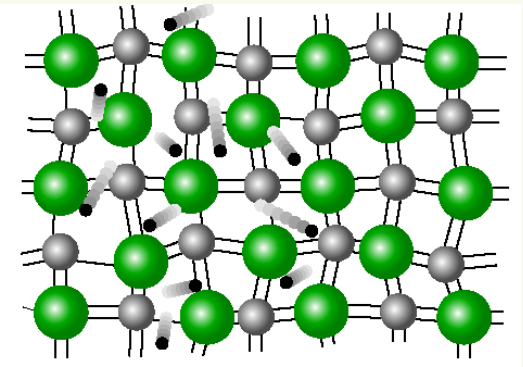

Kayaking in Ipswich Bay, Sept 2002

# The Mazur Group

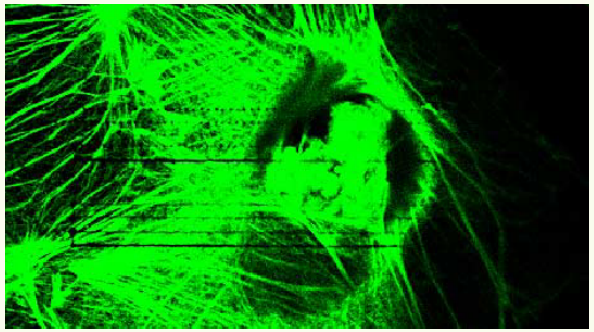
black silicon



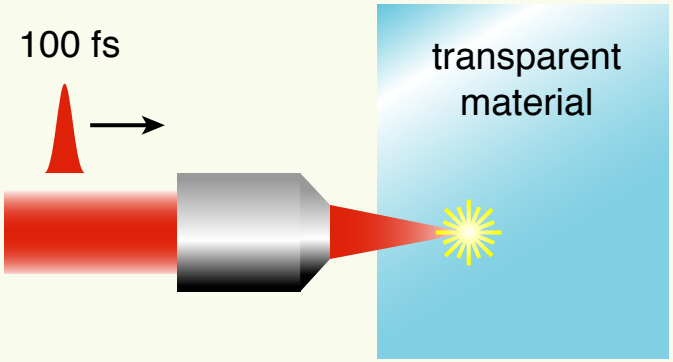
ultrafast dynamics



nanosurgery



micromachining




science education

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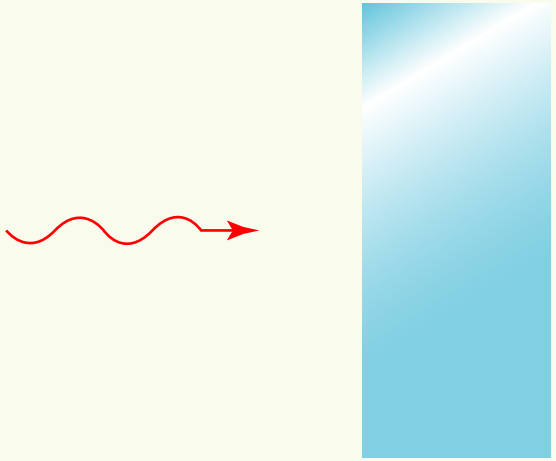
# Linear absorption

Normally, the material characteristics define the way light behaves



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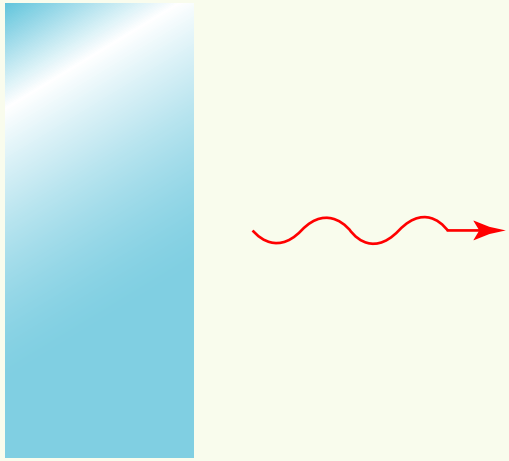

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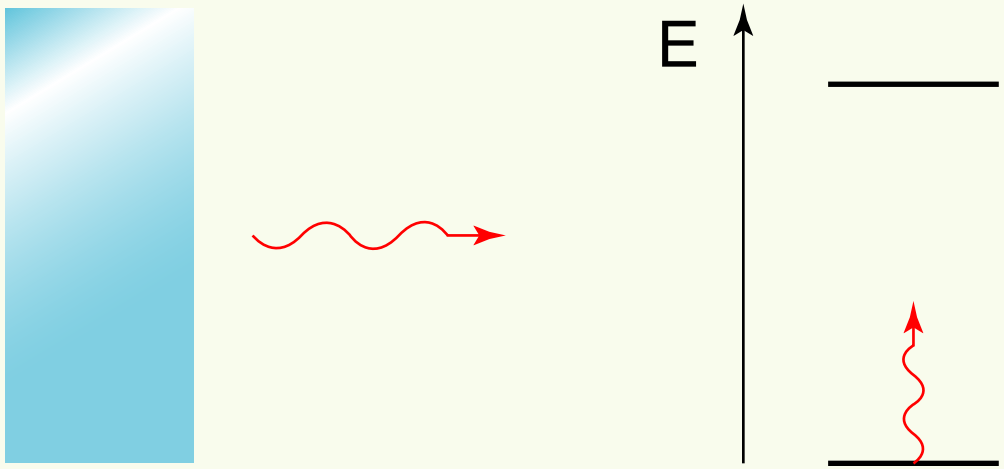
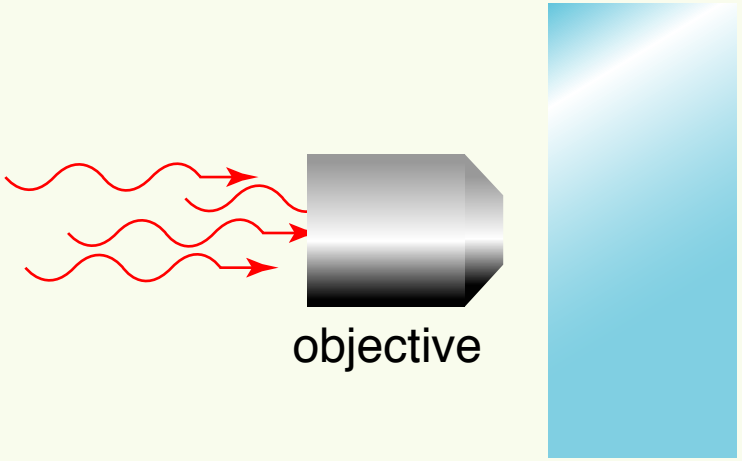



Energy of the photon is smaller than energy gap

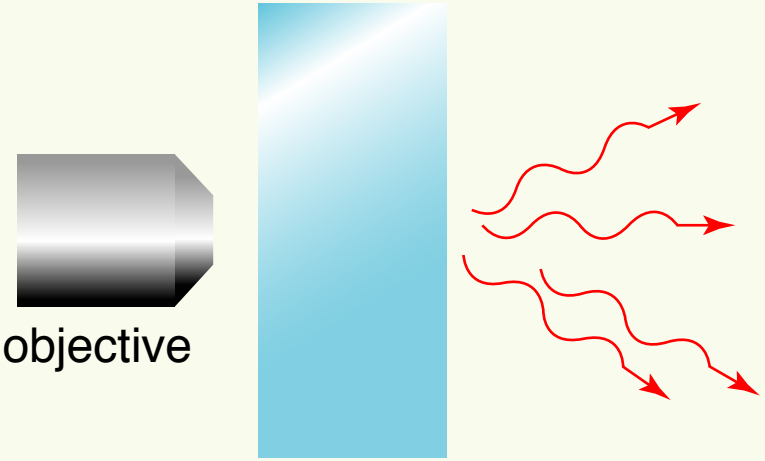
# Linear absorption

What happens if we focus?



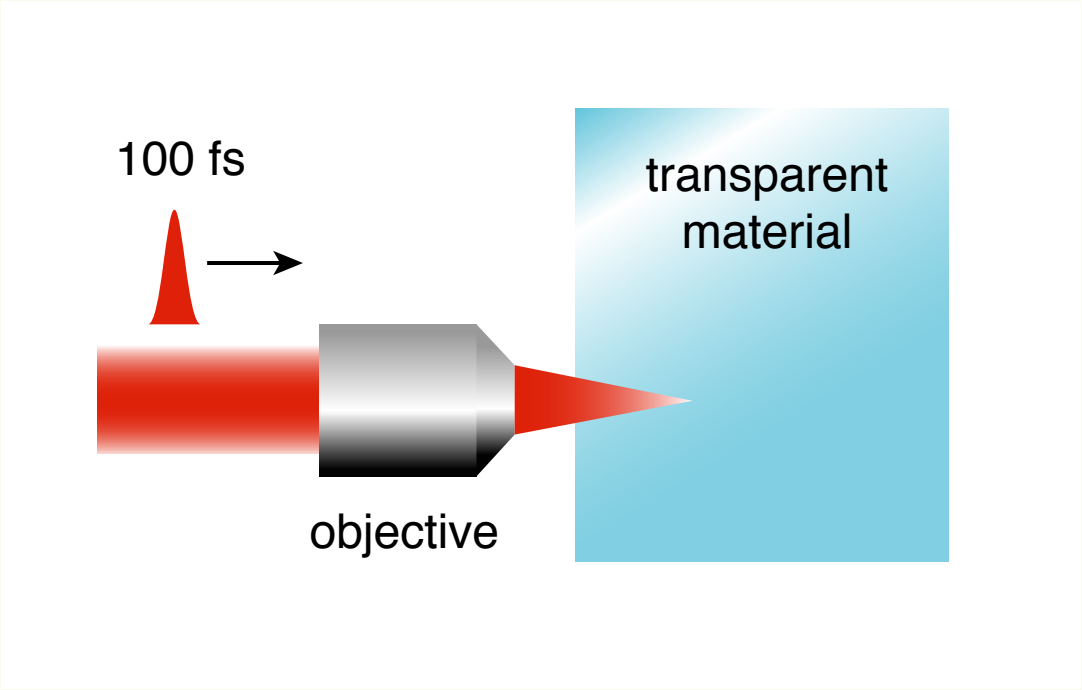
# Linear absorption

What happens if we focus?
Nothing...



# Nonlinear absorption

Now, compress these photons in time AND space



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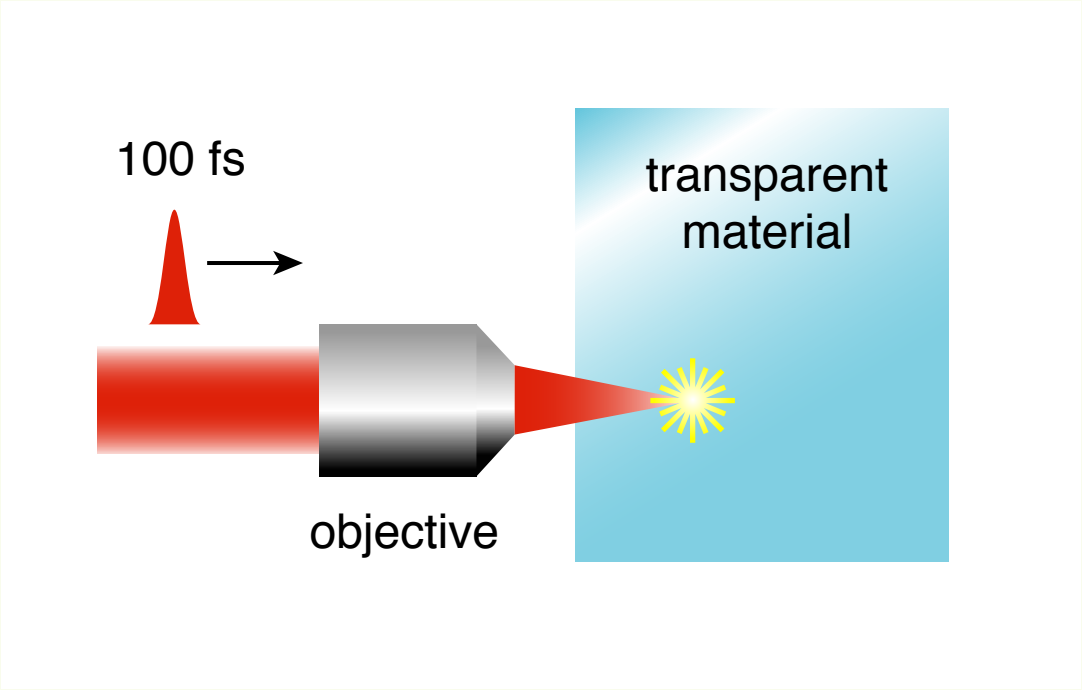

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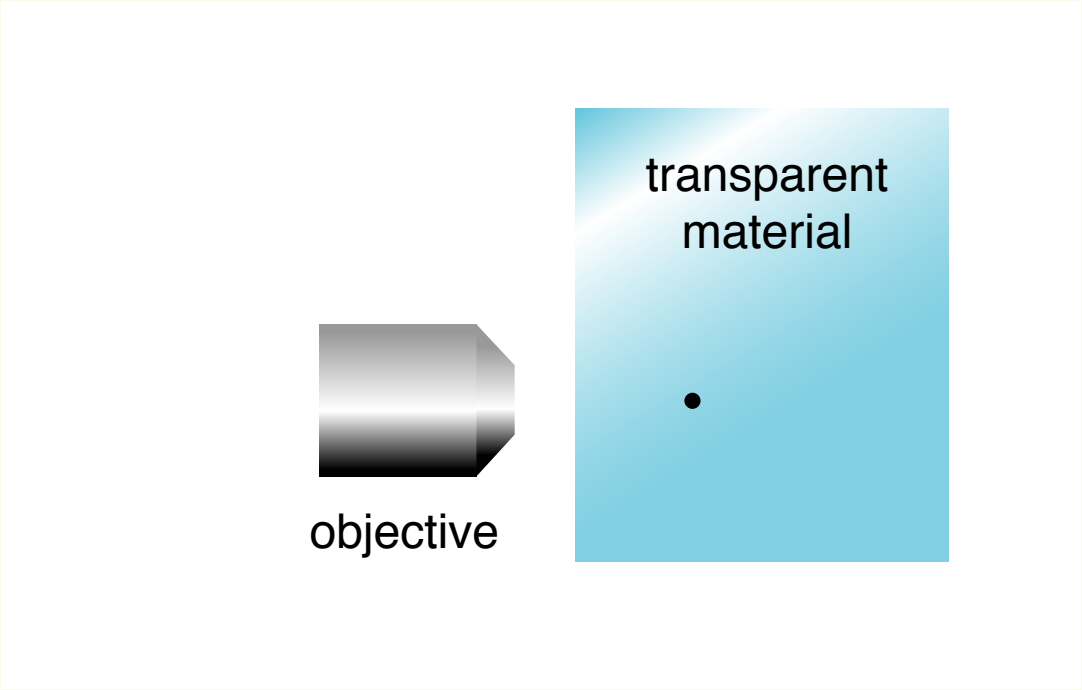

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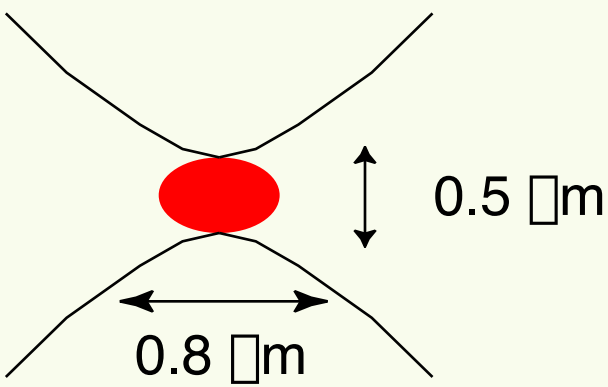
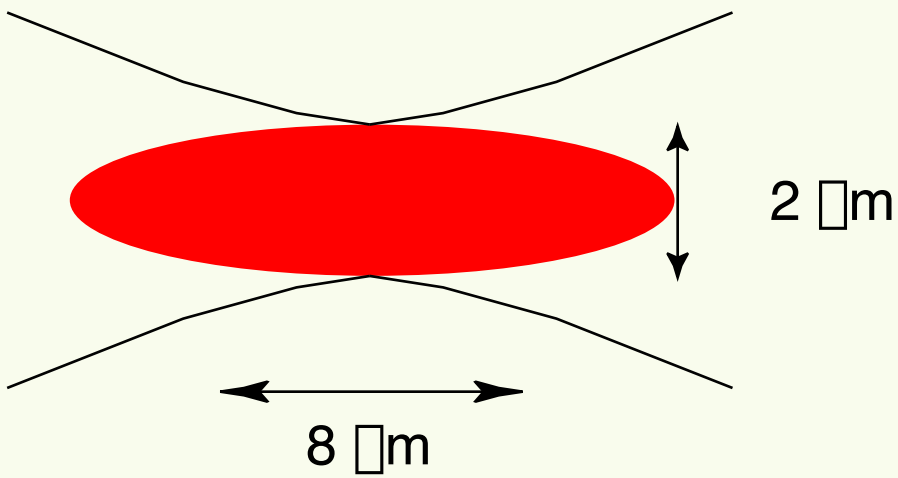
# Focusing dependence

Damage localized to the focal volume

Process is intensity dependent




for a 1.4 N.A. objective



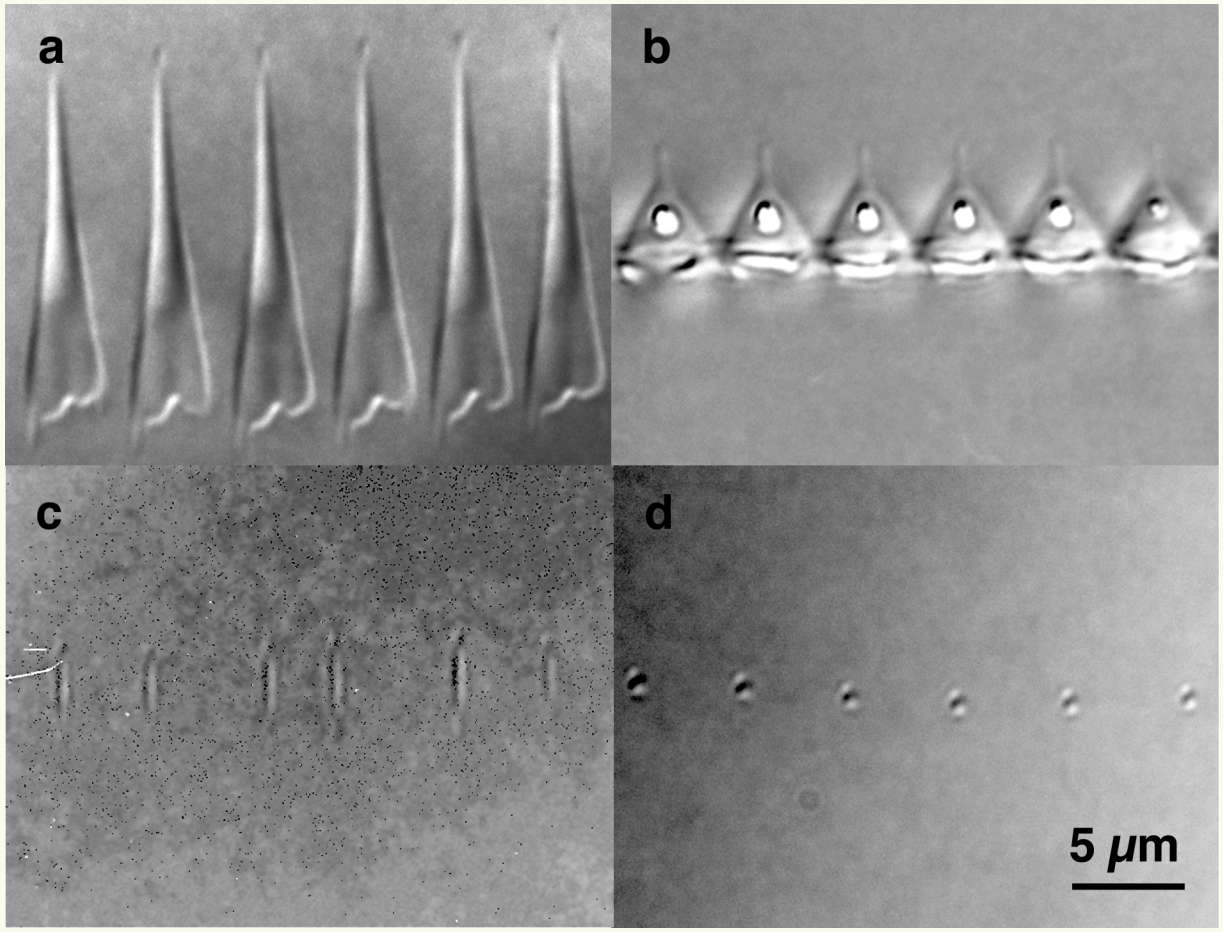

for a 0.25 N.A. objective

# Focusing dependence

Damage localized to the focal volume

500 nJ

50 nJ




500 nJ

15 nJ

k

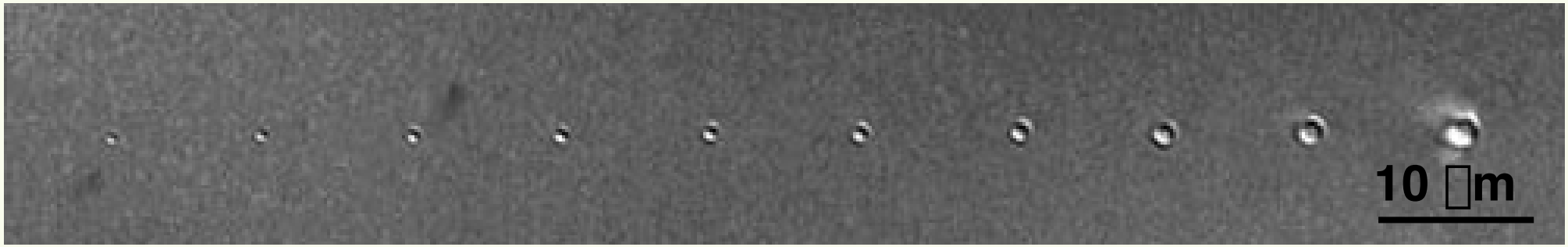
0.45 NA

1.4 NA

# Focusing dependence

Damage localized to the focal volume

**6.6 nJ** **13 nJ** **33 nJ** **66 nJ**

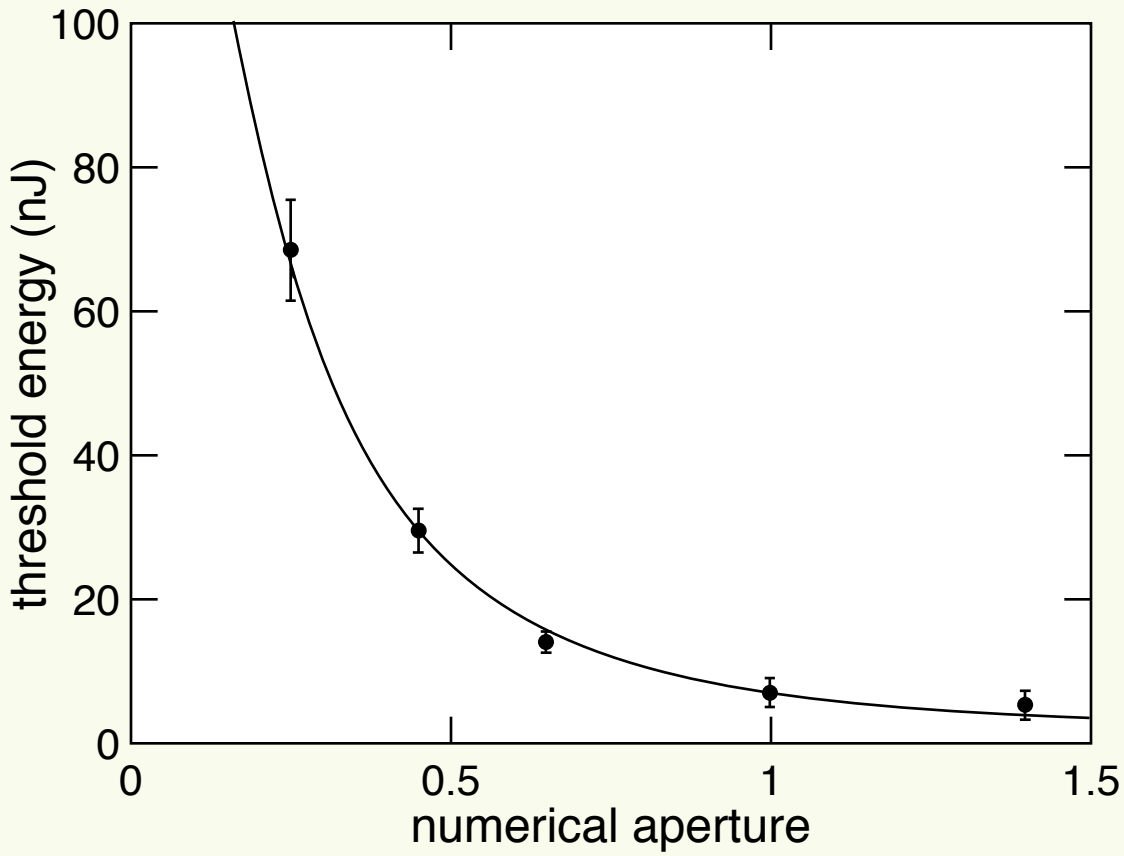



**100 fs**
**1.4 NA**
**Corning 0211**

$\otimes k$

# Focusing dependence

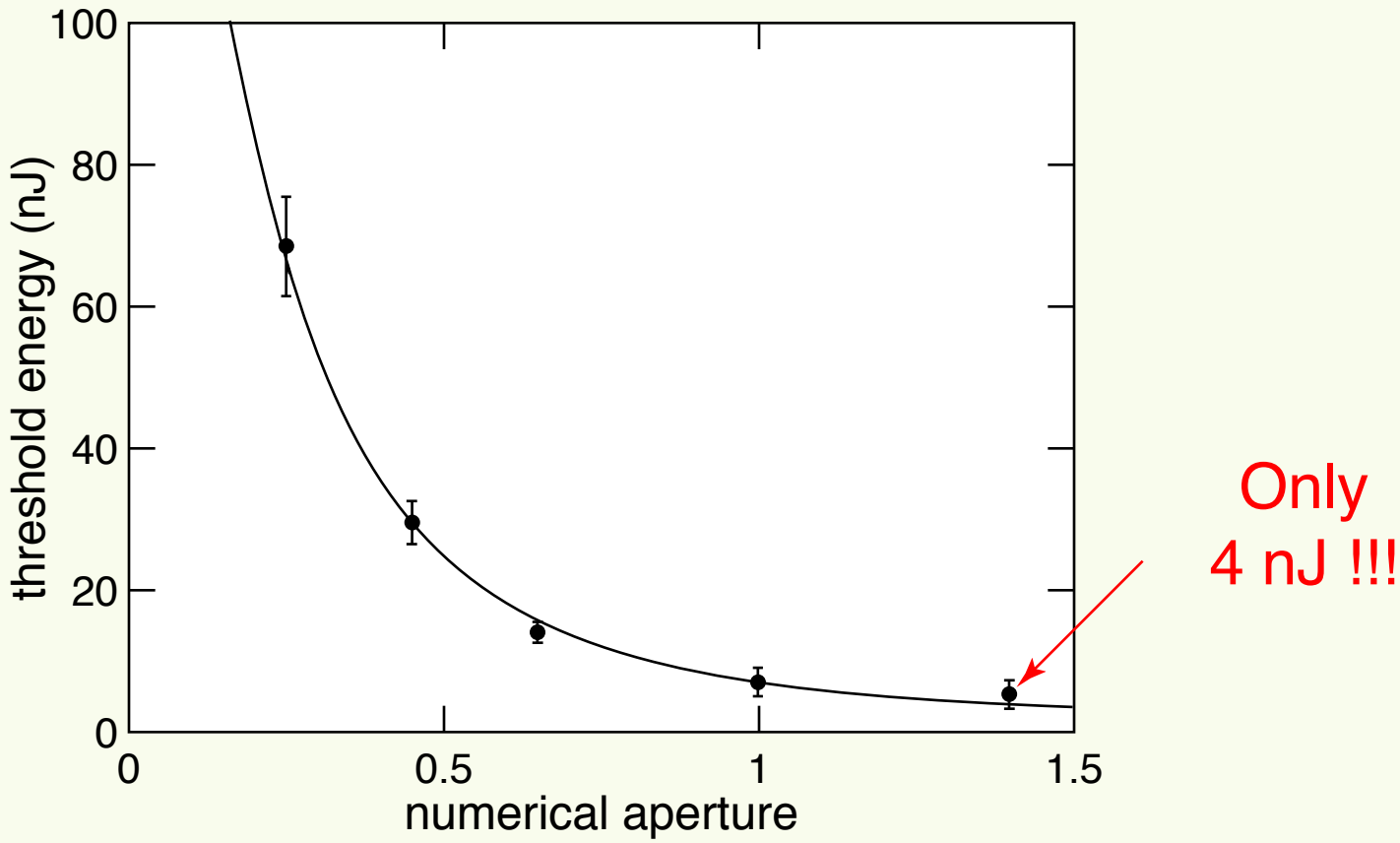
Focusing dependence for Corning 0211 glass




Schaffer *et al.*, Opt. Lett. 26, 93 (2001)

# Focusing dependence

Focusing dependence for Corning 0211 glass

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# Thermal machining

Mechanisms overview

| Time scale (s) | Effect |
| --- | --- |
| $10^{-15}$ | Absorption of laser pulse |
| $10^{-12}$ | Plasma recombination with ions |
| $10^{-6}$ | Thermal diffusion time out of focal volume |

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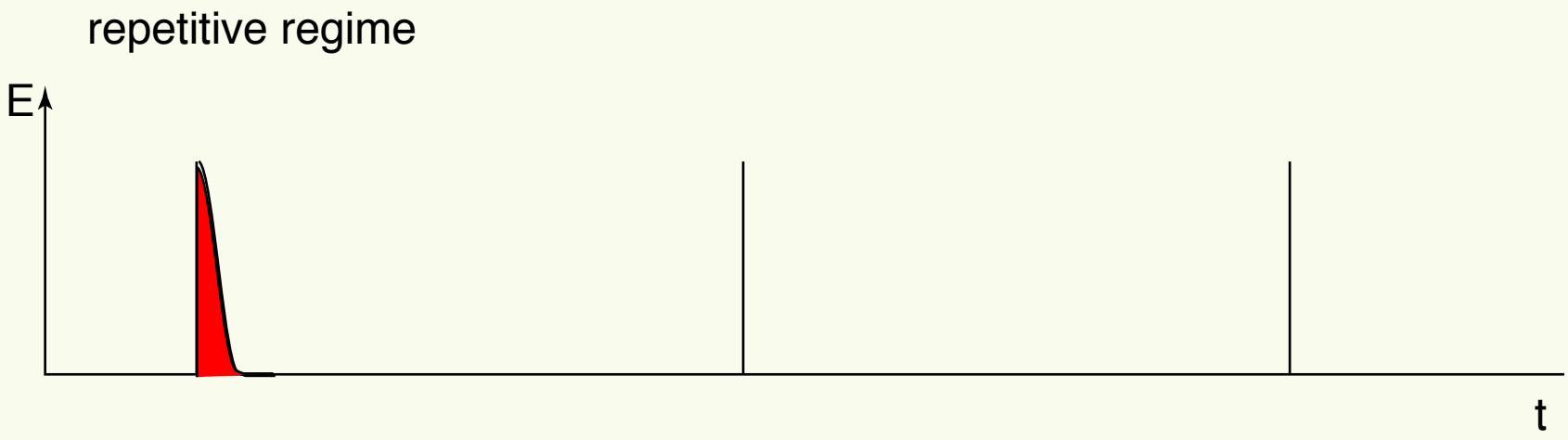
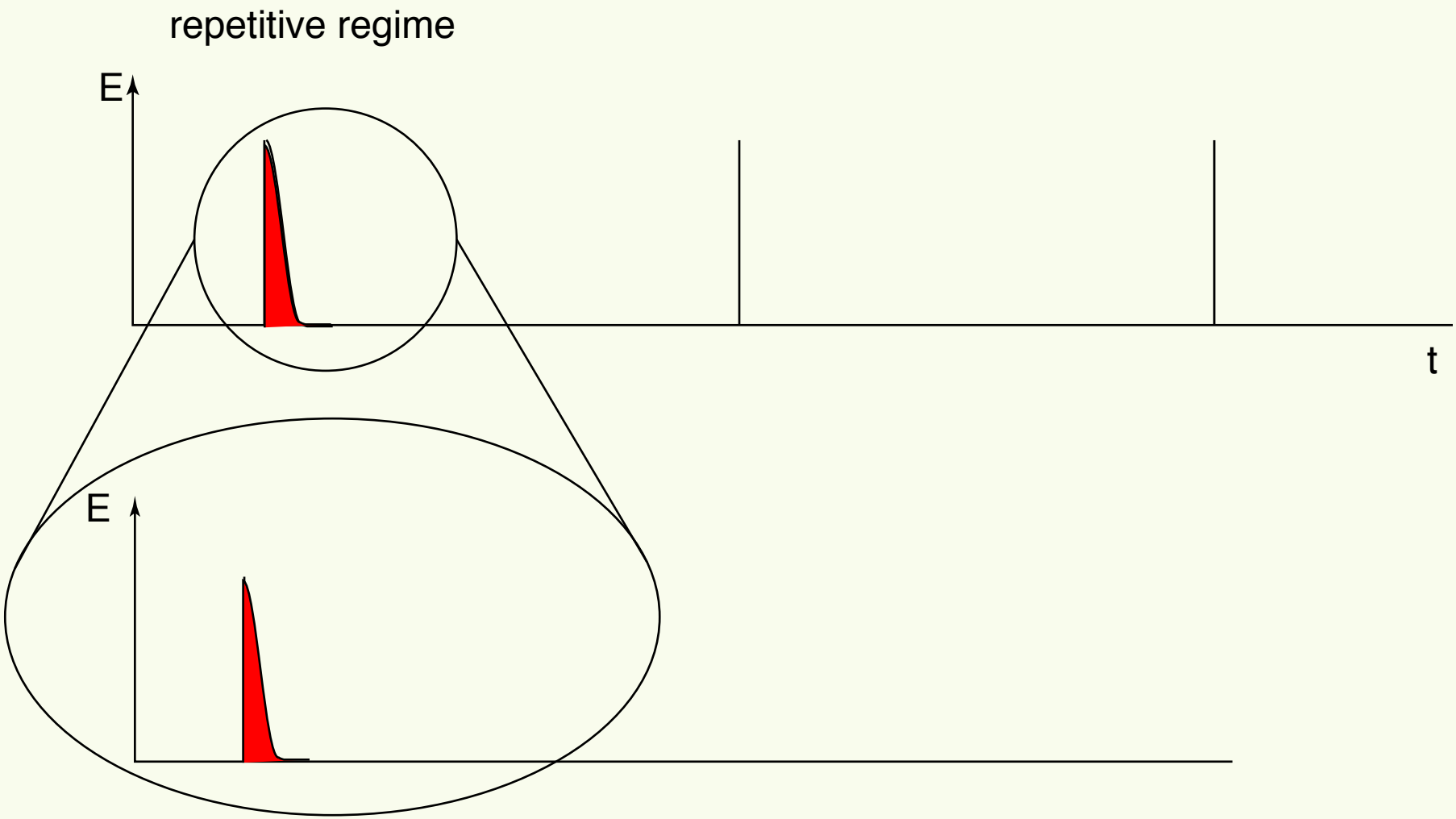
Material Modification

Energy deposition in the repetitive and cumulative regime



Energy deposition in the repetitive and cumulative regime



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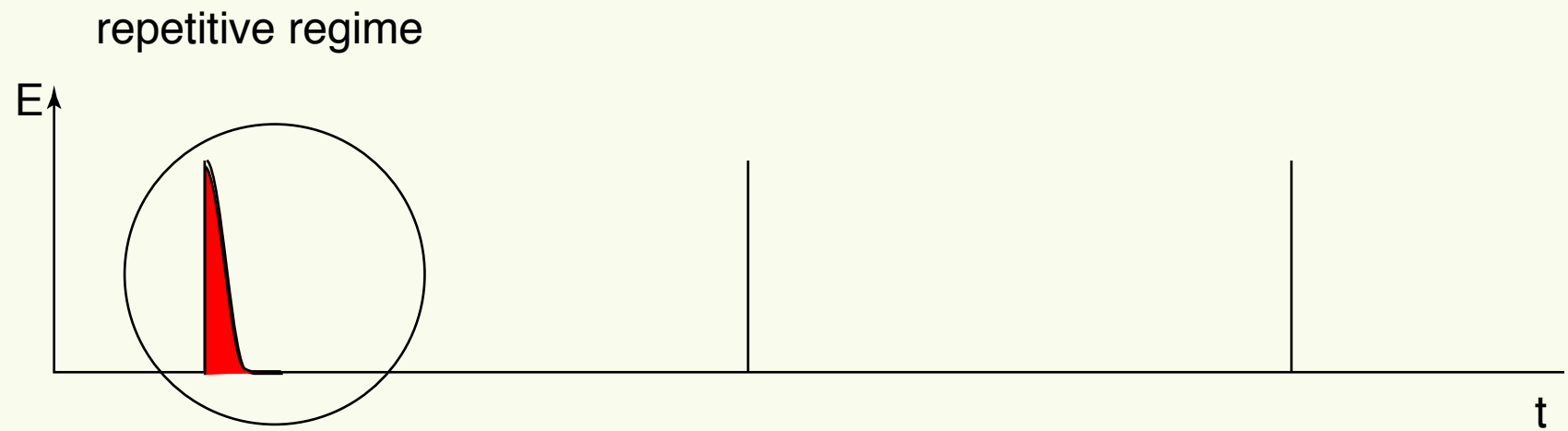
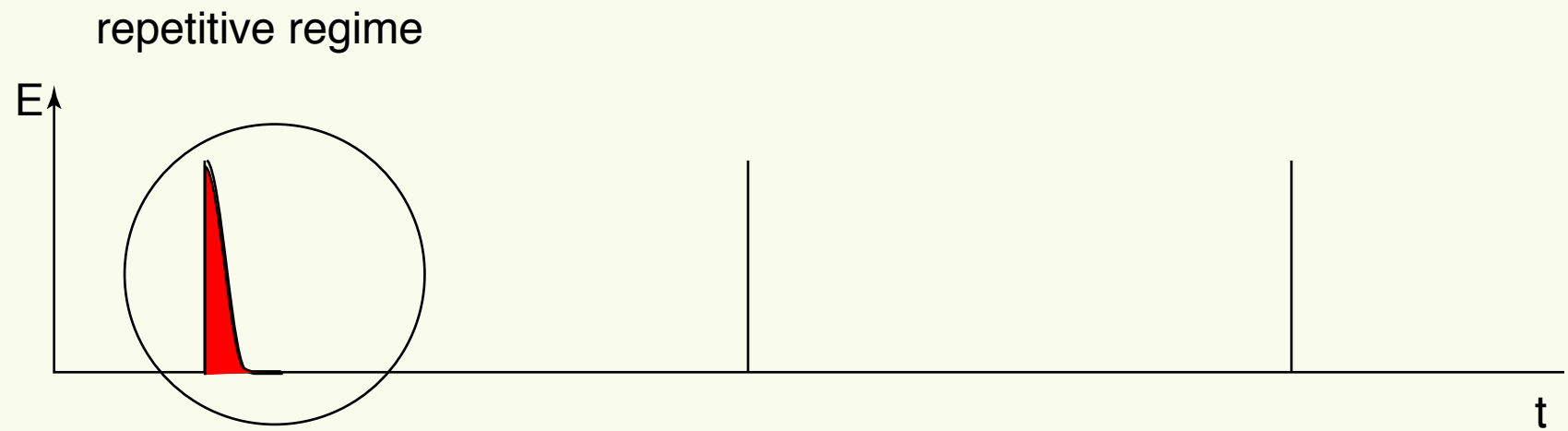
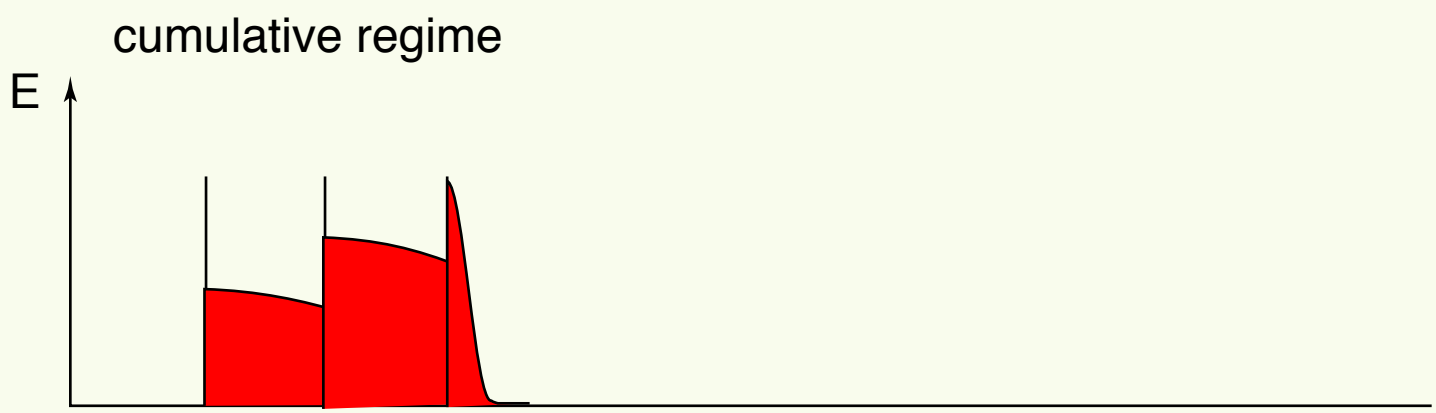



Energy deposition in the repetitive and cumulative regime



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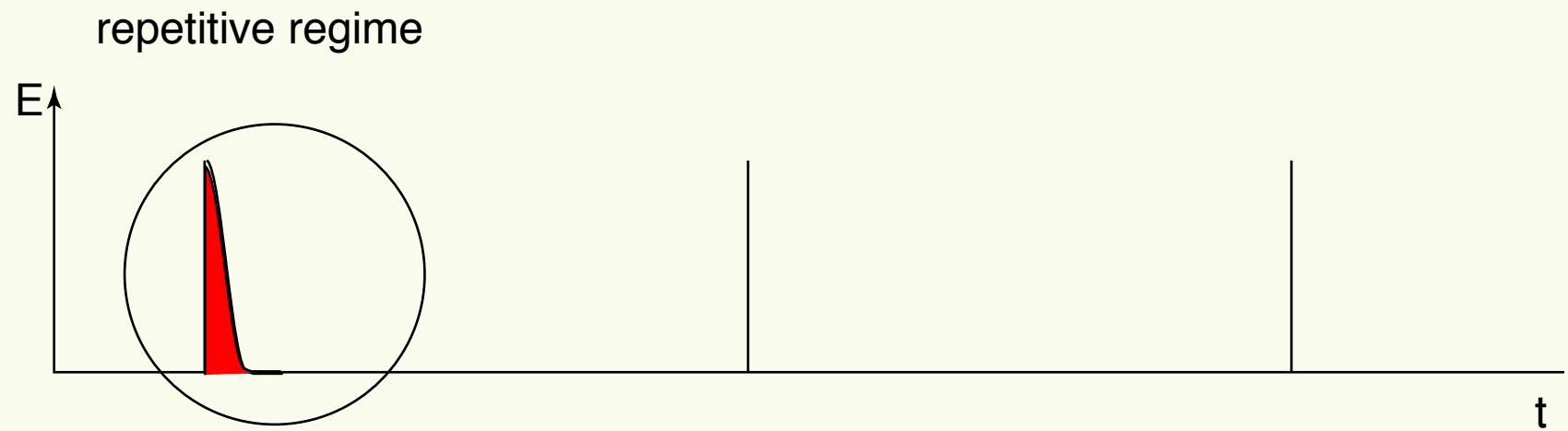


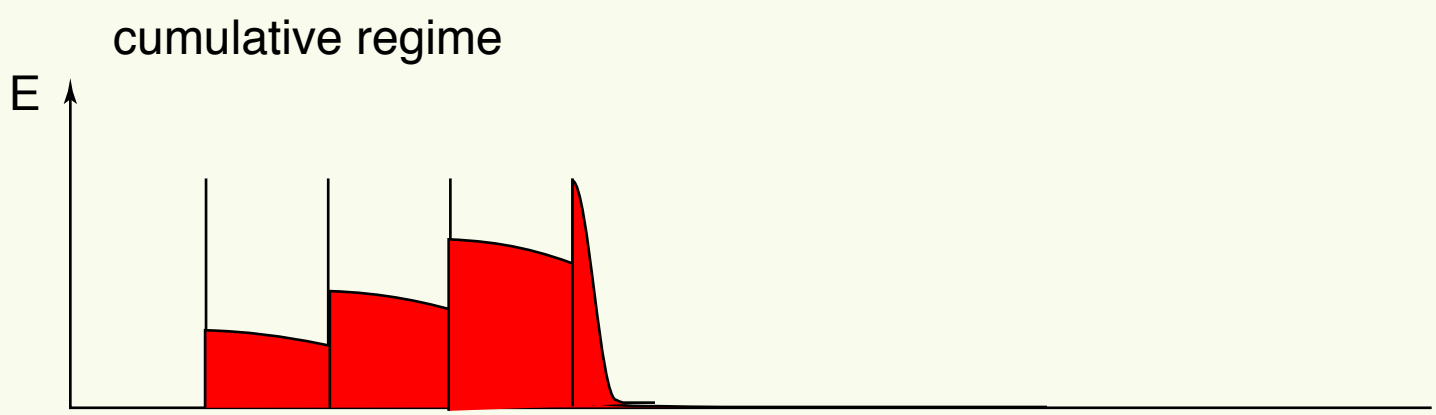

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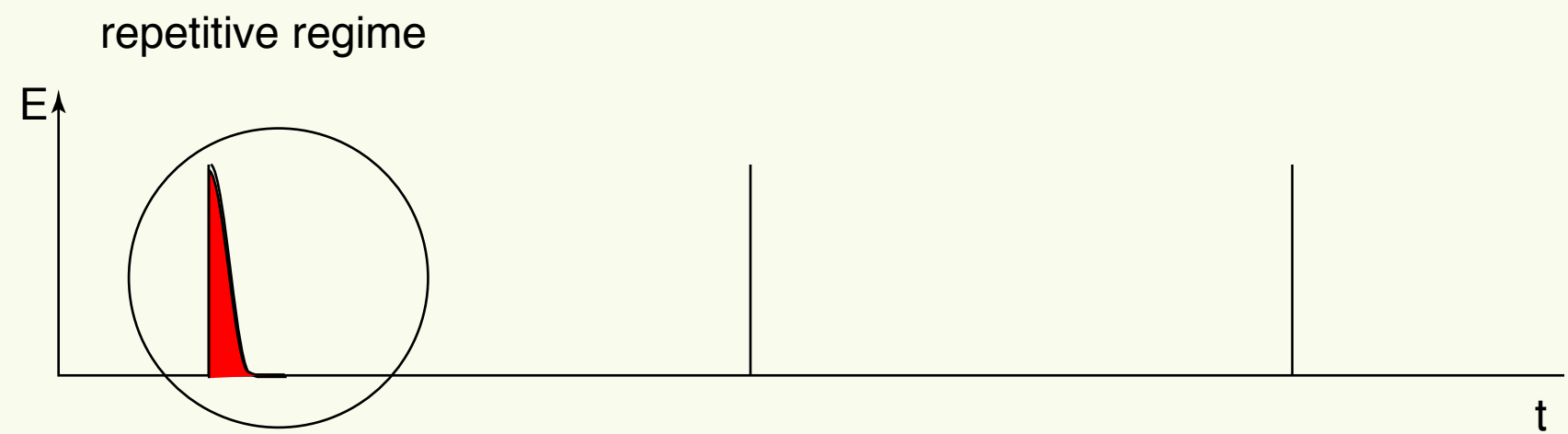
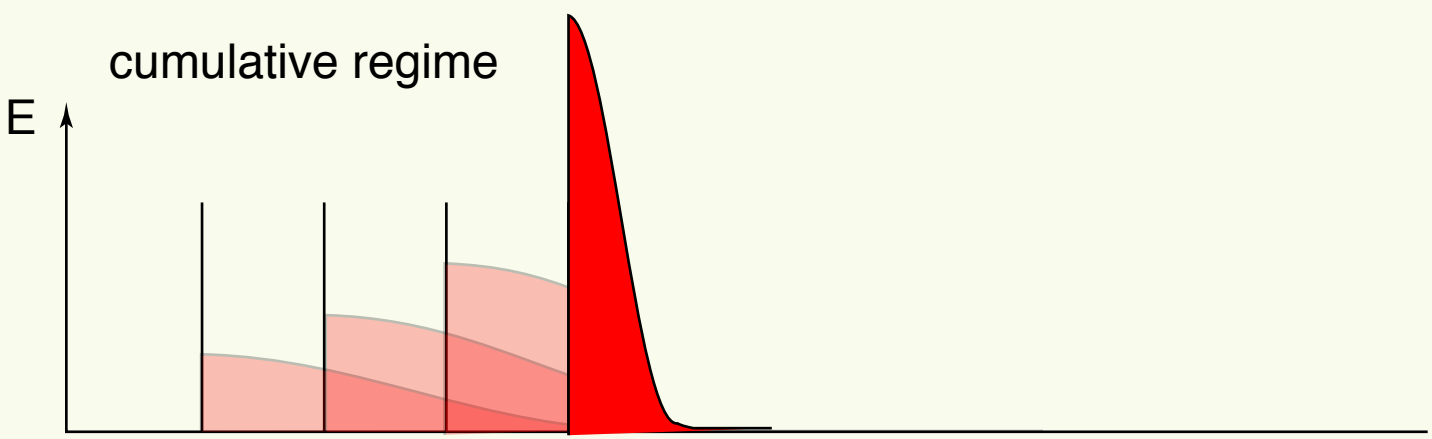
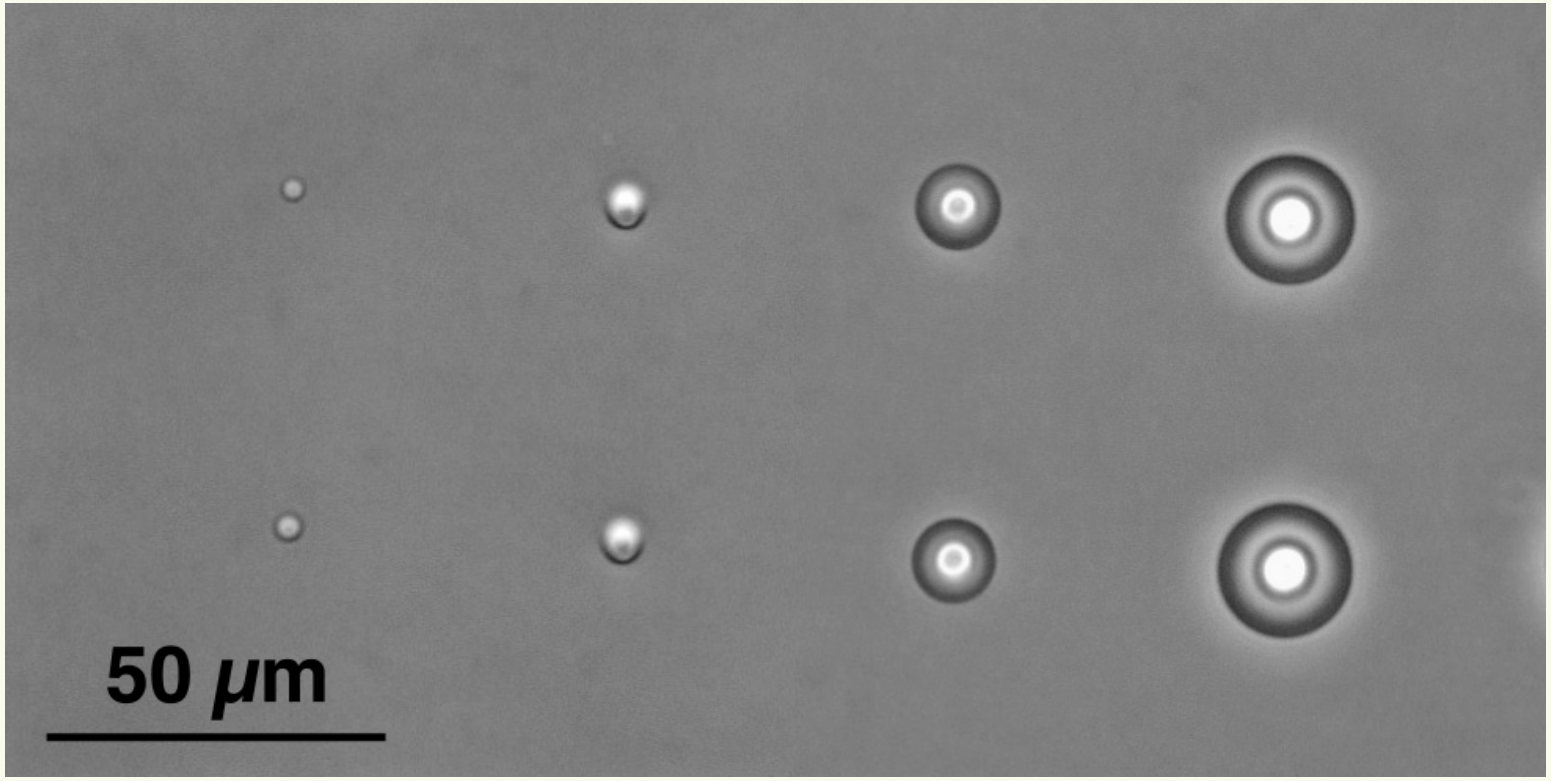


# Thermal machining

Structural changes exceed focal spot

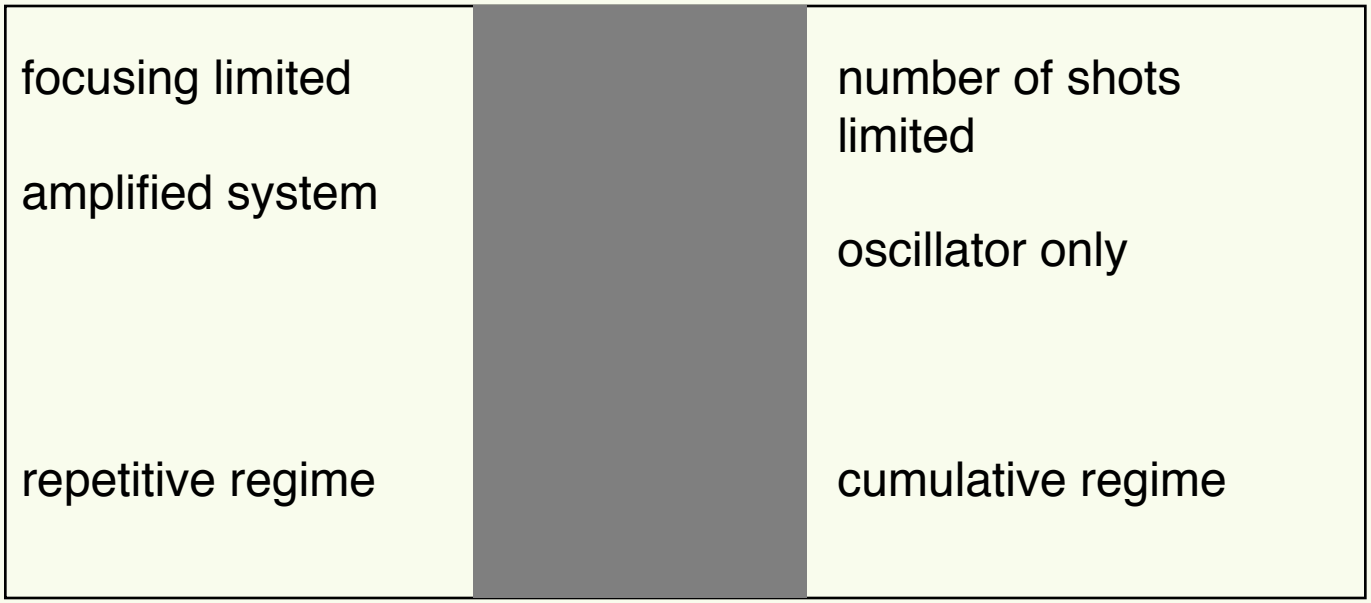



$10^2$ $10^3$ $10^4$ $10^5$

Schaffer *et al.*, Opt. Lett. 26, 93 (2001)

# Thermal machining

Transition point

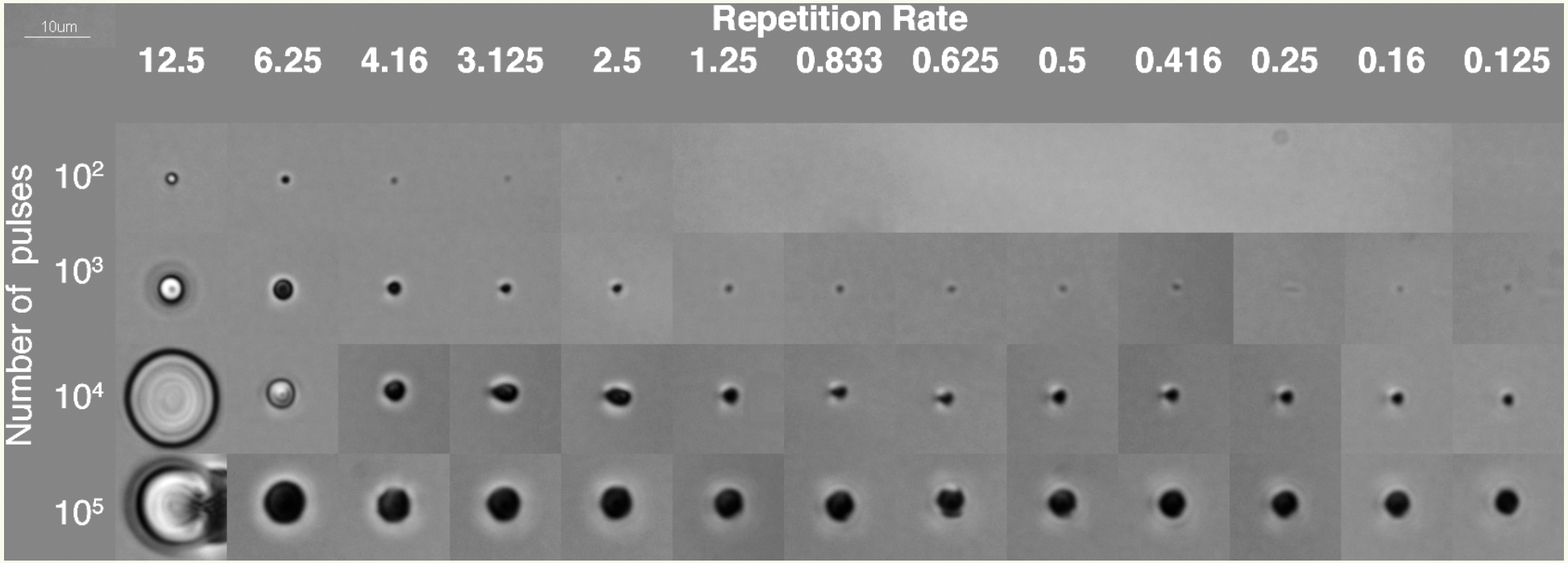



kHz
low repetition rate

?

MHz
high repetition rate

# Thermal machining



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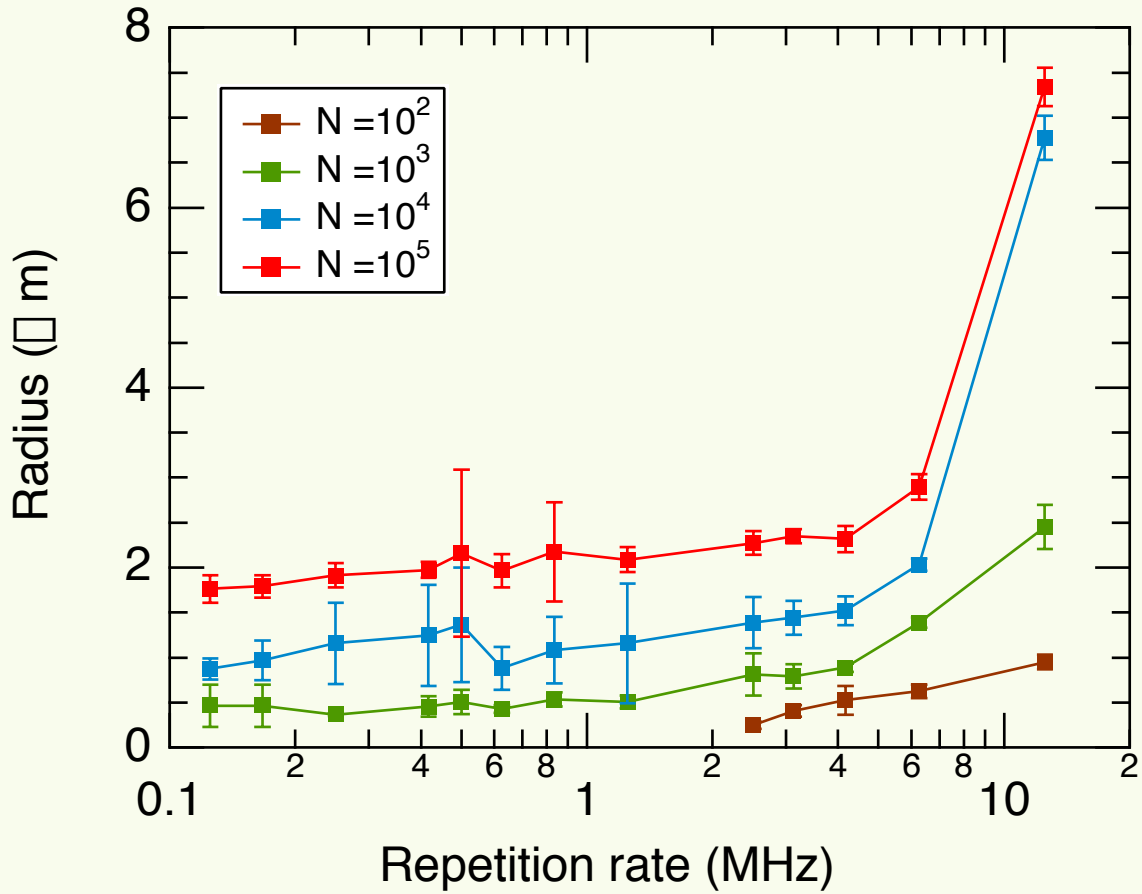

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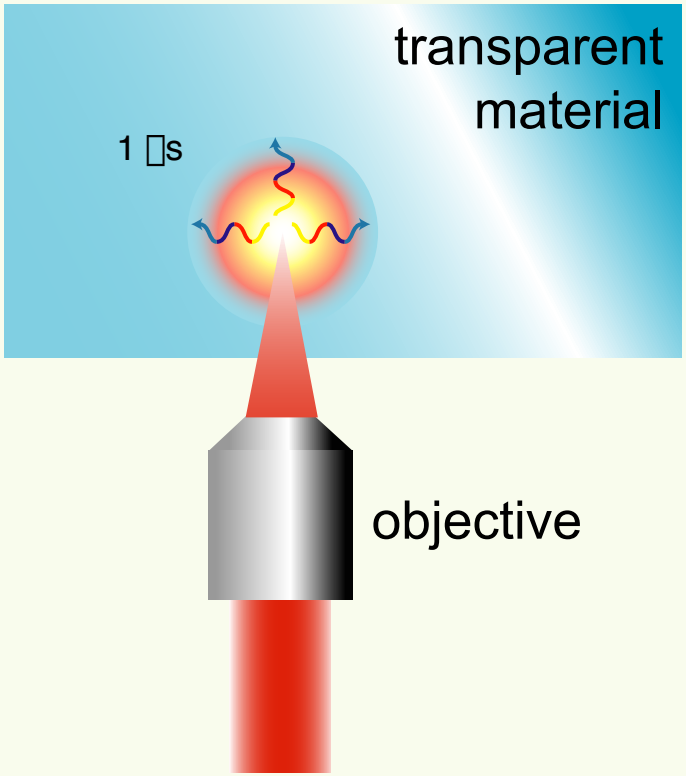
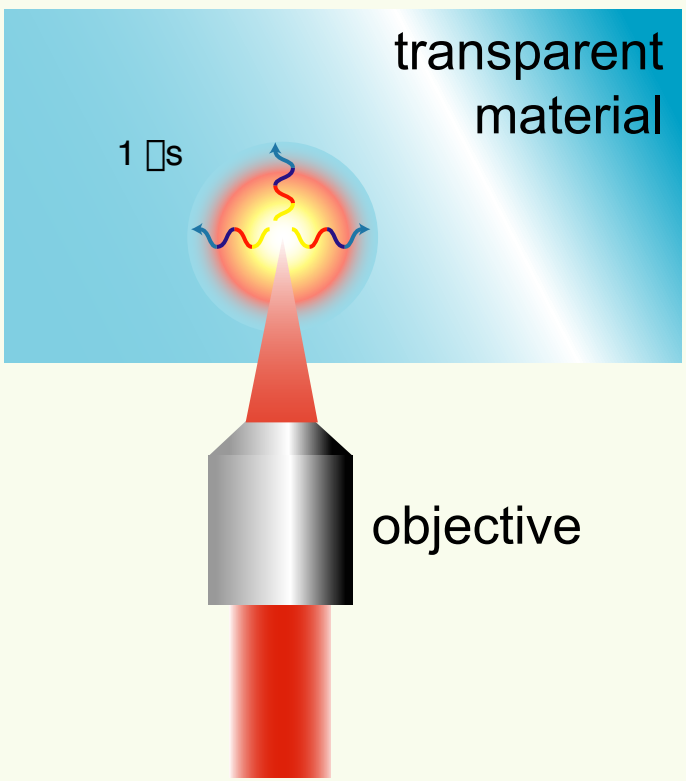
# Applications

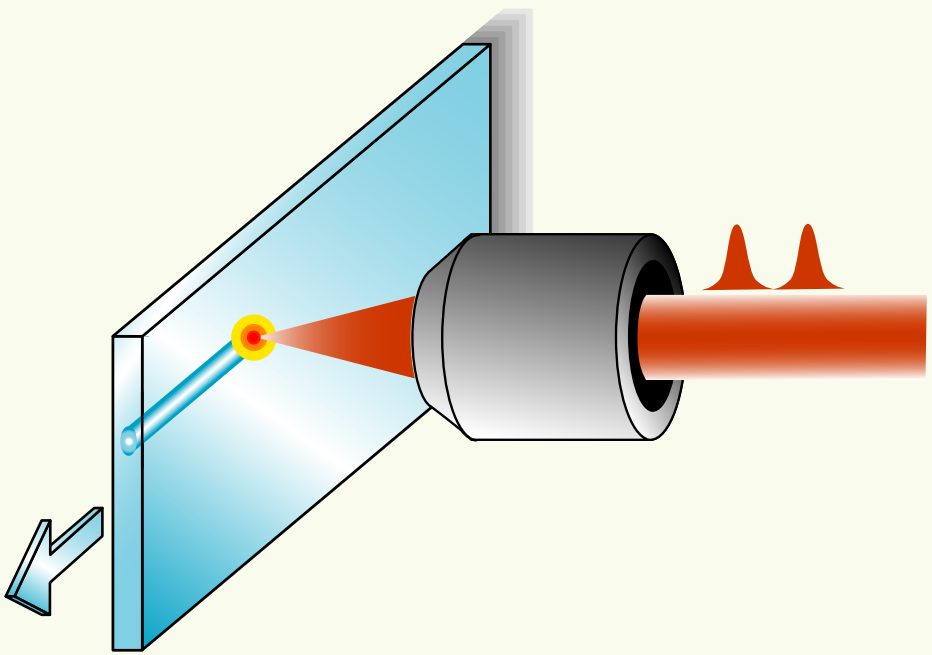
In the cumulative regime, the energy deposited by a train of pulse accumulates in the focal volume. This results in a point source of heat.



# Applications

Translating the sample with respect to the laser beam generates a continuous structure.



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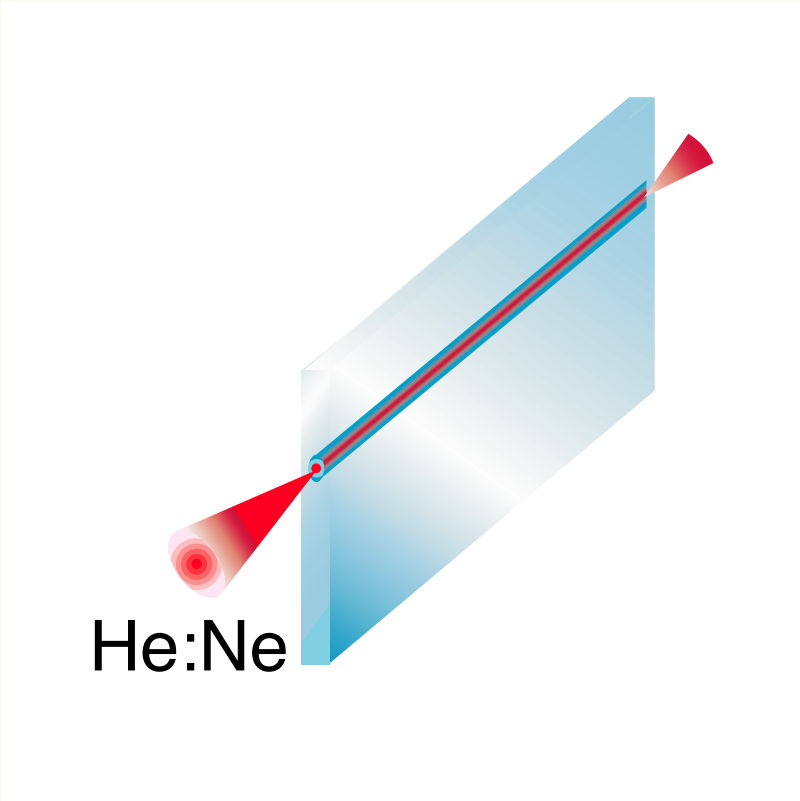
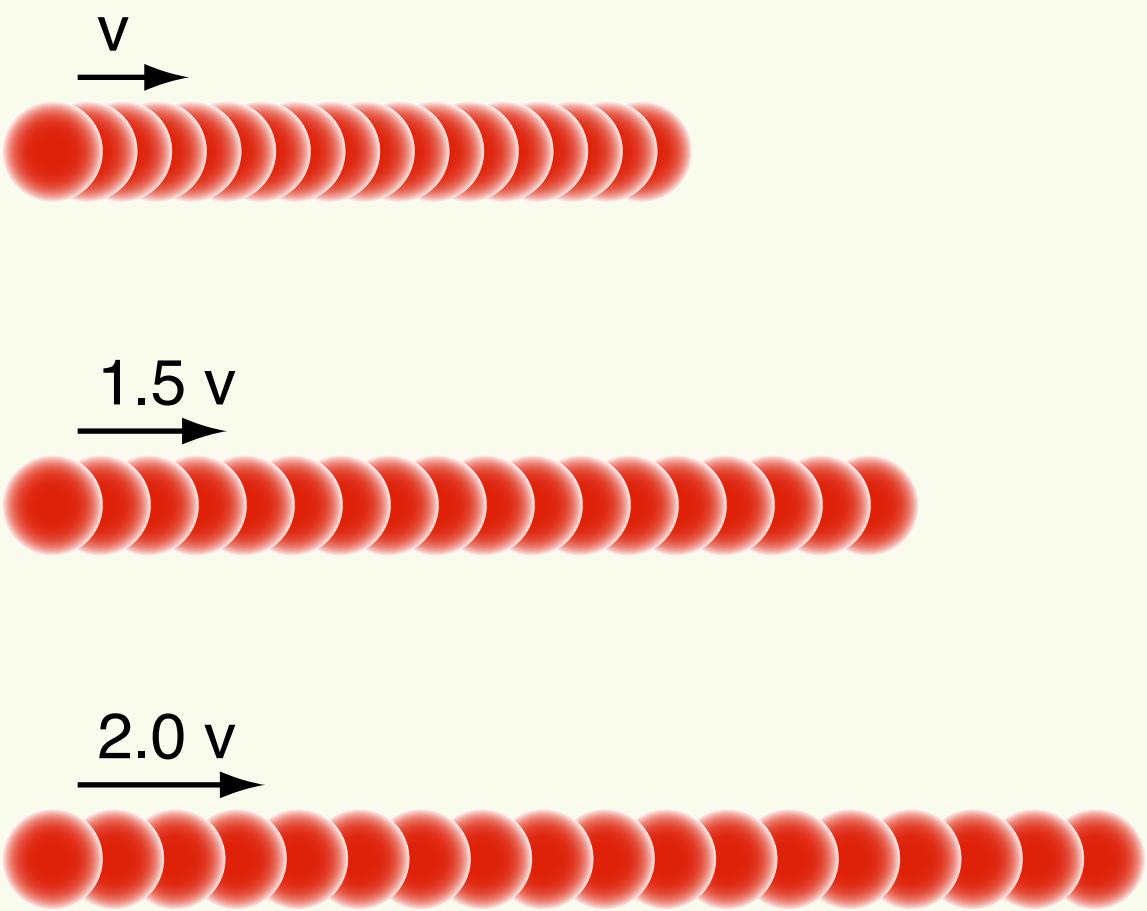


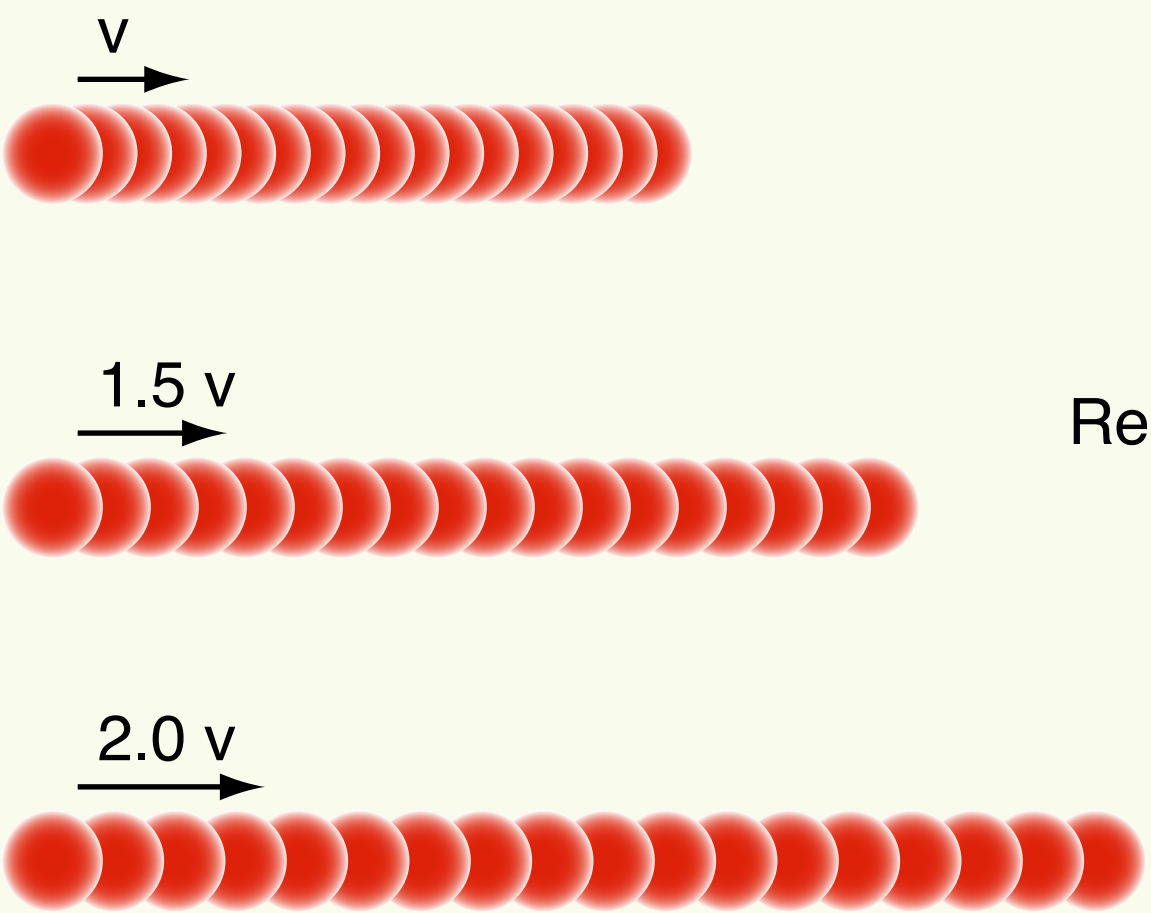
# Waveguides



# Waveguides

Number of pulses vs. index of refraction

Effective change in the number of shots at each spot




v= 20 mm/s

$2\square_0$ = 0.5 $\square$m

Rep. Rate = 25Mhz

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Number of pulses vs. index of refraction

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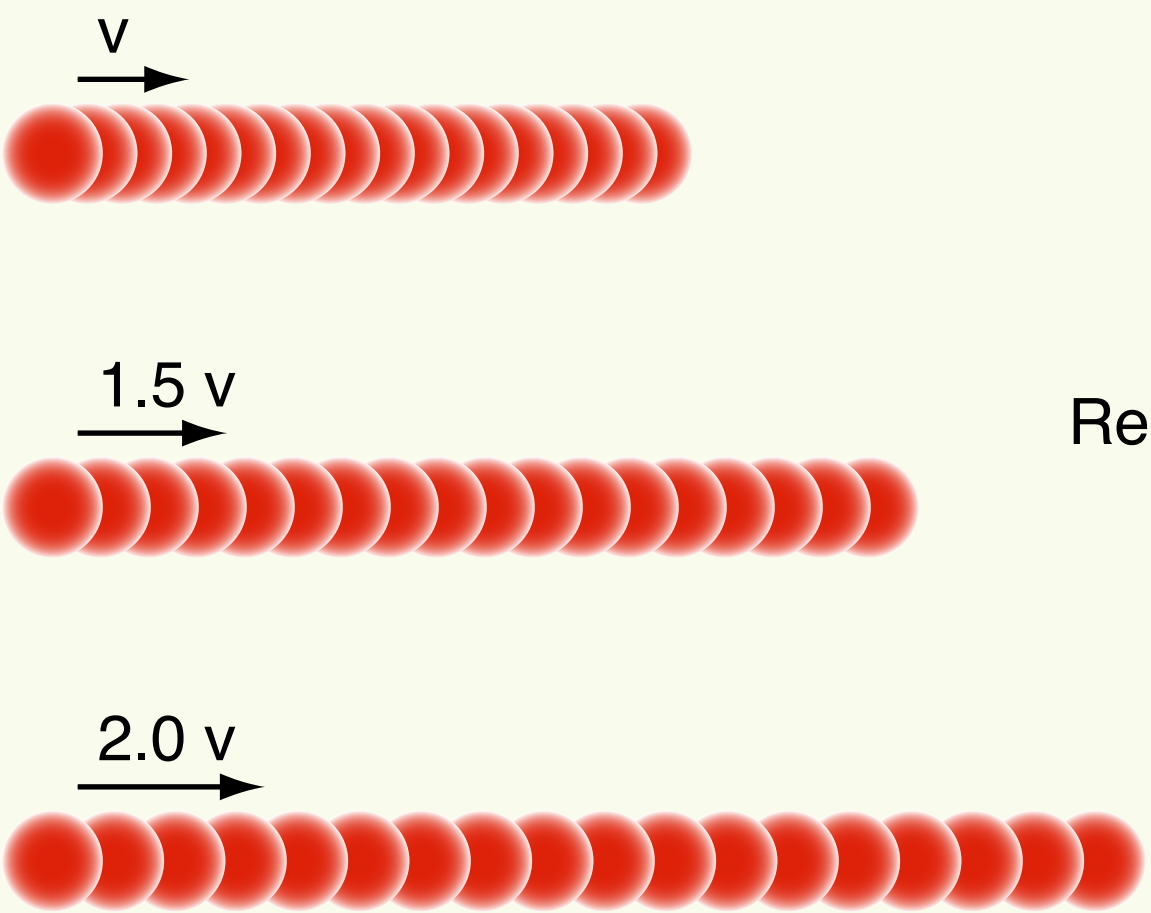


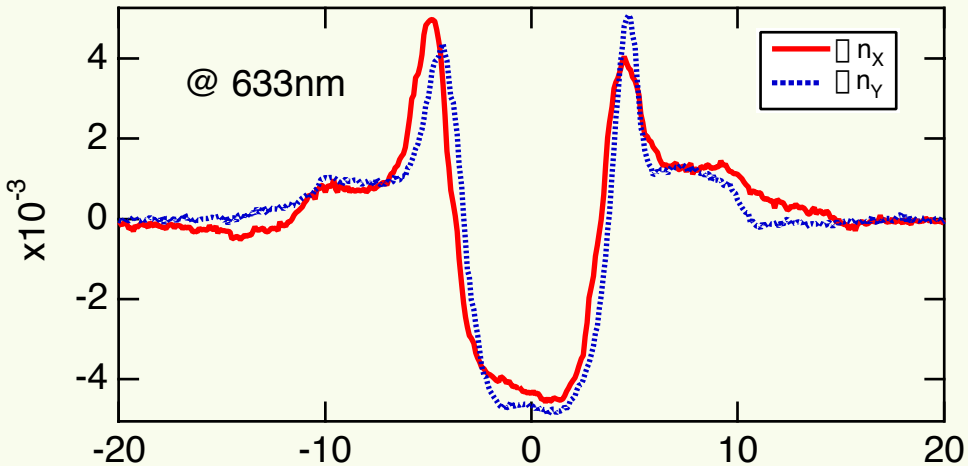

$$\left.\begin{array}{c} v = 20\ \text{mm/s} \\ 2\square_0 = 0.5\ \square\text{m} \\ \text{Rep. Rate} = 25\text{Mhz} \end{array}\right\} N_{max} = 6 \times 10^2$$

# Waveguides

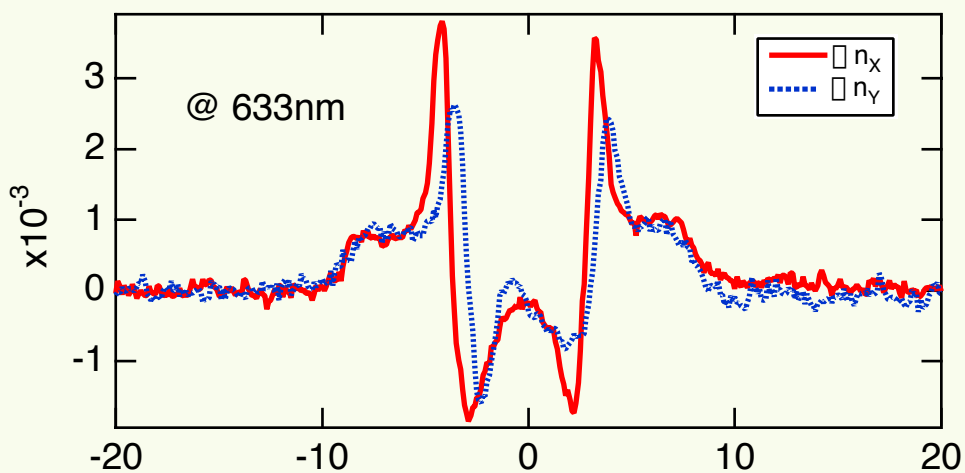
## Number of pulses vs. index of refraction

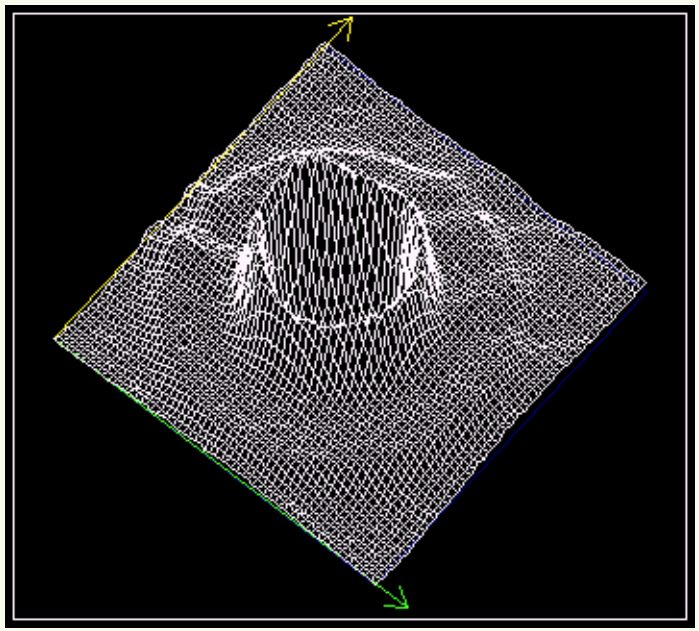
Translation speed

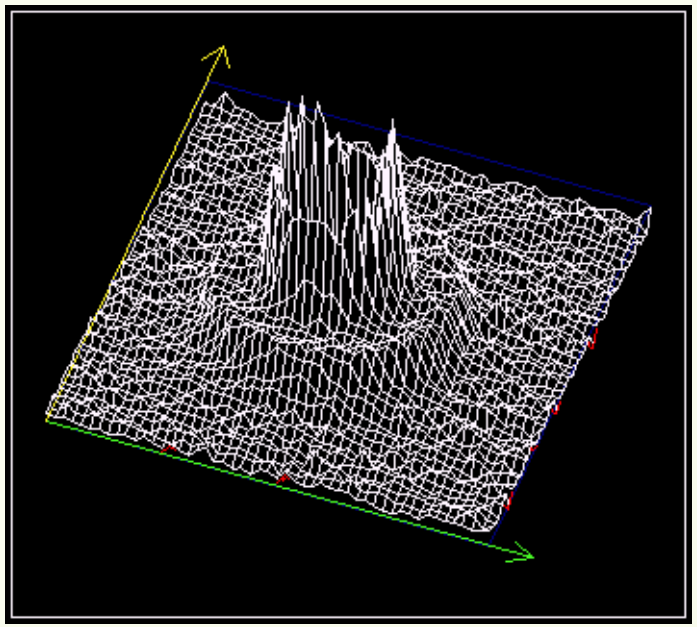
2.5 mm/s




20 mm/s



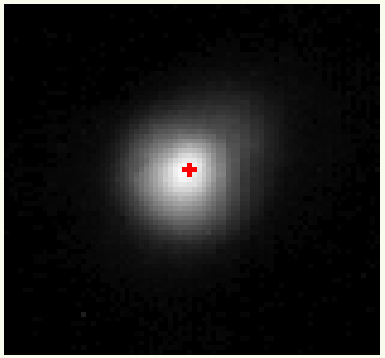


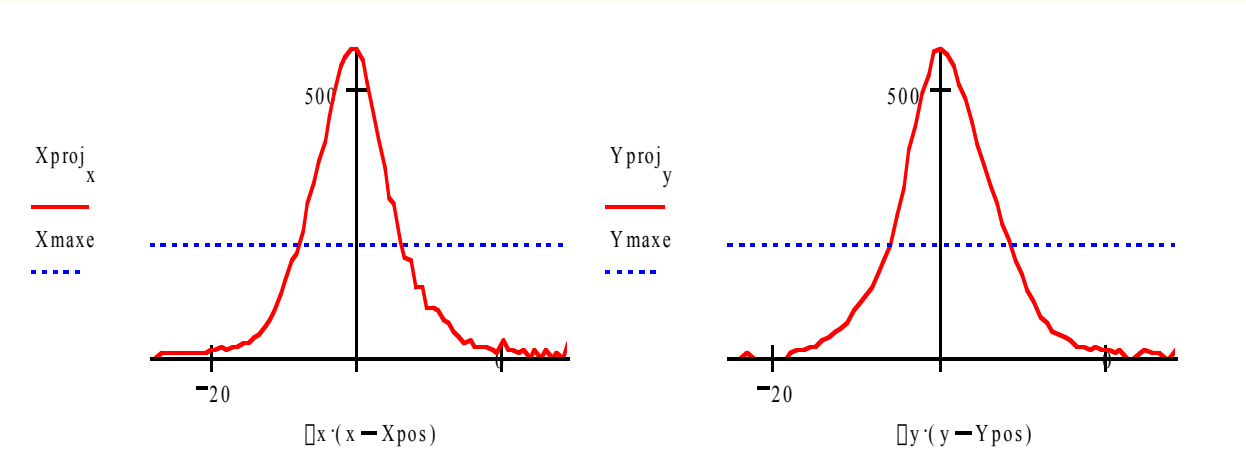
Sagitta Inc., internal doc.

# Waveguides

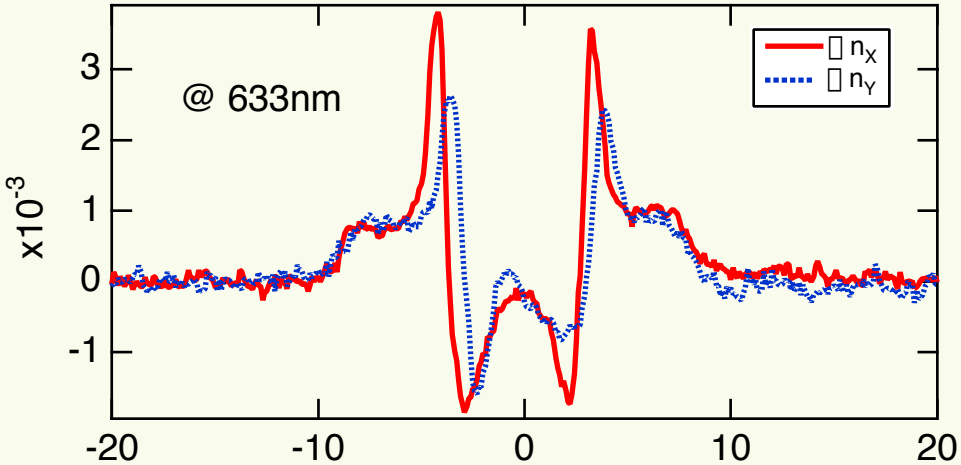
## Number of pulses vs. index of refraction

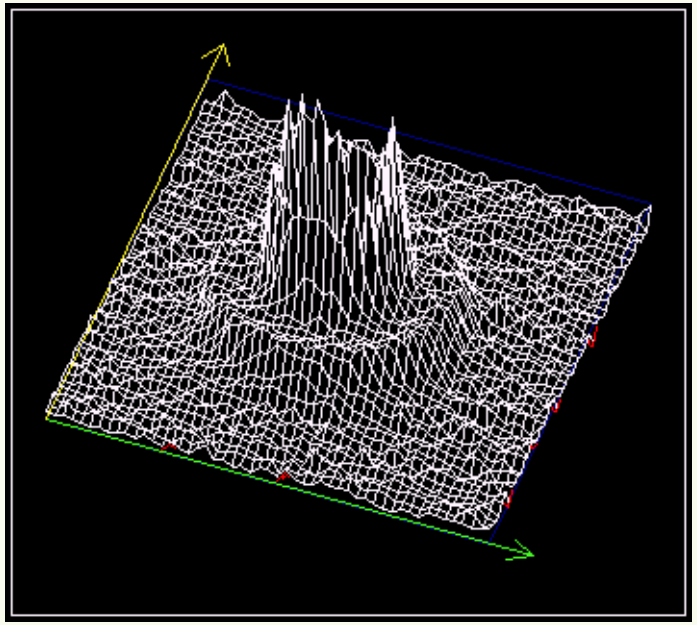
Near Field mode at 1550 nm





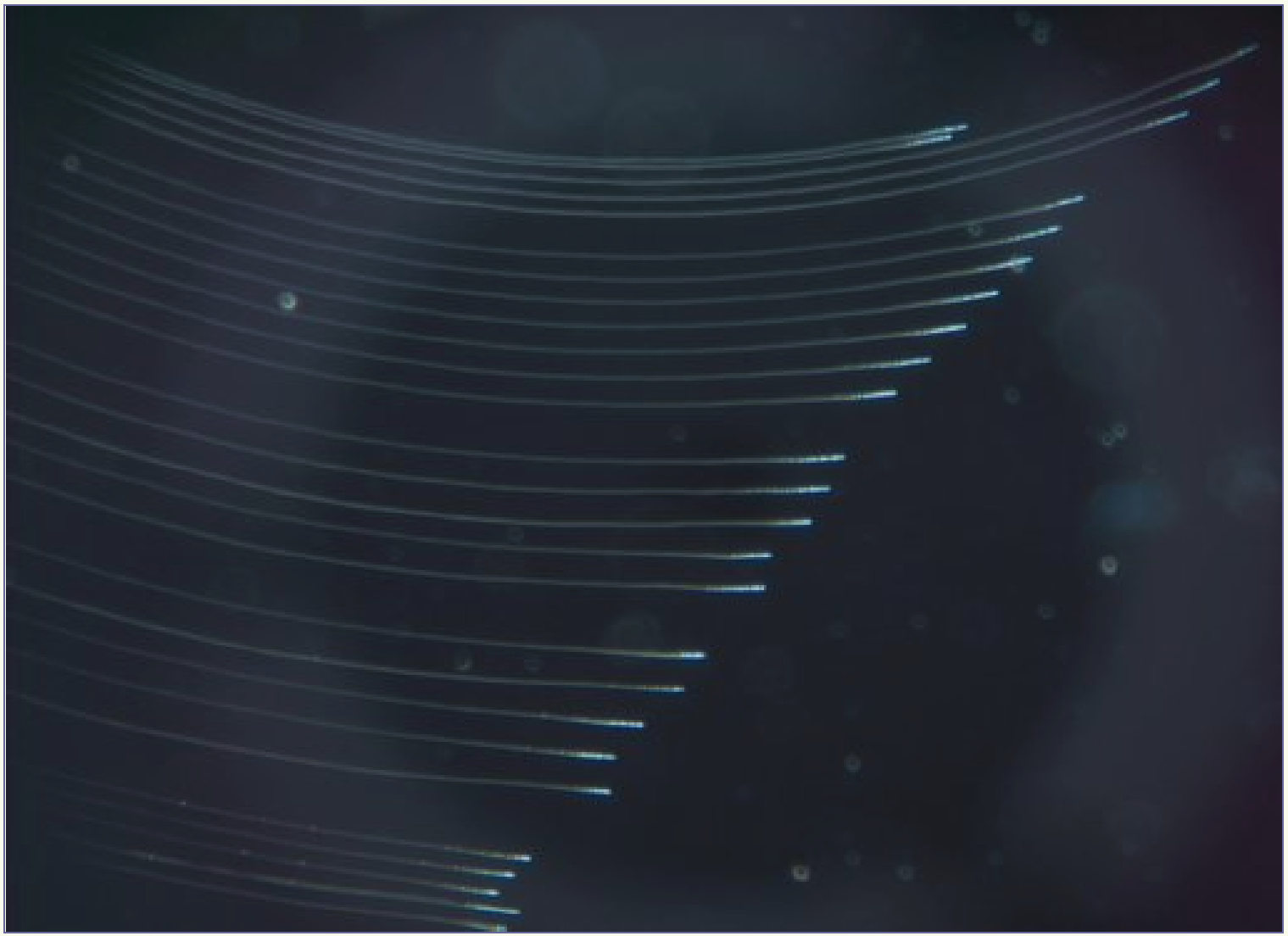

Translation speed 20 mm/s



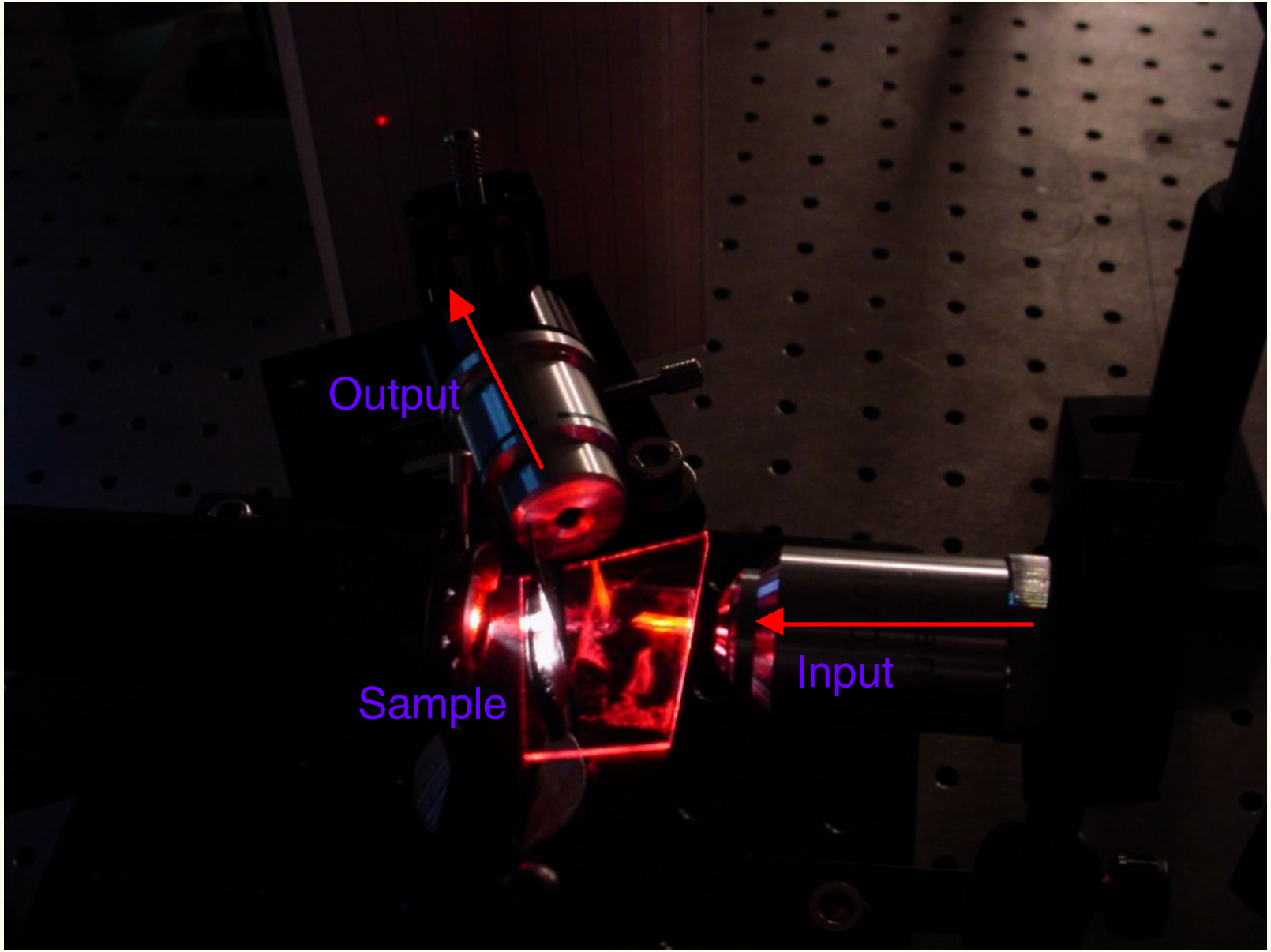
Sagitta Inc., internal doc.

# Curved Waveguides



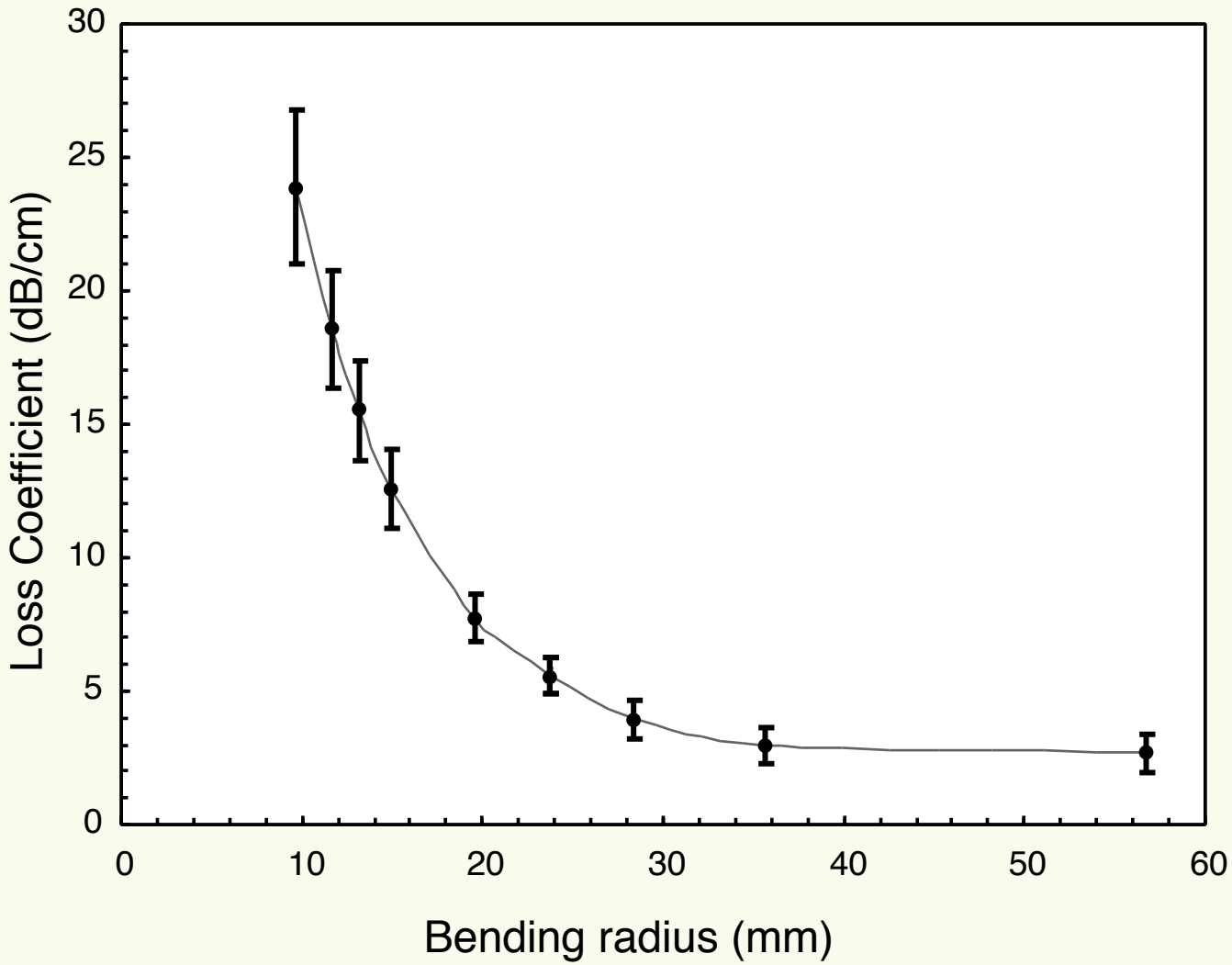
# Curved Waveguides

Bend Loss



# Curved Waveguides

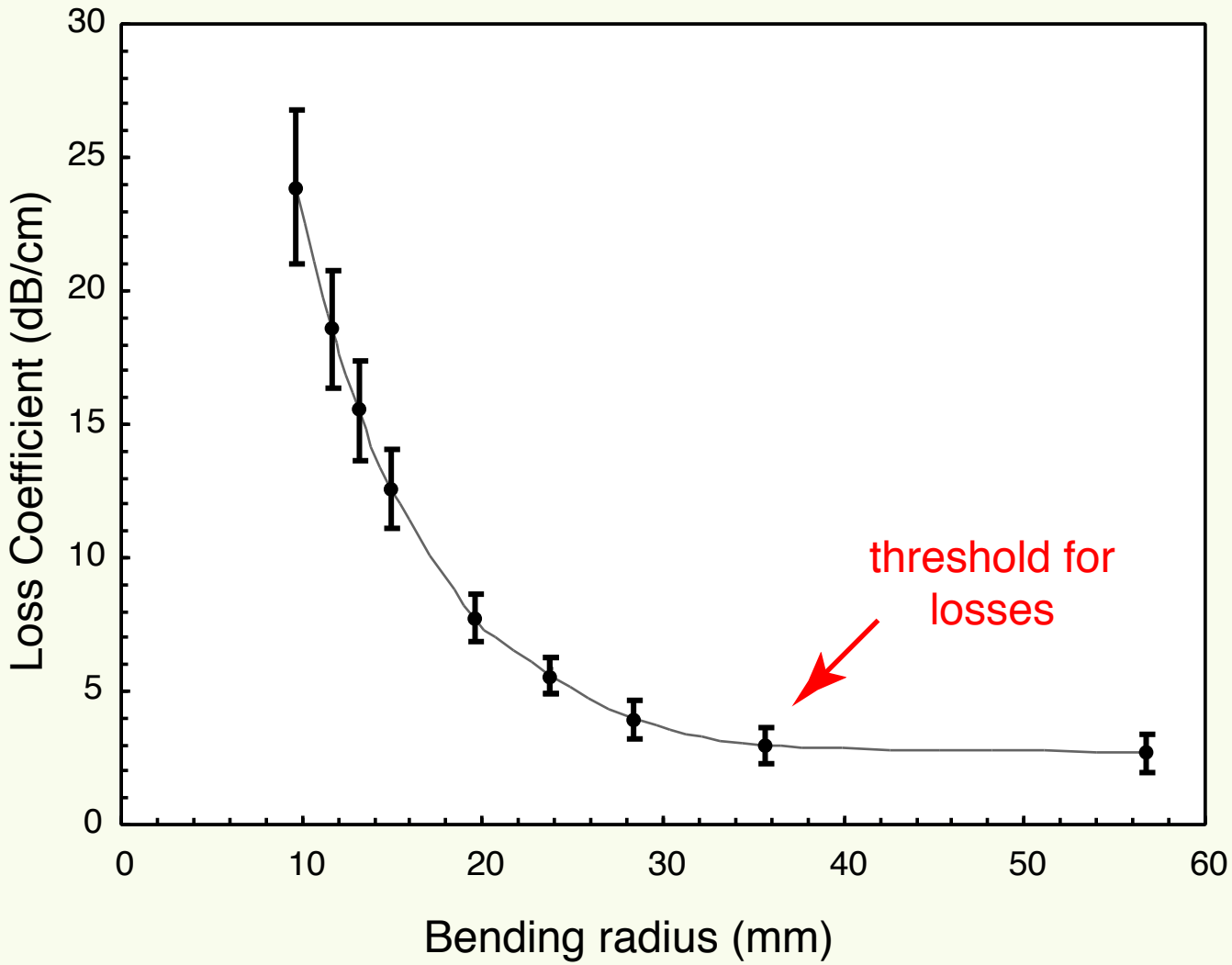
## Bend Loss




Limin Tong *et al.* submitted to Opt. Comm.

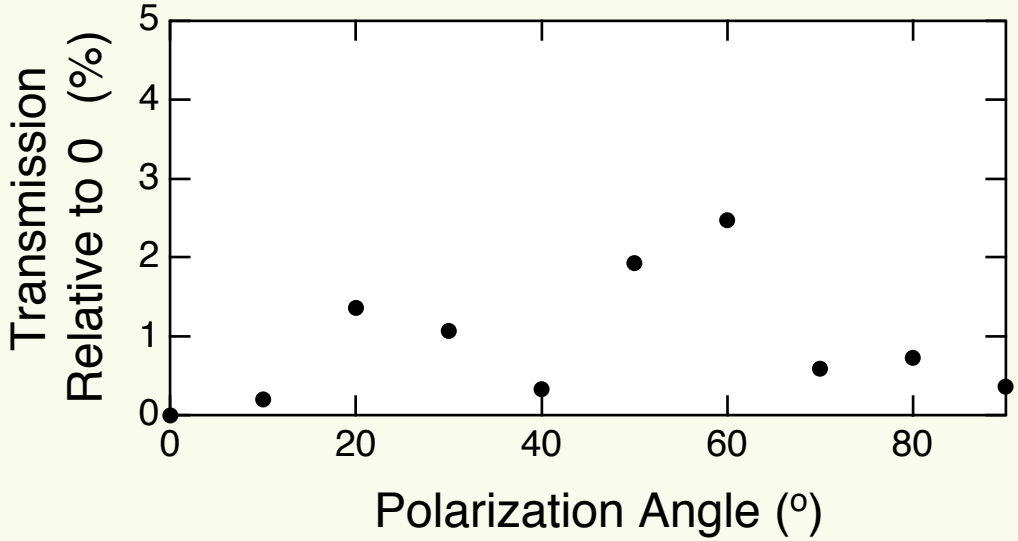
# Curved Waveguides

## Bend Loss



# Curved Waveguides

## Polarization Loss




No significant change in the polarization

Max. change 2%

# Conclusion

- nonlinear absorption in transparent media is possible
- two definite regimes of repetitive vs. cumulative thermal

- what are the underlying mechanisms
- myriad of applications

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