ULTRAFAST OPTICS

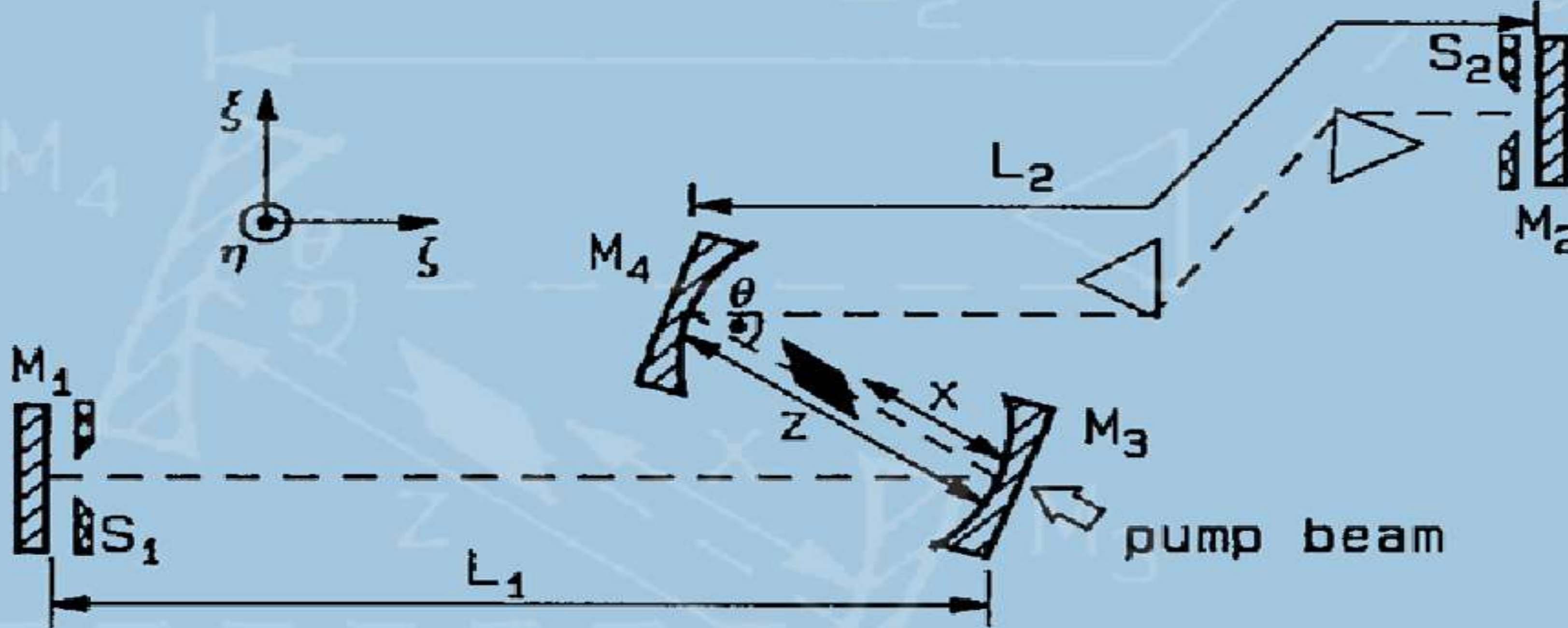


image from G. Cerulio et al., Opt. Lett. 19, 807 (1994), © OSA

by PIOTR WASYLCZYK

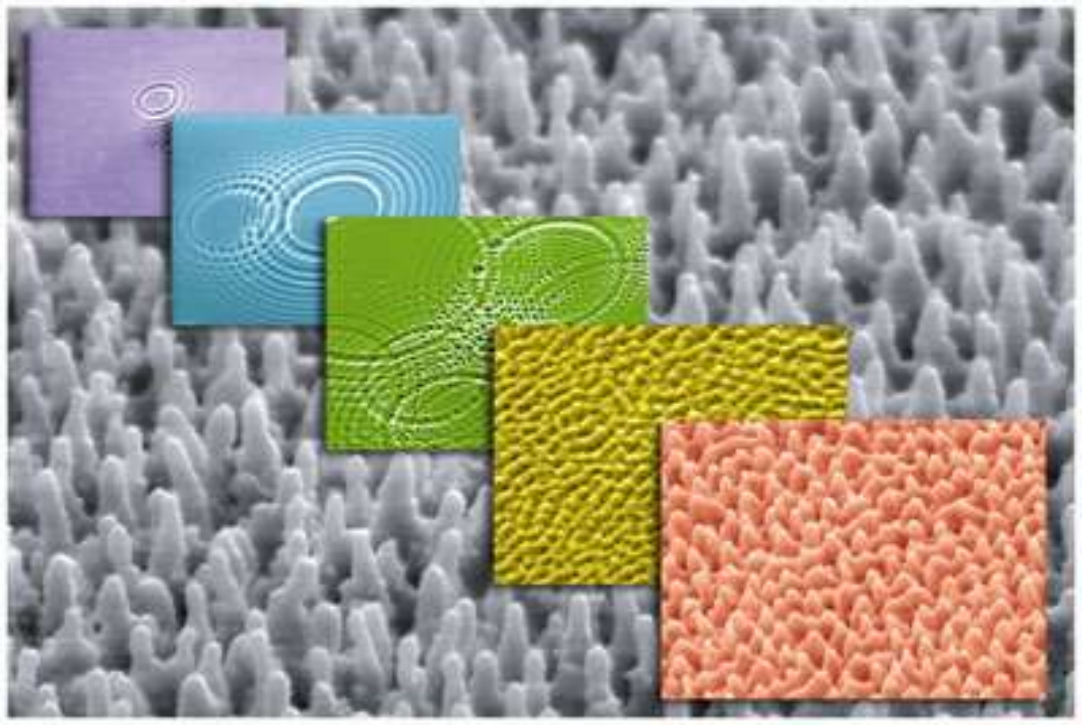
Ultrashort Laser Pulses in Micro-machining and Micro-fabrication

Why femtosecond micro-machining is a great idea

Basic properties of fs micro-machining

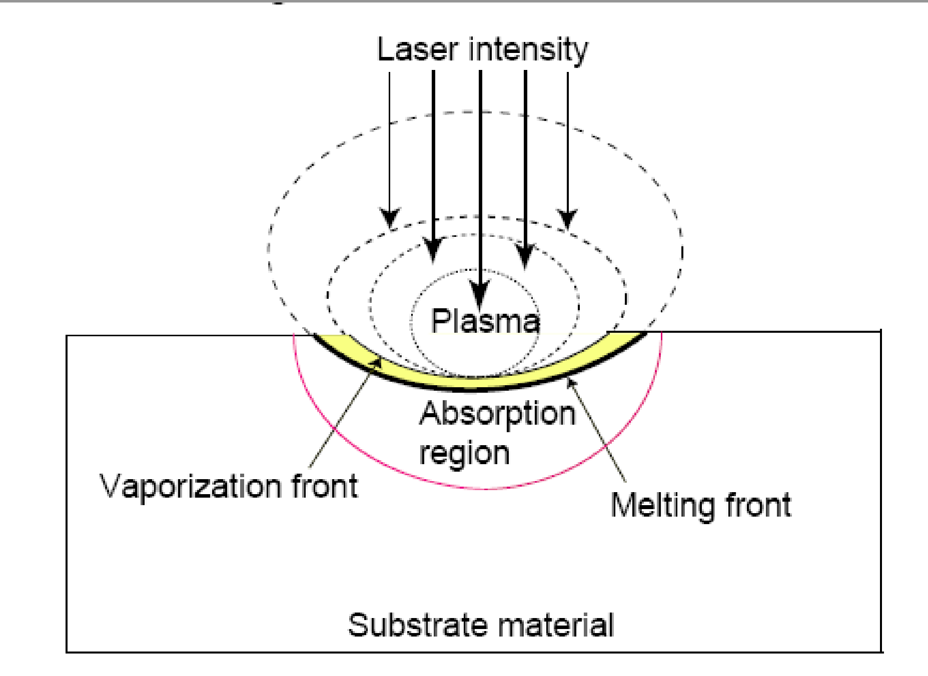
Theory

Applications



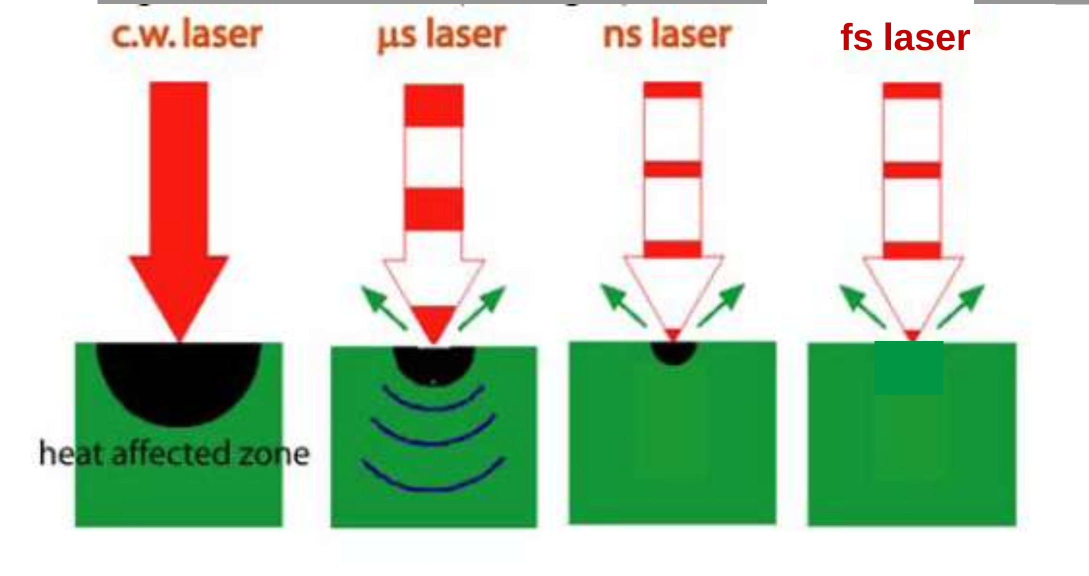
Some slides thanks to Eric Mazur, Harvard University and
M.D. Feit, A.M. Komashko, A.M. Rubenchik, *Lawrence Livermore National Laboratory*

Laser micromachining

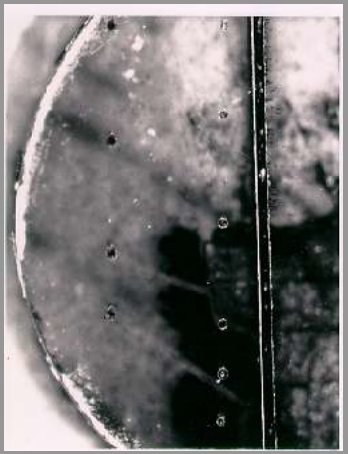


Materials:
- polymers
- metals
- semiconductors
- glass
- ceramics
- composites
- tissue

What happens depends on:
- material
- wavelength
- intensity (energy)
- pusle duration

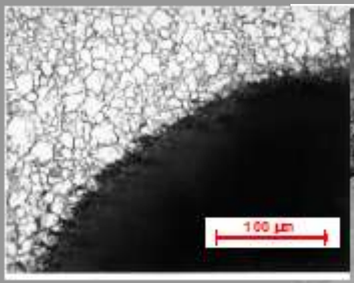


Ultrashort pulse lasers can precision machine many materials.

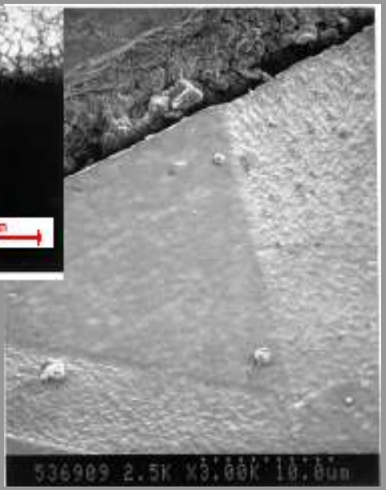


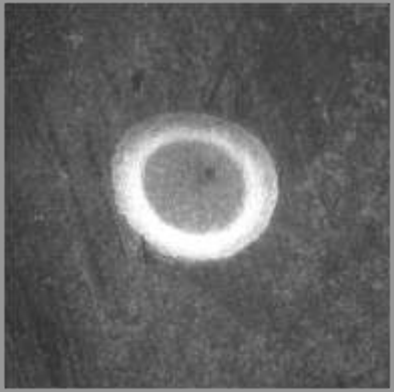
Diamond

Ceramics

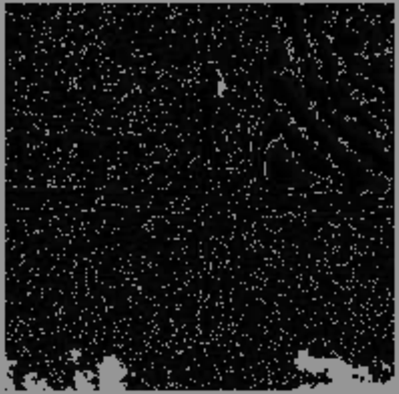


Metals





Teeth



Polymers

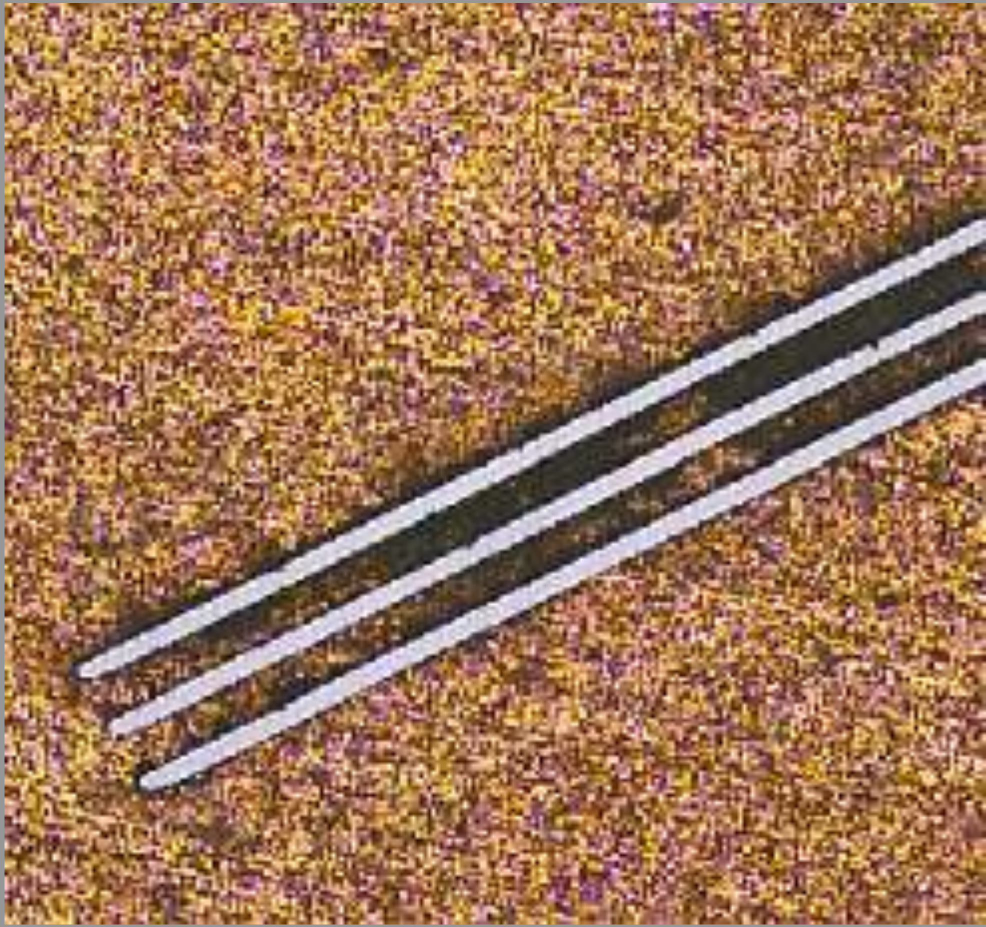
High Explosives

M.D. Feit, A.M. Komashko, A.M. Rubenchik, *Lawrence Livermore National Laboratory*

Laser micromachining

Light sources:

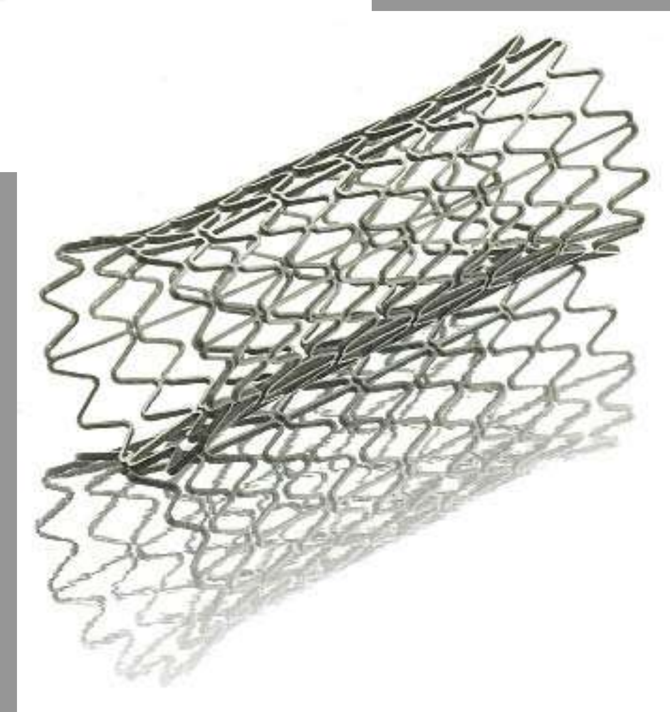
* DUV excimer lasers;
* High rep-rate UV solid-state laser;
* High rep-rate visible solid-state lasers;
* High rep rate infra-red lasers;
* Ultrafast solid-state lasers.
* Other lasers as required.



40 μm slits in 100 μm thick zirconia

Laser micromachining

stents



Ultrashort pulses are ideal for micro-machining.

Energy-deposition time is short compared to the electron-phonon time (a few ps), so thermal conduction and hydrodynamic motion are generally negligible, and ejecta carry away most of the deposited energy. As a result, there’s minimal collateral damage to remaining material.

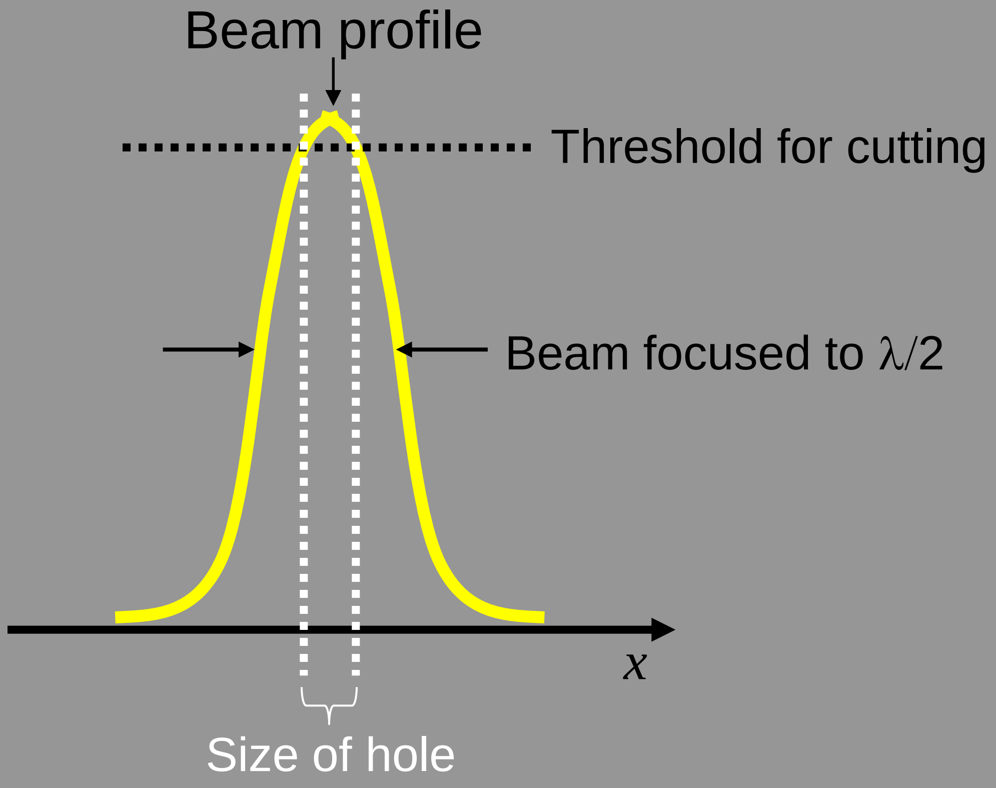
In metals, laser energy is deposited over the skin depth rather than being spread over a thermal conduction length, yielding very high energy densities, temperatures (10 eV), and pressures (Mbar) during the pulse.

In dielectrics, dielectric breakdown is seeded by electrons produced by nonlinear absorption to achieve full breakdown during the pulse.

M.D. Feit, A.M. Komashko, A.M. Rubenchik, *Lawrence Livermore National Laboratory*

Ultrashort-pulse micro-machining can make sub-wavelength holes.

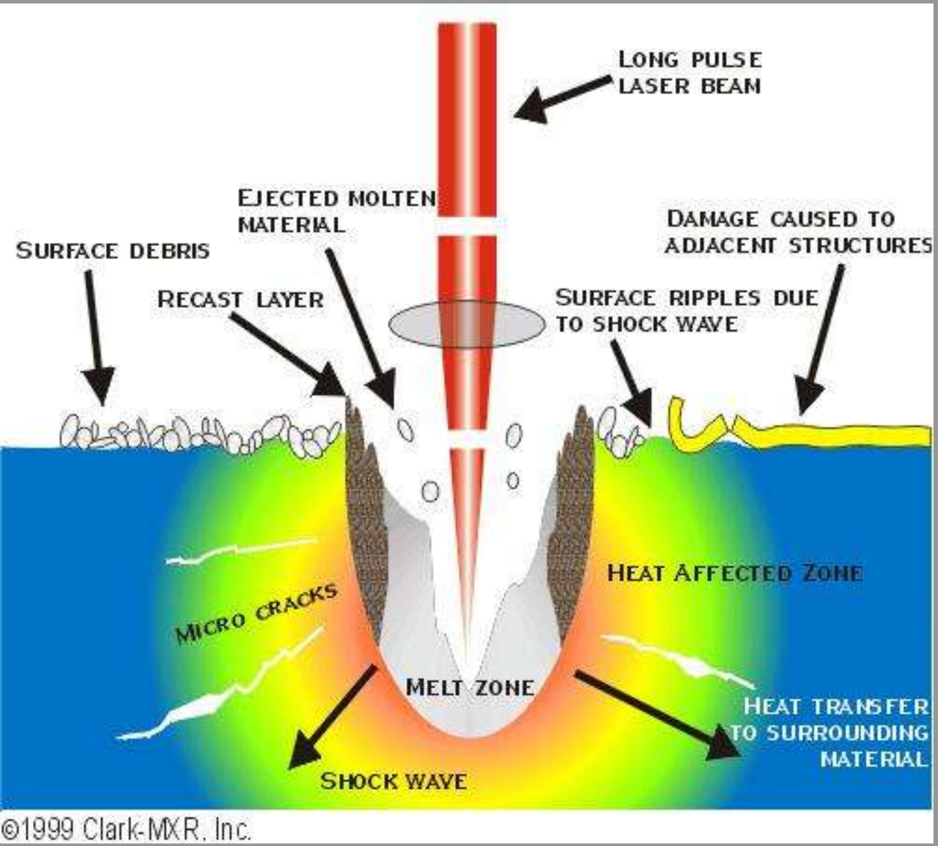
Because high-order nonlinear-optical processes are responsible for cutting, there is effectively a threshold for cutting. This means that careful control of the intensity can yield a very small hole.



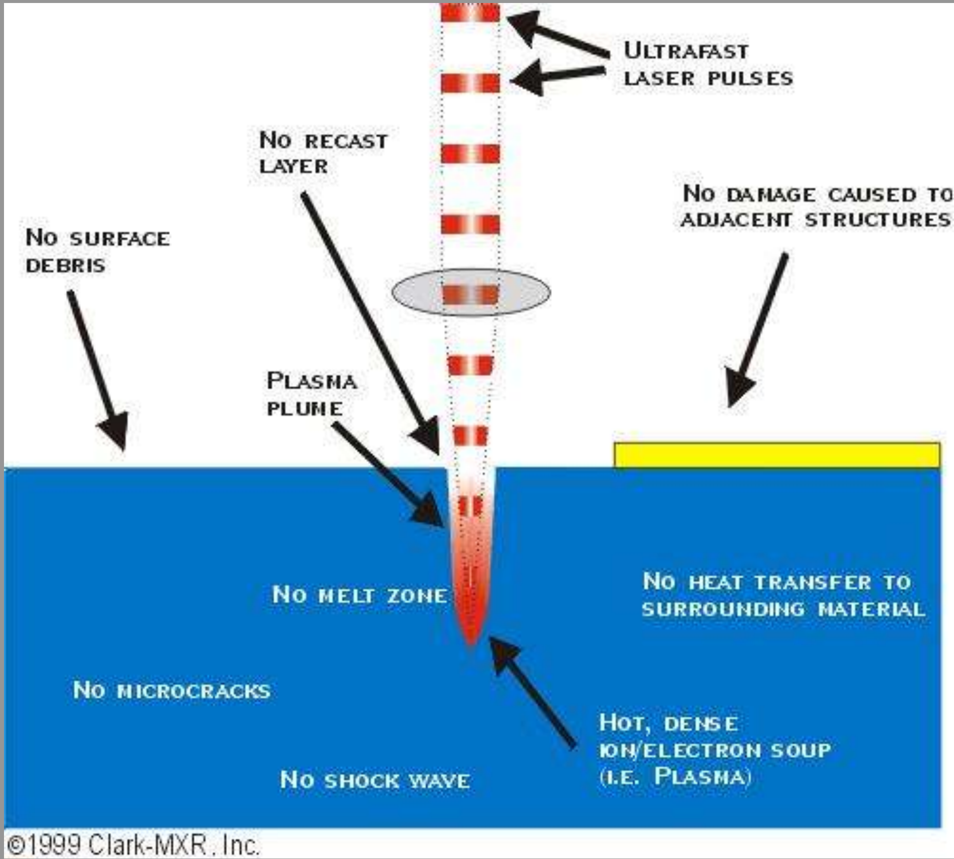
Holes as small as ~100 nm have been created.

Long- vs. short-pulse micromachining

Long pulse

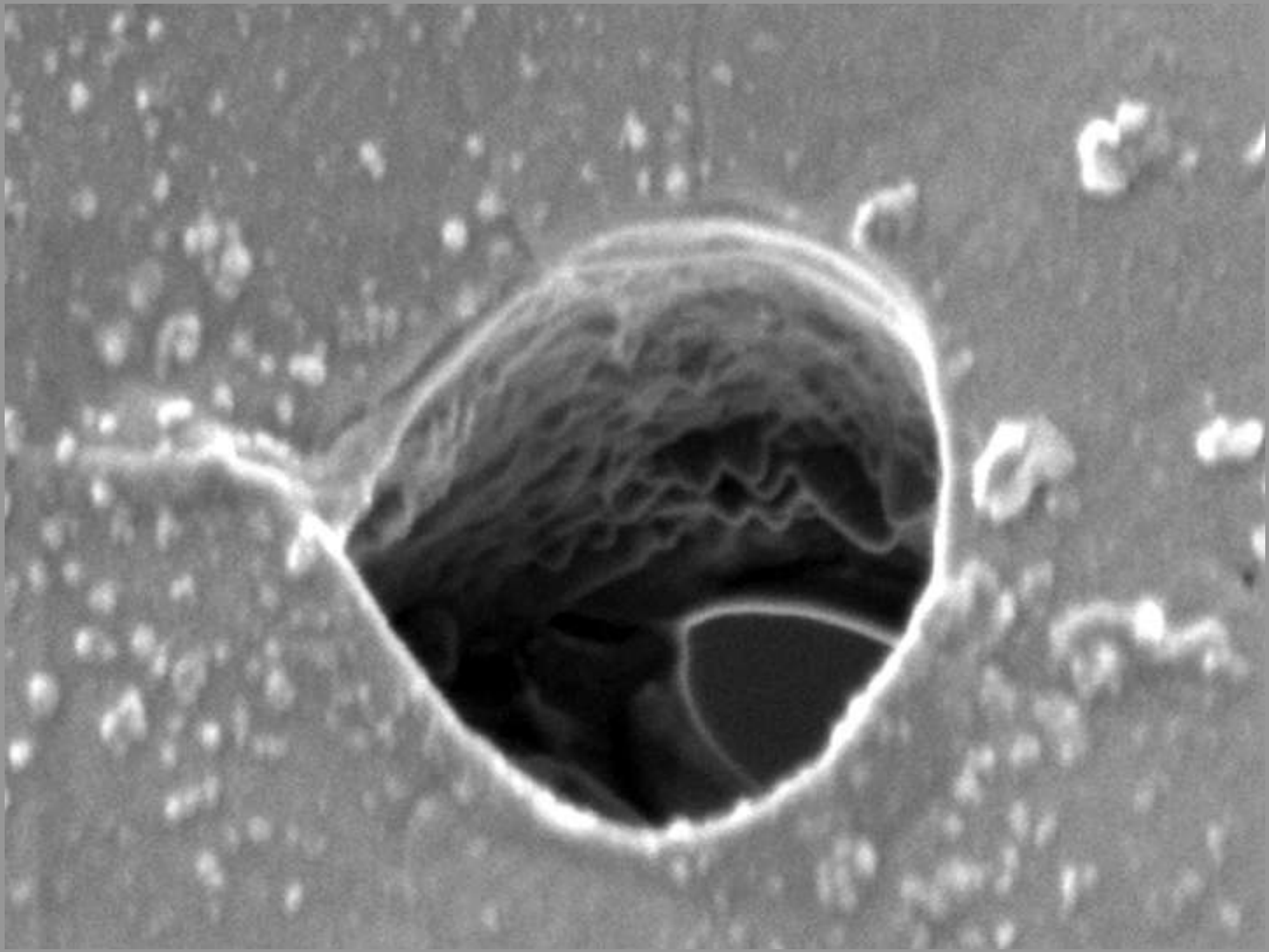


Short pulse

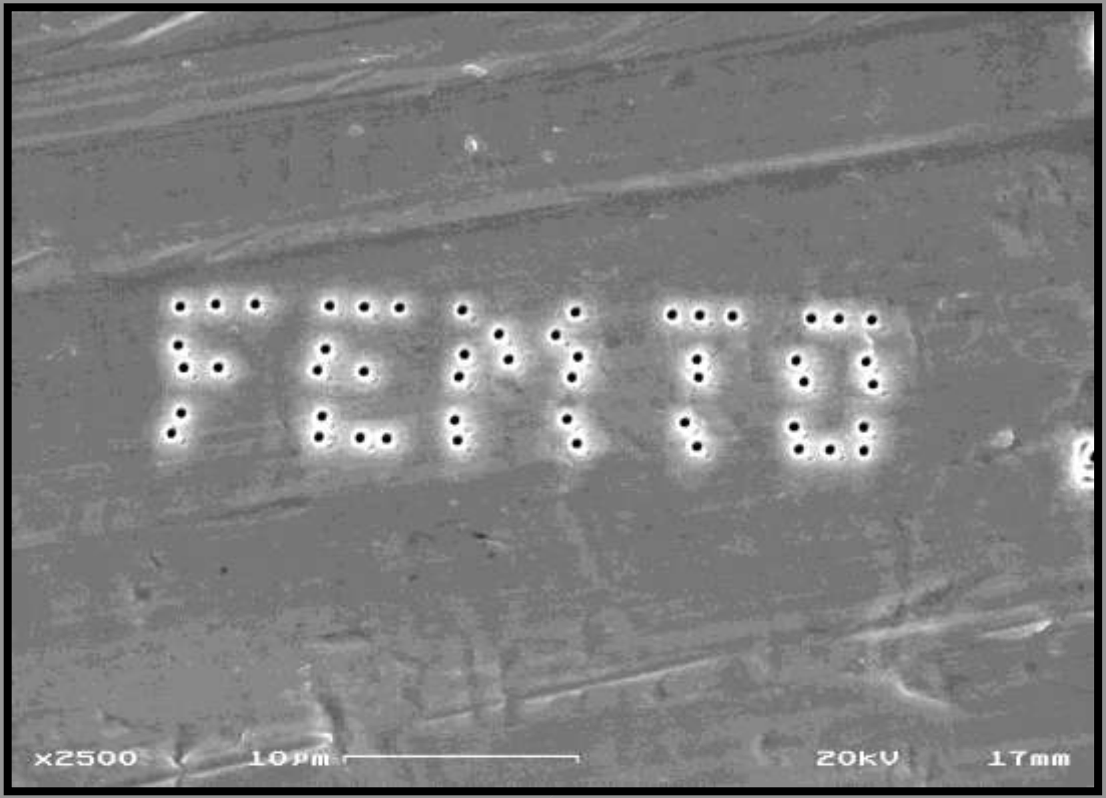


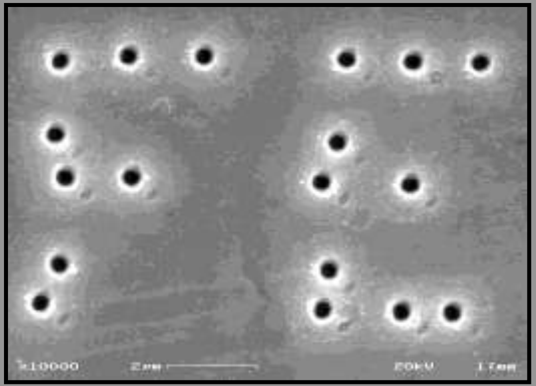
Clark-MXR web site

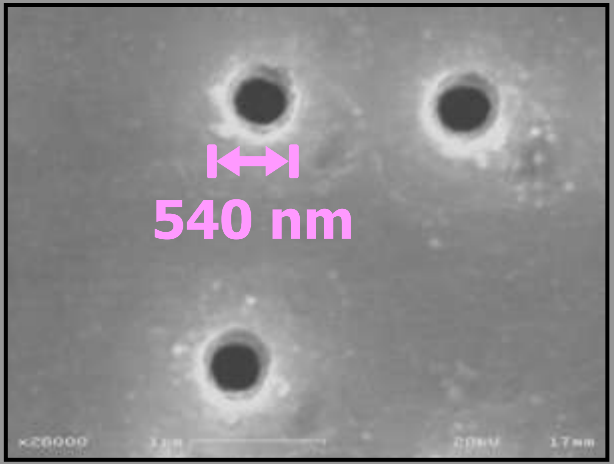
A Femtosecond-Pulse Drilled Hole



Sub-micron holes in stainless steel

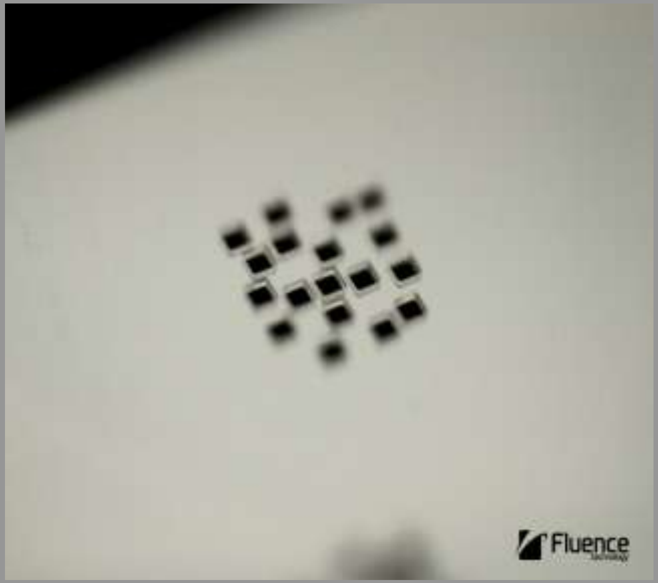




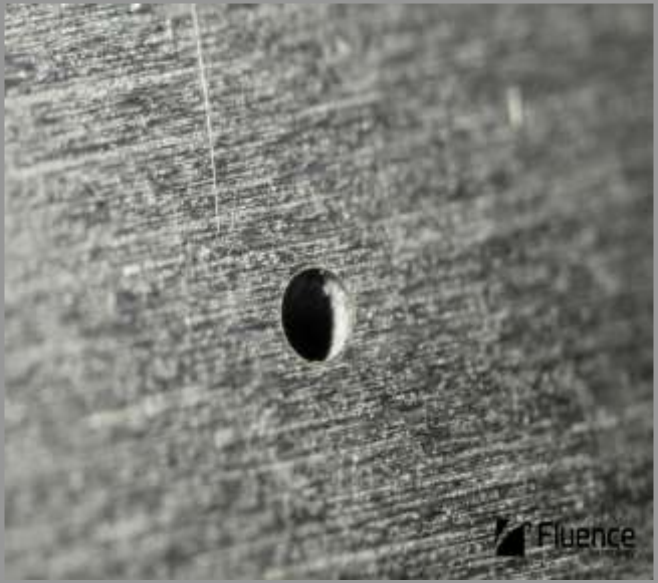


Eric Mazur, Harvard University

Cutting and drilling in the microscale



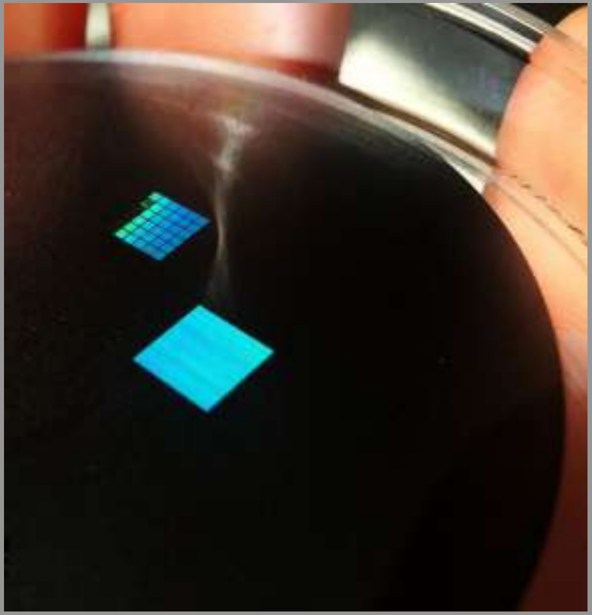
200 x 200 micron square holes in a glass coverslip

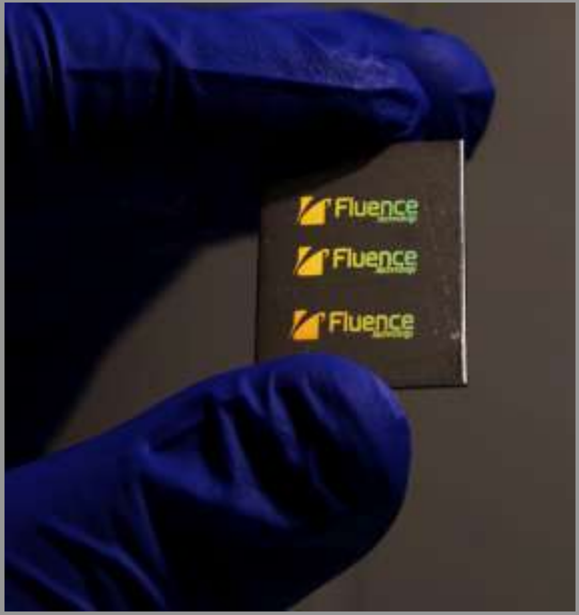


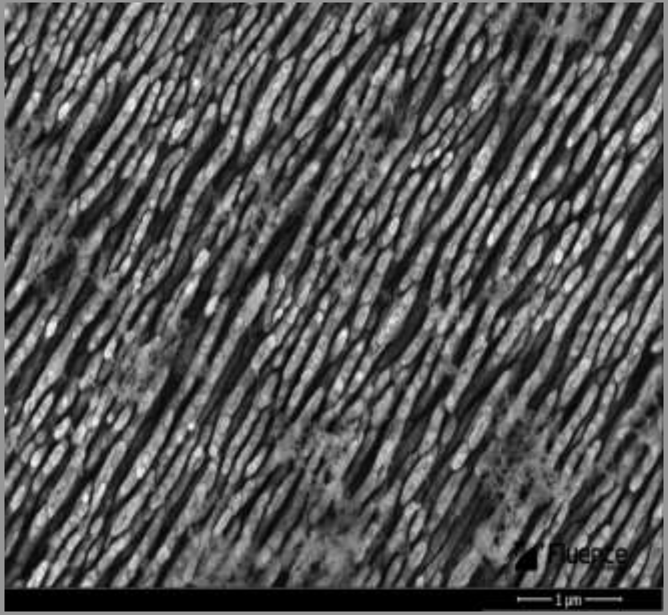
220 micron diameter hole in an aluminium alloy

Fluence .technology

Microstructuring of surfaces



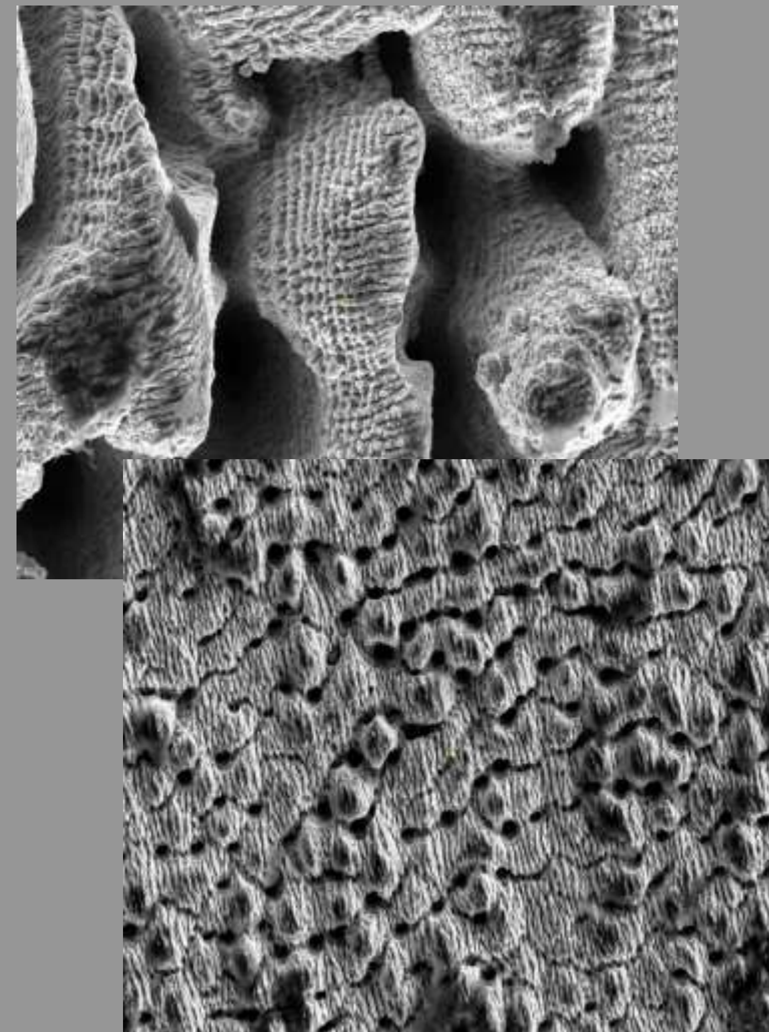




Structural colours due to self-organizing structures on silicon and steel.

Fluence .technology

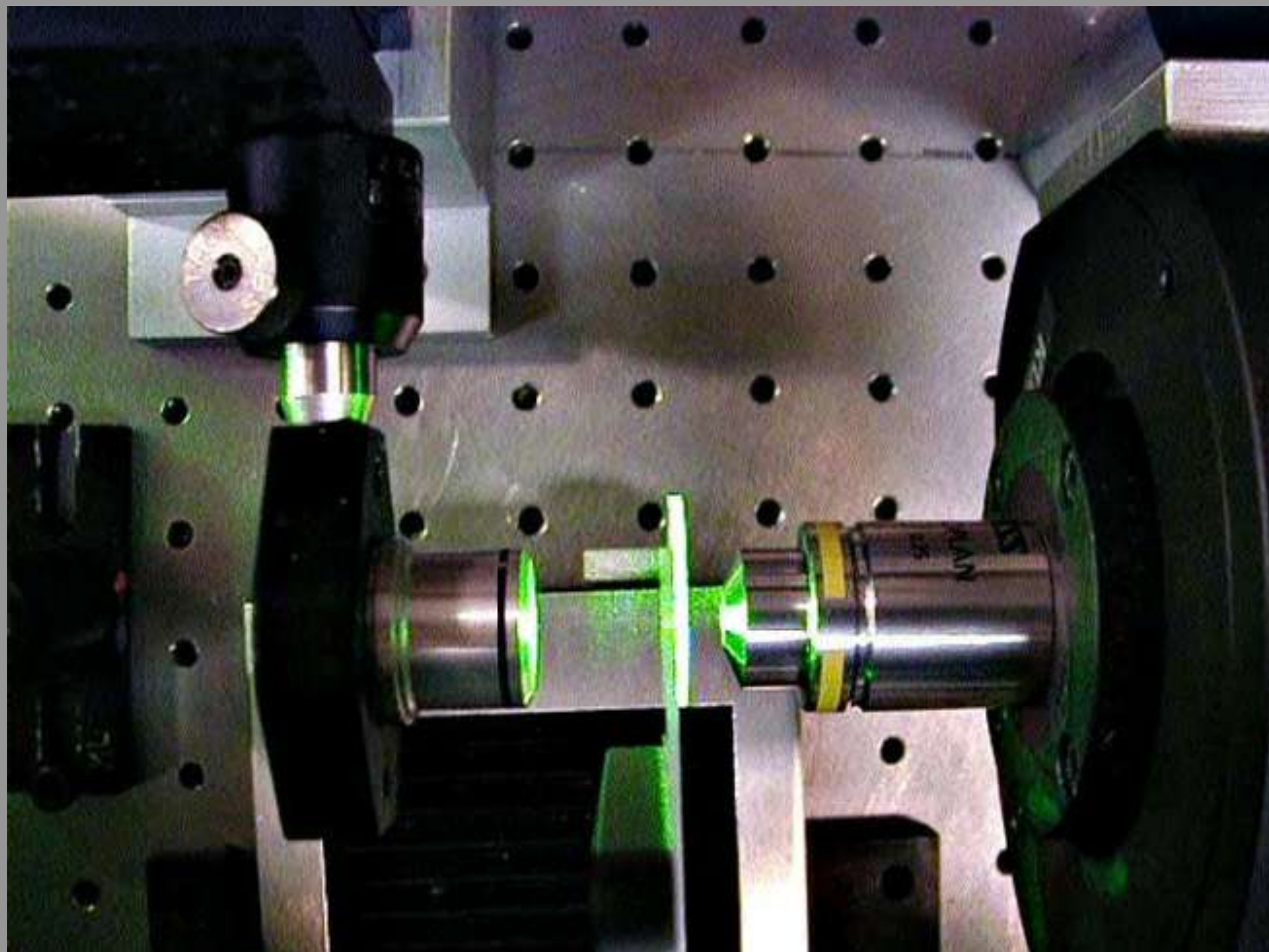
Making metals black and superhydrofobic



Up to 98% absorption across UV to NIR

Fluence
.technology

Ultrafast machining set up



Not much to it!

Things can get mighty hot at the focus of even a fairly low-energy fs pulse!

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!

Eric Mazur, Harvard University

Not to mention the pressure…

What pressure?

Treat ionized material as an ideal gas:

$$pV = nRT$$

Gives

$$p = 10\ \text{MBar!}$$

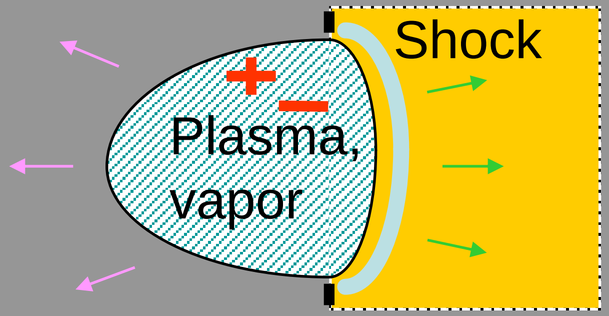
It’s almost as if it’s inside the sun…

	microexplosion	sun
T	$\approx$1 MK	2–15 MK
p	$\approx$10 MBar	
ρ	2.2×10^3 kg/m^3	$0.15–150 \times 10^3$ kg/m^3

Our physical understanding of ultrashort-pulse micro-machining is incomplete.

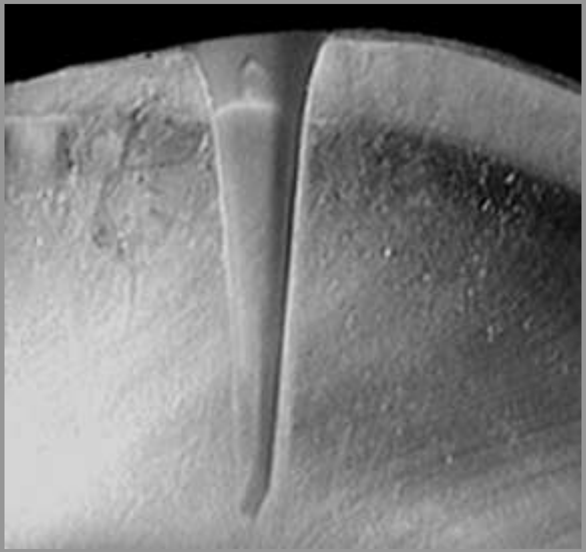
One of the main features is very localized energy deposition resulting in low collateral damage, allowing high precision material drilling.

Factors include: laser energy absorption, material ionization and expansion, shock wave propagation, thermal and radiation transport. More complete description would require addition of phase transitions, chemical reactions, material strength, material re-deposition and much more.

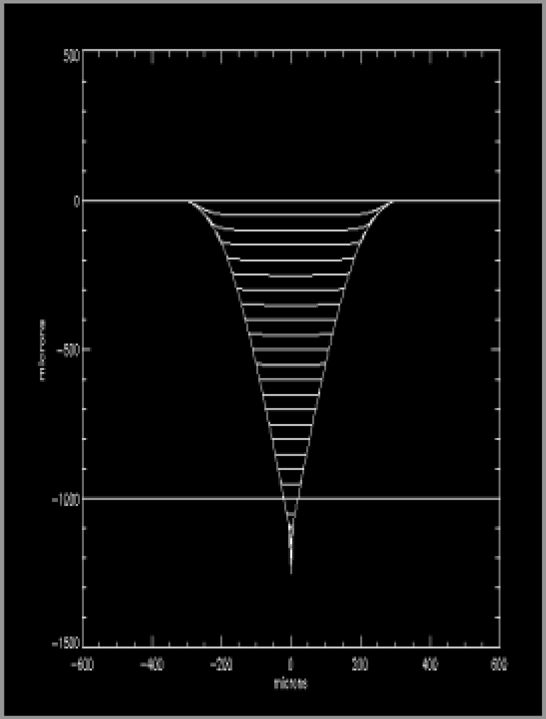


M.D. Feit, A.M. Komashko, A.M. Rubenchik, *Lawrence Livermore National Laboratory*

Hole shape and depth in dielectrics can be predicted.



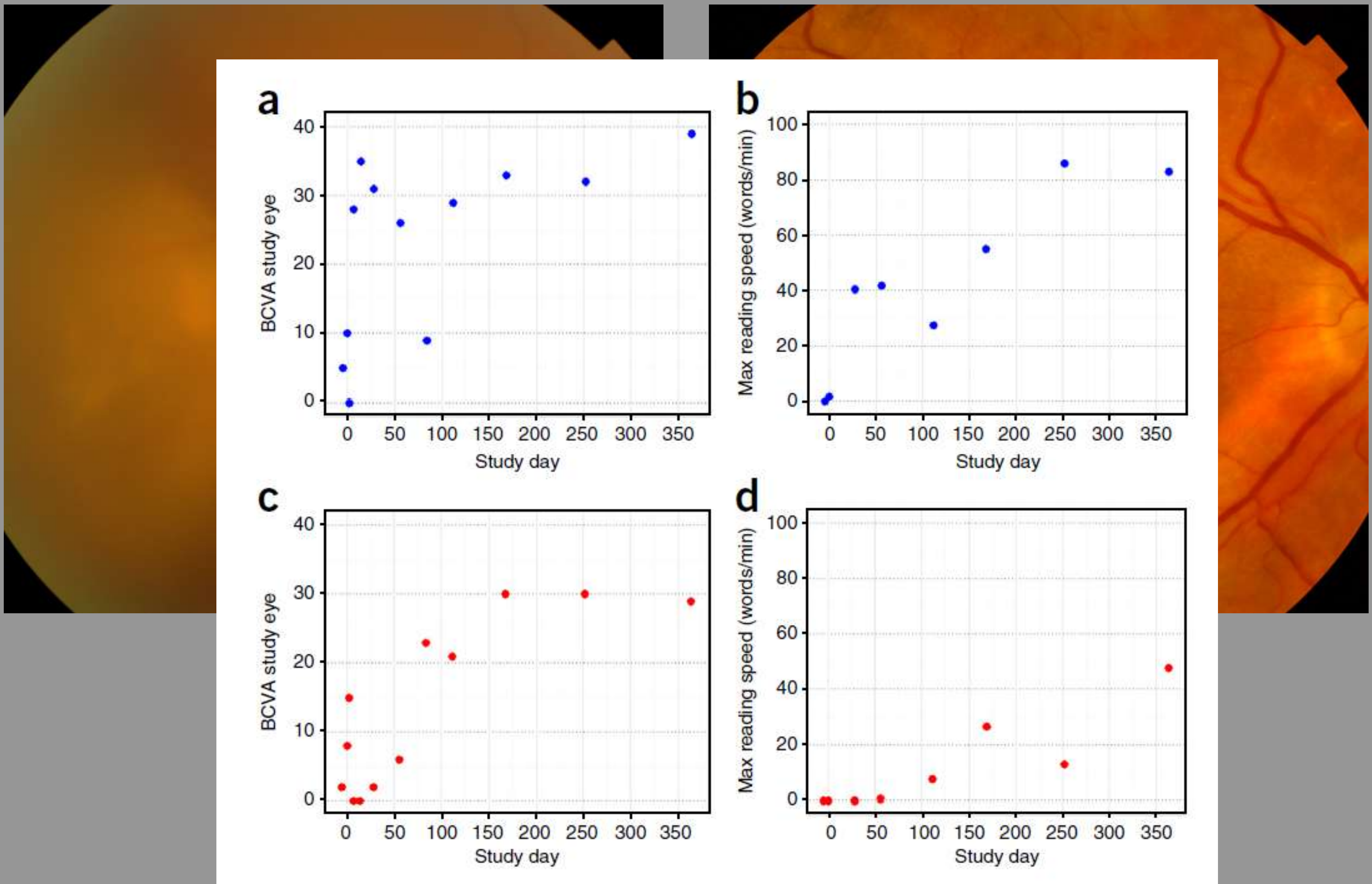
Cross section of a conical hole drilled in tooth by a fs laser system. With no thermal shock, there is no collateral damage to adjacent tissue.



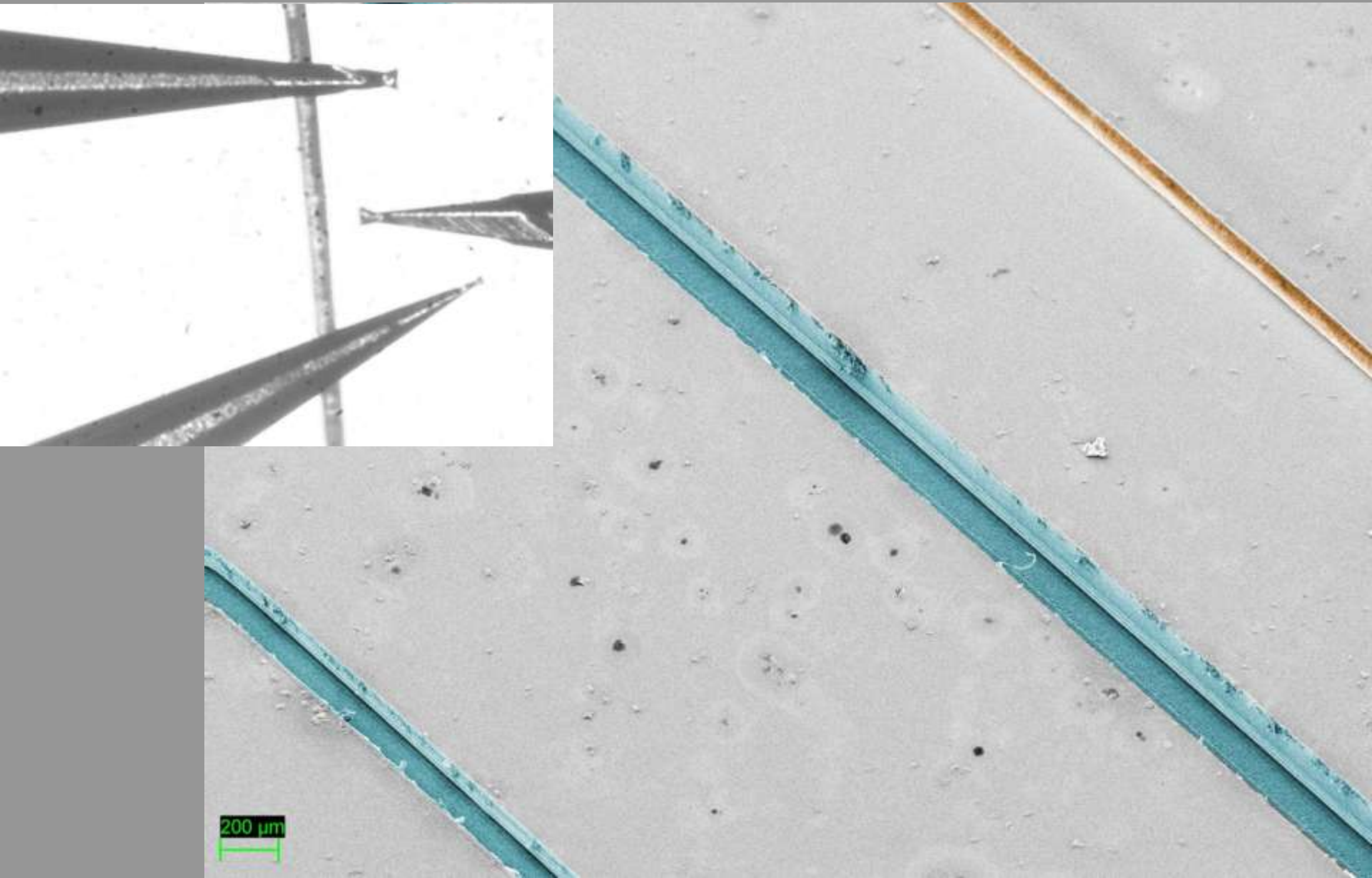
Numerical simulation of hole drilled in human dentin by train of 350 fs pulses.

M.D. Feit, A.M. Komashko, A.M. Rubenchik, *Lawrence Livermore National Laboratory*

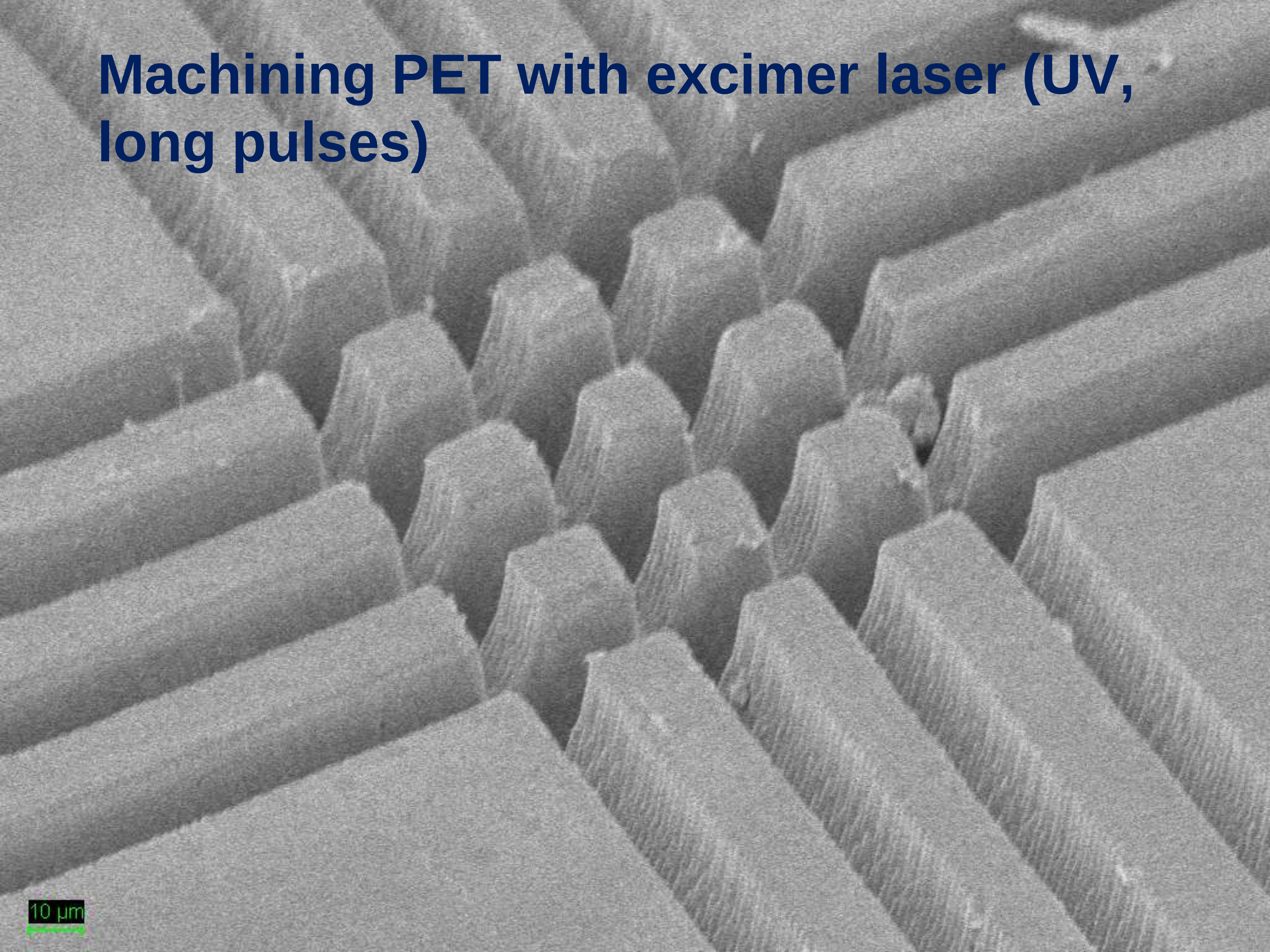
Retinal implant in AMD



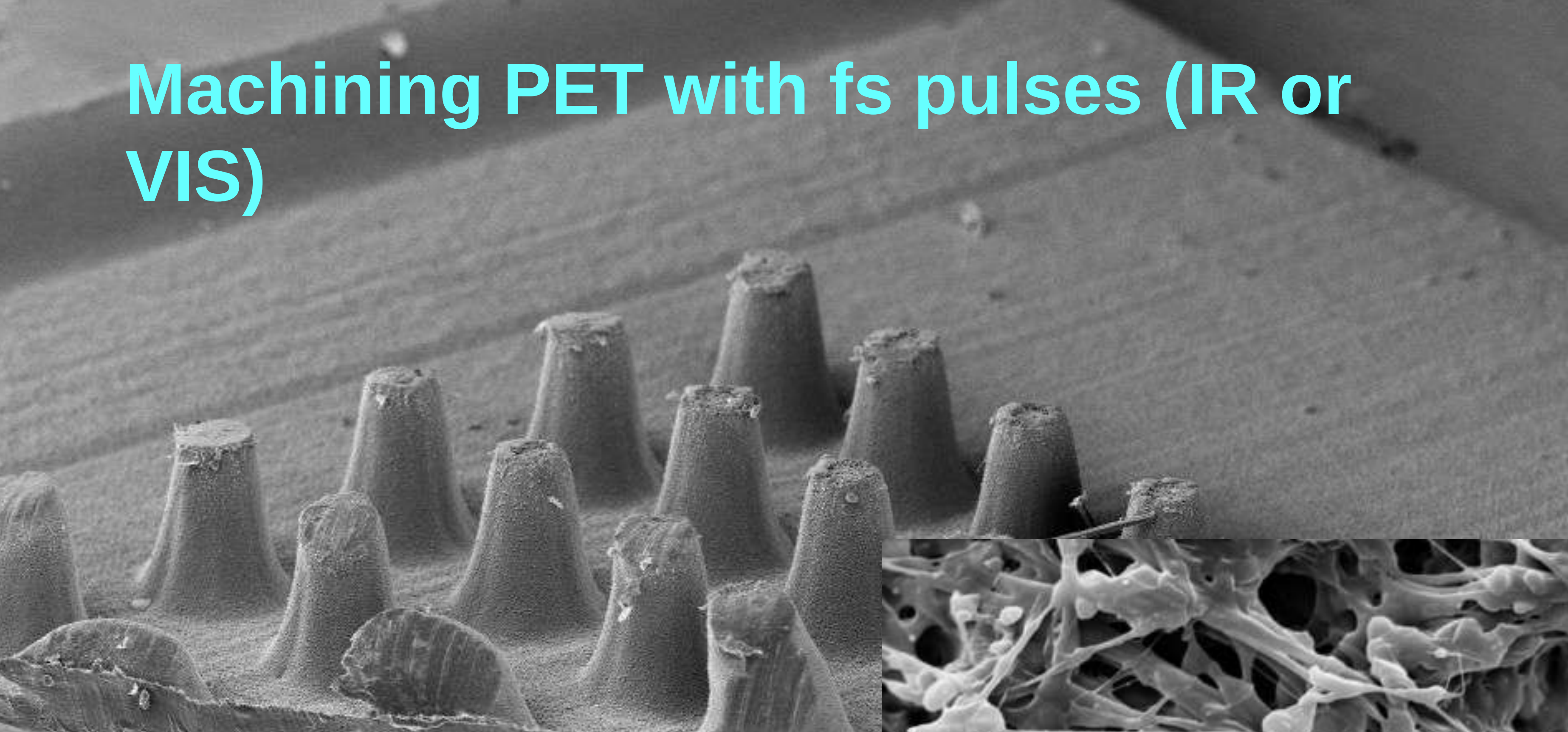
Machining PET with mechanical milling

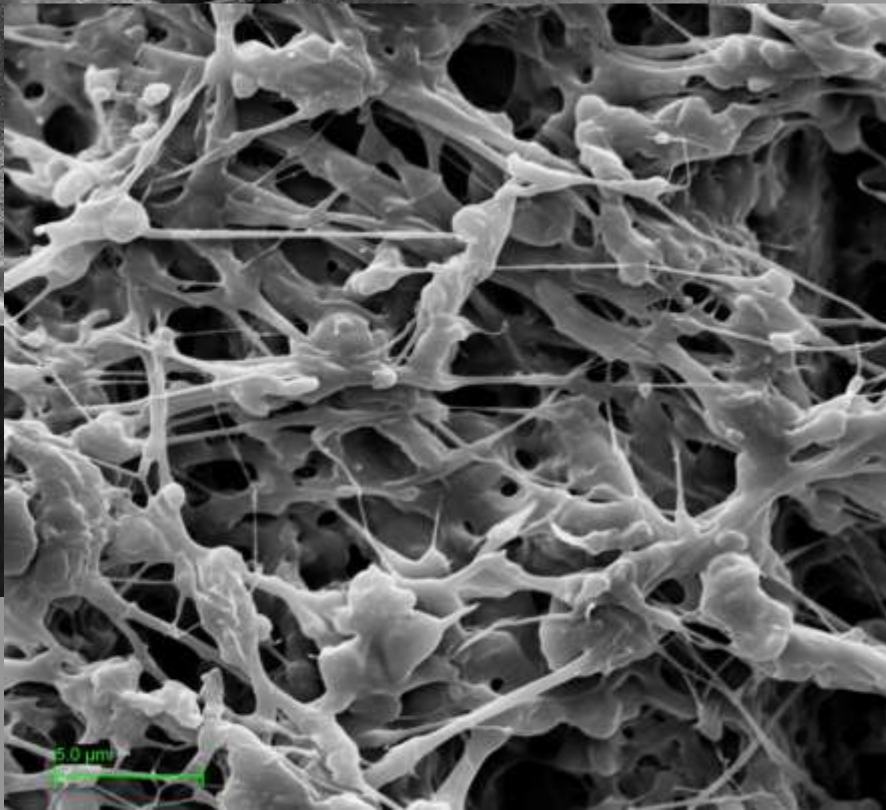


Machining PET with excimer laser (UV, long pulses)



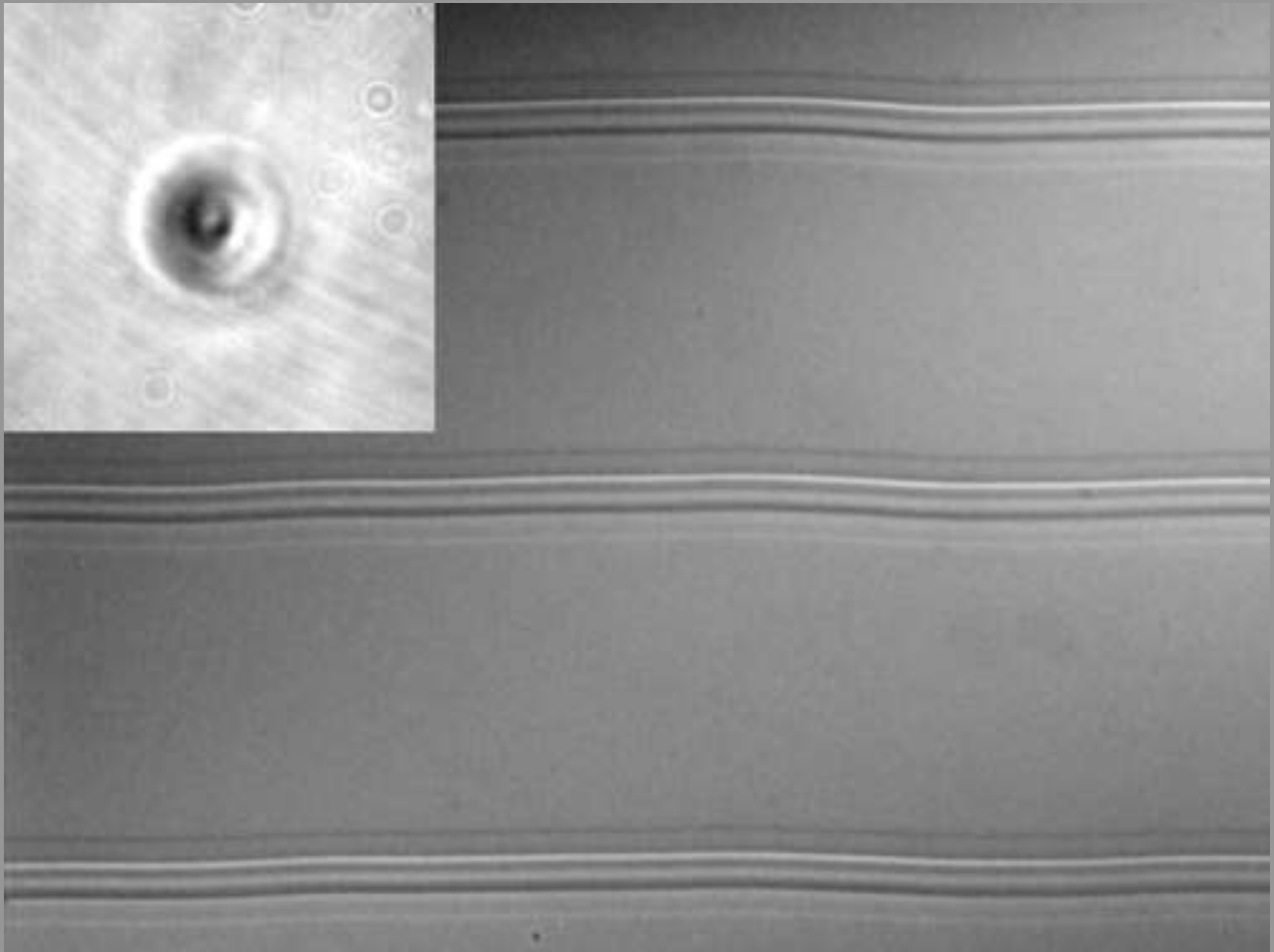
Machining PET with fs pulses (IR or VIS)





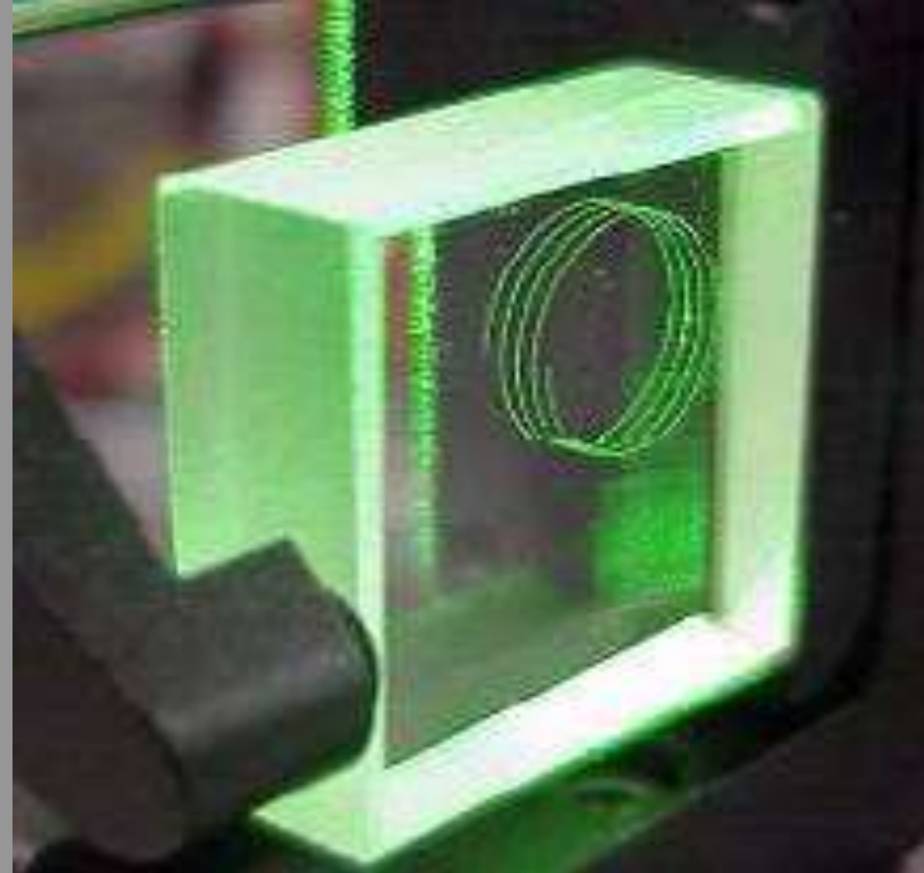
Electrospinning – material ejected
in strong E-field

2D and 3D material modifications in dielectric materials

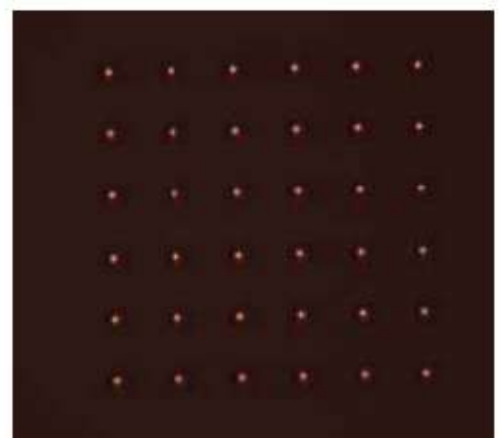


Mazur and coworkers

Waveguides in a glass block

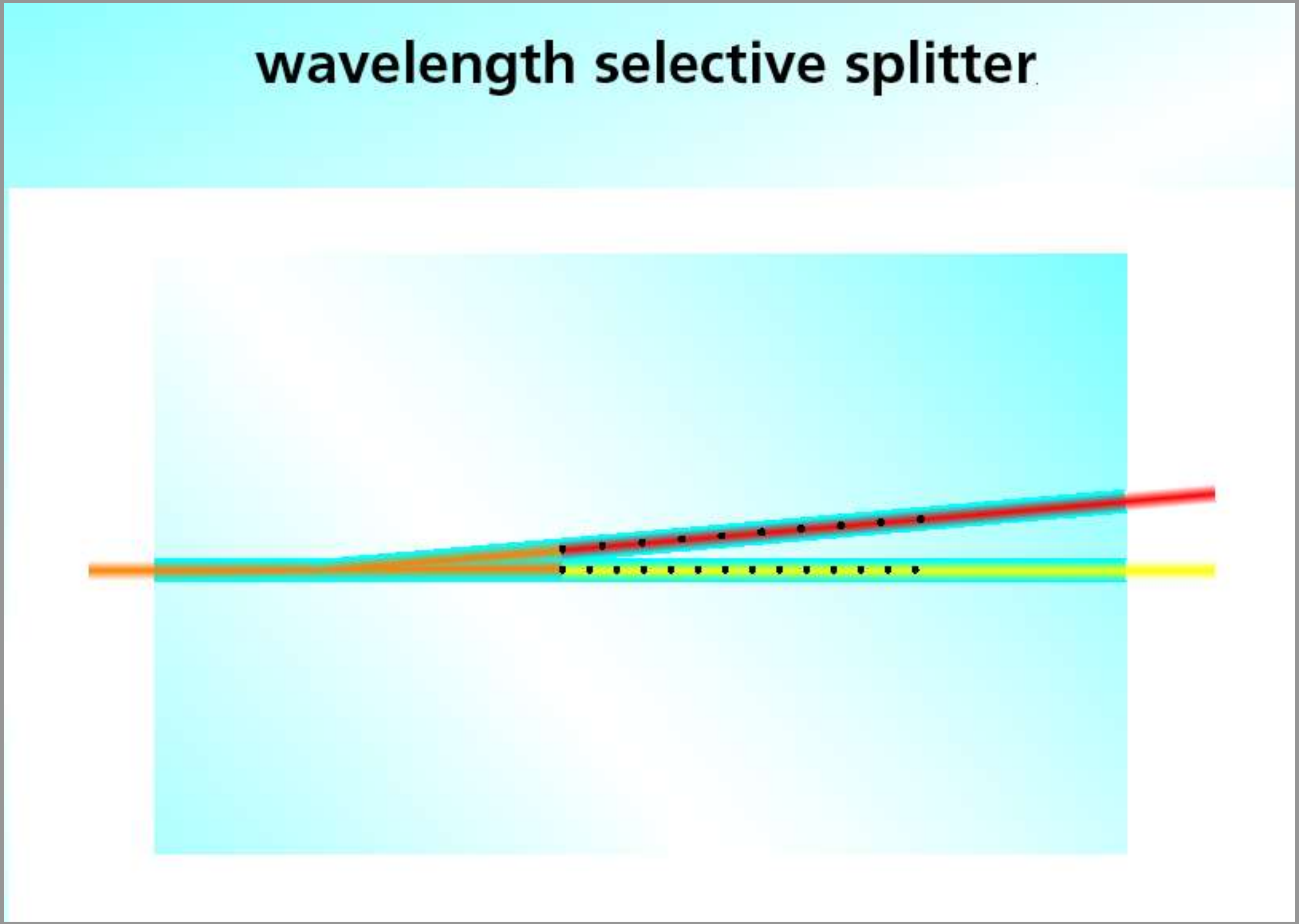


curved waveguides



6x6 waveguide array

Applications of ultrafast machining



Intralase performs vision-correction surgery using fs lasers.

Safe fs-pulse cutting of explosives and propellants confirms that absorbed energy is removed with ejecta.

Otherwise, these guys might not be here to tell us about it!

Comp B
high explosive

Double-base propellant - HPC-95
Composition:

- Nitrocellulose - 78%
- Nitroglycerin - 21%
- other - 1%

Courtesy E.Roos,LLNL

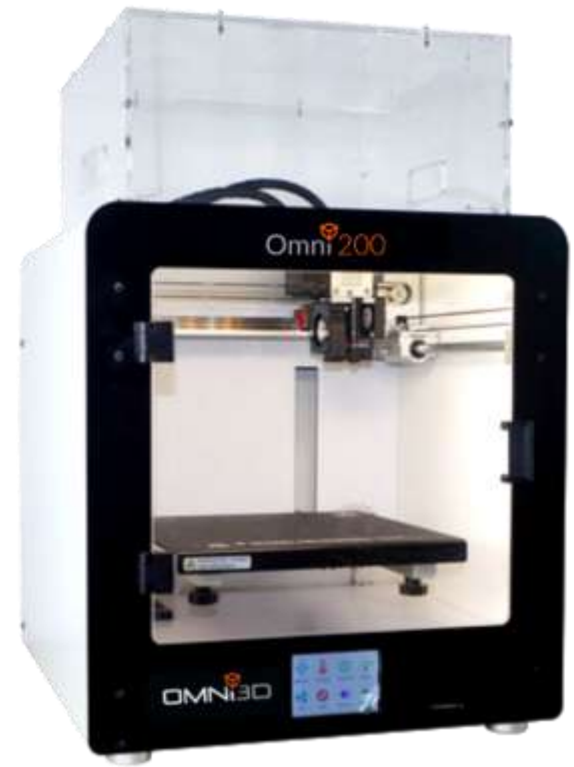
3D printing in a (very) small scale

Additive manufacturing:

- **depositing more material**

- sintering a powder

- solidifying a liquid



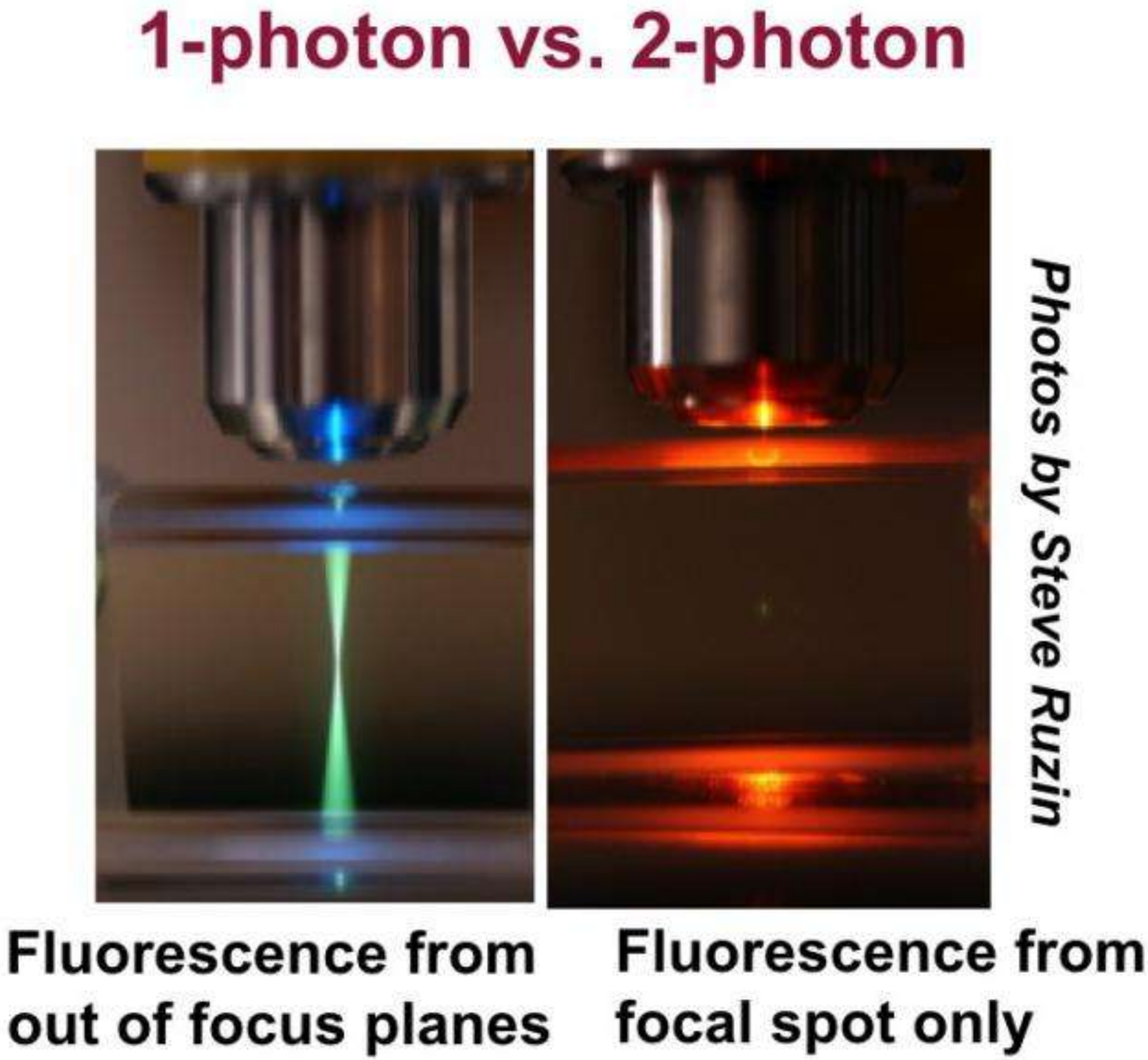
omni3D, Poznań, Poland

3D printing in a (very) small scale

Additive manufacturing:

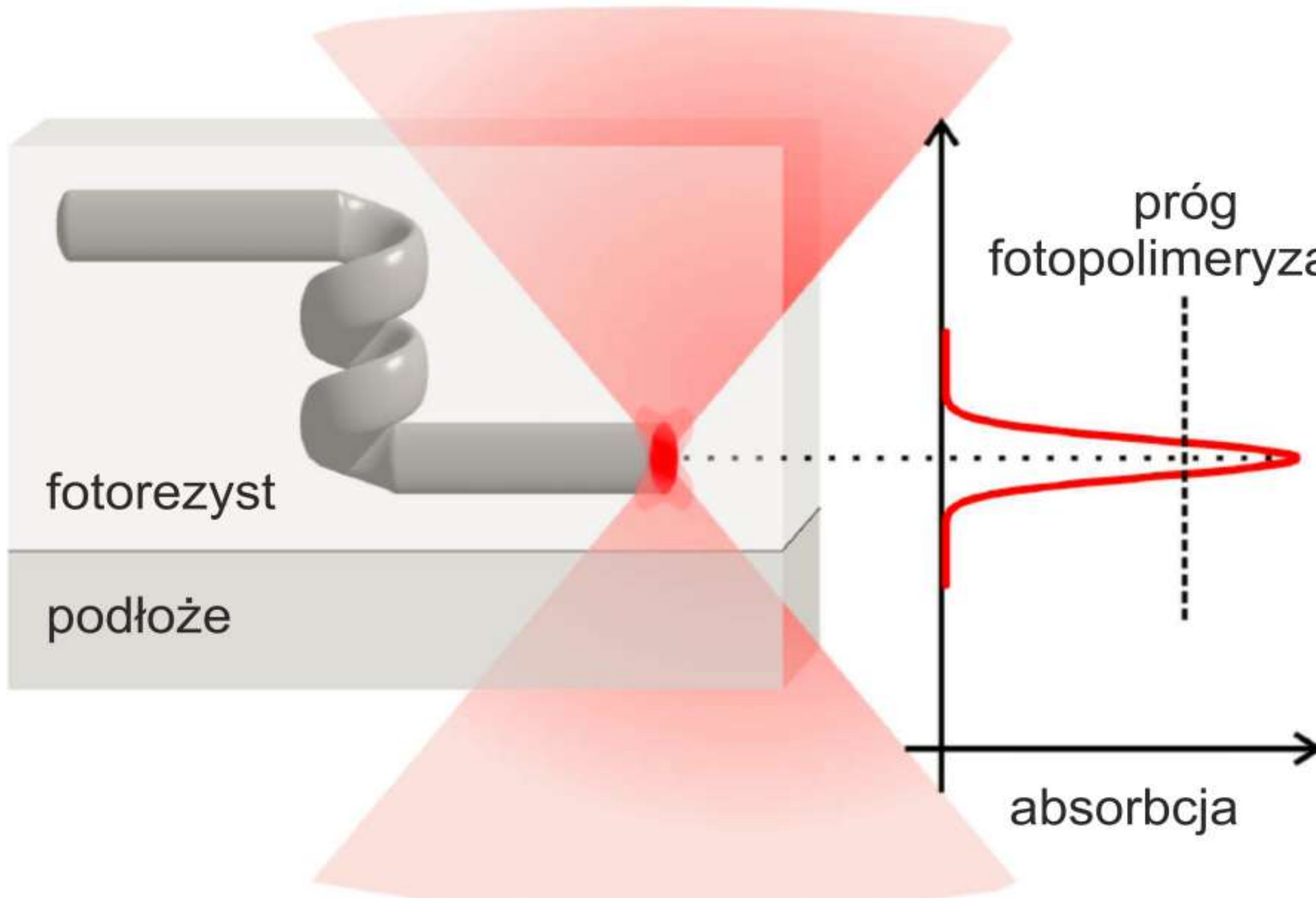
- depositing more material
- sintering a powder
- **solidifying a liquid**

Sub-micron 3D printing

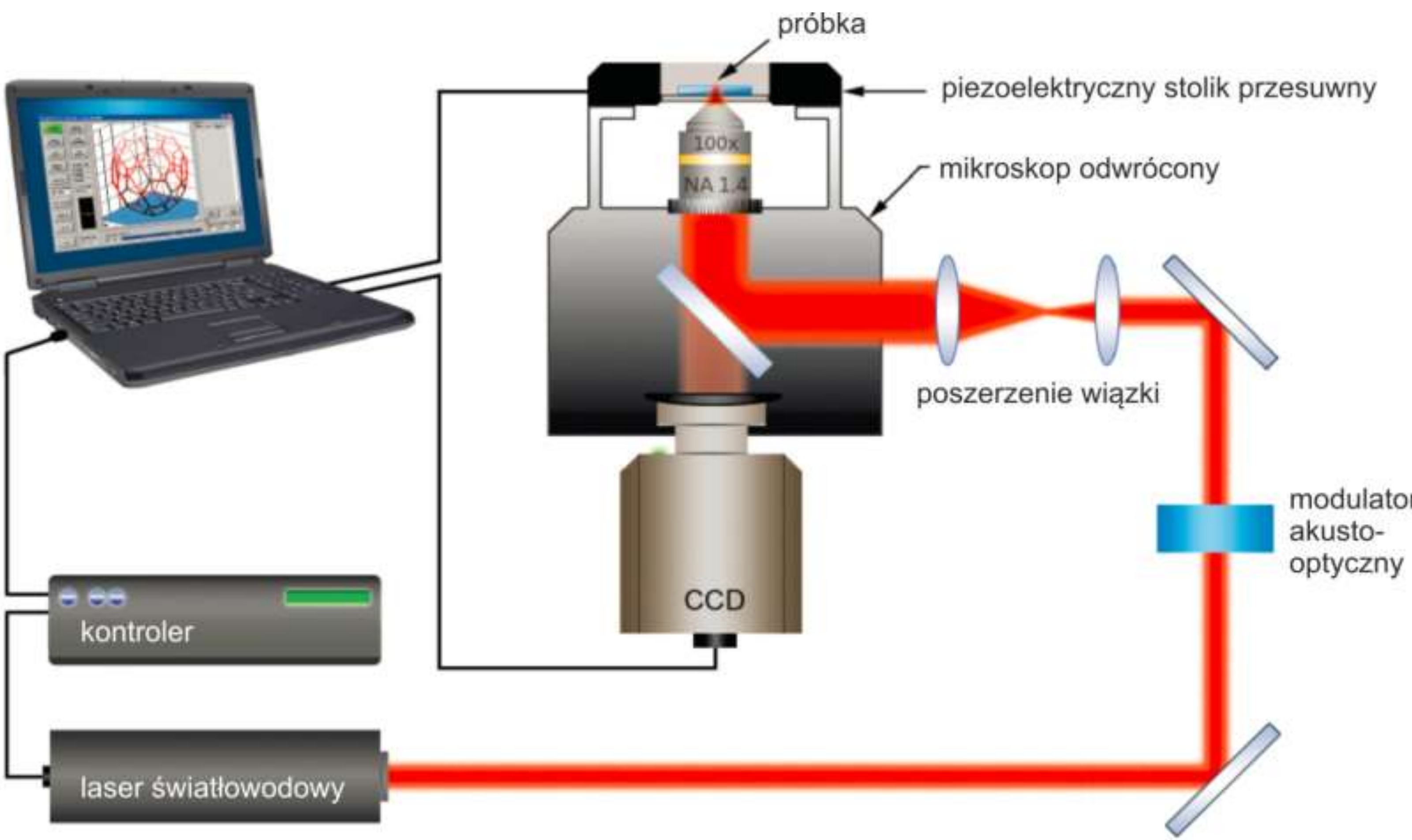


The Robey Lab, Berkeley

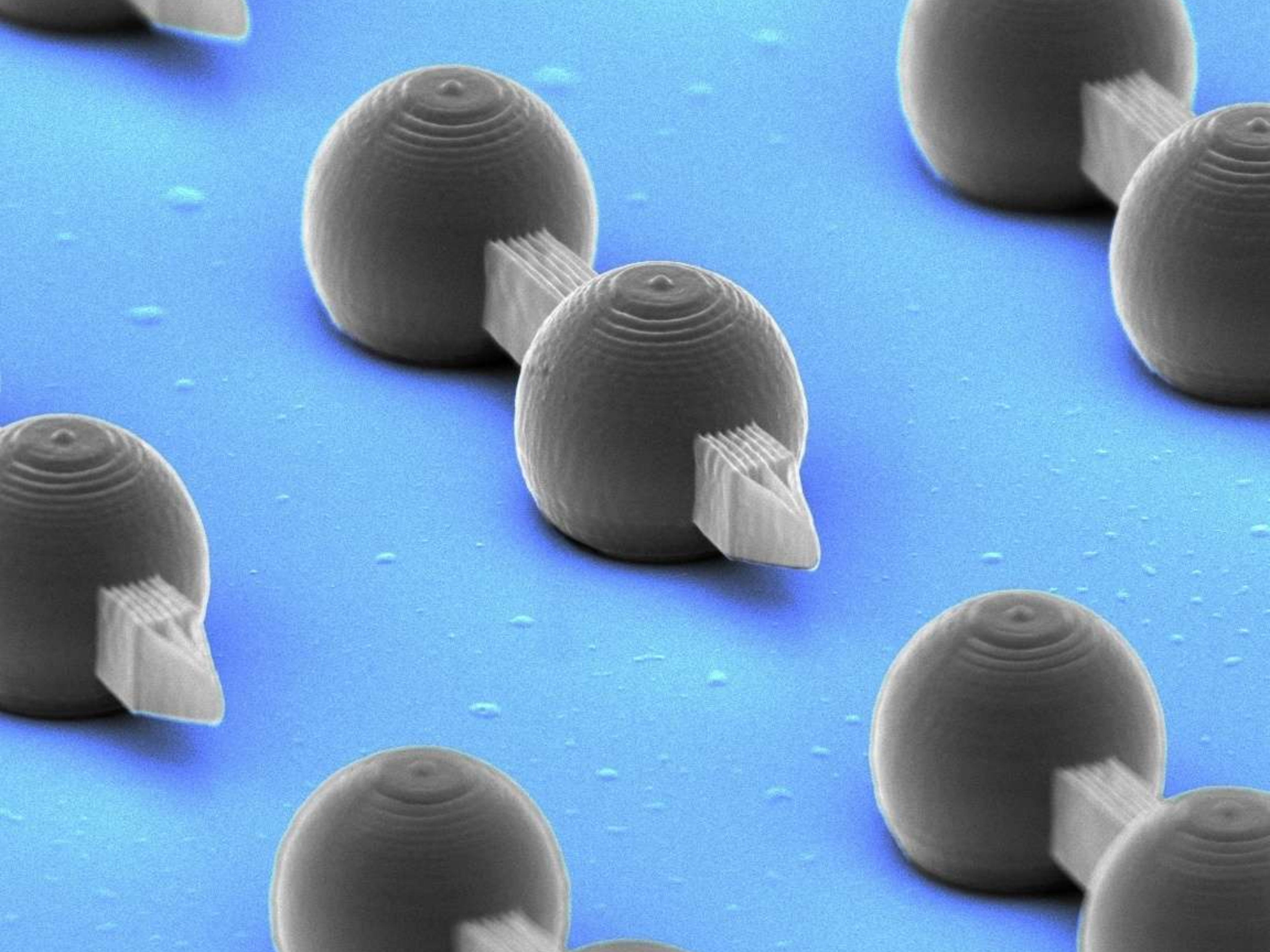
Two-photon light absorption in liquid resin is used to write 3D structures with sub-micron resolution

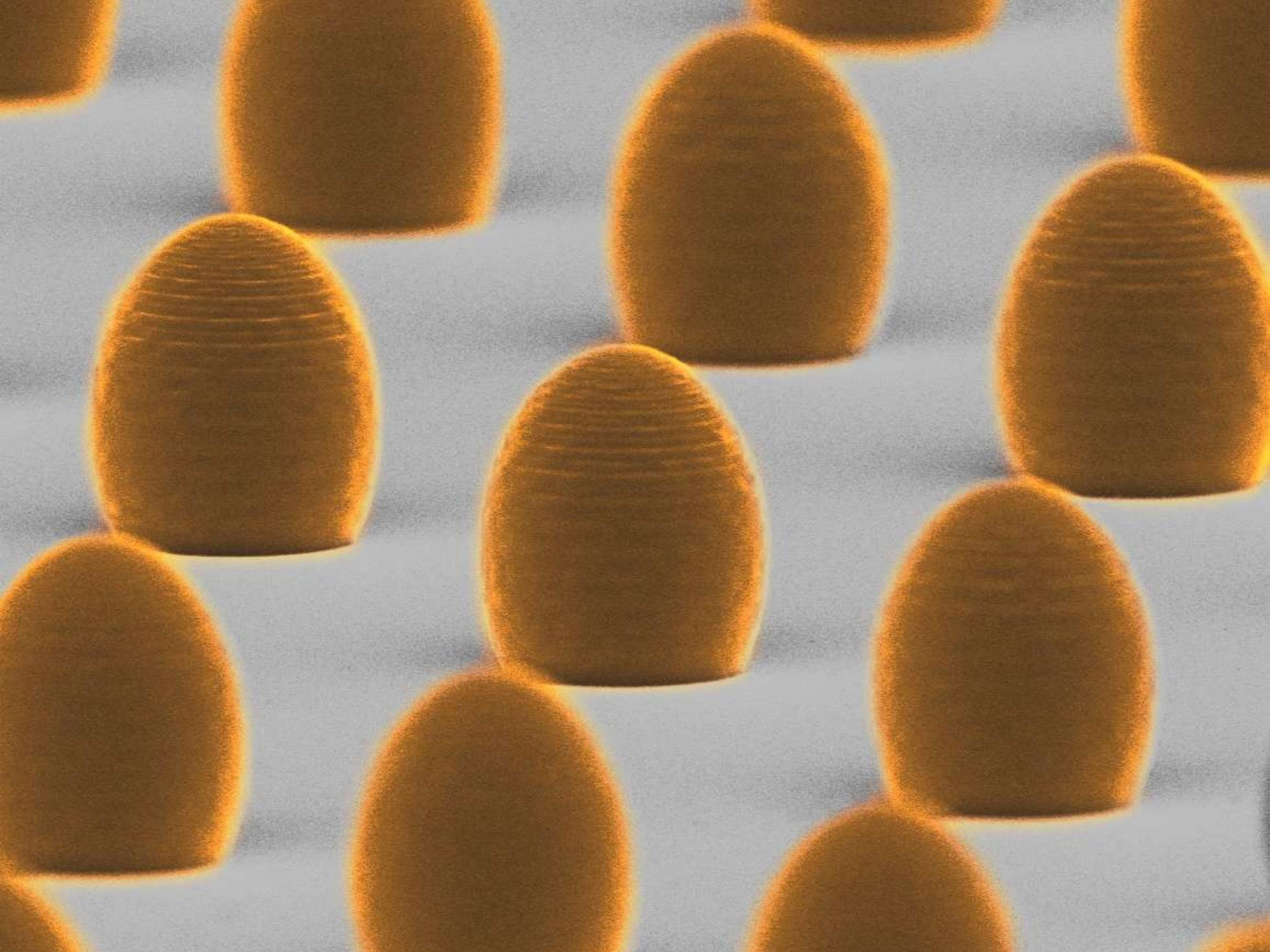


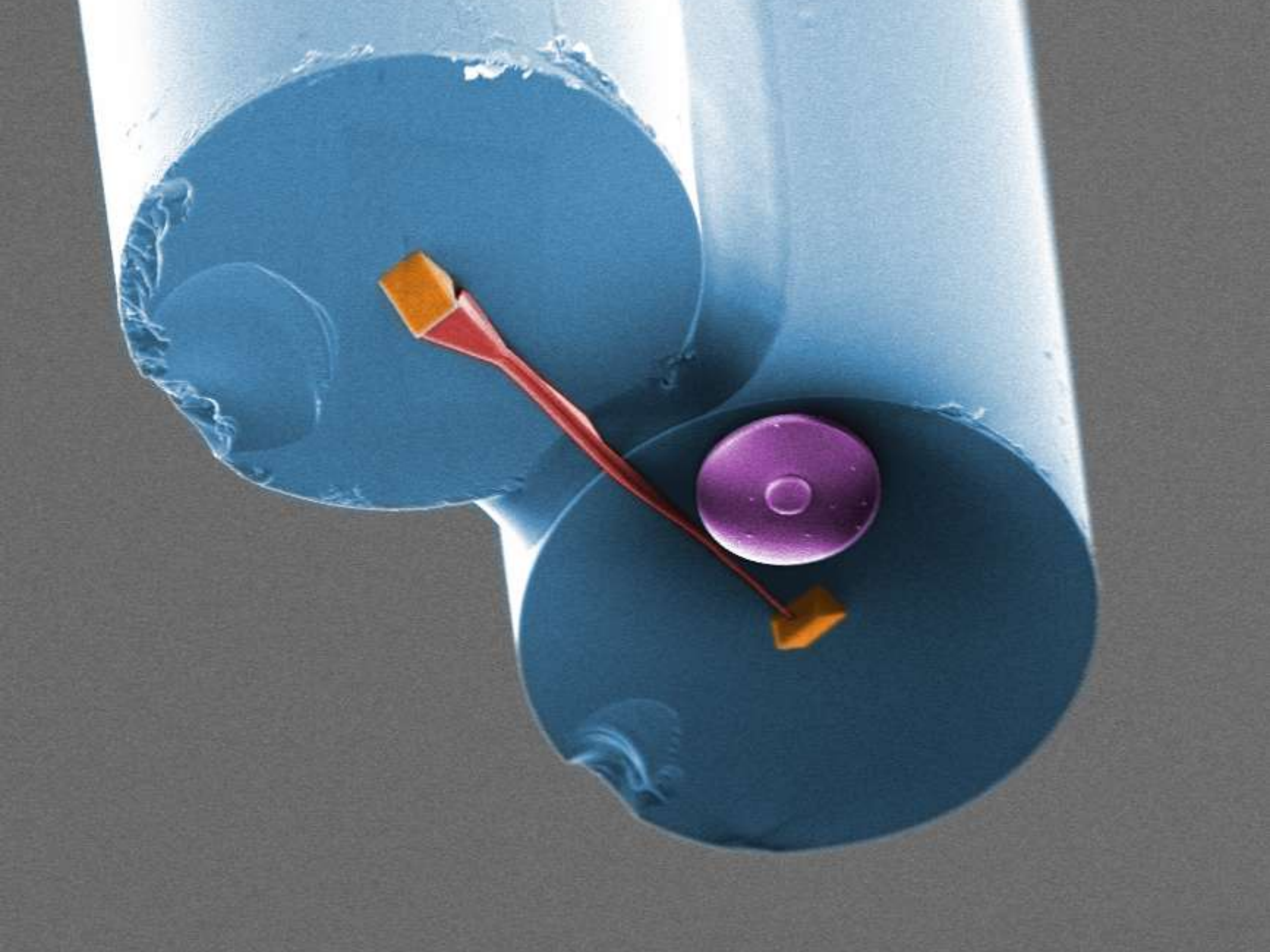
A commercial photolithography workstation from Nanoscribe (Germany)

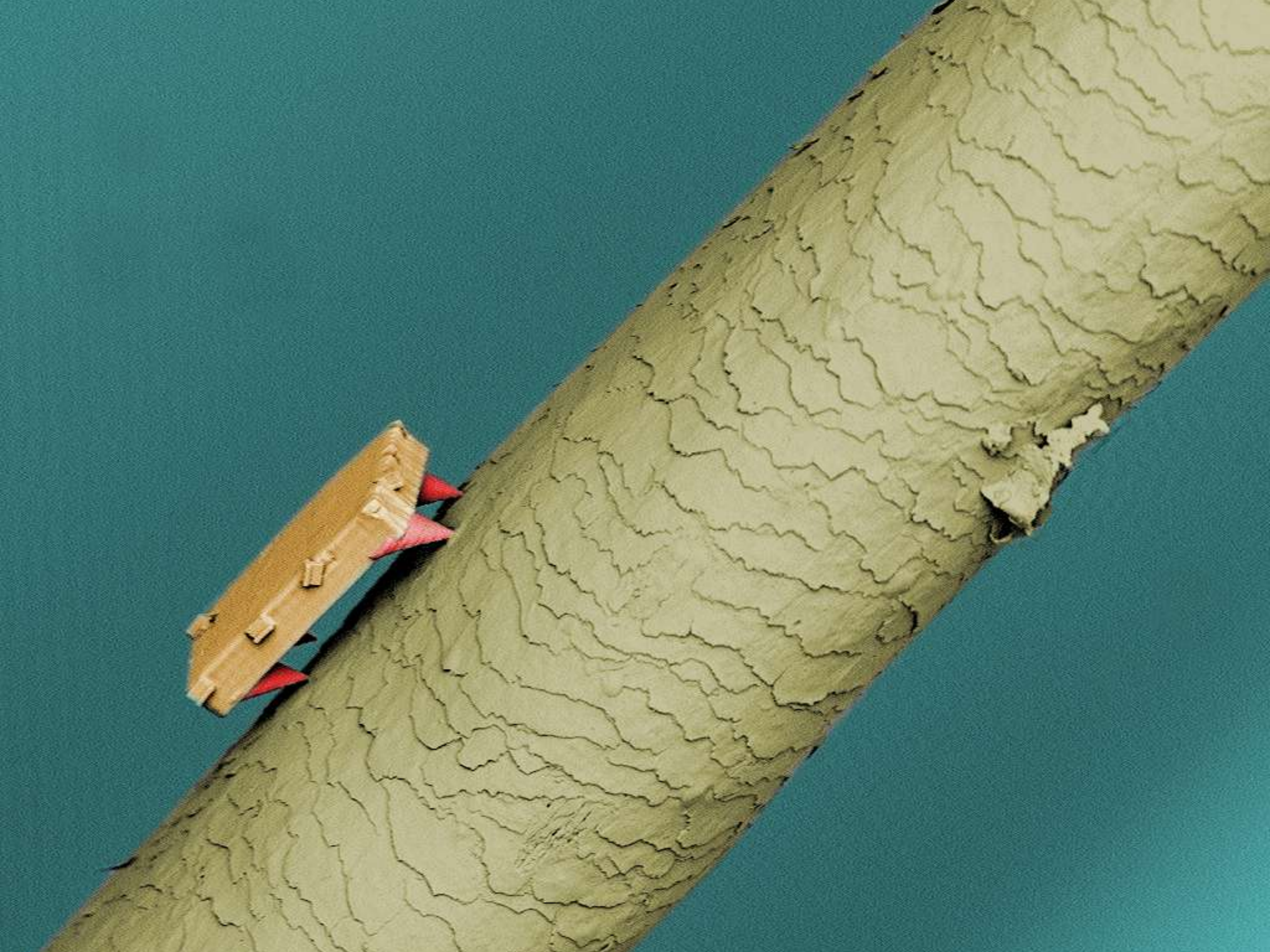



EVO MA10







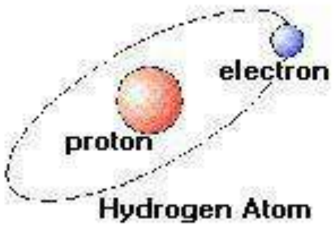


Why do we want shorter laser pulses?

Some slides courtesy Yurii Stepanenko (IChF, Fluence)

Electron Orbits in Bohr Model

$T_{orbital}$=150 as



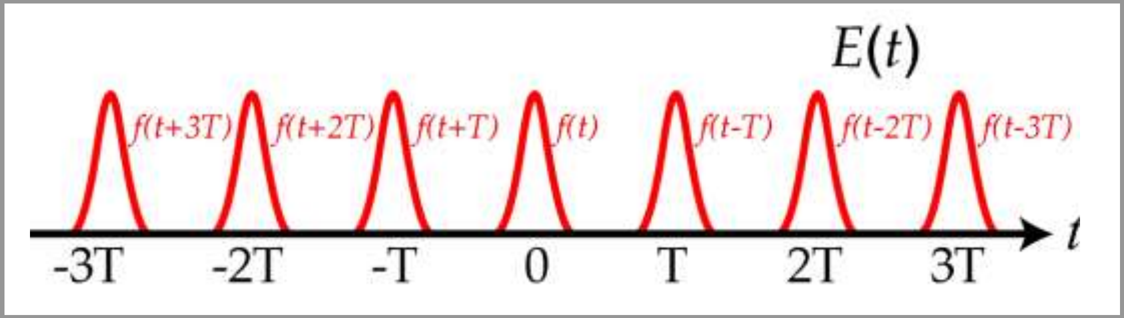
<u>Attosecond science:</u>
research field studying
dynamical processes
on attosecond timescales

$1as=10^{-18}$ s

An Infinite Train of Pulses and its Fourier Transform

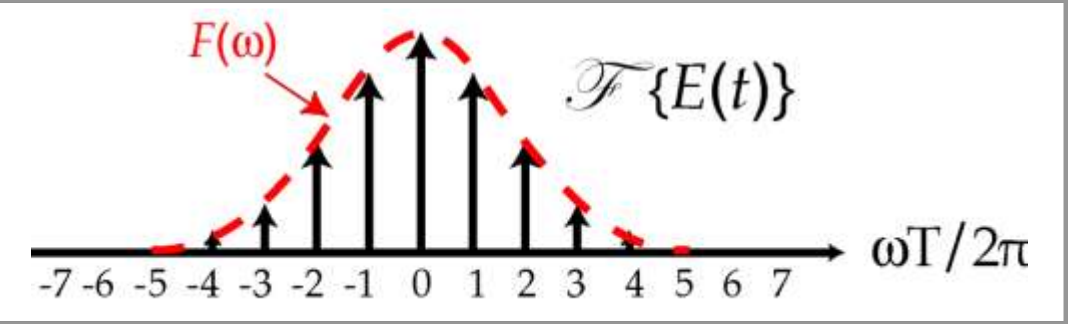
An infinite train of identical pulses can be written:

$$E(t) = \text{III}(t/T) * f(t)$$



where $f(t)$ represents a single pulse and T is the time between pulses. Its Fourier transform:

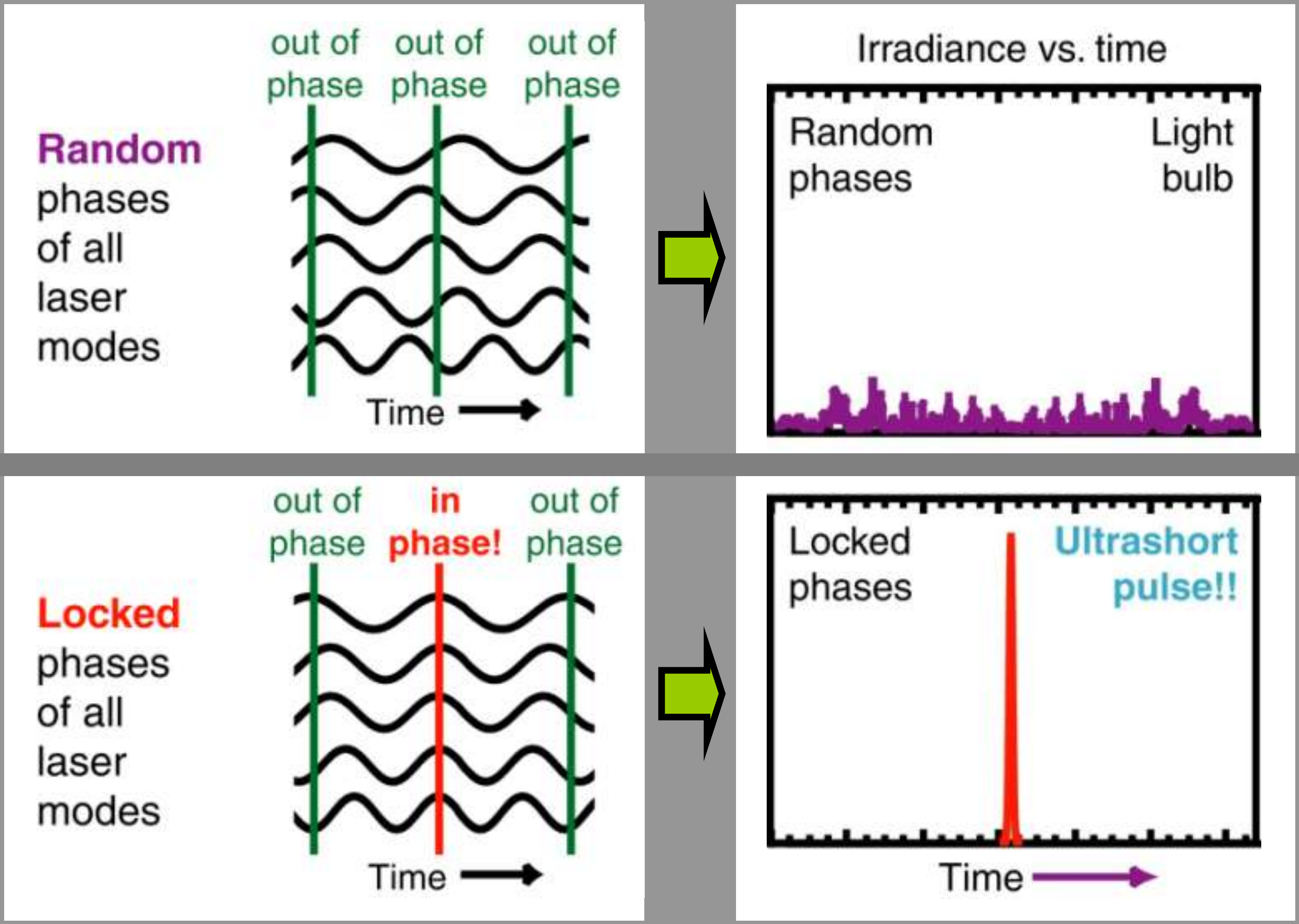
$$\tilde{E}(\omega) \propto \text{III}(\omega T / 2\pi) F(\omega)$$



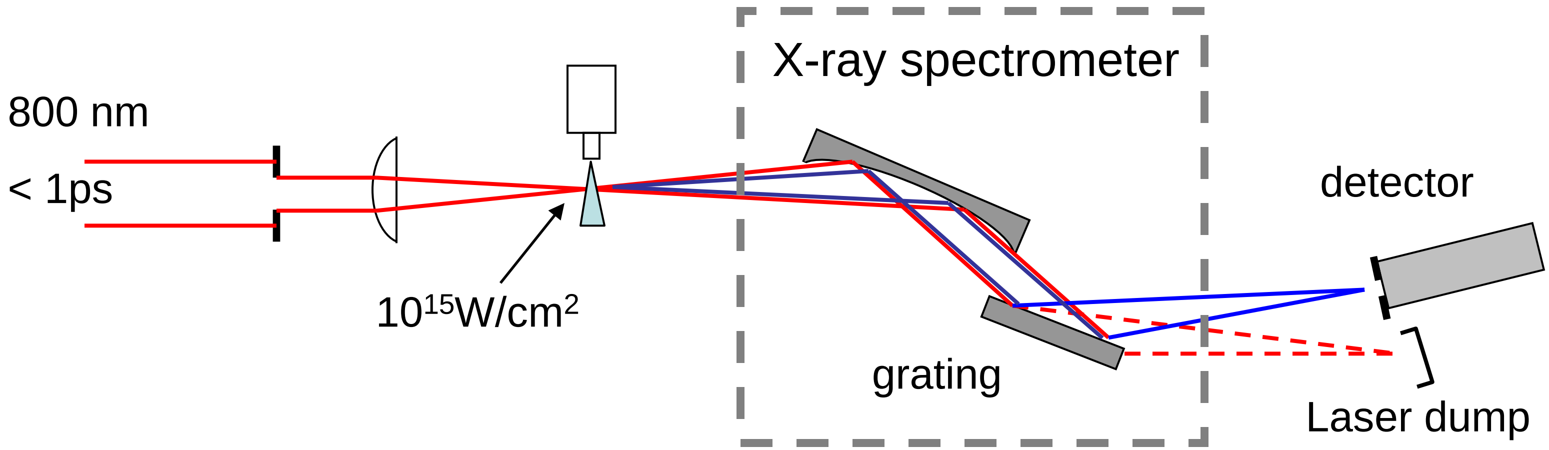
A series of modes, and the shorter the pulse the broader the spectrum.

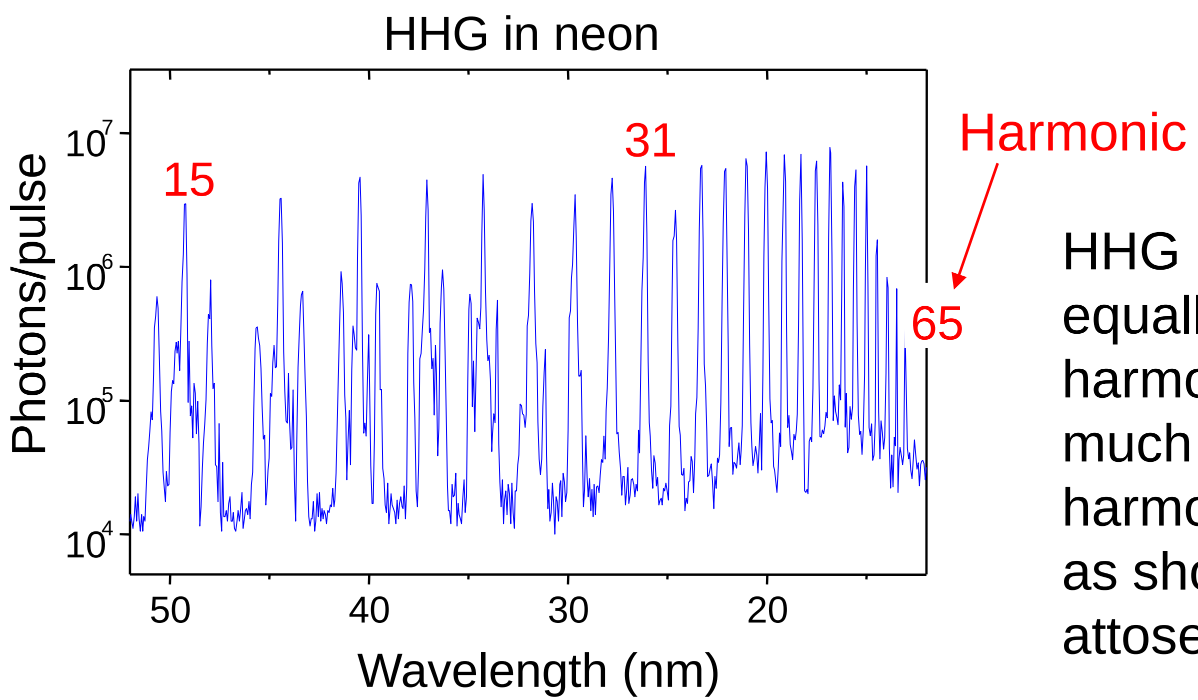
Generating short pulses = mode-locking

Locking the phases of the laser modes yields an ultrashort pulse.



High Harmonic Generation in a gas

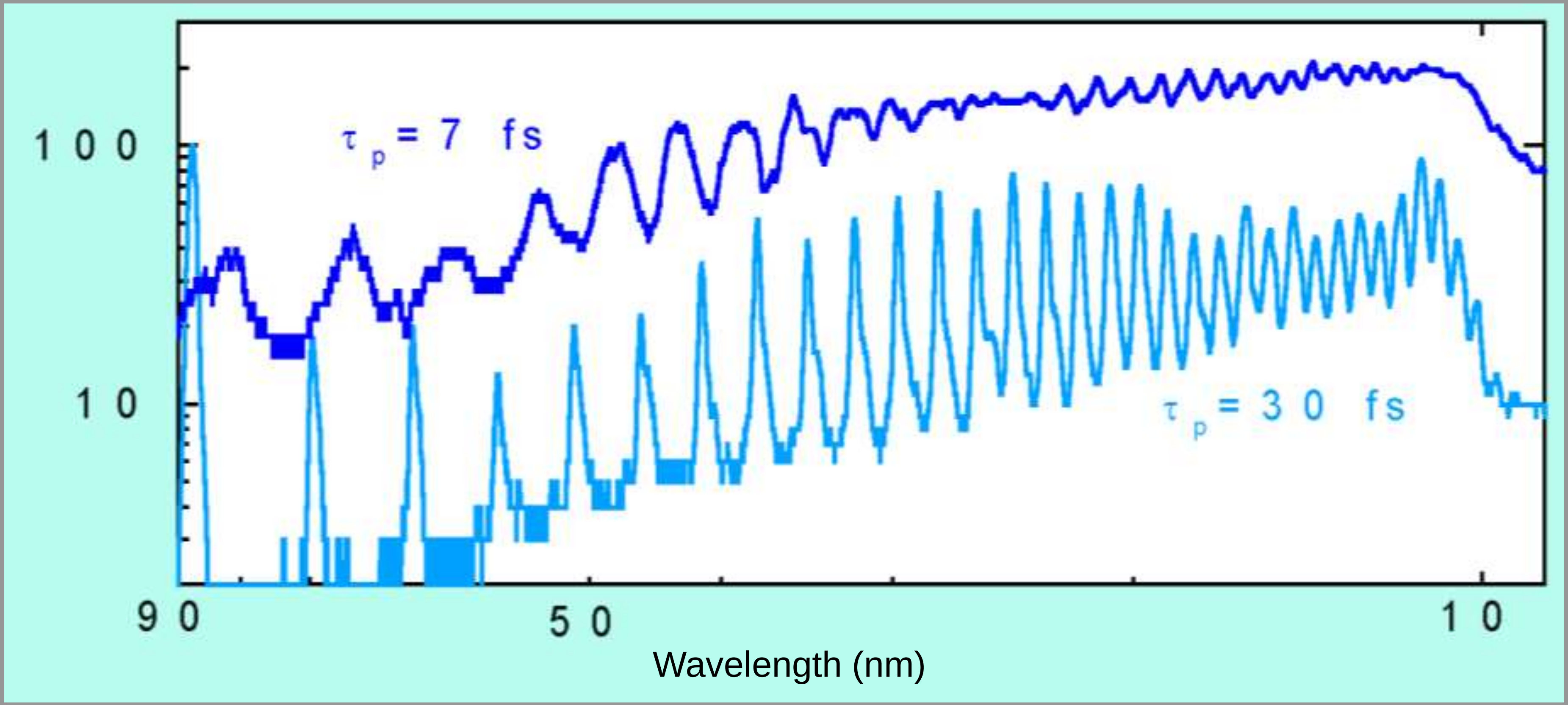




HHG produces equally spaced harmonics out to as much as the 300th harmonic, potentially as short as 10 attoseconds!

Few-cycle-driven XUV/HHG emission is also more efficient.

Measured XUV spectral intensity from neon



M. Schnürer *et al*., PRL **83**, 722 (1999)
Ch. Spielmann *et al*., Science **278**, 661 (1997)
Z. Chang *et al*., PRL **79**, 2967 (1997)

High-harmonic generation has all the features needed for attosecond pulse generation.

XUV region.

Equally spaced frequencies and lots of ‘em.

Overall very broad bandwidth (> 10^{15} Hz).

Spatial coherence.

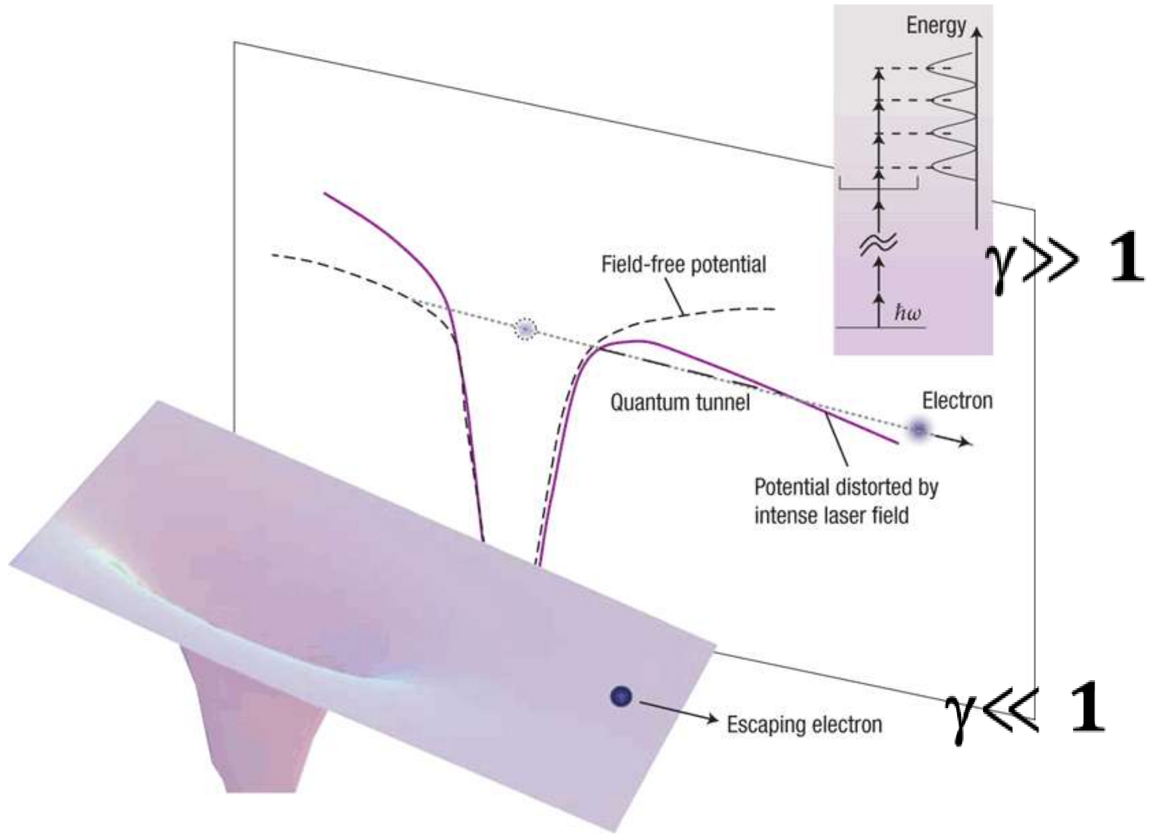
Reasonable stability.

The physics seems to imply that the XUV pulse should be really short…

Maybe HHG just naturally produces attosecond pulses without even trying…

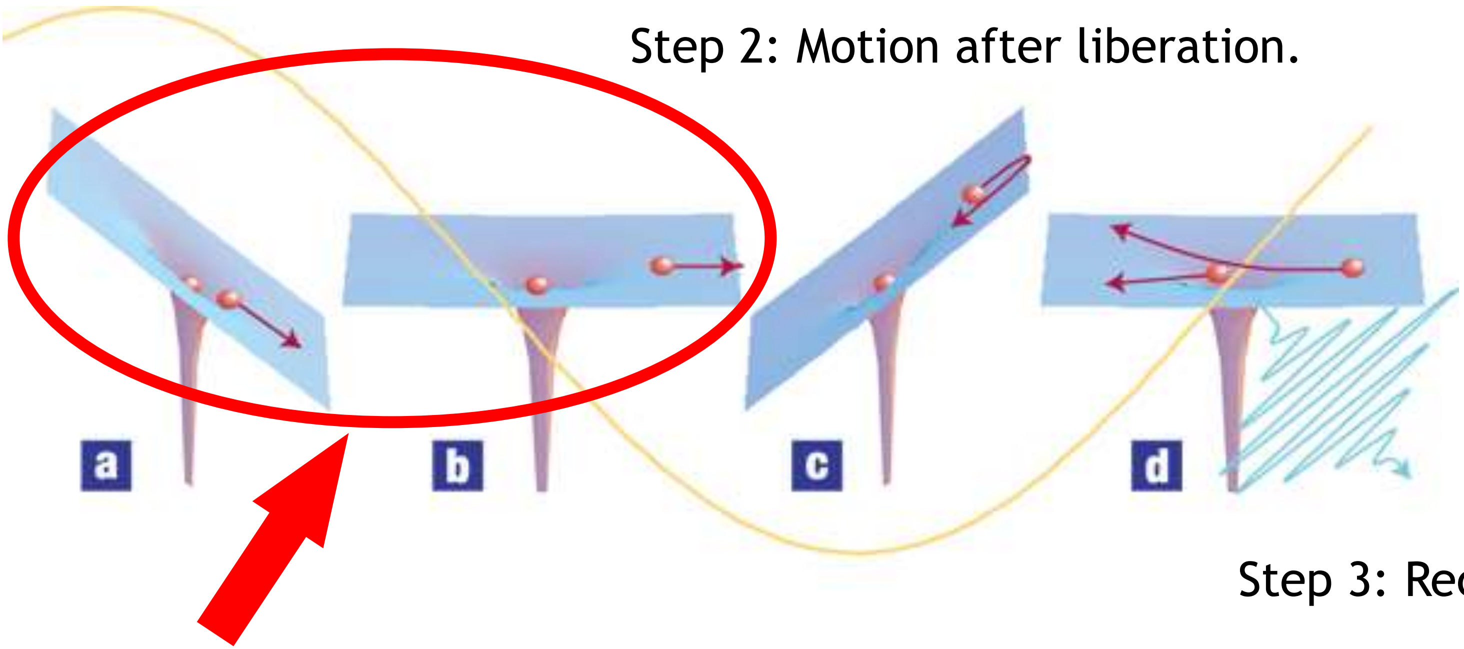
Creating an attosecond pulse

$\gamma = a/\lambda I$



Keldysh, L. *V Sov. Phys. JETP* **20**, 1307–1314 (1965).

Creating an attosecond pulse



Step 2: Motion after liberation.

Step 3: Recollision.

Step 1: Ionization.

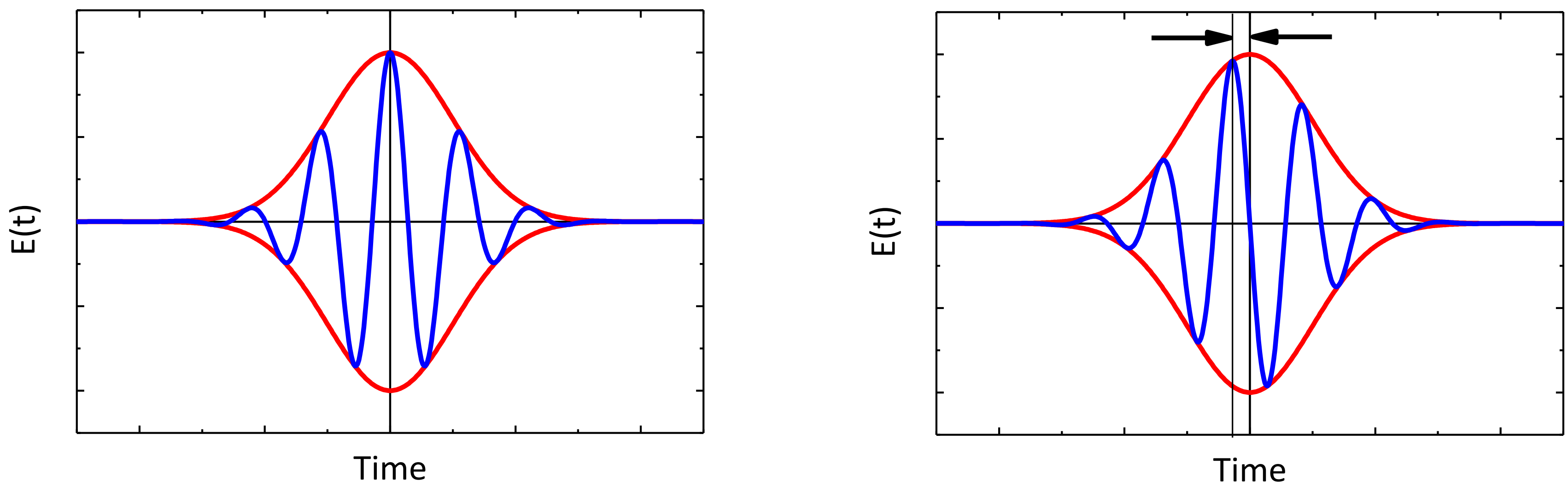
The result is a train of attosecond bursts of extreme ultraviolet (XUV) light spaced by $T_{osc}/2$

P. B. Corkum & Ferenc Krausz
Nature Physics **3**, 381 - 387 (2007)

Controlling carrier envelope phase

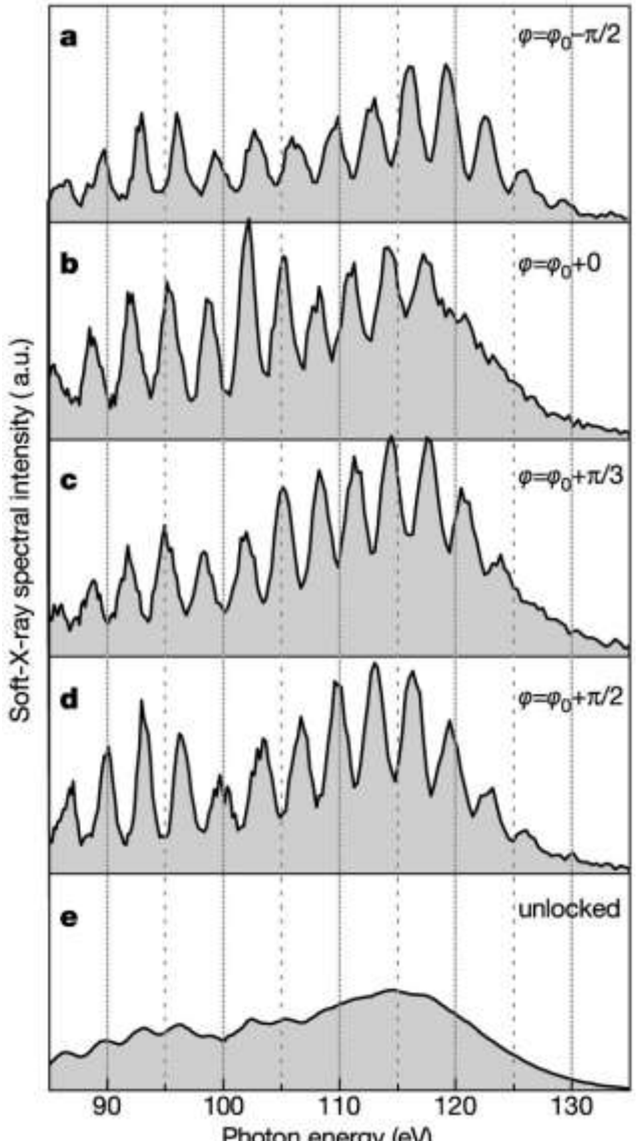
CEP

$$E(t) = E_0 \cos(\omega t + \varphi)$$



The CEP is an important parameter for many strong-field processes, e.g. attosecond pulse generation

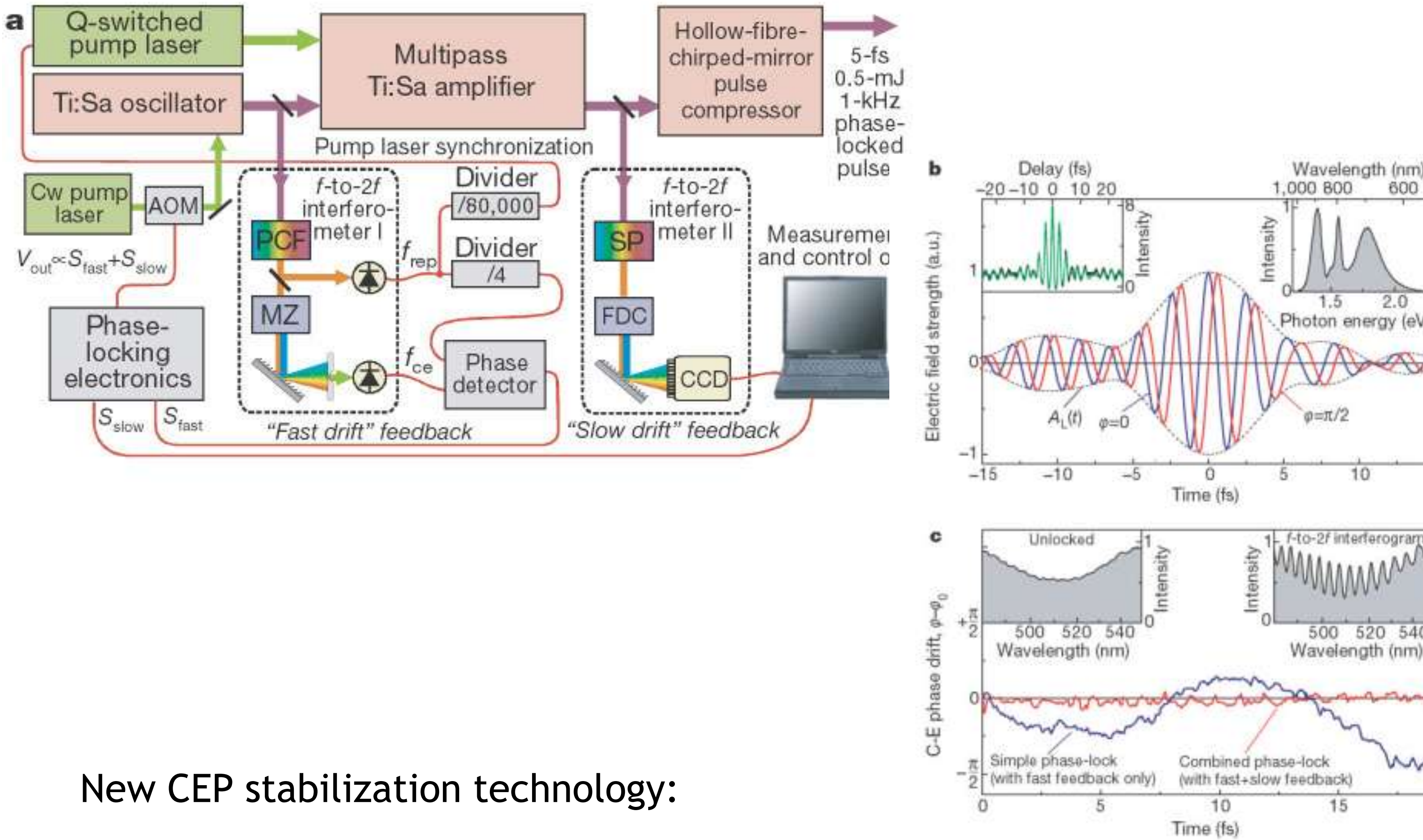
Controlling carrier envelope phase



We need to learn how to control CEP

Baltuska *et al*. Nature **421** 611 (6th Feb 2003)

Controlling carrier envelope phase



New CEP stabilization technology:

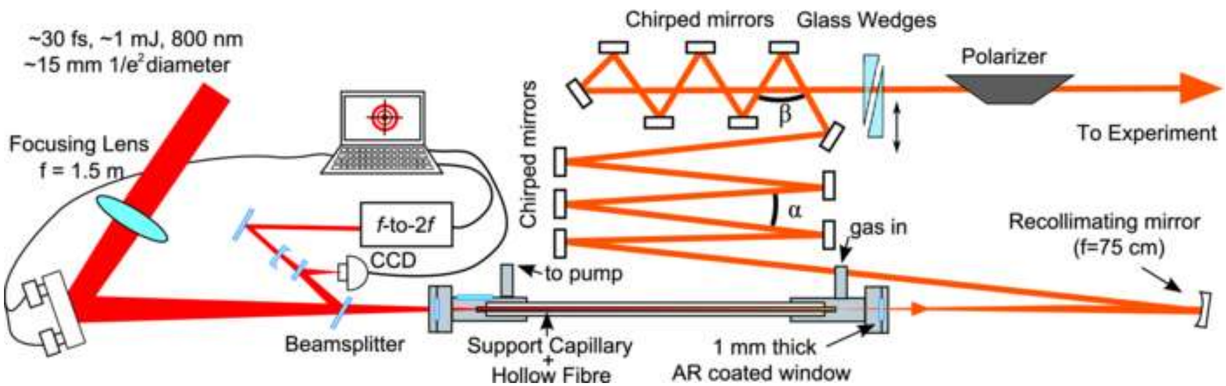
50 mrad phase drift over 10 hours

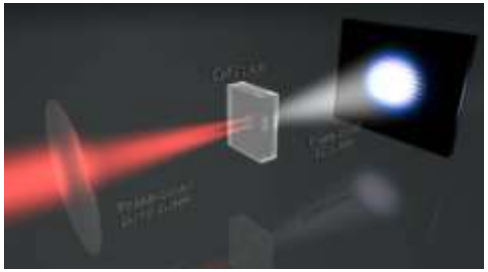
sub-12 attoseconds residual timing jitter

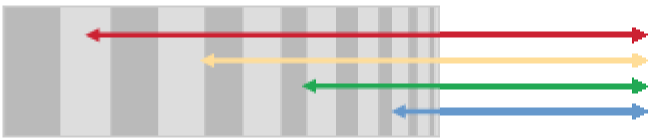
Baltuska *et al*. Nature **421** 611 (6th Feb 2003)

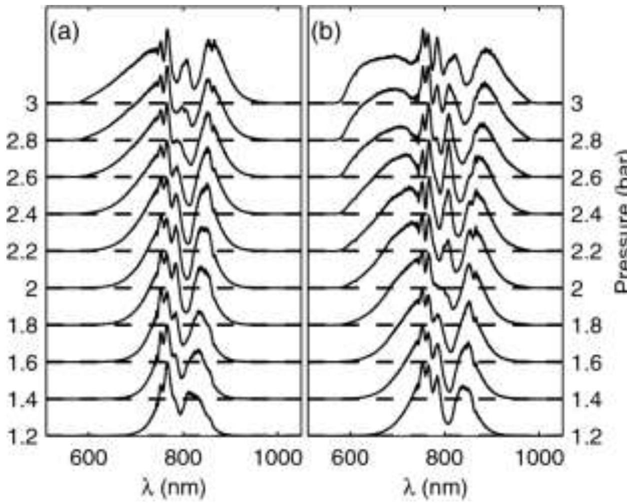
Extremely short laser pulse generation

Laser intensity of 10^{14}-10^{15} W/cm^2 is needed for HHG

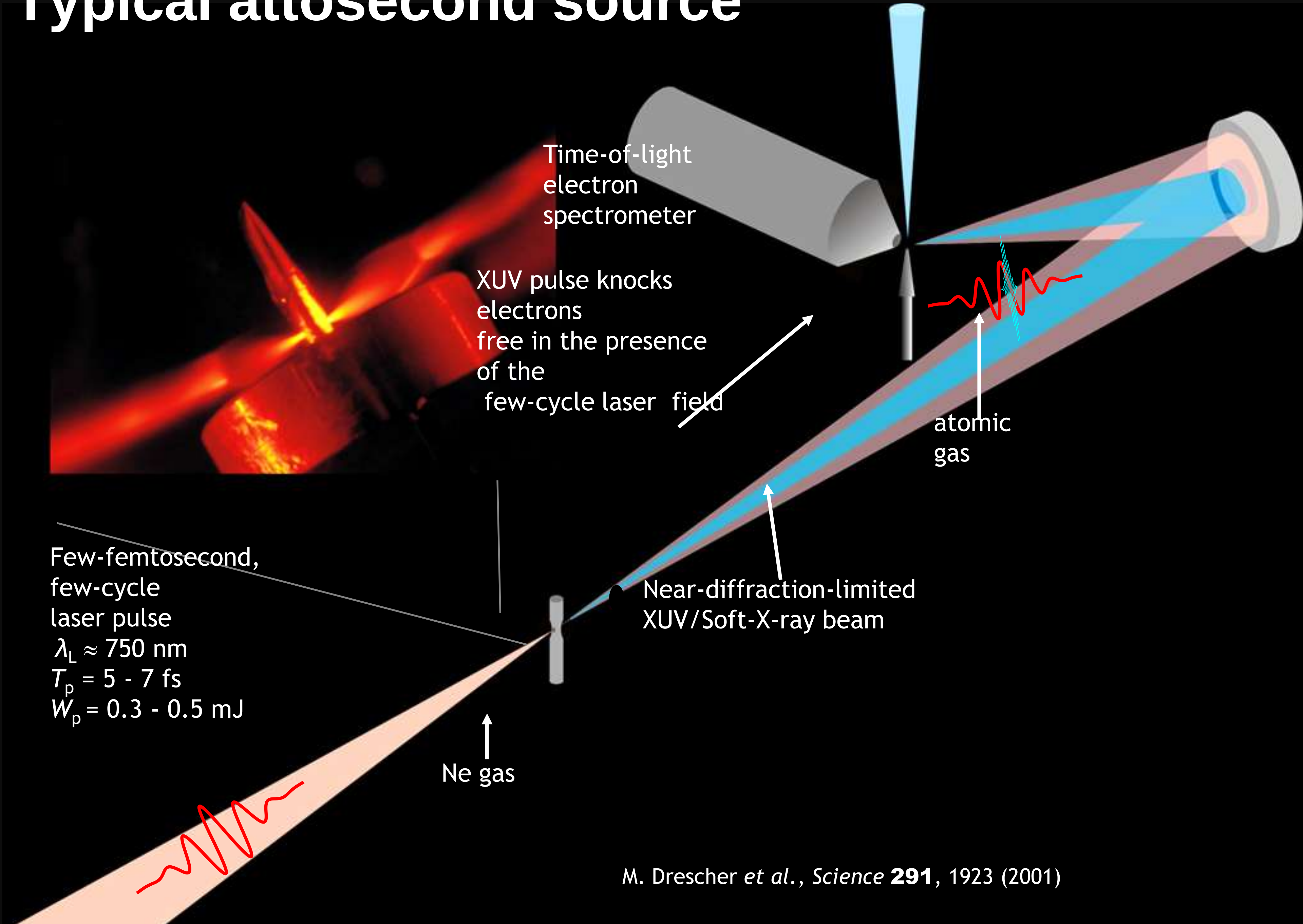






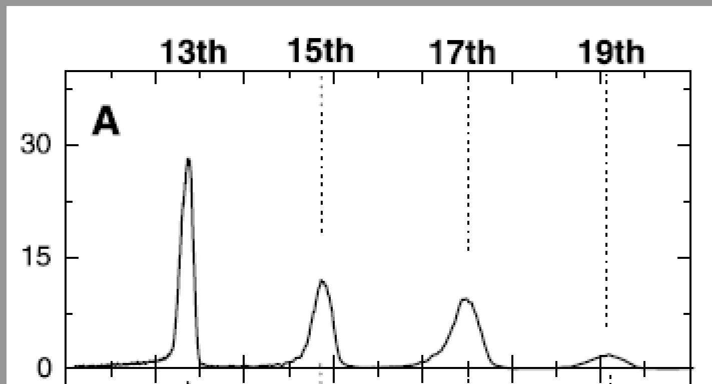


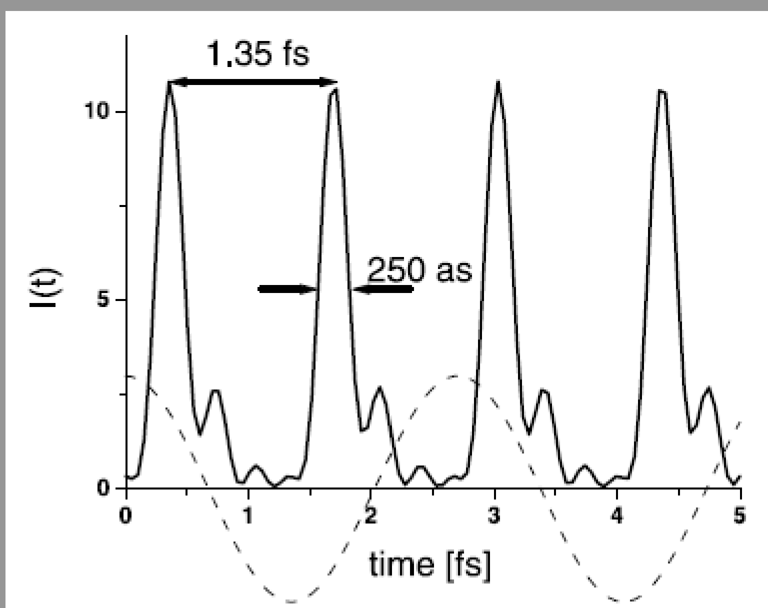
Typical attosecond source

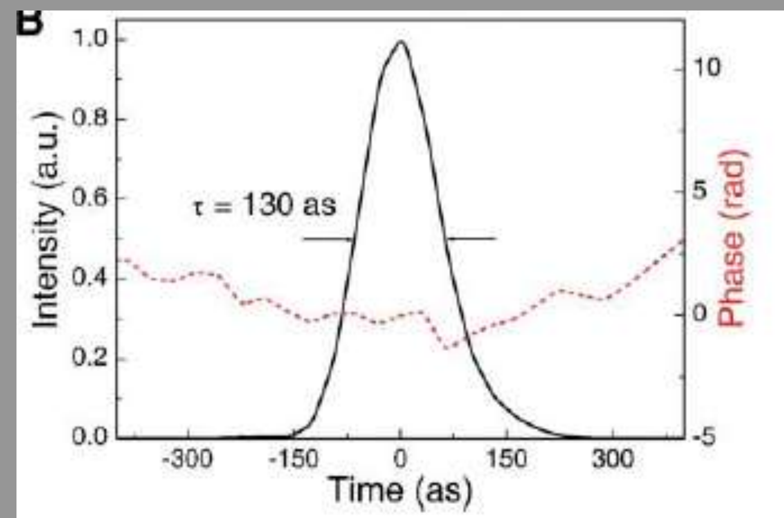


M. Drescher *et al.*, *Science* **291**, 1923 (2001)

Attosecond pulses – some results



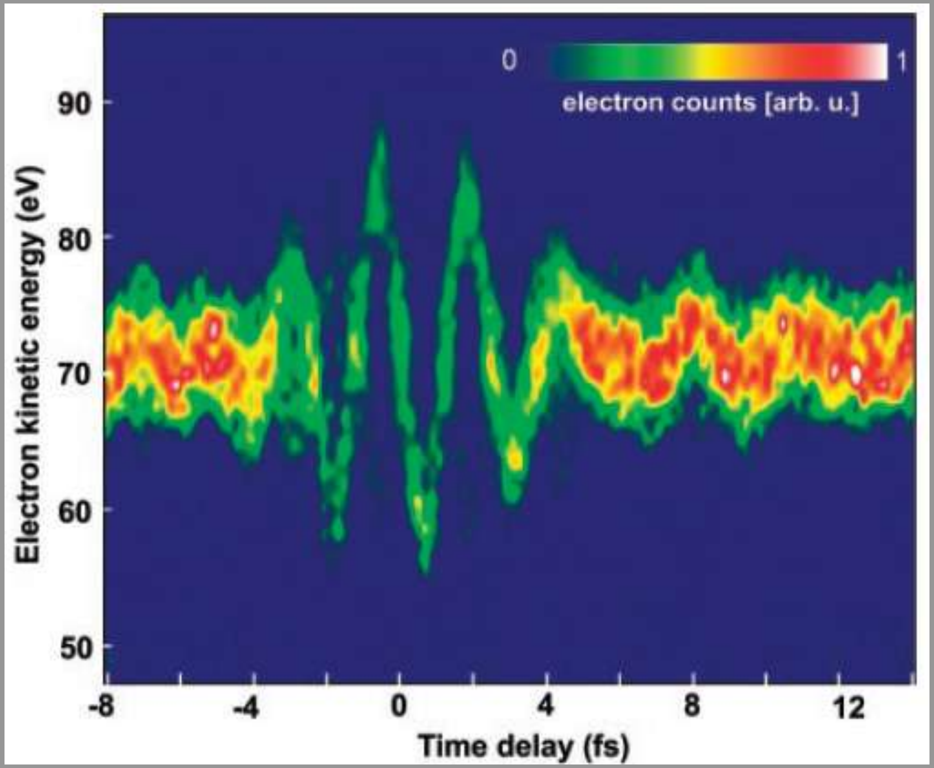




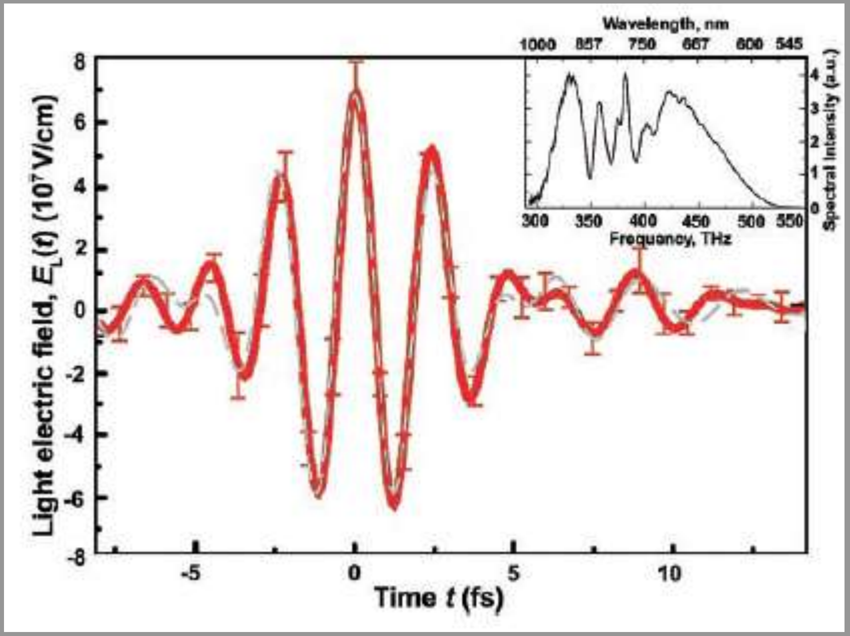
P. M. Paul et al., Science 292, 1689 (2001)

G. Sansone et al., Science 314, 443 (2006)

Measuring the oscillations of the optical EM field



Kinetic energy spectrum of electrons
Pump pule 250 as, 93 eV
Probed pulse 5 fs, 750 nm



Retrieved electric field
of the fs light pulse

E. Goulielmakis et al., Science 305, 1267 (2004)