Empa
Materials Science and Technology

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

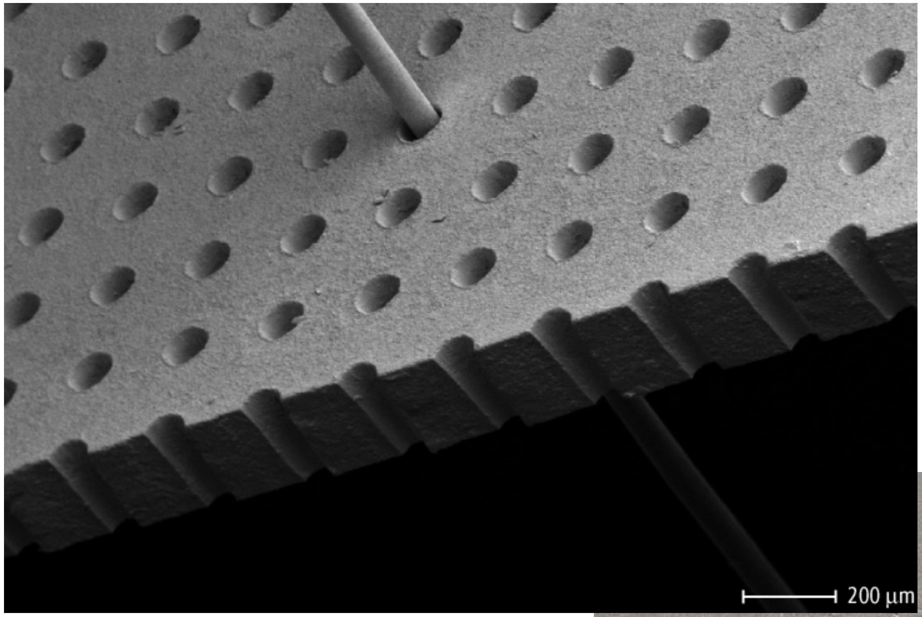
Laser Processing of Materials

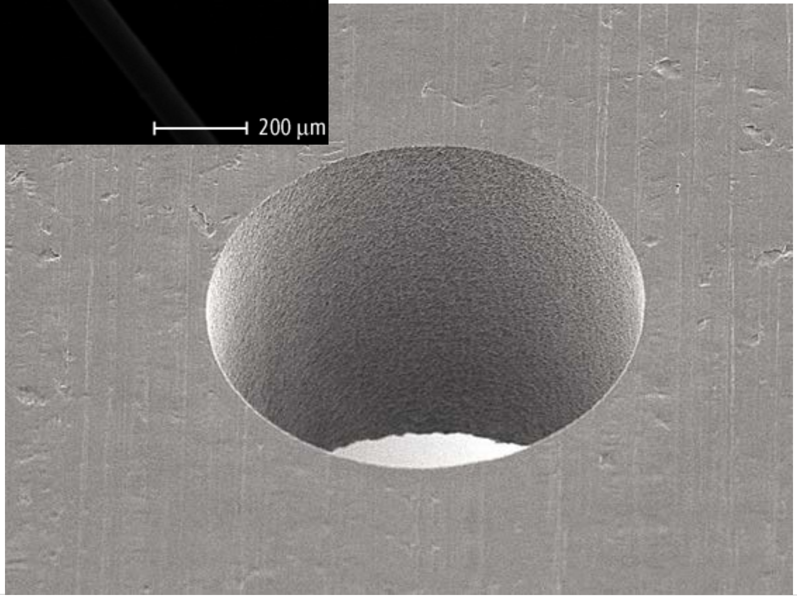
Applications: Ultrafast Laser Ablation

Patrik Hoffmann

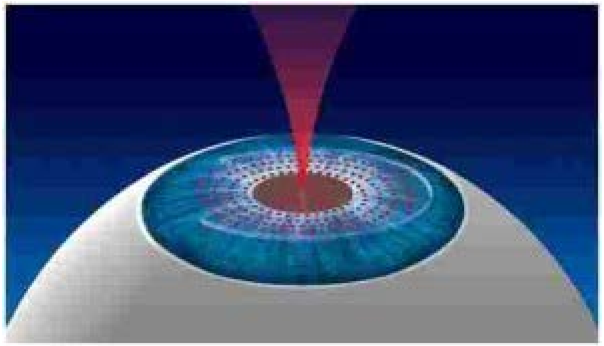
Applications: Ultrafast (modelocked) Lasers

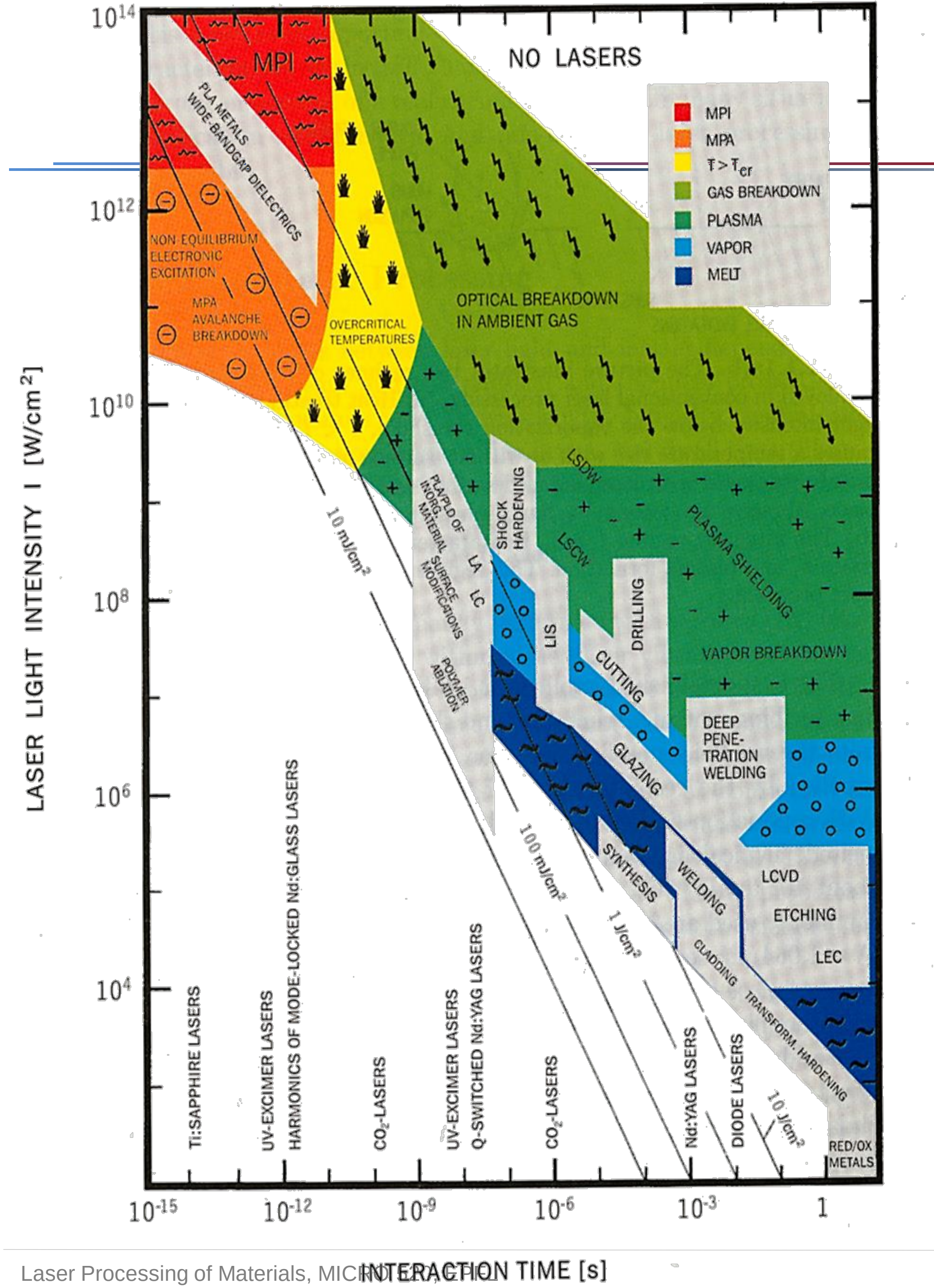
high precision laser machining





no blade cut
eye correction





D. Bäuerle;
Laser Processing and Chemistry, 3rd ed.
Springer, Berlin, 2000

Application of lasers in materials processing:
Intensity-Time Diagram

PLA/PLD – pulsed laser ablation/ deposition

LA – laser annealing

LC – laser cleaning

LIS – laser induced isotope separation/IR – laser photochemistry

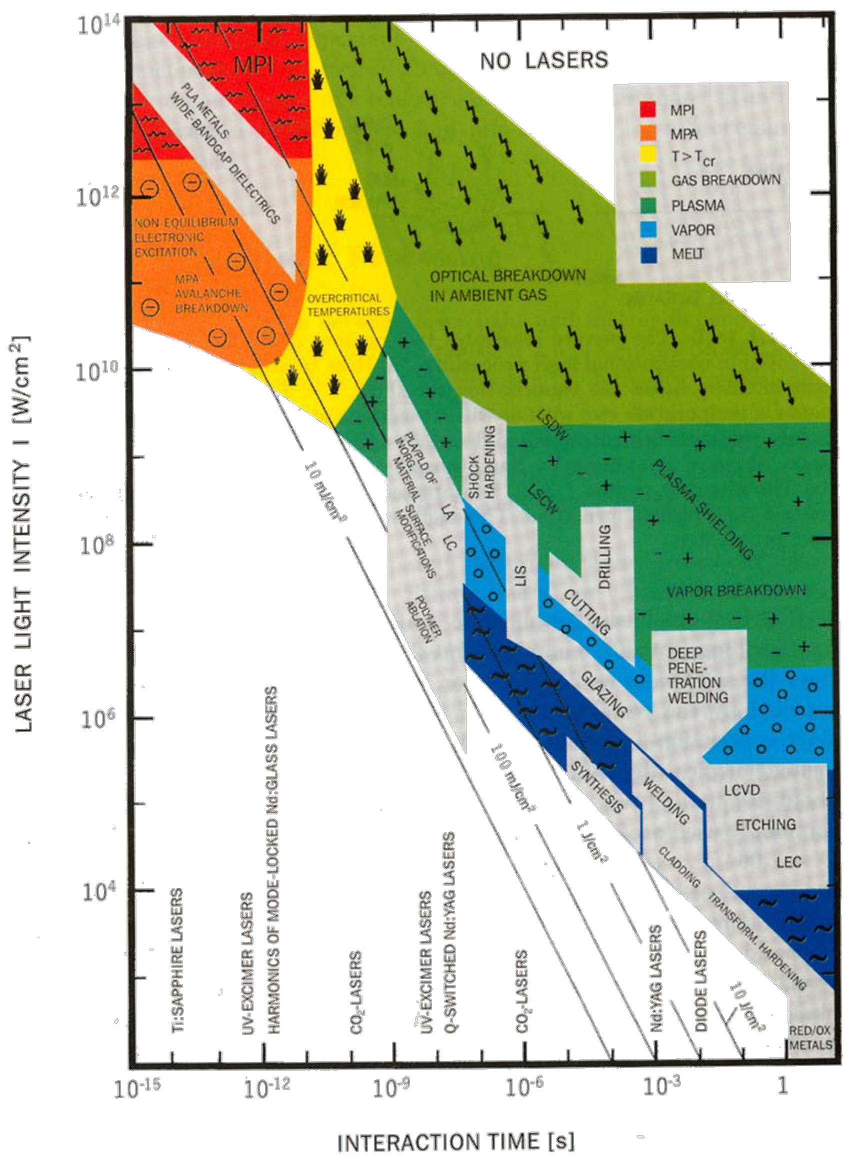
MPA/MPI – multiphoton absorption ionization

LSDW/LSCW – laser supported detonation/combustion waves

LCVD – laser induced chemical vapour deposition

LEC – laser induced electrochemical plating/etching

RED/OX – long pulse or cw CO_2-laser induced reduction/oxidation



D. Bäuerle; Laser Processing and Chemistry, 3rd ed. Springer, Berlin, 2000

Laser Types: Pulsed & CW

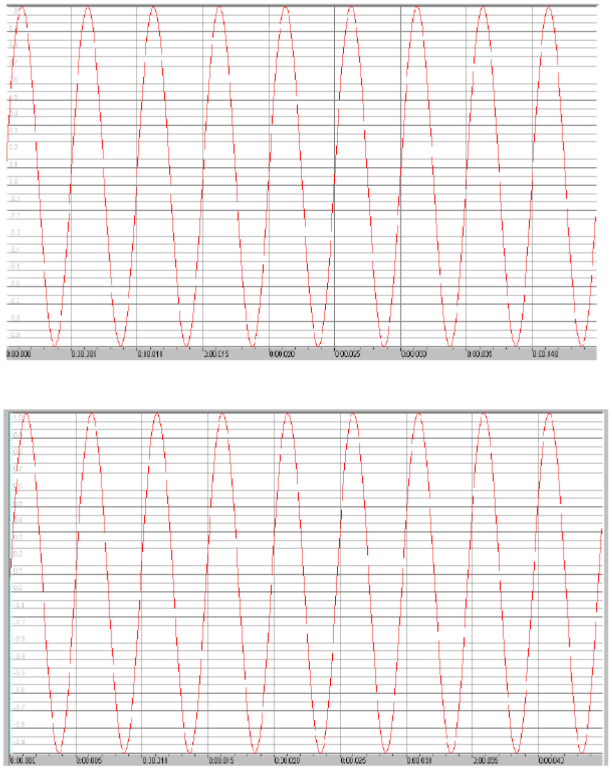
Type of laser	Pulse length determined by	Typical pulse length	Characteristic pulse peak power
Continuous wave (cw)	-	∞	Ws – kWs
Free running laser	Pump pulse length (flash lamp)	100 µs – 1ms	kWs
Q-switched laser	Time constants of active material and modulating element	1 ns – 100 ns	MWs
Mode-locked laser	Number of coupled modes, pulse compression	10 fs – 10 ps	GWs

Why do you want very short pulses?

Mode-locking regime

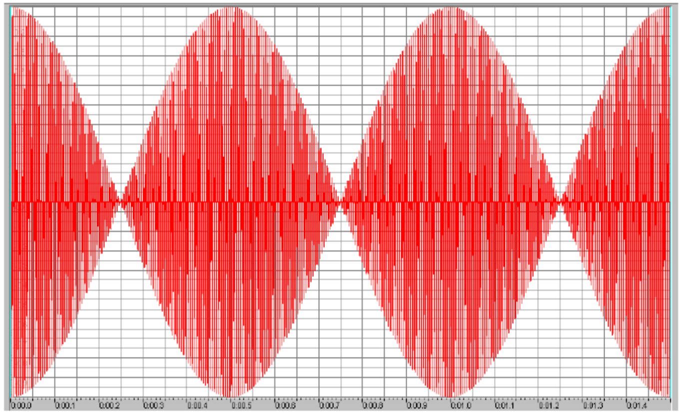
Mode-locked pulses – result of inteference of many „locked“ (phase/frequency related) light waves

interference of waves with two different frequencies



t [s]

$$A_{S2}(t) = A_1(t) + A_2(t) = \sin(2\pi\nu_1 t) + \sin(2\pi\nu_2 t)$$



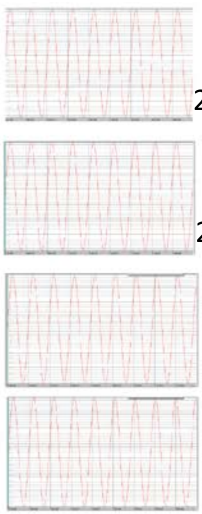
200 Hz

t [s]

202 Hz

Mode-locking regime

interference of waves
with four equidistant frequencies



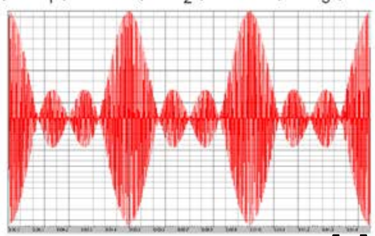
200 Hz

202 Hz

204 Hz

206 Hz

$A_{S4}(t) = A_1(t) + A_2(t) + A_3(t) + A_4(t)$
$= \sin(2\pi\nu_1 t) + \sin(2\pi\nu_2 t) + \sin(2\pi\nu_3 t) + \sin(2\pi\nu$

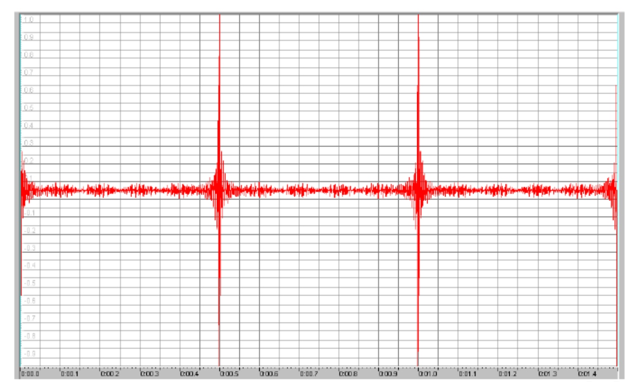


t [s]

interference of waves
with 120 equidistant frequencies

$$A_{S120}(t) = \sum_{n=0}^{120} \sin[2\pi(\nu_1 + n\Delta\nu)t]$$

$\nu_1 = 200$ Hz
$\Delta\nu = 2$ Hz

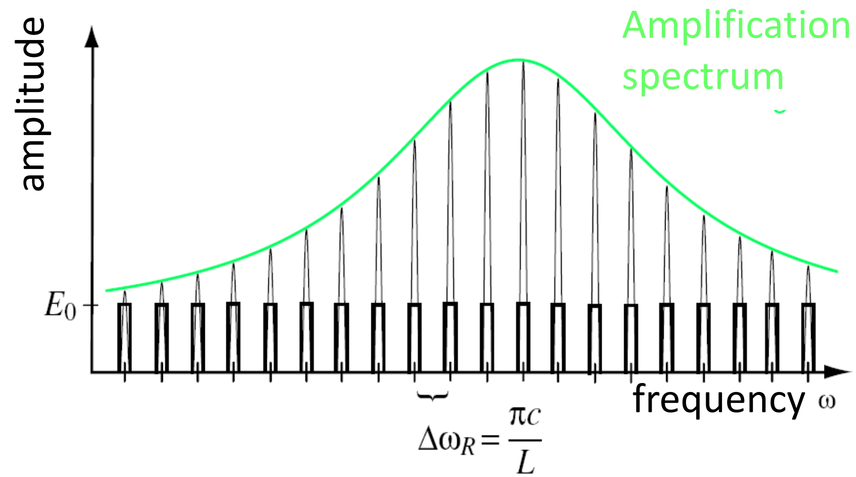


t [s]

Mode-Locking

- Different interfering light waves are longitudinal modes of the resonator
- more modes → shorter the pulse

- Typical mode-locked lasers have:
  ultra short pulses ~ 50 fs – 1 ps
  very high peak power ~ 1MW - 10 GW



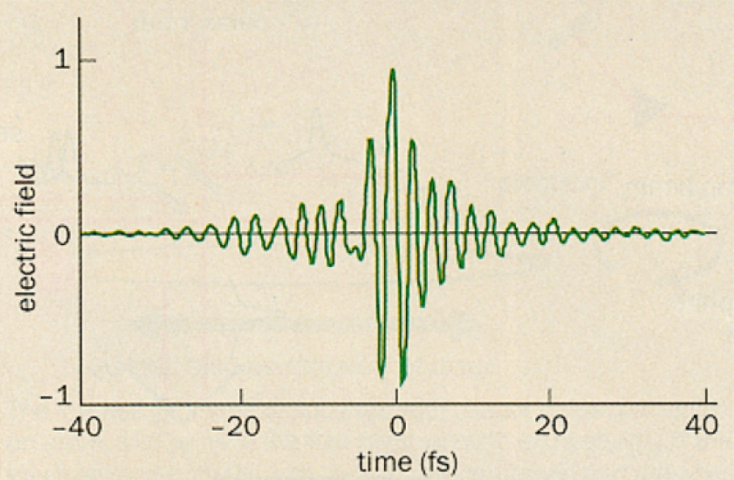
Heisenberg uncertainty principle: $\Delta\nu \cdot \Delta\tau \geq 1$

⇒ very short light pulses cannot be very monochromatic ⇒ special active media with broad emisssion spectrum needed for very short (femtosecond) pulses

Ti:Sapphire is typical active medium for fs-lasers

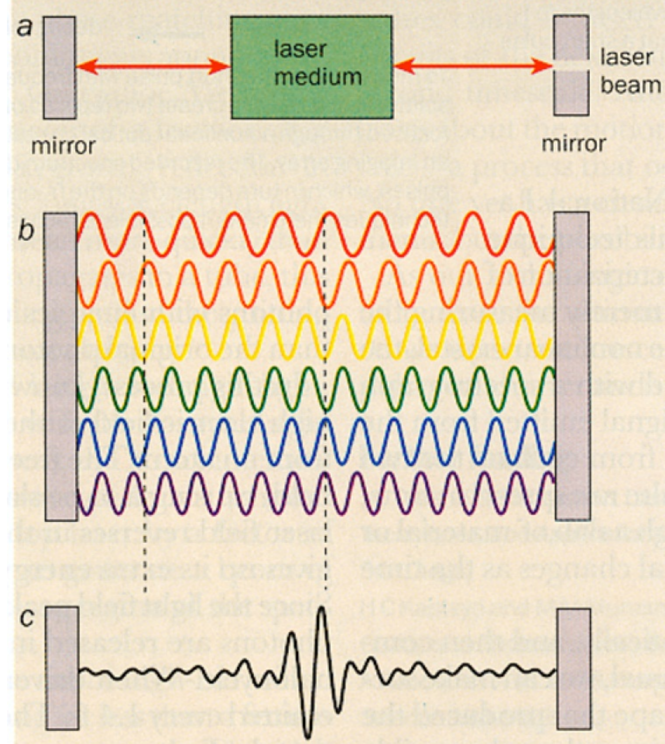
Examples of Ultra-short pulses

2 Short light pulses



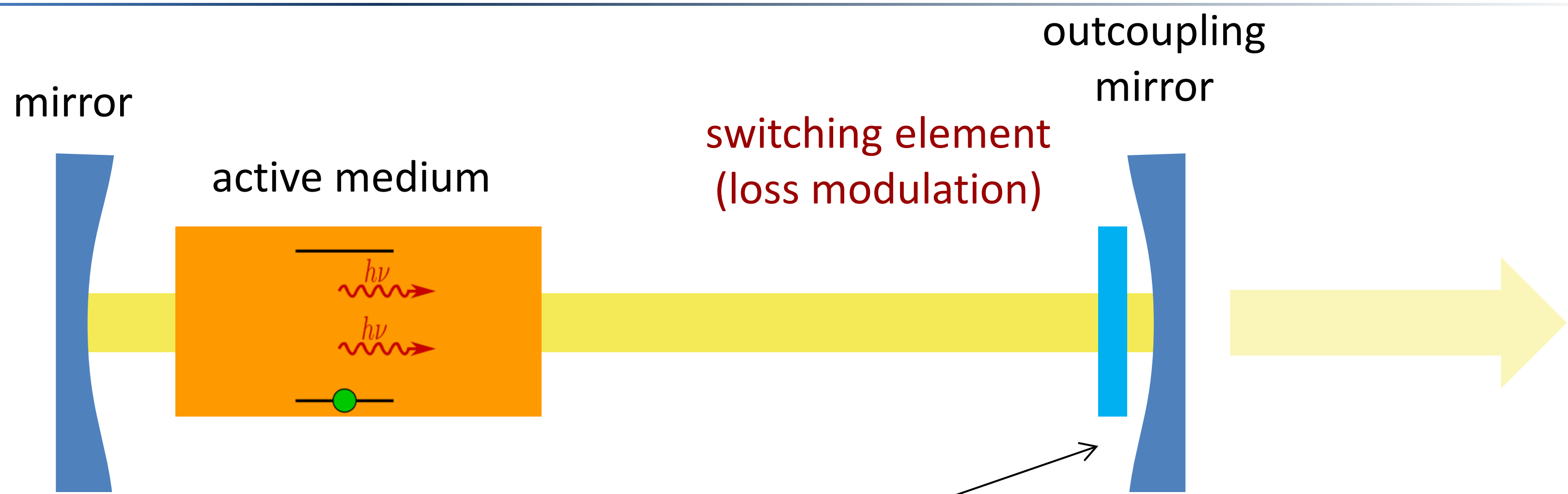
Maxim Pshenichnikov of the University of Groningen in the Netherlands has measured the electric field of a 5 fs light pulse, the shortest complete pulse measurement made to date. The output pulse consists of the two complete cycles centred around 0 fs.

3 Laser modes



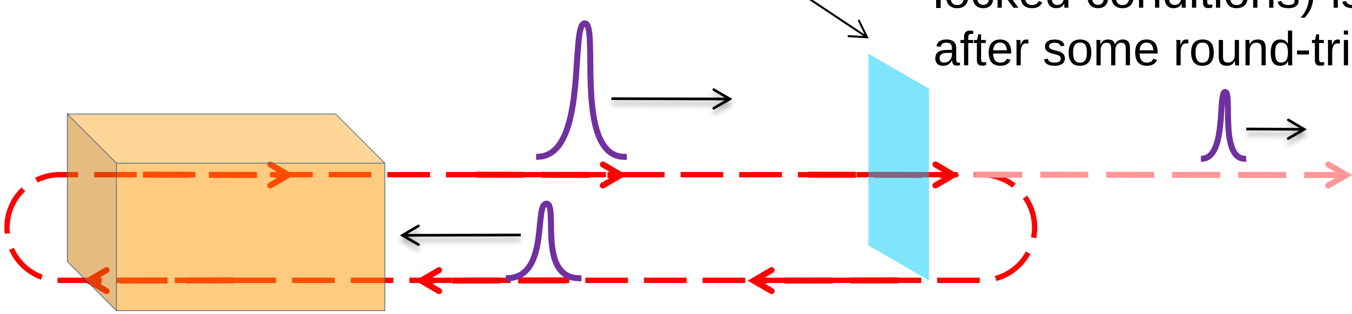
(*a*) A laser essentially consists of a laser medium sandwiched between two mirrors, one of which is partly transmissive. If the amplification of light by the laser medium is greater than the energy loss, light is emitted through the end mirror. (*b*) Many different modes can exist within the laser cavity, under the condition that the cavity length must equal an integer number of wavelengths. Each mode has a different frequency and wavelength. (*c*) In a mode-locked laser the electric field associated with the different modes must add constructively at one point and destructively elsewhere to create a high-intensity spike.

Modes couplés dans la pratique

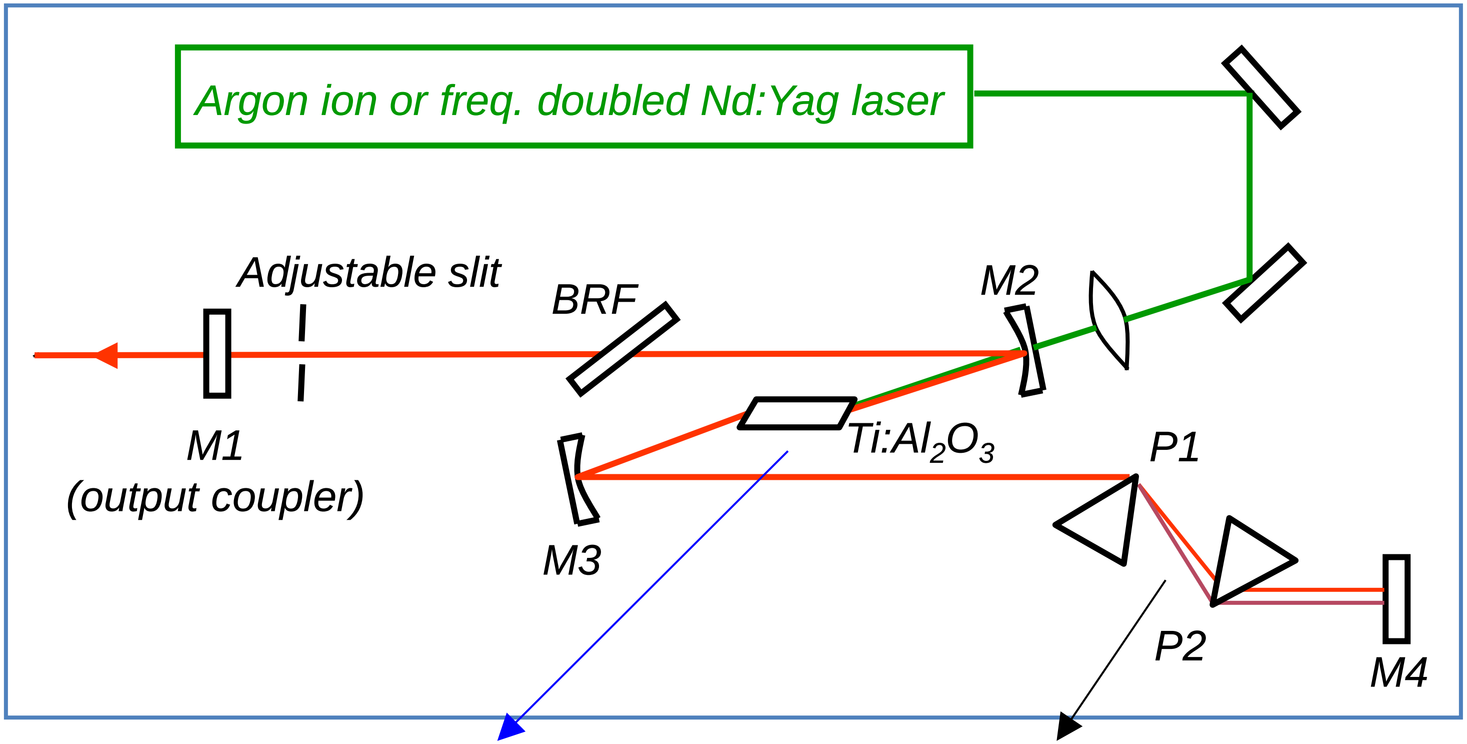


Q-modulating element (1-2%) and pulse round-trip in the resonator are synchronized: actively or passively (automatically)

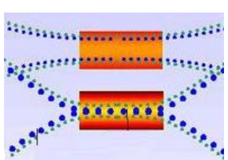
- the synchronized bunch of light is amplified, out-of-phase emission is supressed
- a single travelling pulse (= mode-locked conditions) is established after some round-trips



Schematics of a Femtosecond Laser

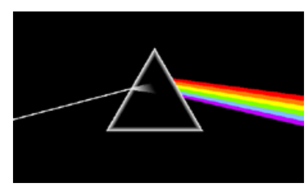


Astigmatismus, dispersion
and Kerr lens effect



$\tau_{blue} > \tau_{red}$

Dispersion compensation

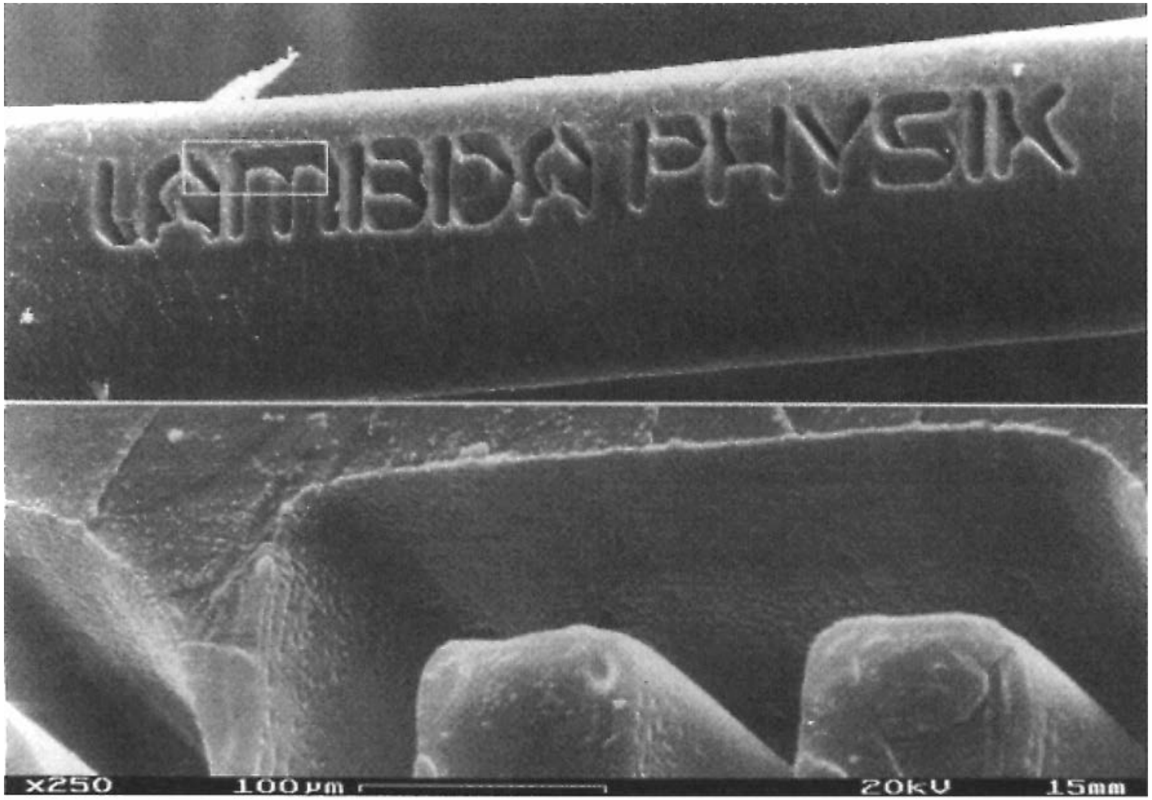


$\tau_{red} > \tau_{blue}$

→ minimum pulse width: ~30 fs,   special thin crystal and chirped mirrors: 4-5 fs

Example: Human Hair Marking

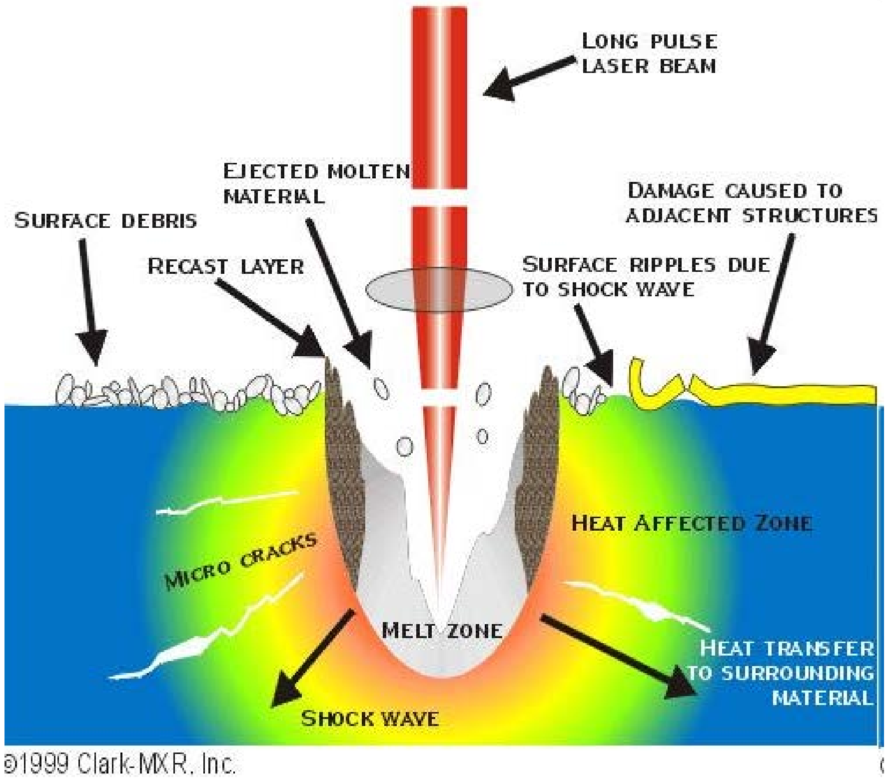
„Cold“ ablation?

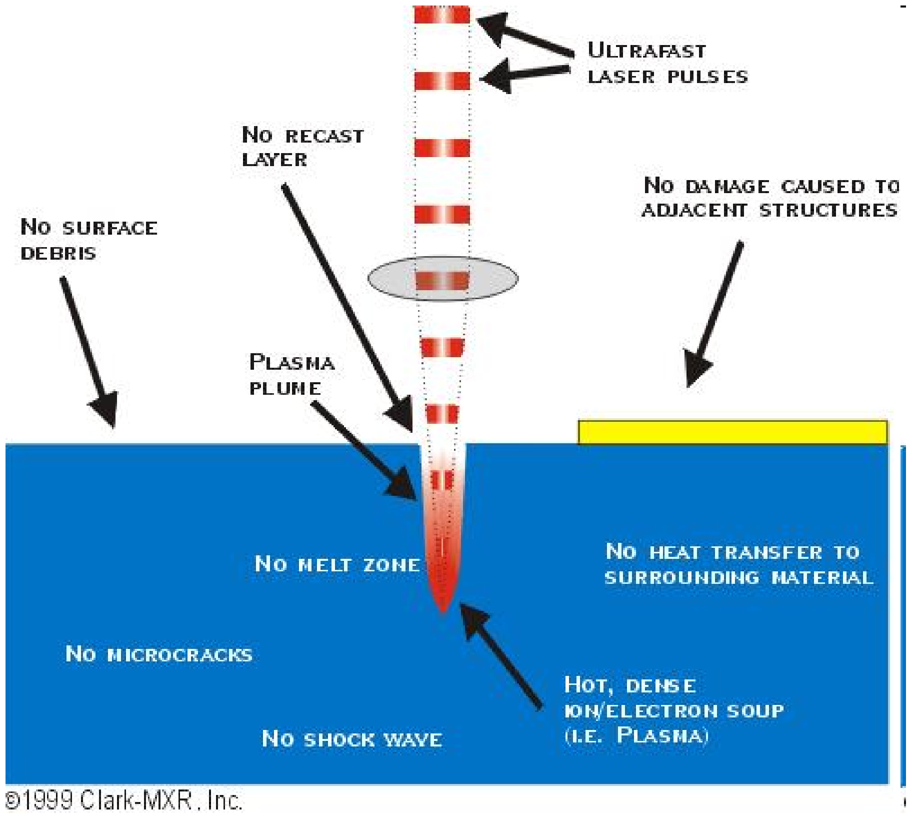


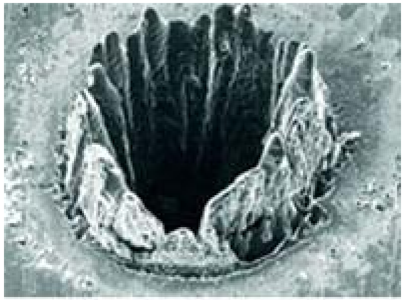
Scanning electron micrograph showing writing by excimer laser induced ablation on a human hair

Srinivasan, 1982, IBM Yorktown Heights;
Cold ablation by UV photon bond scission

ns-Machining vs. fs-Machining



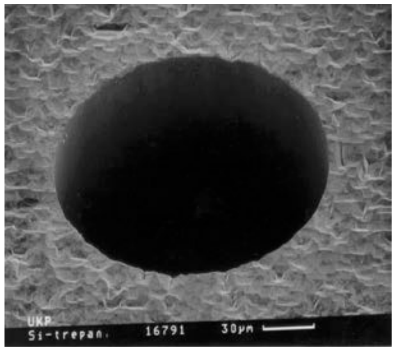




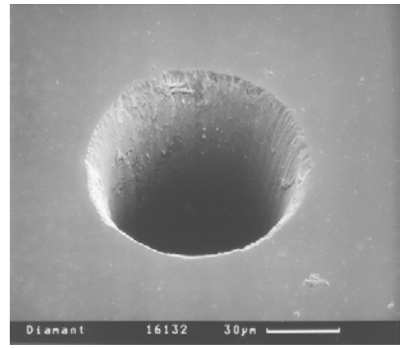
ns

fs

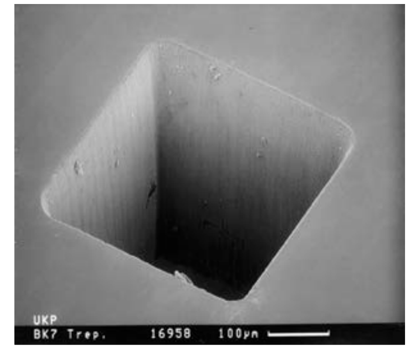
fs-Laser Machining



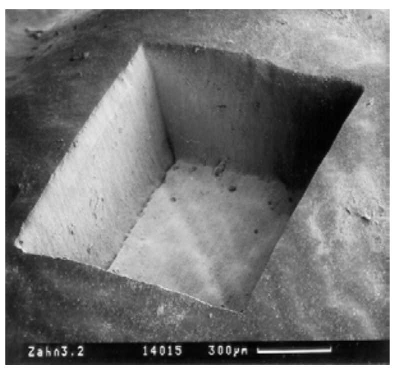
Silicon



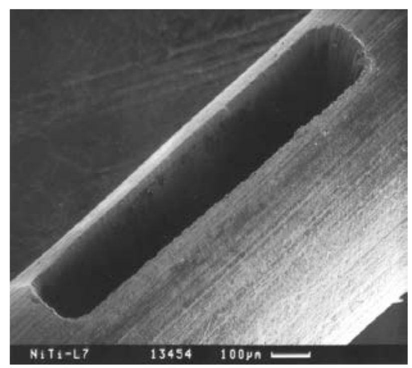
Diamond



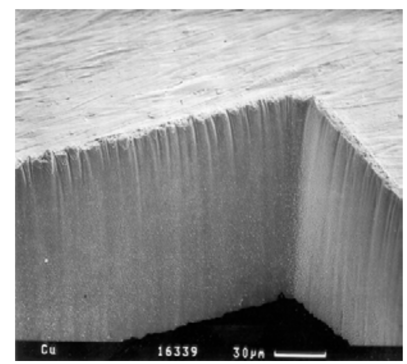
Glass



Tooth Enamel



Special Alloy

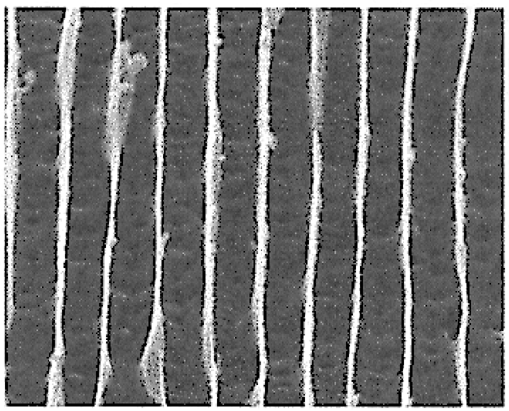


Copper

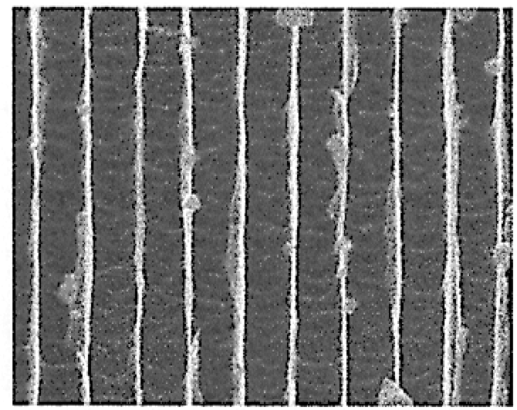
LASER ZENTRUM HANNOVER E.V.

Ablation quality pulse duration

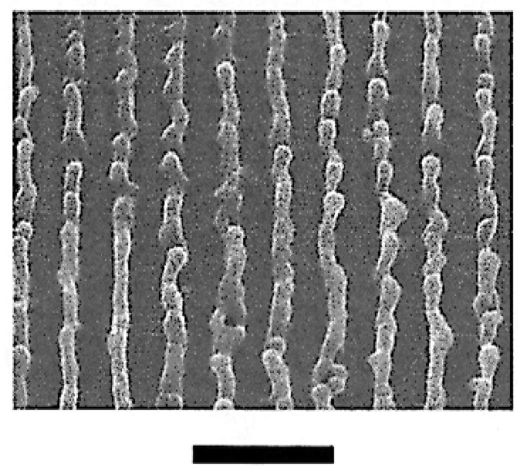
Material: **Copper**
Laser: **248 nm, 600 mJ/cm², 1 pulse**



0.5 ps



5 ps

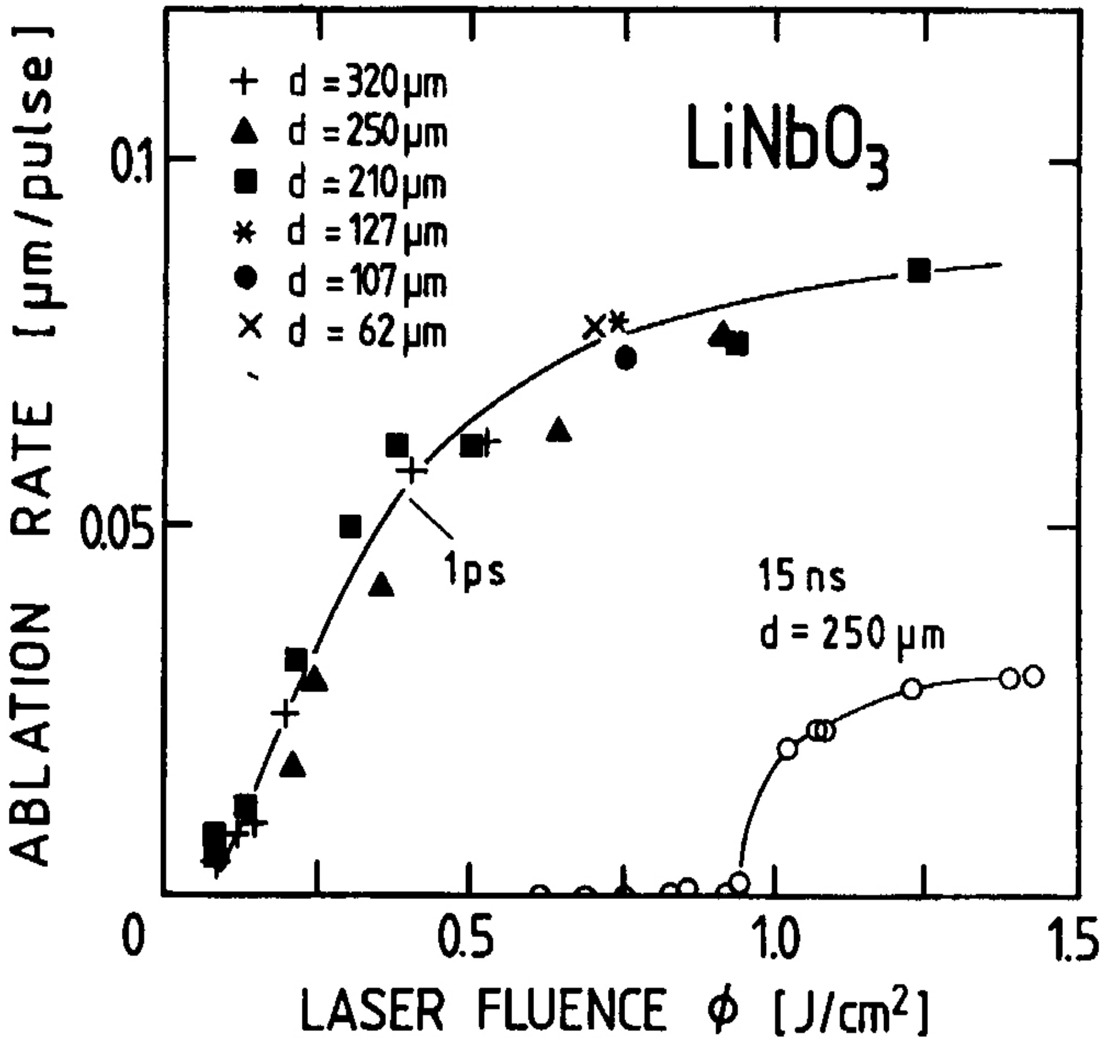


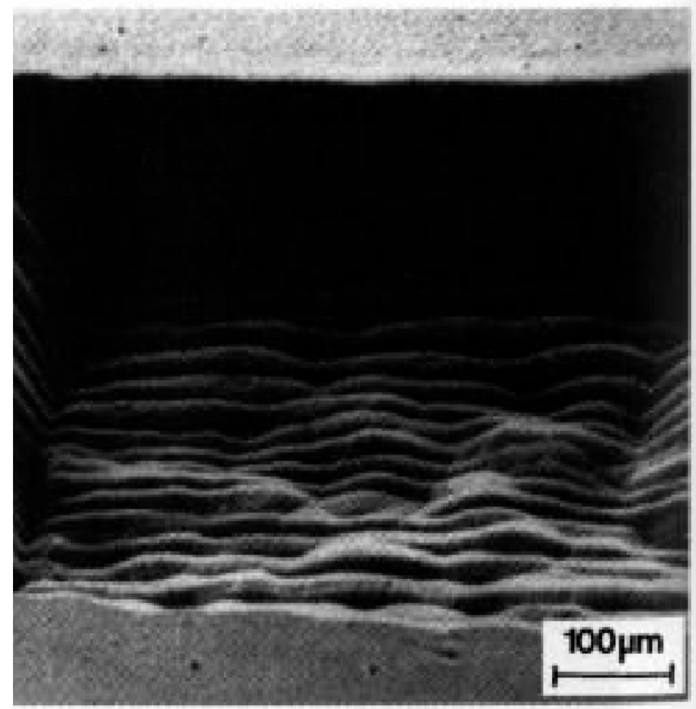
50 ps

1 µm

Laser-
Laboratorium
Göttingen e.V.

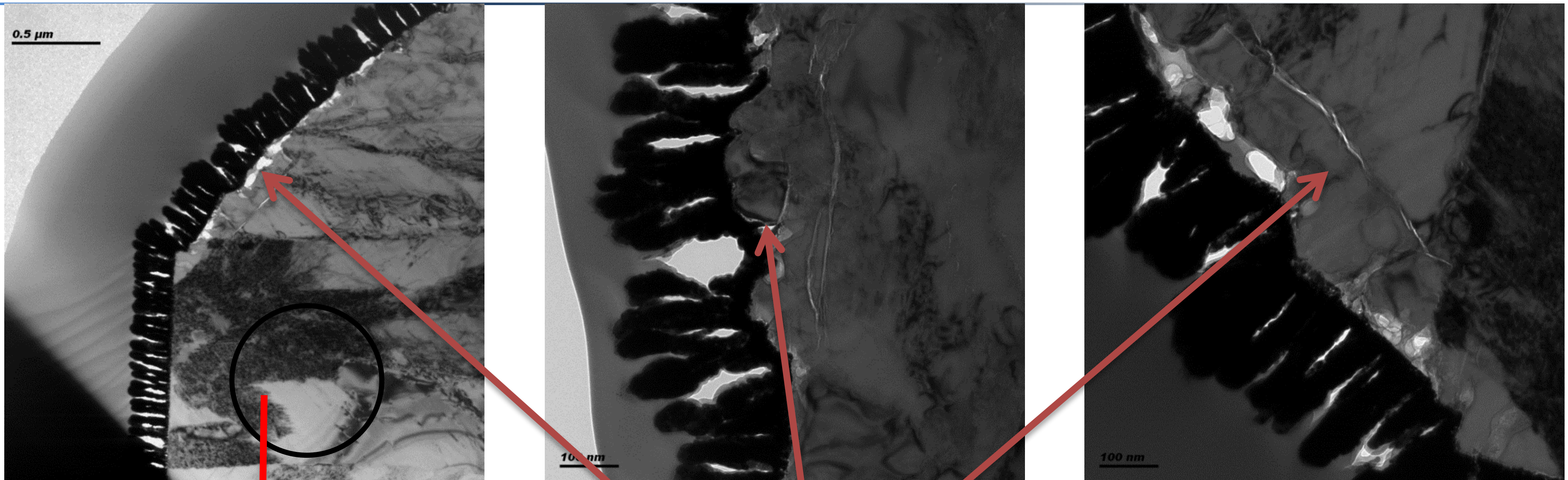
Ablation Influences

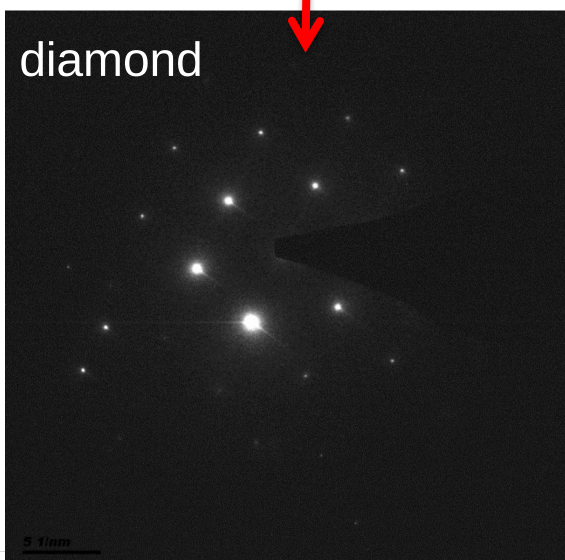




48 nm KrF-laser radiation. (a) Irradi-
) = 4.2 J/cm^2). An undefined crater is
naterial. (b) Irradiation with fs pulses
elatively smooth and no cracks are

Diamond Ablation (ps)





cracks

TEM Images

no graphite, no amorphous carbon

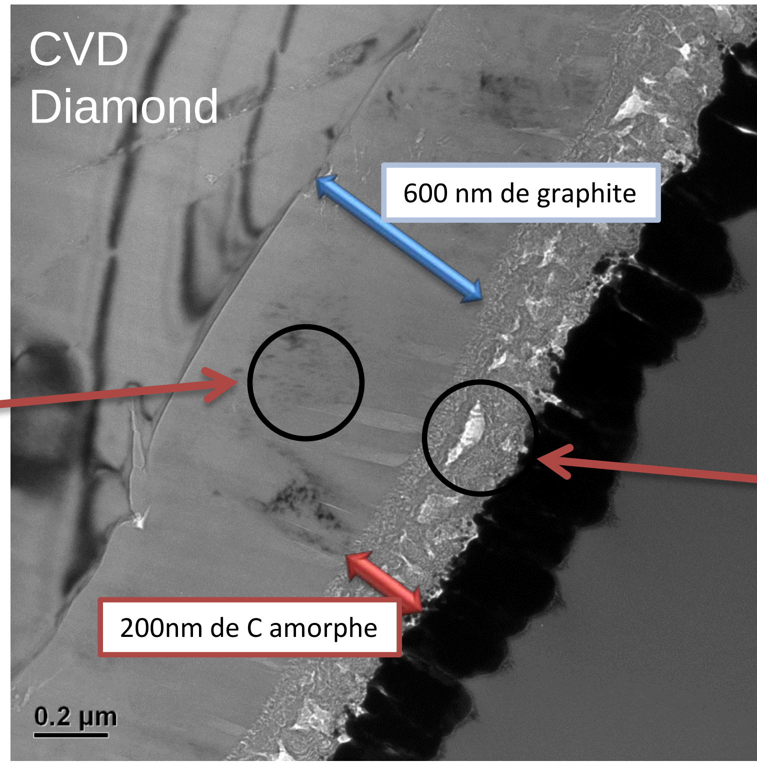
SHG Nd:YAG, 532 nm,

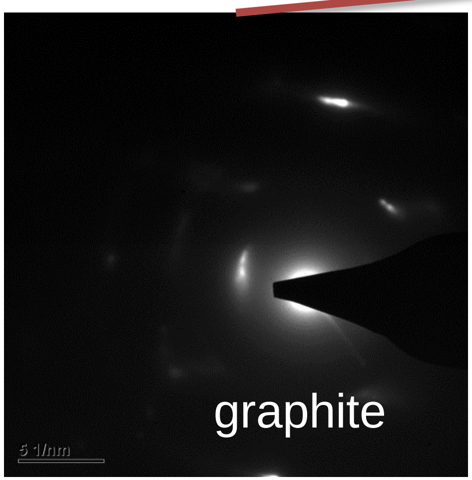
ps-pulses, 5.25 J/cm^2

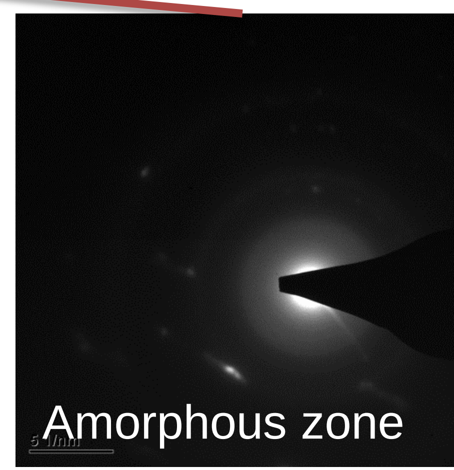
Diamond Ablation (ns) - Graphitization

SHG Nd:YAG, 532 nm,

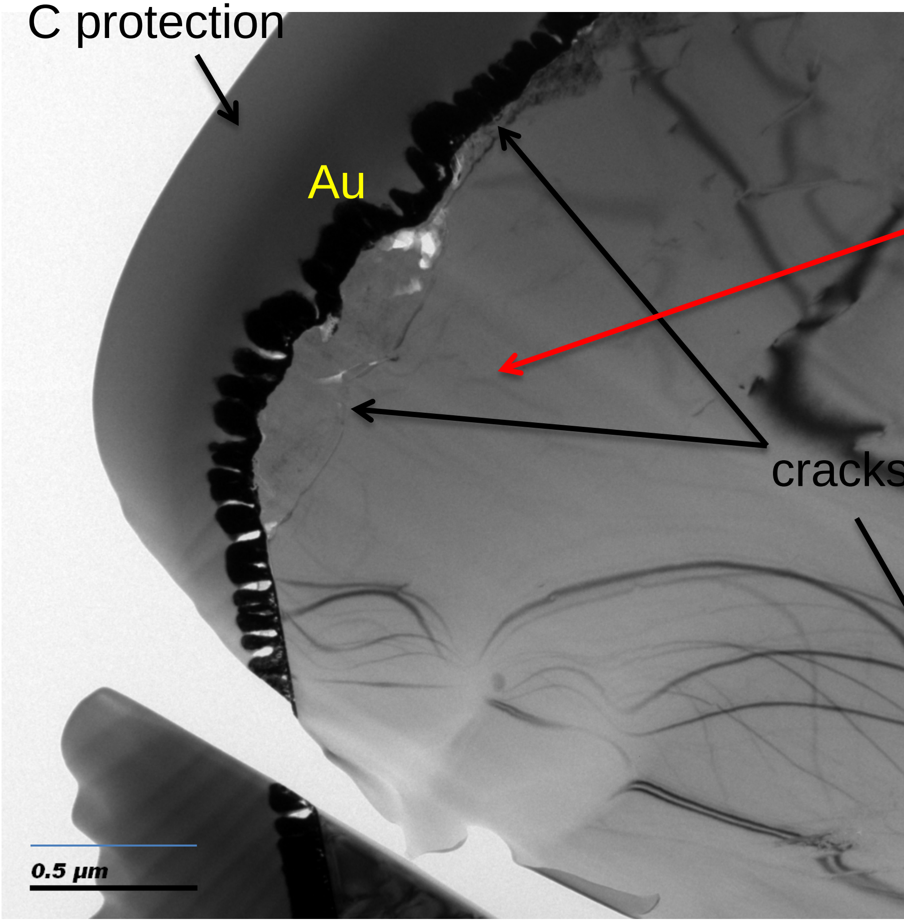
40 ns, 5 J/cm^2

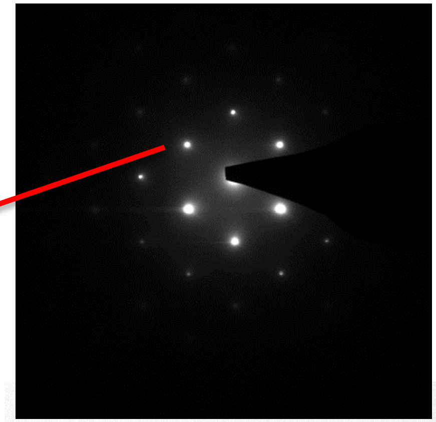






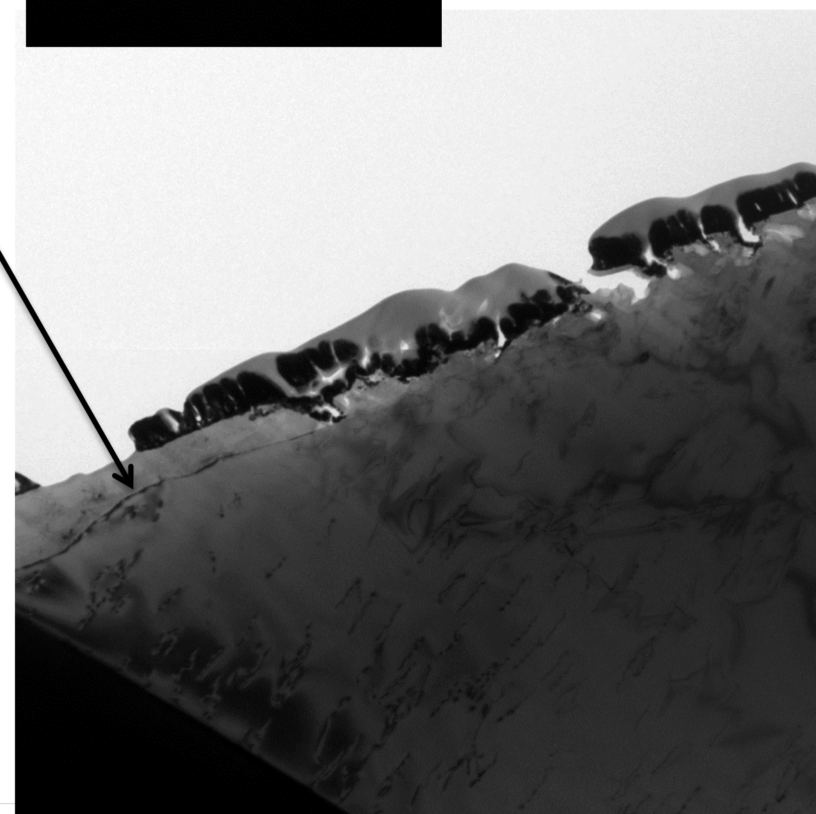
Diamond Ablation (ns) - Graphitization





TEM Images

no graphite – only diamond



SHG Nd:YAG, 532 nm,

40 ns, 35.8 J/cm^2