Ultra Short Pulses for Laser Microprocessig

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- Introduction / Motivation
- Optimize ablation efficiency
- Synchronization and machining strategies
- High throughput?
- Summary / Conclusions

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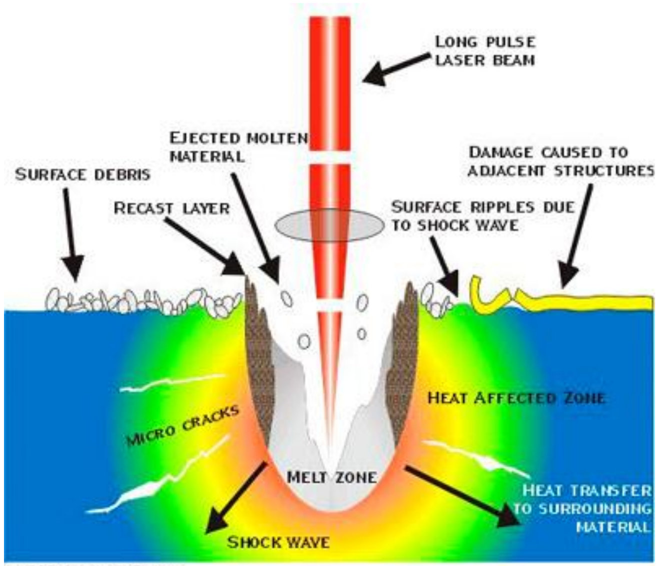
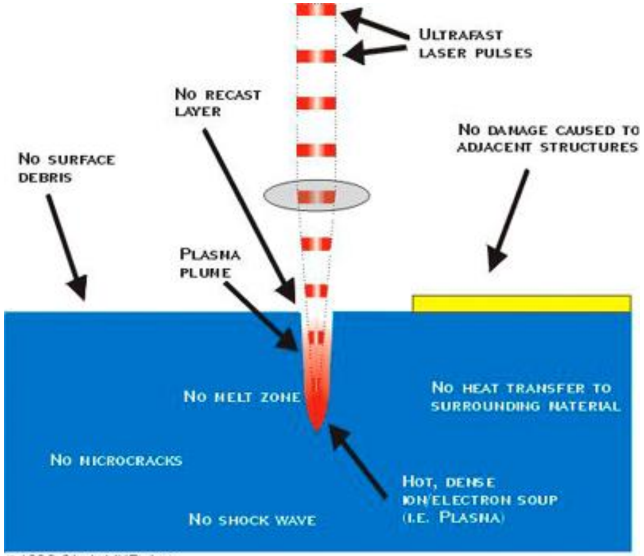
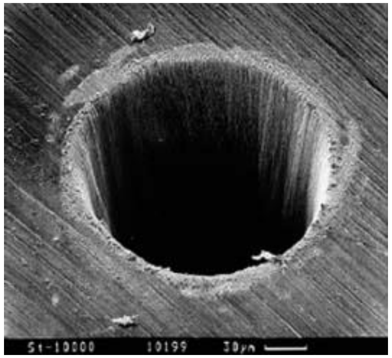
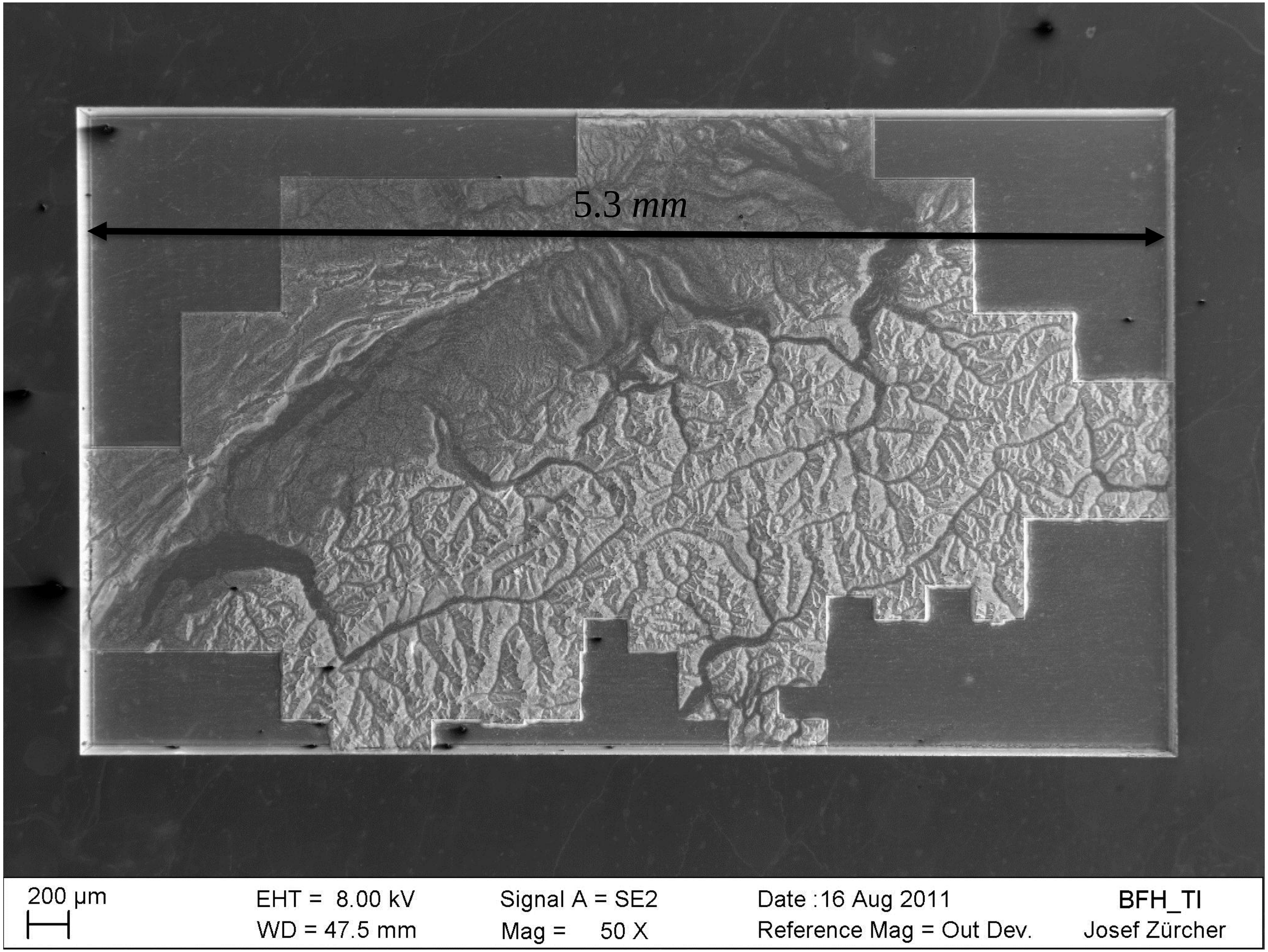
„Hot“ versus „cold“ ablation



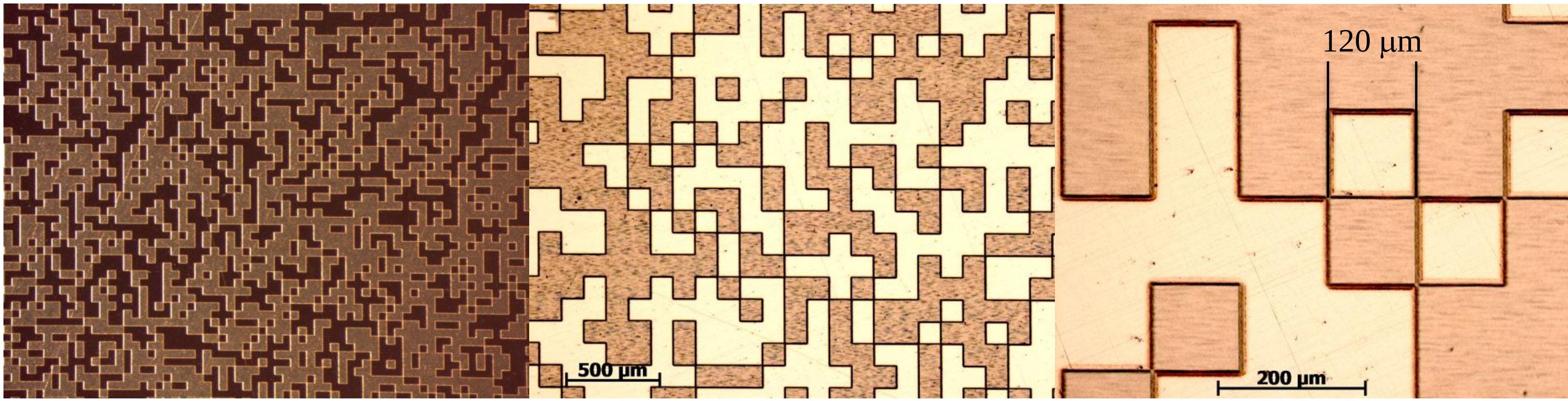


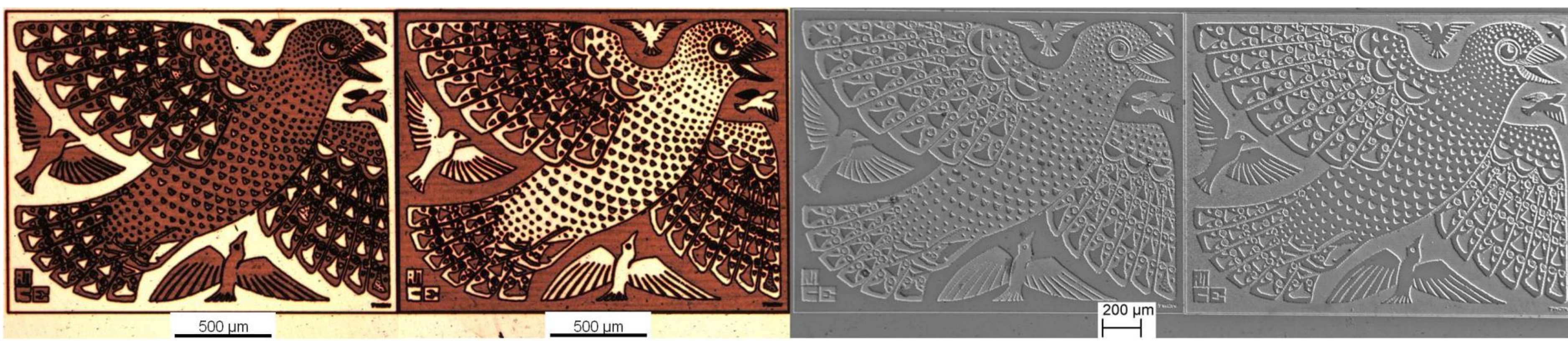


Laser machined microstructures in Copper



Laser machined microstructures in Copper

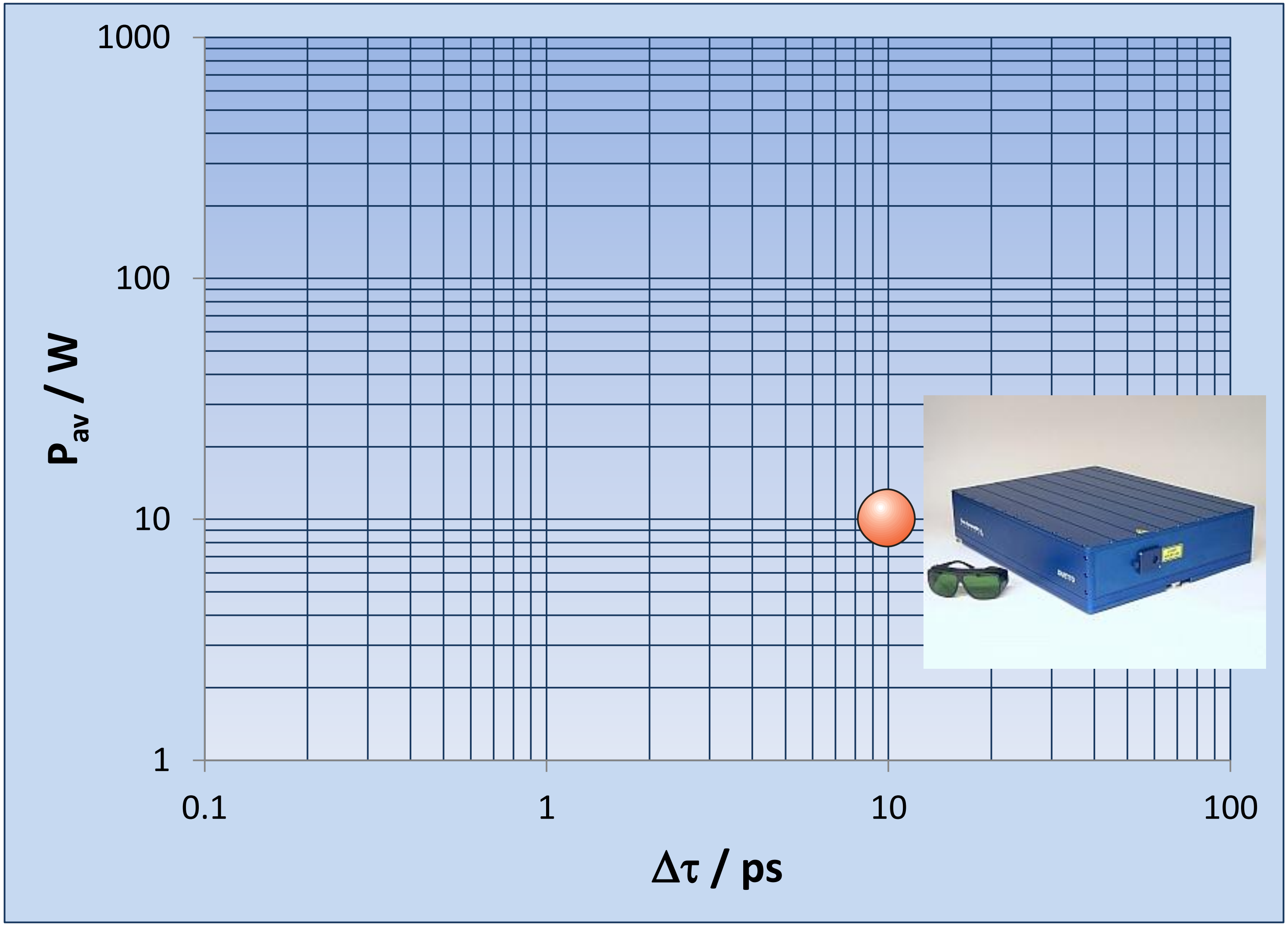




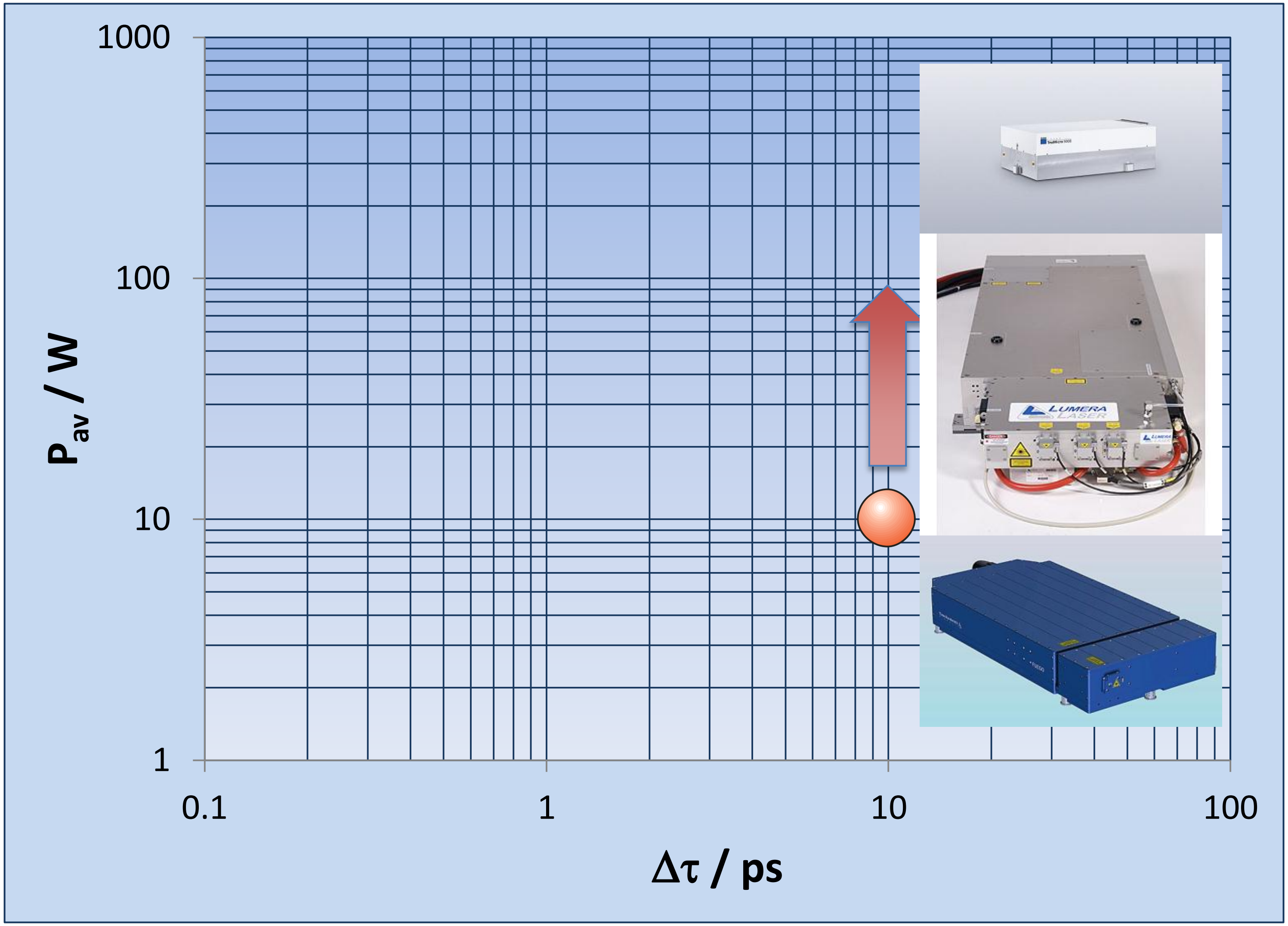
120 mW, 300 kHz, 3 µm pitch, 30 slices

Ultra short laser pulses are really well suited for laser microprocessing.

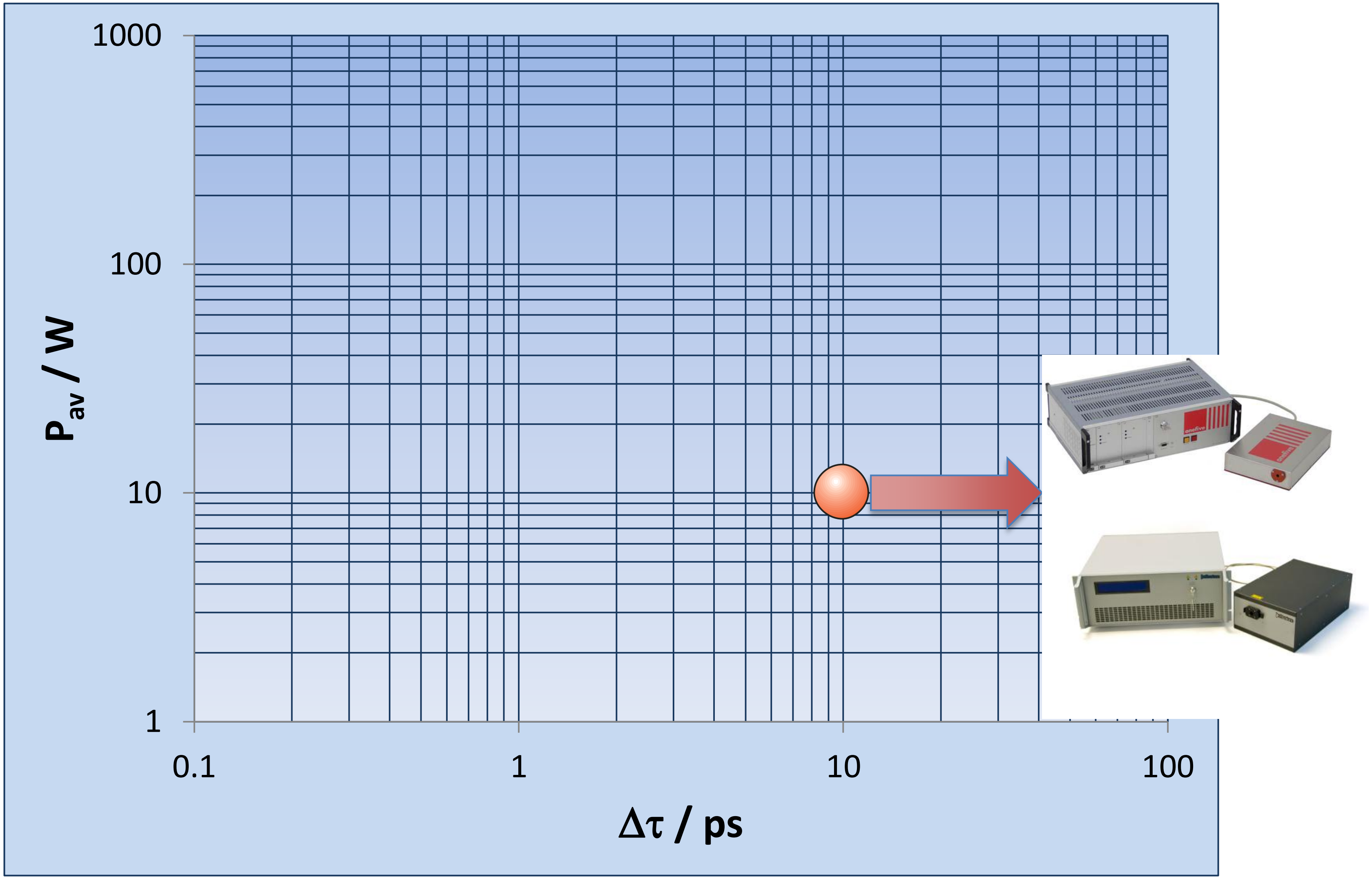
Industrial suited ultra-short pulsed Systems



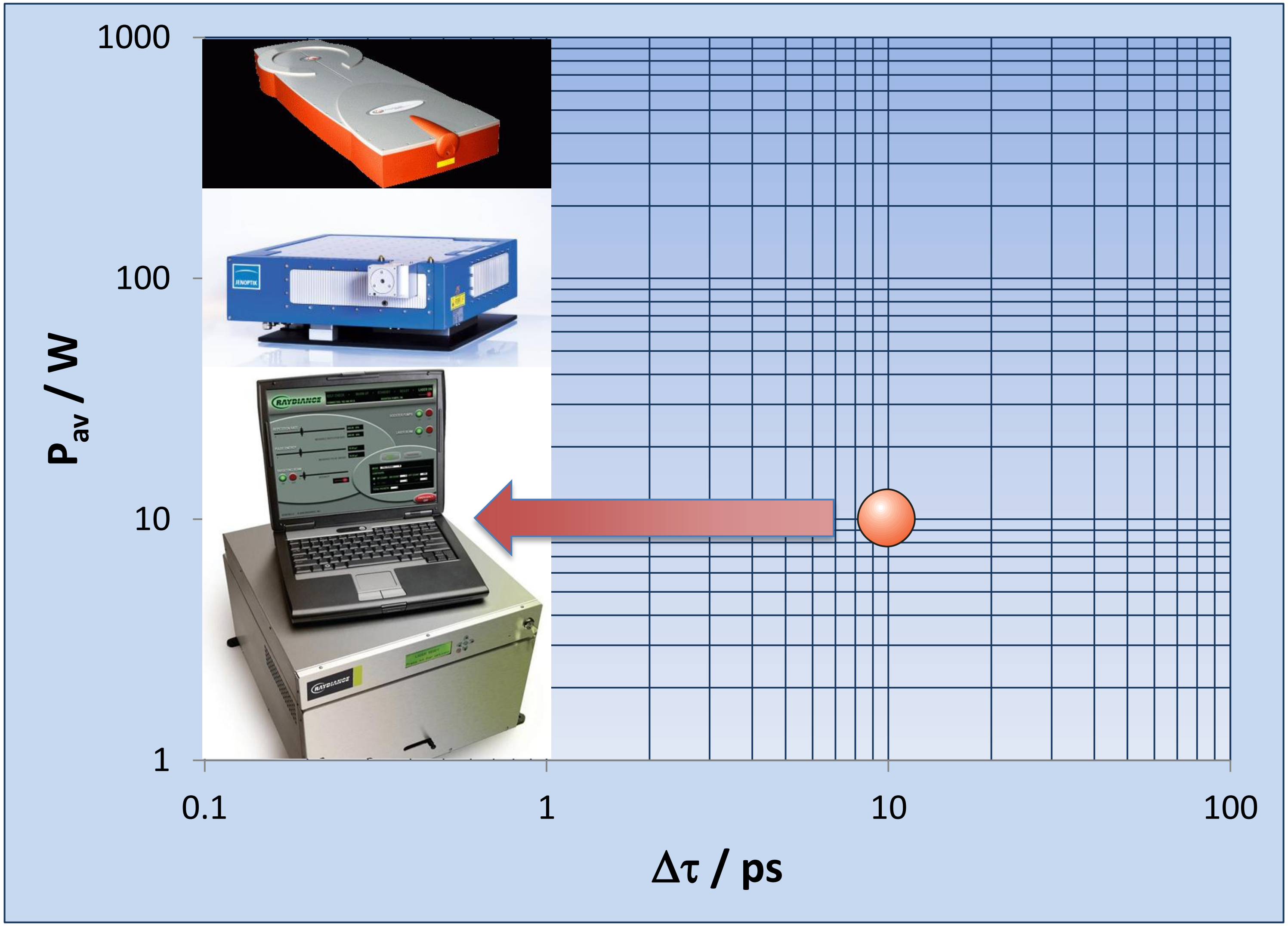
Industrial suited ultra-short pulsed Systems



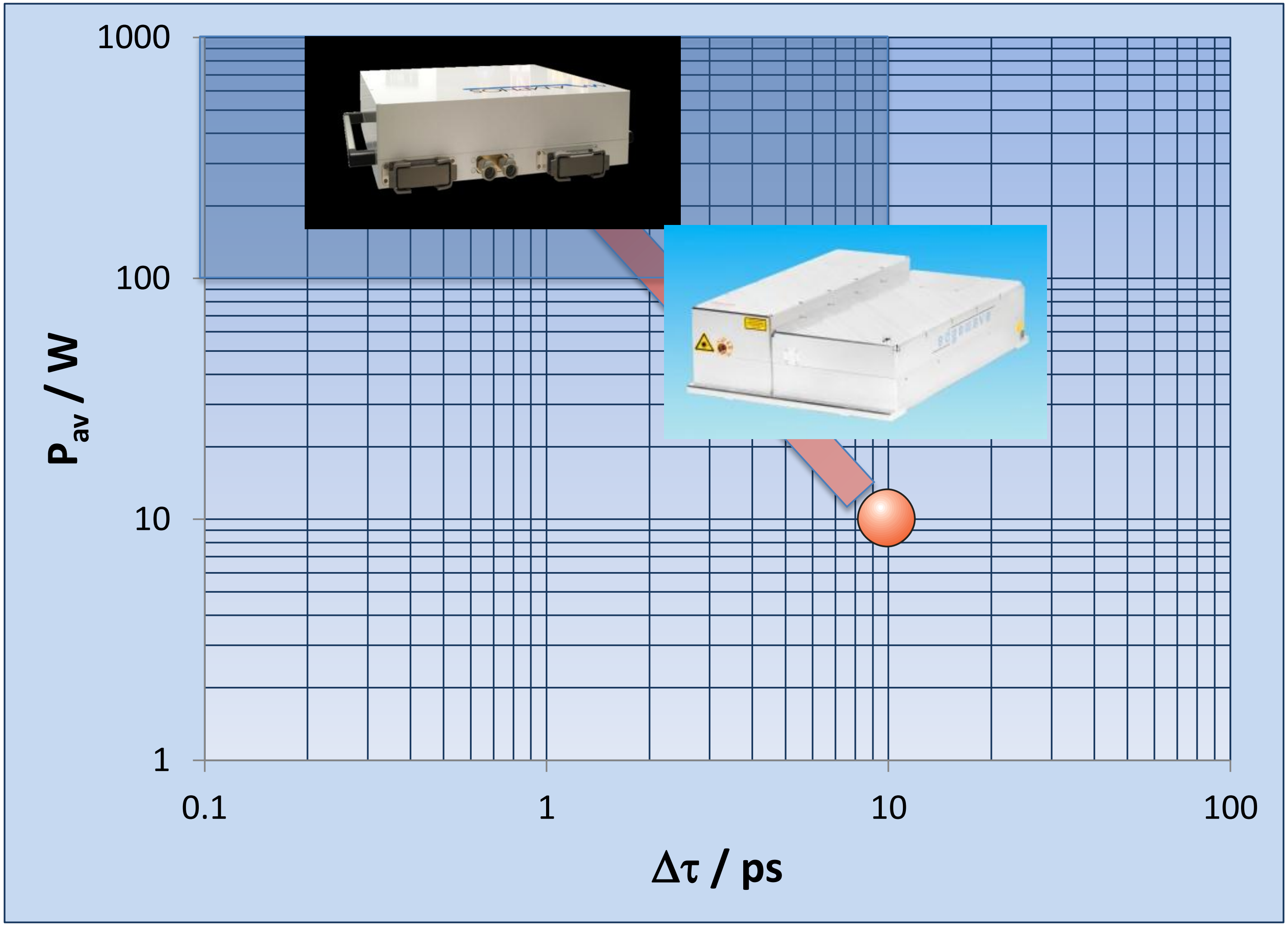
Cost effective fiber based systems



Systems with shorter pulses



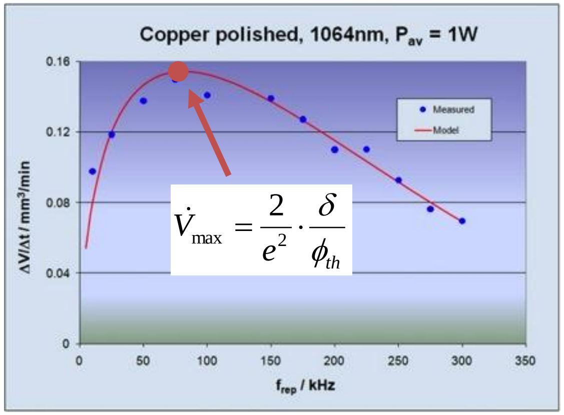
High power with short pulse duration



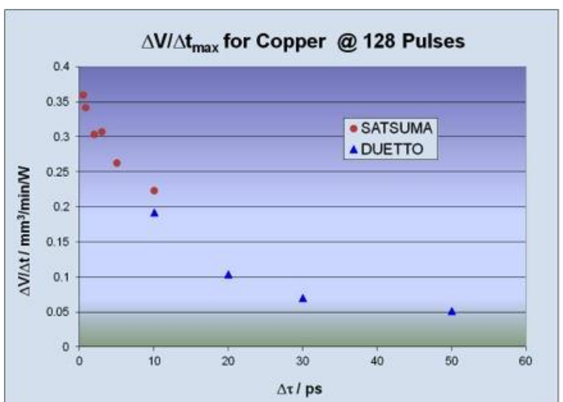
Optimization tasks

Efficiency

Maximize process efficiency

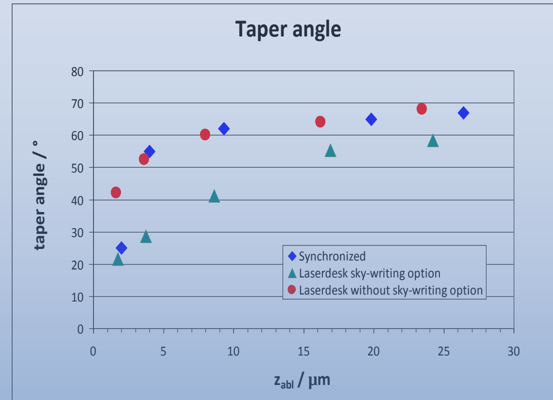


and use best suited pulse duration

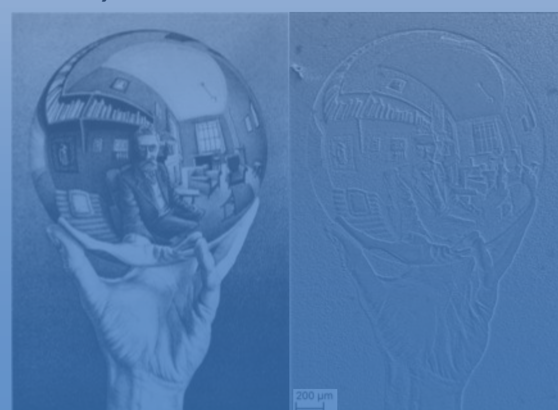


Strategy

Optimize the structuring strategy

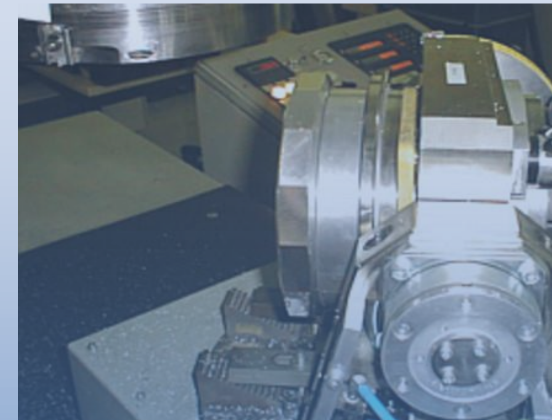


and synchronize axes with the laser



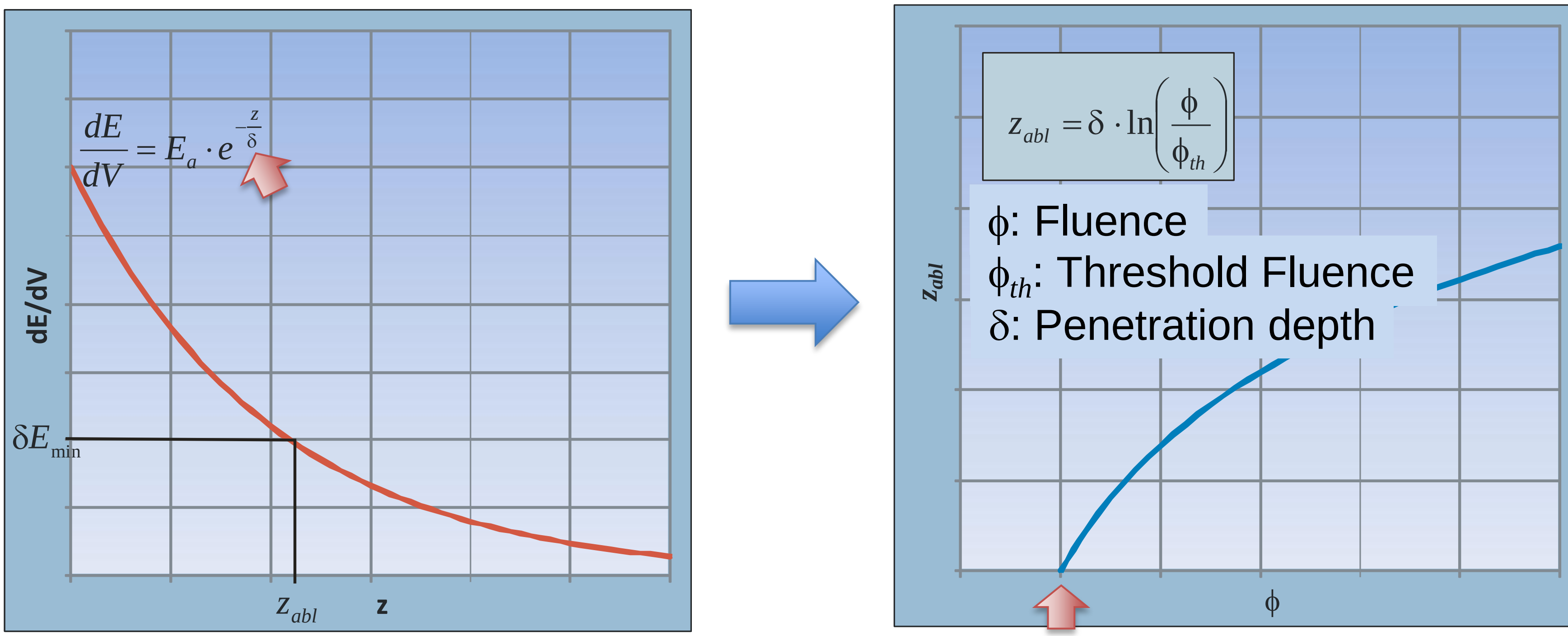
Throughput

Use fast moving axes



to obtain high throughput

Ablation Process

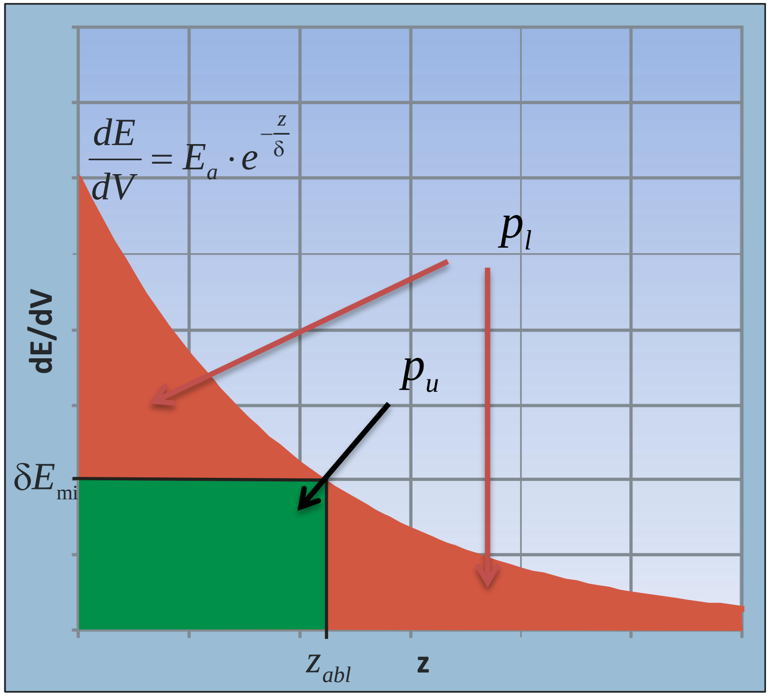


For ultra-short pulses it is assumed that the energy is deposited before the evaporation starts. The deposited energy is assumed to drop exponentially with the distance z to the surface.

Only a certain energy per unit volume, δE_{min}, is needed to evaporate the material. This defines the ablation depth z_{abl}.

This will finally end up in the well known logarithmic ablation law.

Ablation Efficiency: Top Hat



The total energy corresponds to the area under the curve p_c.

But only a part, p_u, is used to evaporate the material.

The remaining part, p_l, is lost.

The efficiency of the ablation process can be defined by:

$$\eta = \frac{p_u}{p_c} = \frac{p_u}{p_u + p_l}$$

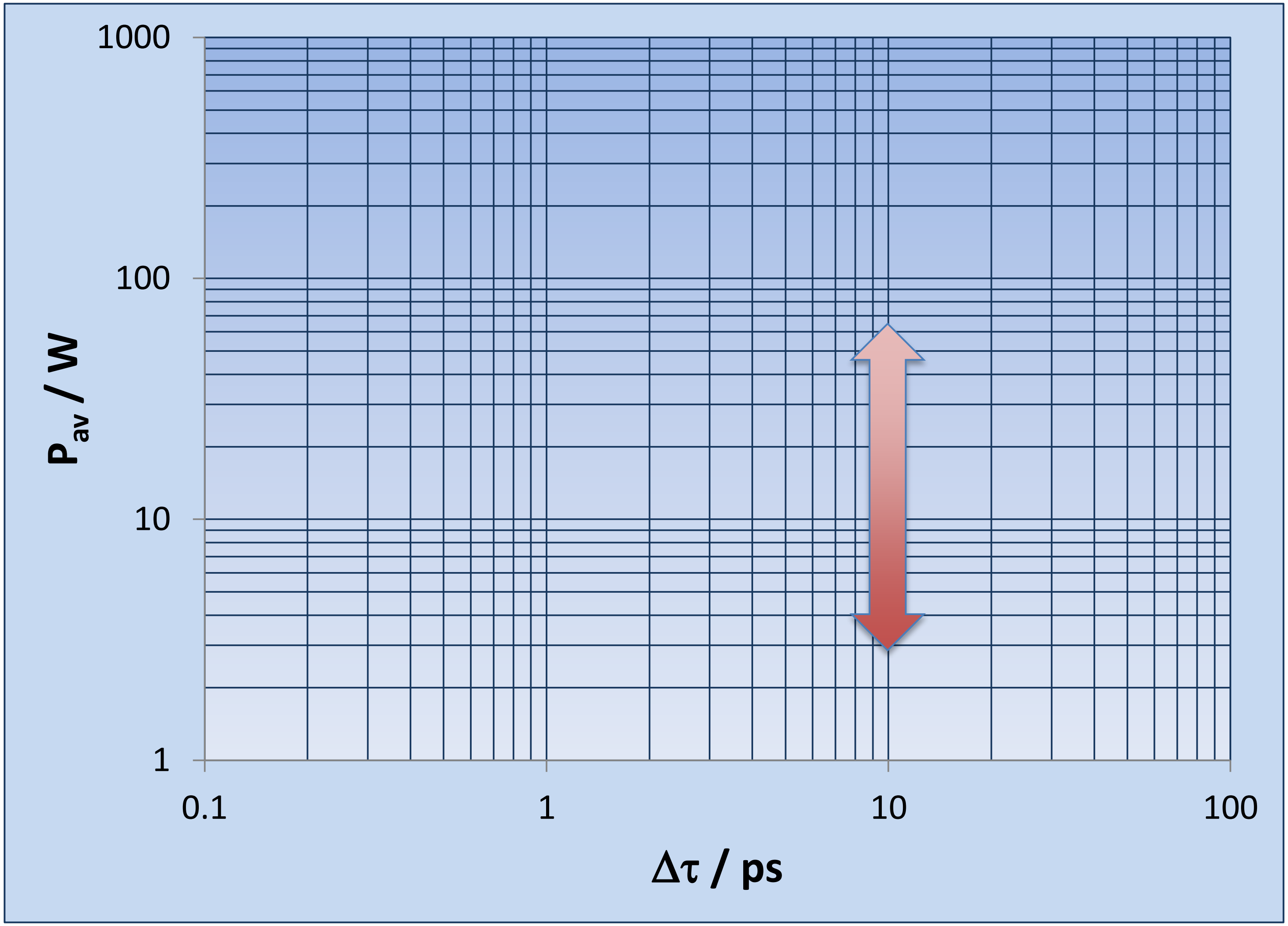
A short calculation shows that this efficiency is given by: $\eta = \frac{\phi_{th}}{\phi} \cdot \ln\left(\frac{\phi}{\phi_{th}}\right)$

With a maximum value at $\frac{\phi}{\phi_{th}} = e$ resulting in a maximum efficiency of $\eta = 36.8\%$.

The ablation depth and volume per pulse then read: $z_{abl} = \delta$ and $\Delta V = \pi \cdot w_0^2 \cdot \delta$

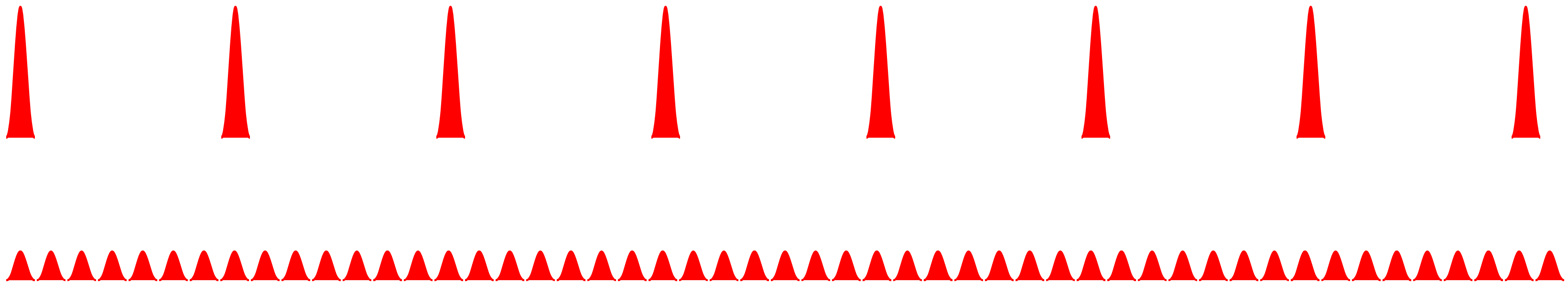
For a Gaussian beam one obtains: $z_{abl,centre} = 2\delta$ and again $\Delta V = \pi \cdot w_0^2 \cdot \delta$

Varying the average power



Varying the average power

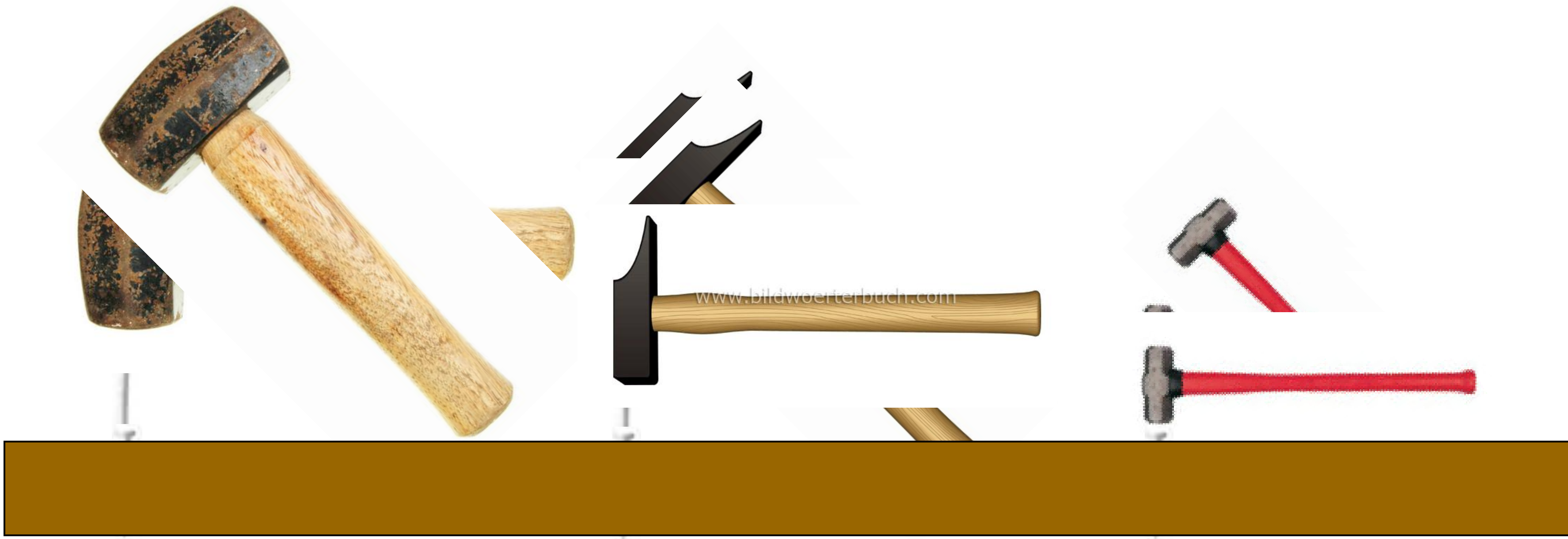
$$P_{av} = \boxed{f_{rep}} \cdot \boxed{E_P}$$



We can enlarge the average power by raising the pulse energy E_P or the repetition rate of the system f_{rep}.

What‘s the difference between these two possibilities.

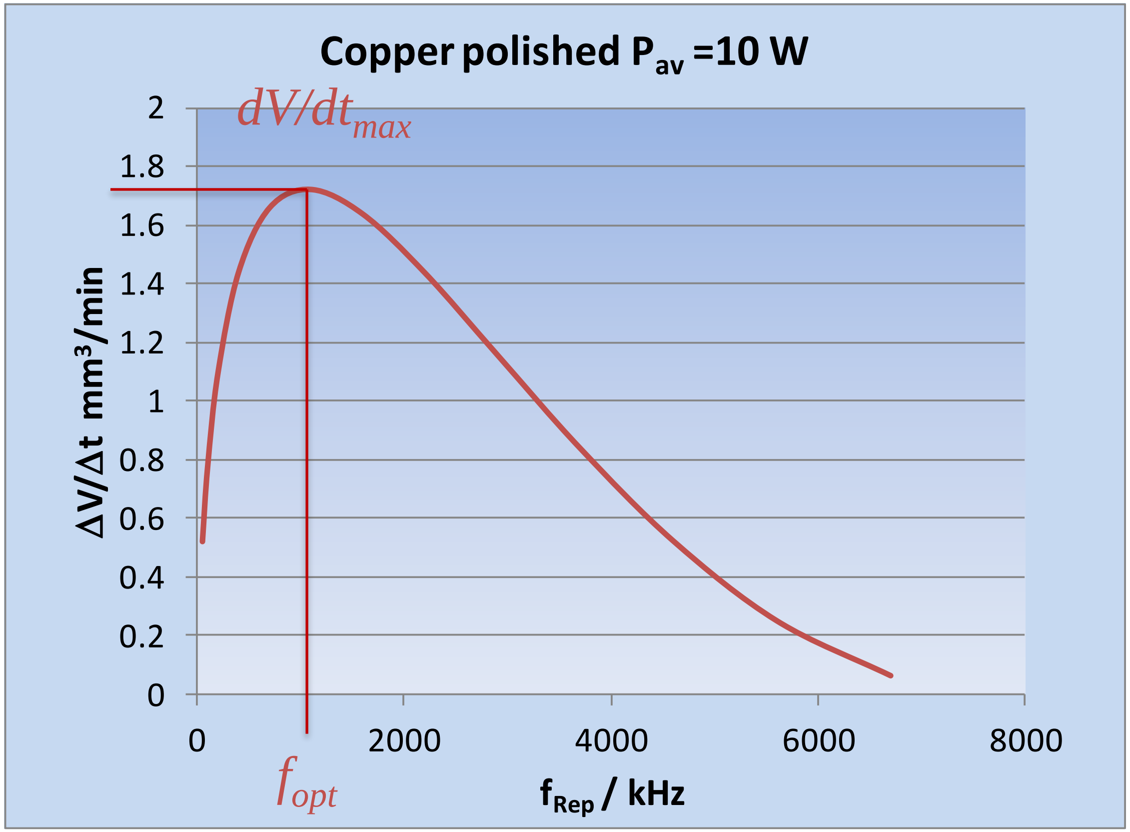
Hammer and Nail



We already know:

At the optimum point the ablated volume per pulse reads $\Delta V = \pi w_0^2 \cdot \delta$

Gaussian Beam: Volume ablation rate at constant average power



$$P_{av} = 10\,W,\quad w_0 = 16.5\,\mu m$$

$$\phi_{th} = 0.30\,\frac{J}{cm^2}$$

$$\delta = 32\,nm$$

$$\frac{\dot{V}_{\max}}{P_{av}} = \frac{2}{e^2}\cdot\frac{\delta}{\phi_{th}}$$

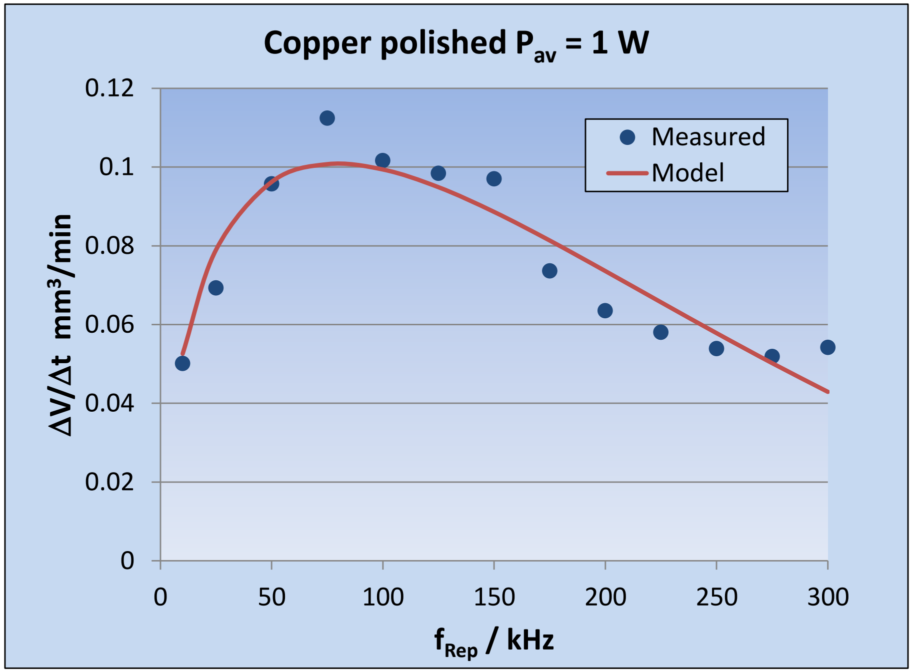
$$\frac{f_{opt}}{P_{av}} = \frac{2}{e^2}\cdot\frac{1}{\pi\cdot w_0^2}\cdot\frac{1}{\phi_{th}}$$

$$\frac{\Delta V}{Pulse} = w_0^2\cdot\pi\cdot\delta$$

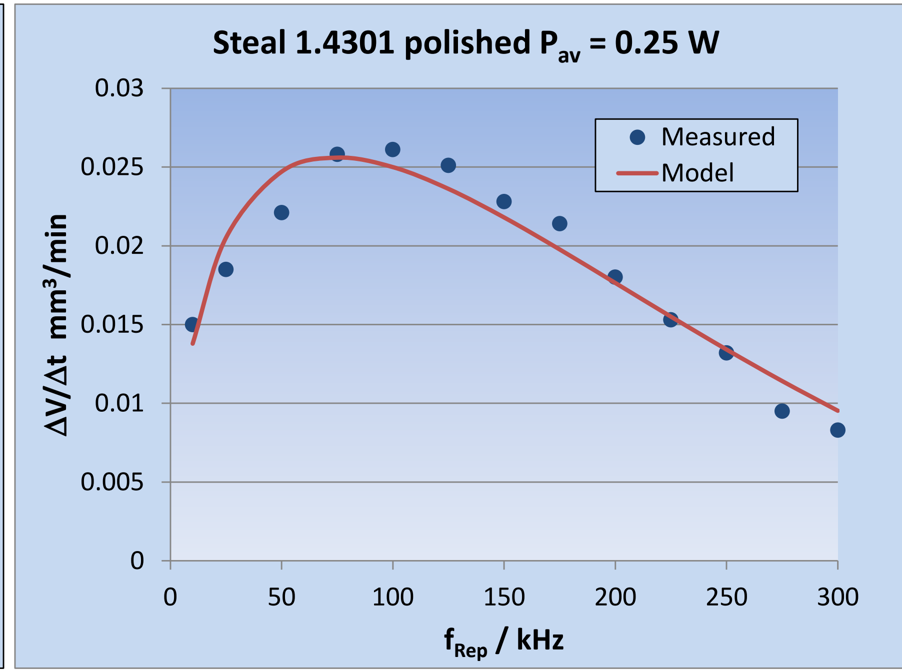
There exist an optimum repetition rate f_{opt} going with a maximum ablation rate.

At the optimum point the ablated volume per pulse reads $\Delta V = \pi w_0^{2}\cdot\delta$

Volume ablation rate at constant average power



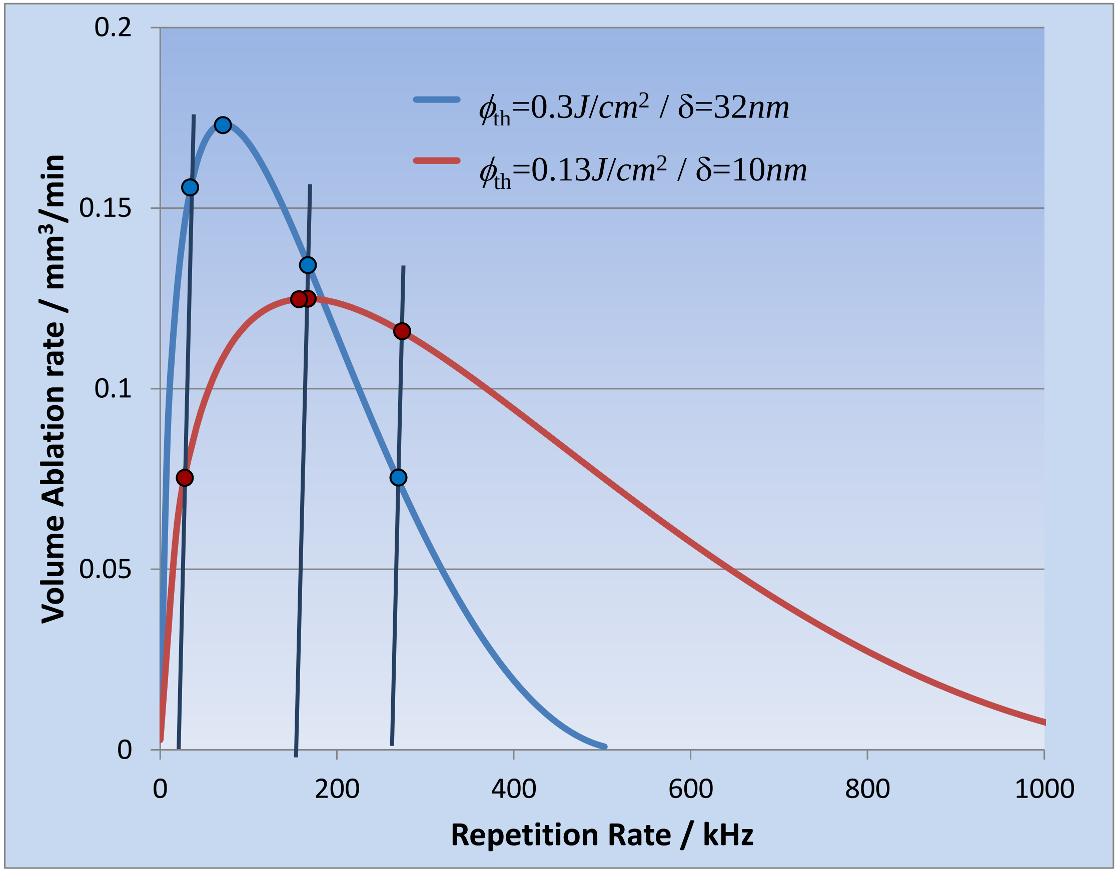
Fitted: $\phi_{th} = 0.3\ J/cm^2\ ,\ \ \delta = 22\ nm$



Fitted: $\phi_{th} = 0.08\ J/cm^2\ ,\ \ \delta = 5.5\ nm$

Good agreement between measured values and model.

Comparison of different situations



$$P_{av} = 1W, \quad w_0 = 20\ \mu m$$

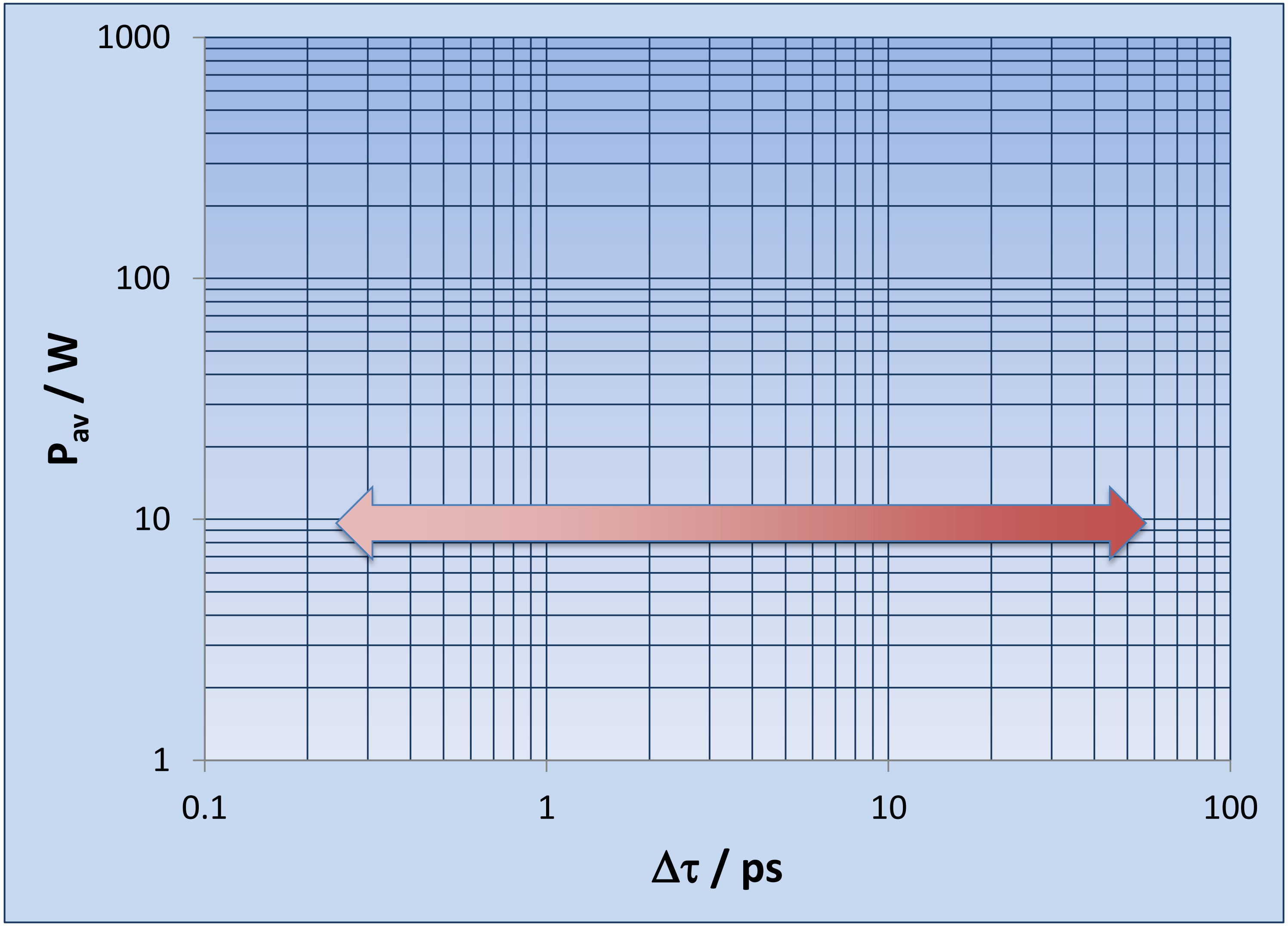
$$\frac{\dot{V}_{\max}}{P_{av}} = \frac{2}{e^2} \cdot \frac{\delta}{\phi_{th}}$$

$$\frac{f_{opt}}{P_{av}} = \frac{2}{e^2} \cdot \frac{1}{\pi \cdot w_0^2} \cdot \frac{1}{\phi_{th}}$$

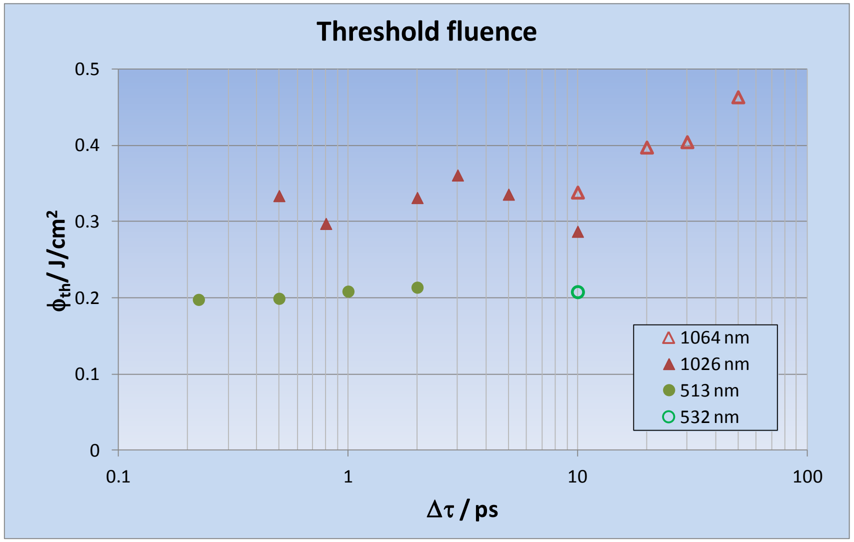
To prevent from conflicting results a comparison between different materials or systems should be done at the optimum points.

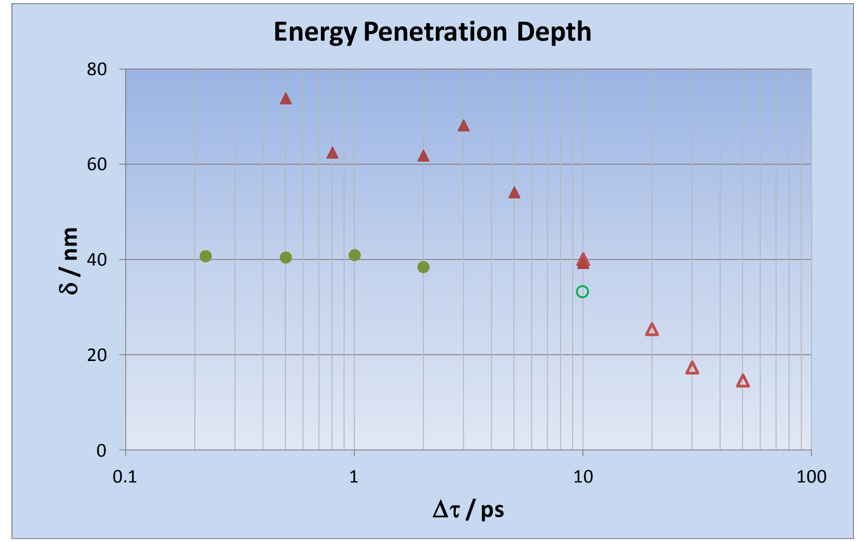
Its values are given by the **threshold fluence, ϕ_{th}**, and **penetration depth, δ**, which have to be measured for the same number of pulses applied (incubation).

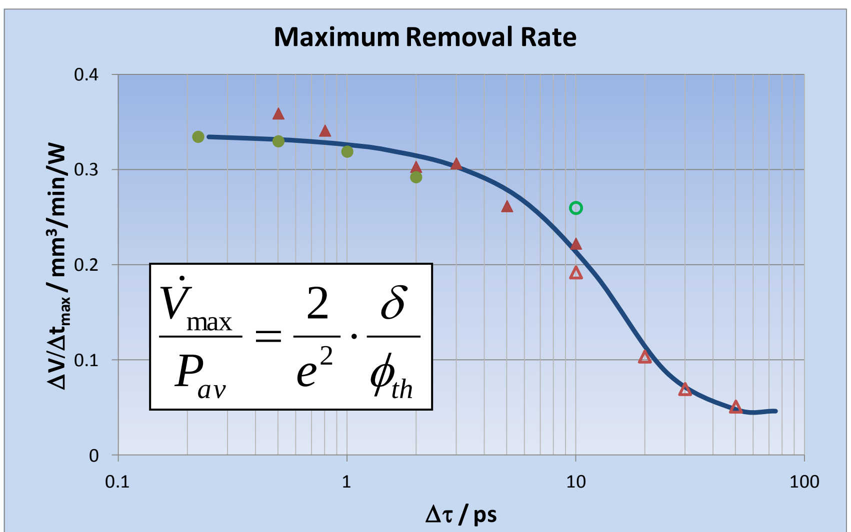
Varying the pulse duration



Copper: Ablation study (128 pulses)







Threshold slightly decreases for pulses >10ps

Rests almost constant for shorter pulse

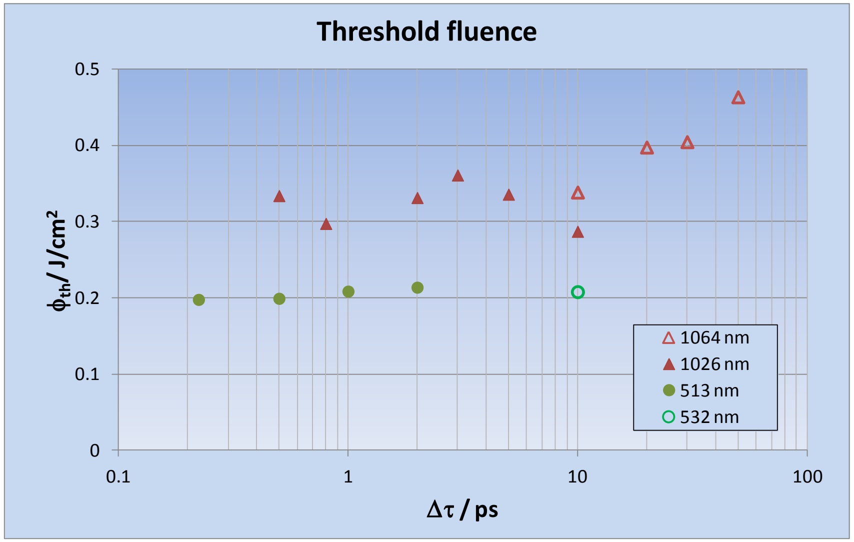
Increase of the energy penetration depth for IR

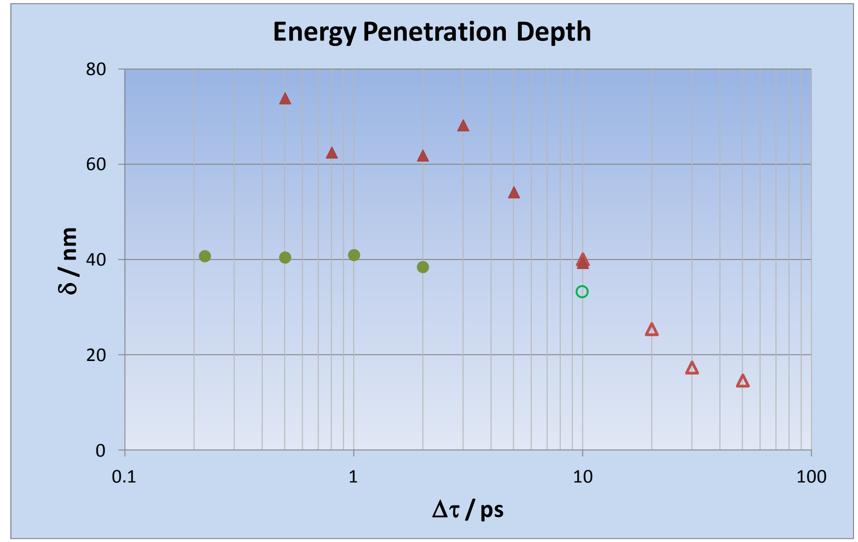
513nm shows the same tendency for pulses shorter than 10ps

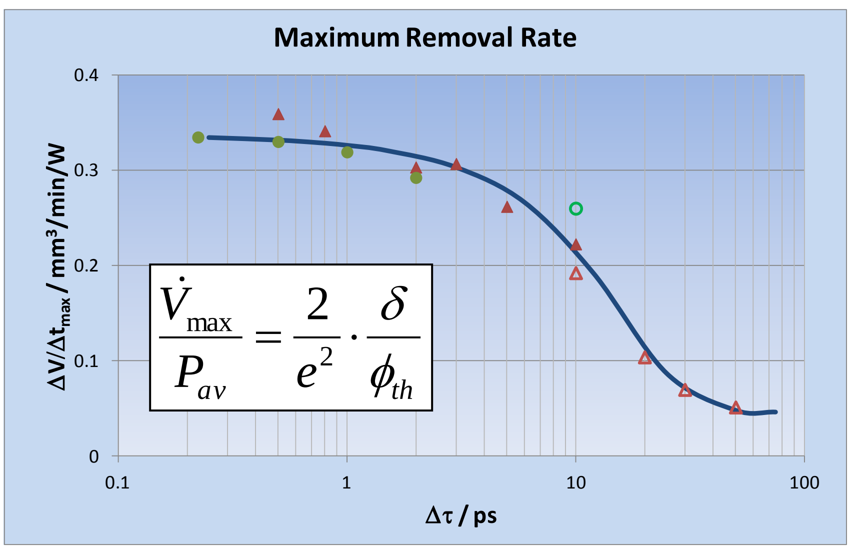
Continuous grow of the maximum removal rate by reducing $\Delta\tau$, but this grow seems to saturate (blue line as guide to the eye).

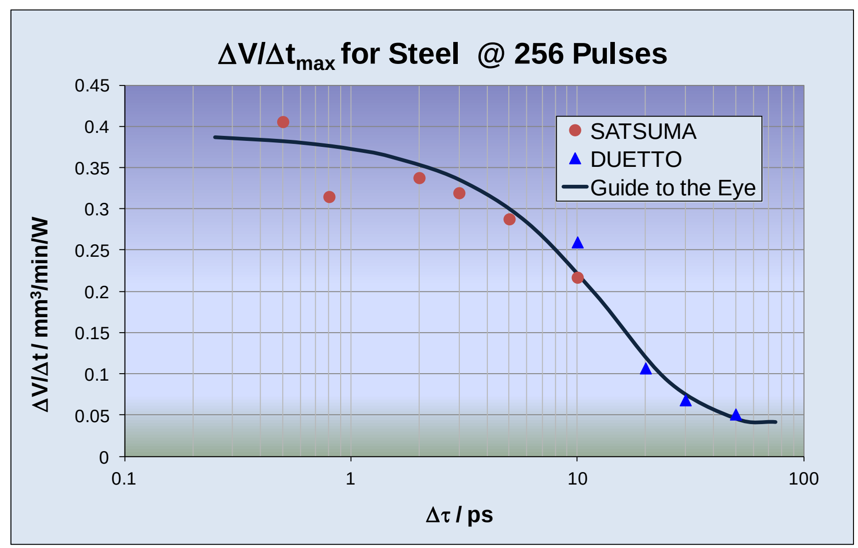
Other metals show identical tendency.

Copper: Ablation study (128 pulses)

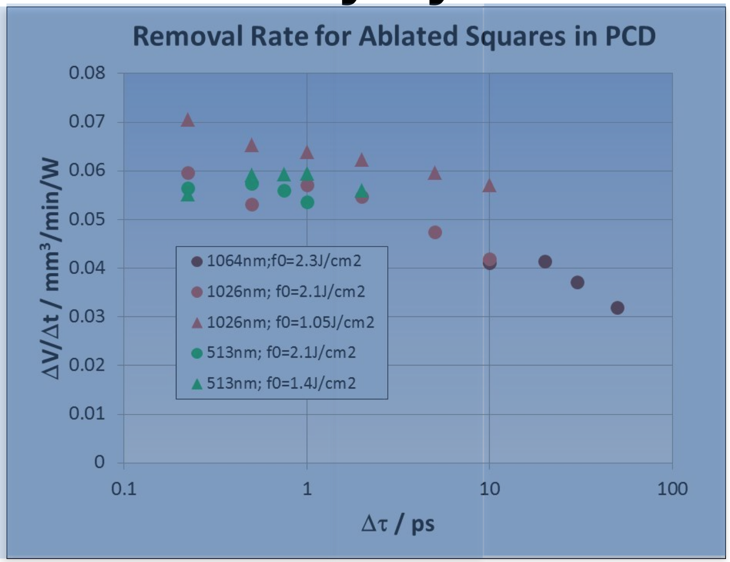








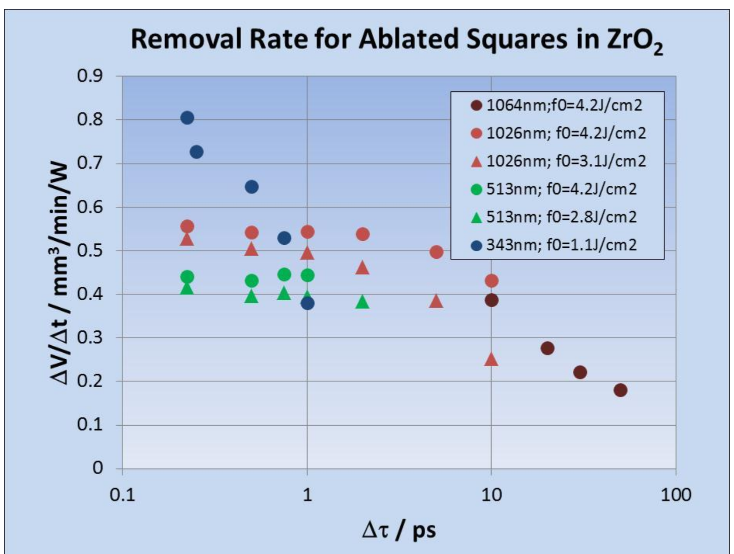
Results: Polycrystalline Diamond PCD and Zirconium Oxide ZrO_2



Quite strong Influence of the pulse duration in the range of 50ps – 10ps.

A small increase of the removal rate is still observed for pulses between 10ps and 2ps.

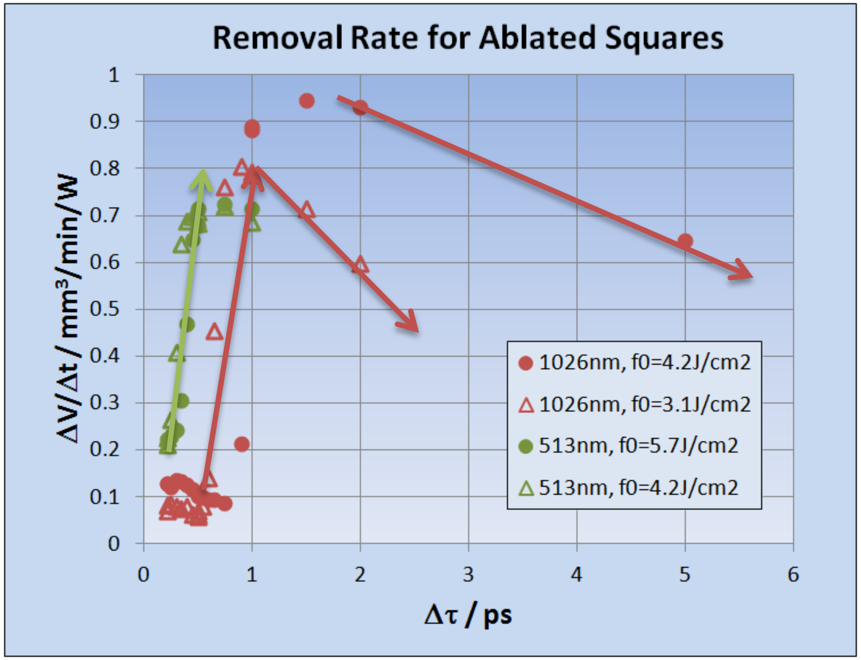
For shorter pulses (2ps – 250fs) no significant change in the removal rate can be observed, also for 513nm.



A similar behavior is observed (513nm and 1026 nm) for ZrO_2.

But in contrast, for 343nm and low fluences the dependence of the removal rate on the pulse duration between 250fs and 1ps is strong.

Ablated squares in Soda-lime Glass

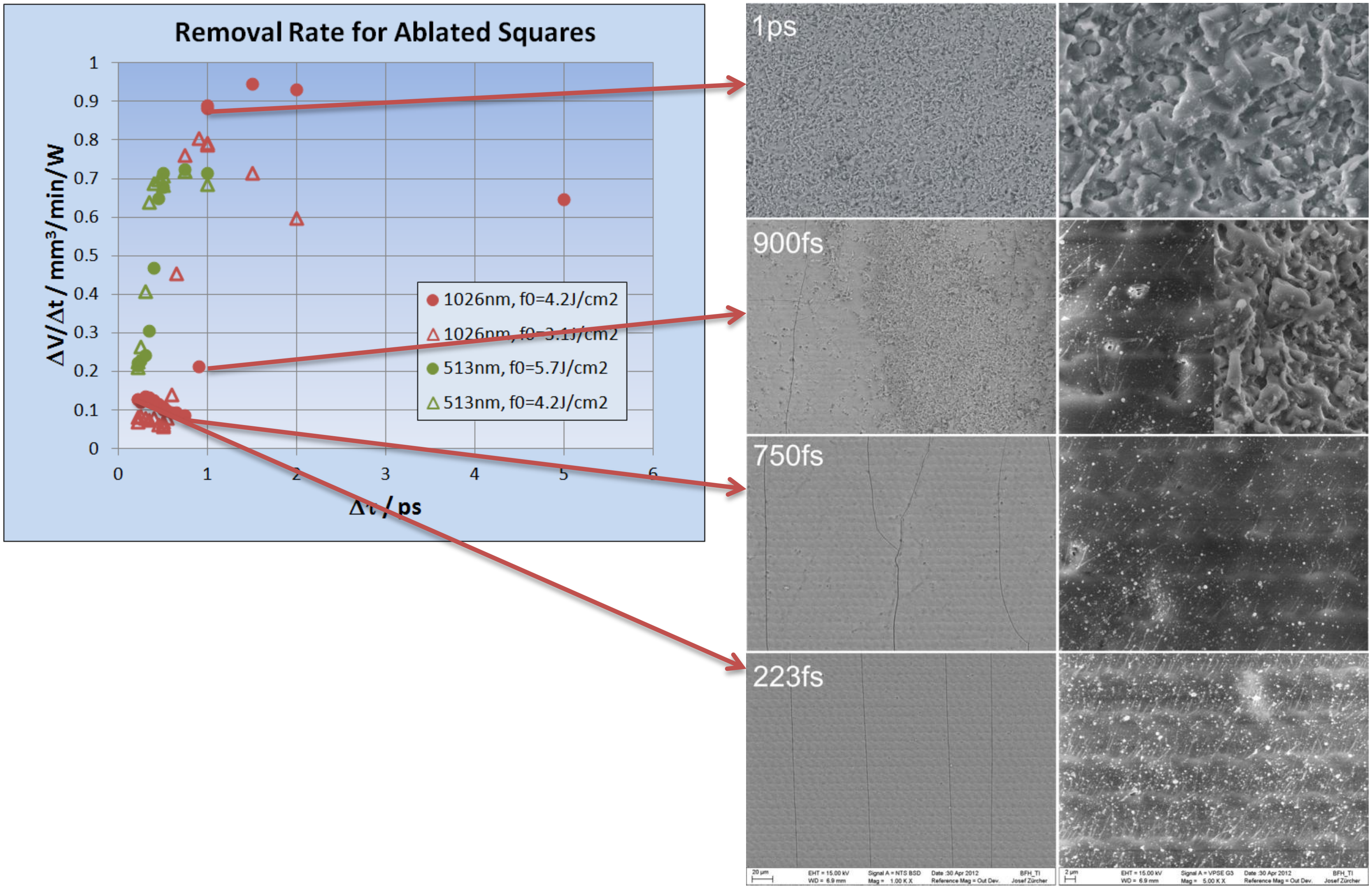


Sharp edge changeover into a second regime with a much higher removal rate is observed.

The "changeover pulse duration" depends on wavelength and peak fluence.

After reaching its maximum value the removal rate continuously drops with increasing pulse duration.

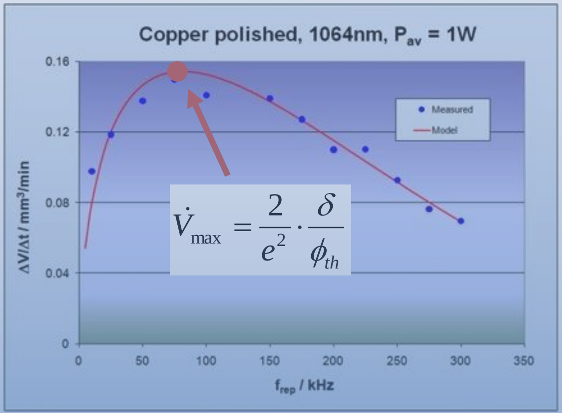
Ablated squares in Soda-lime Glass



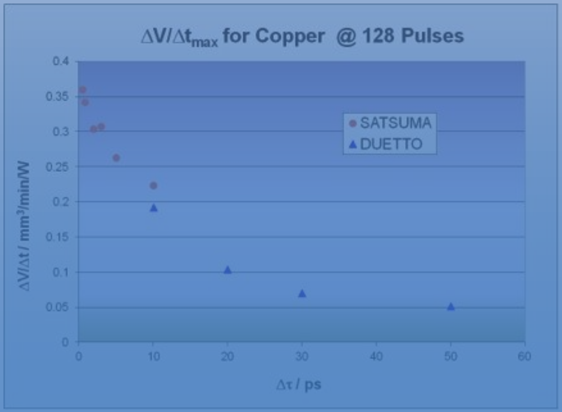
Optimization tasks

Efficiency

Maximize process efficiency

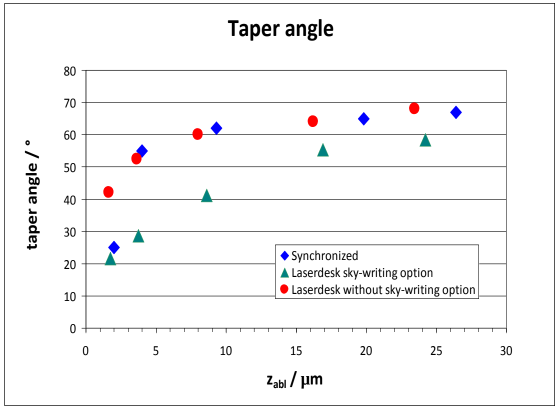


and use best suited pulse duration

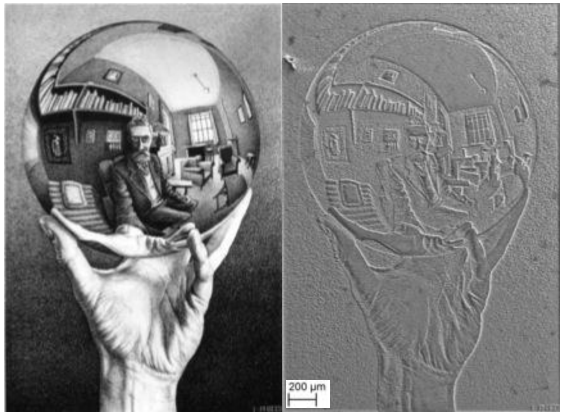


Strategy

Optimize the structuring strategy

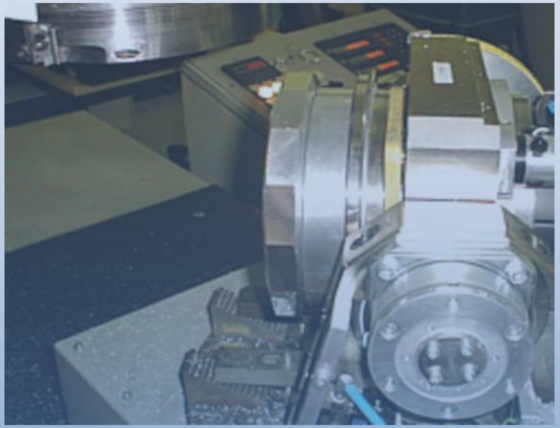


and synchronize axes with the laser

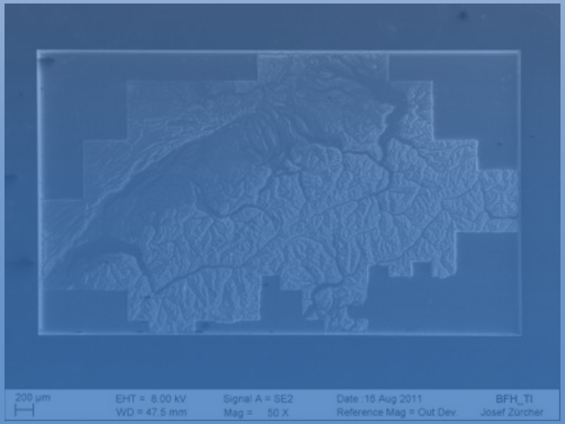


Throughput

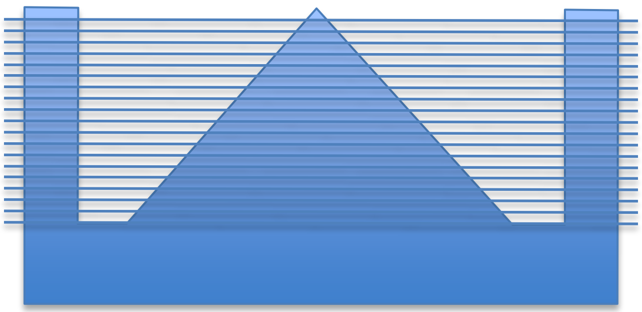
Use fast moving axes

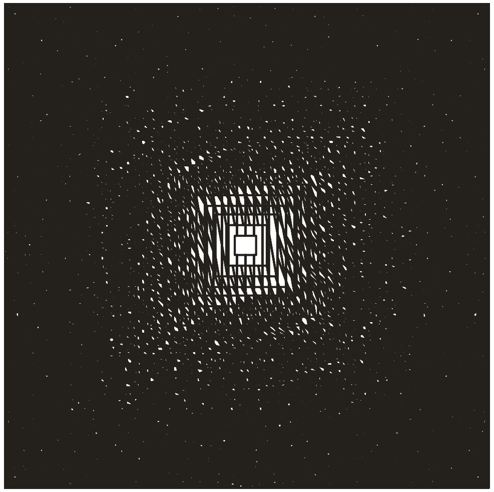


to obtain high throughput



3D Structuring: The „standard“ process



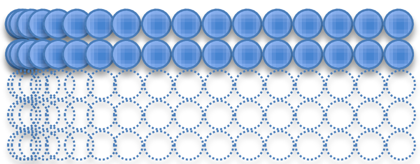


The standard 2½-d process uses a galvo scanner and the 3d-structure is divided into several slices.
Each slice is filled with a pattern of parallel lines.
From slice to slice the hatch pattern is turned around a given angle to avoid regular structures at the bottom.

Line start problem

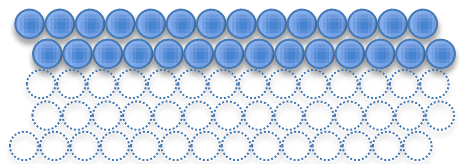
Straight lines have to be generated with mechanical axes, the pulse train is switched on and off via an external modulator

“acceleration” problem



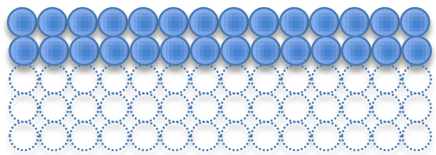
-well defined border
-deep marking at borders

Sky writing

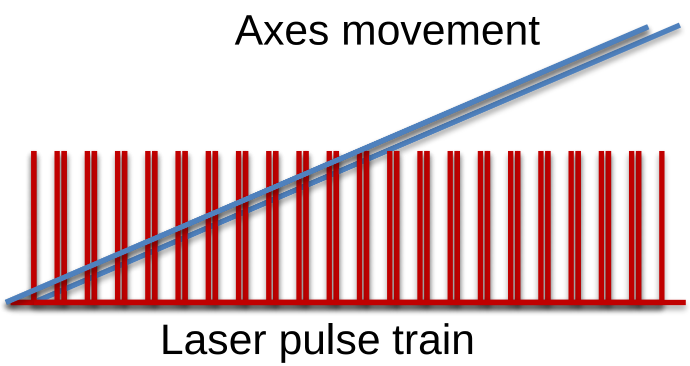


- no deep marking
- diffuse border

Synchronized



- no deep marking
- well defined border

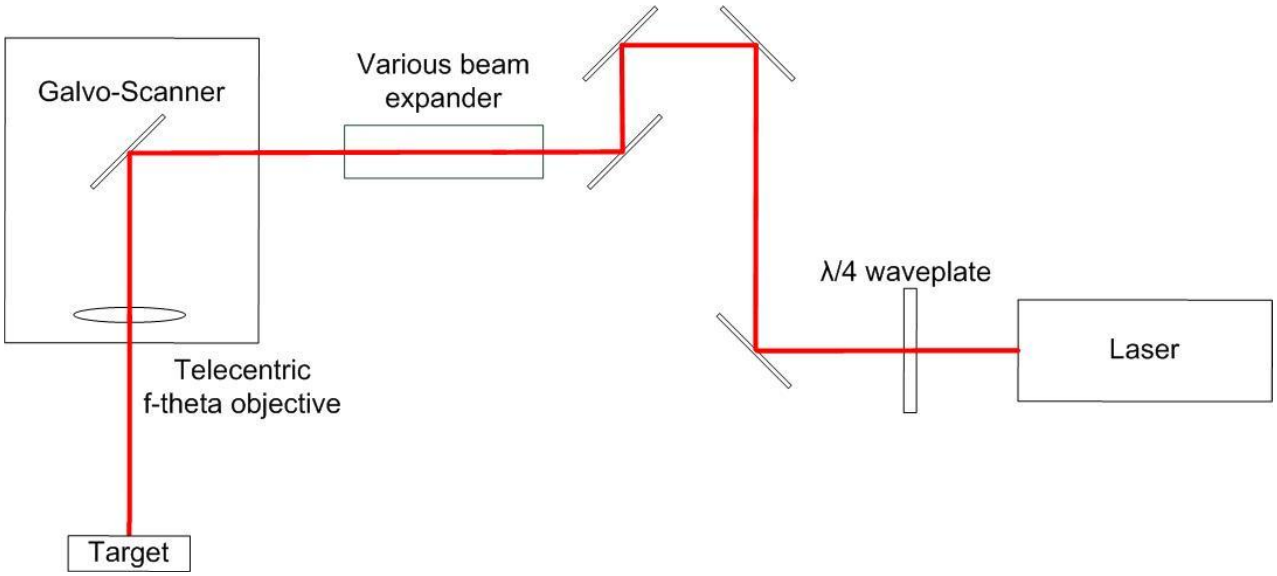


The first movement defines the location of the starting point
For the next movement you can:

- Shift the pulse train
  Can be done for Q-Switched systems, but is not an easy task for standard fs- and ps-systems in MOPA arrangement.
- Tune the axes movement on the pulse train
  needs adapted motion control

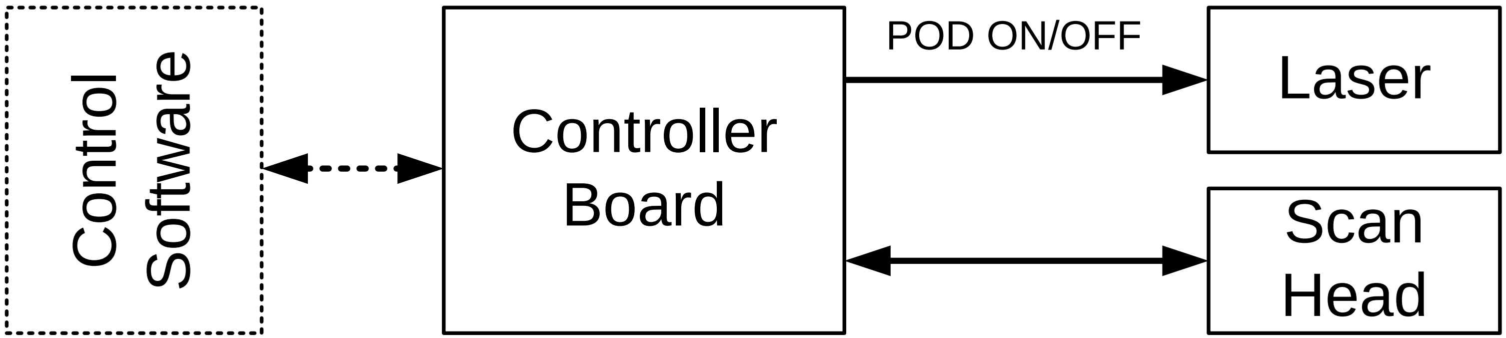
Experimental Set Up

- Industrial ps-Laser System DETTO, $\Delta\tau$ =10ps, λ = 1064nm and 532nm (SHG)
- IntelliSCANde 14 scan head
- Beam quality $M^2 \leq 1.1$, w_0=16.3 µm and w_0=5.7 µm (SHG)
- Focal plane on the target surface



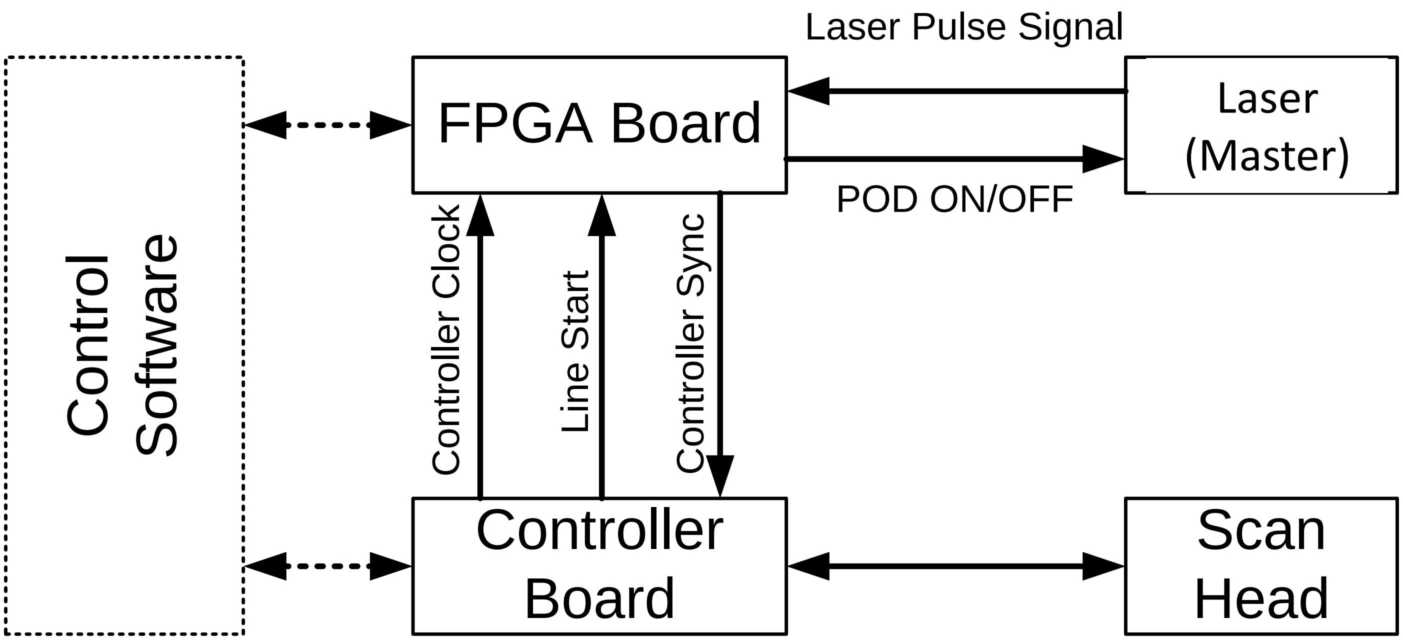
Scanner and Laser Control

Standard laboratory setup with IntelliSCANde 14, RTC5 and DUETTO ps System:

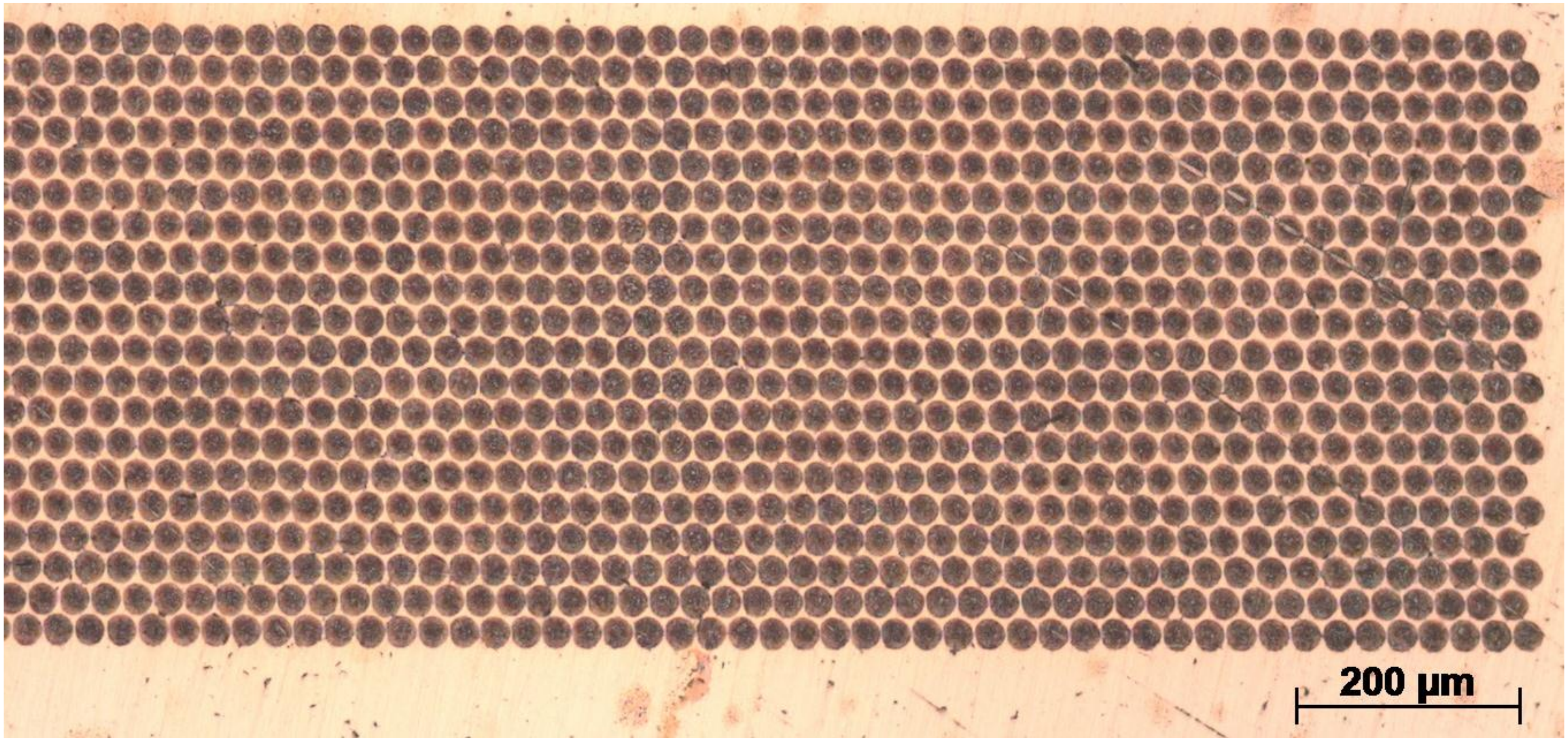


Scanner and Laser Control

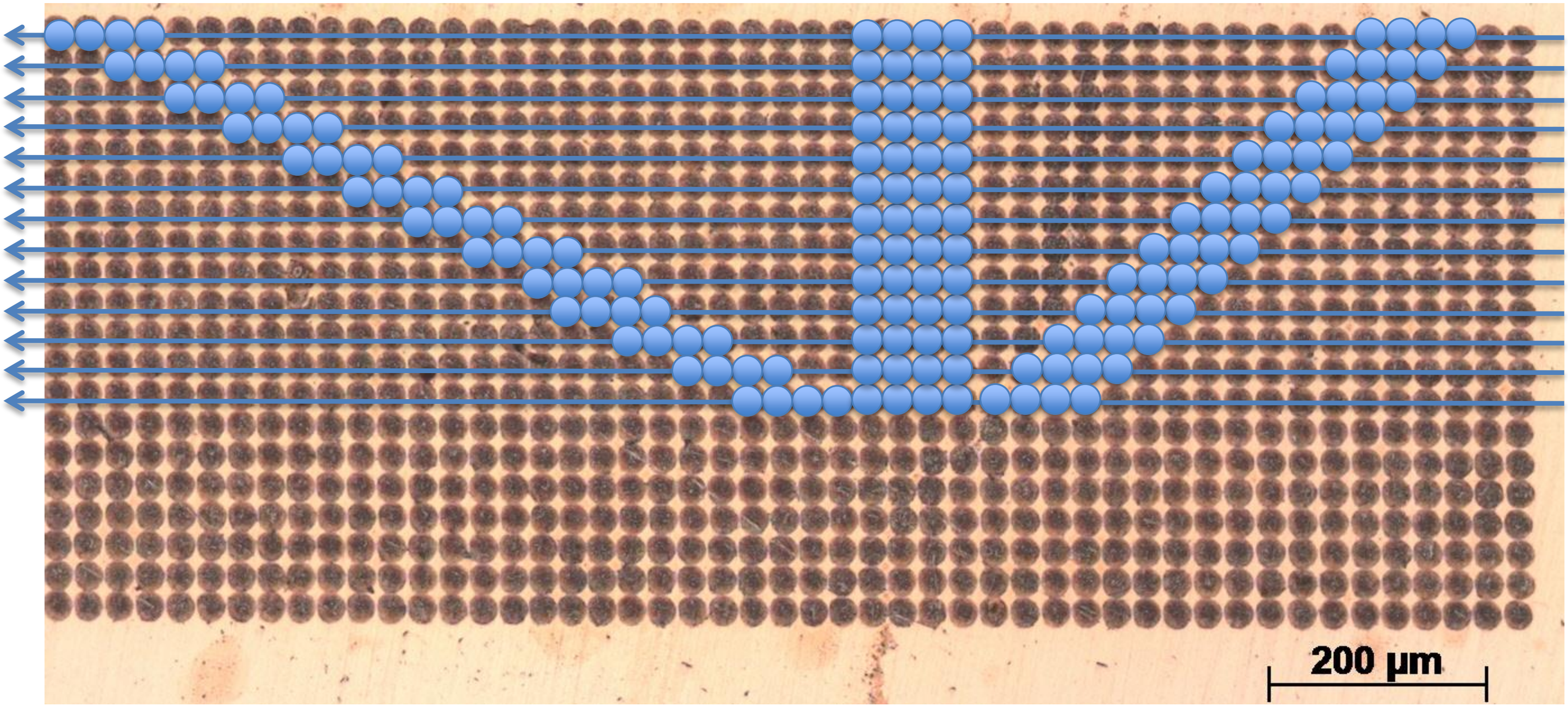
Synchronized setup with additional FPGA Board:



Scanner and Laser Control



Pattern generation

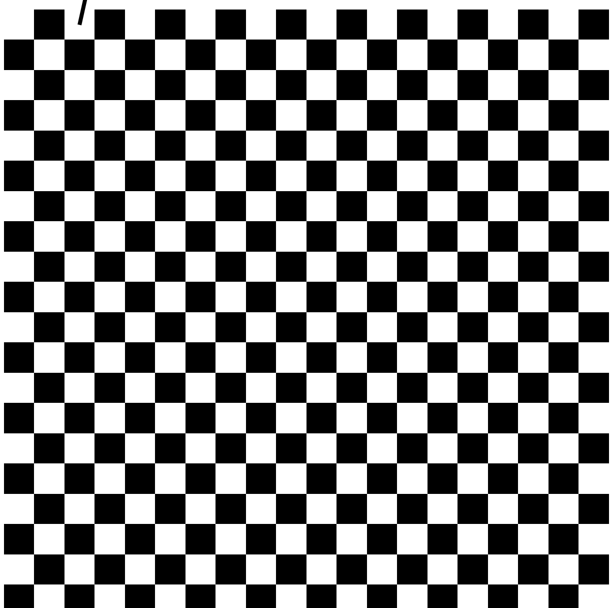


A rectangular region is formed by equally spaced parallel lines.
The single pulses are individually switched on and off by an external modulator.

-> the pattern can be described with a black and white bitmap file.

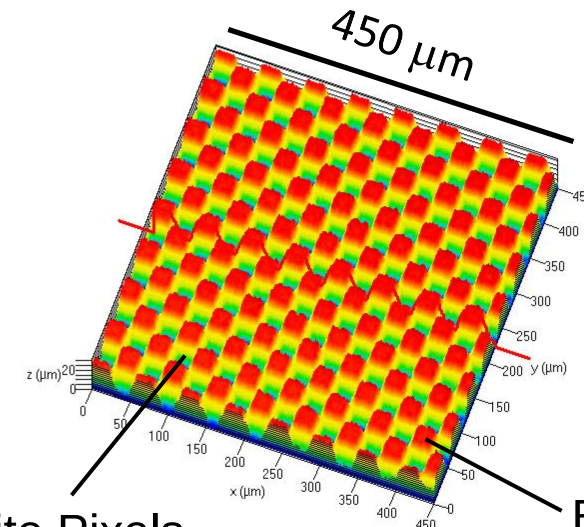
Scanner and Laser Control

White Pixels = Laser on



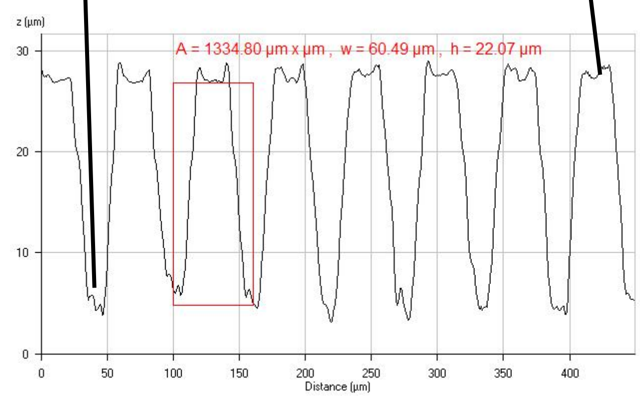
Black Pixels = Laser off

Result:



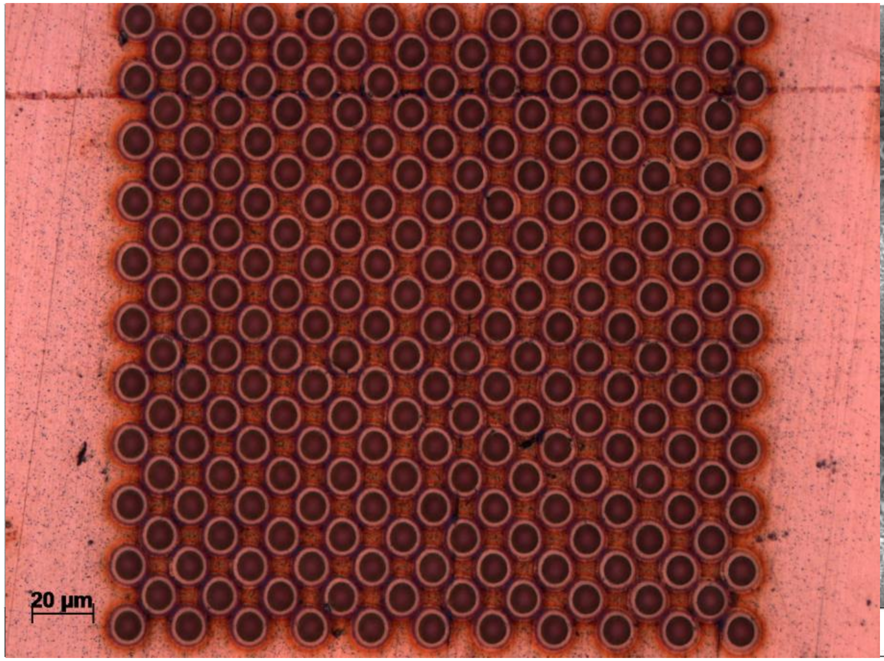
White Pixels

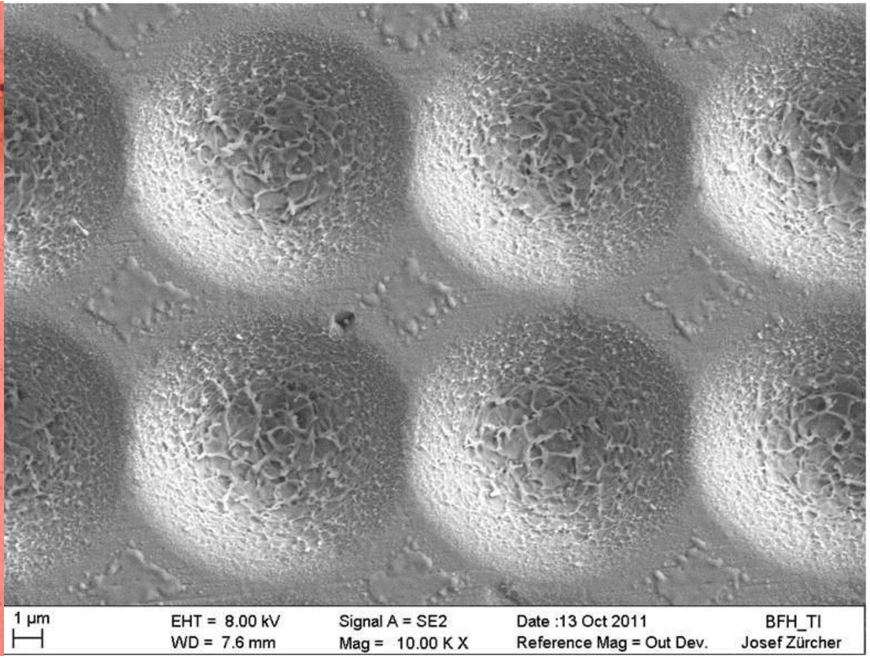
Black Pixels



120 mW, 300 kHz, 3 µm pitch, 100 slices

Surface structuring / „drilling on the fly“

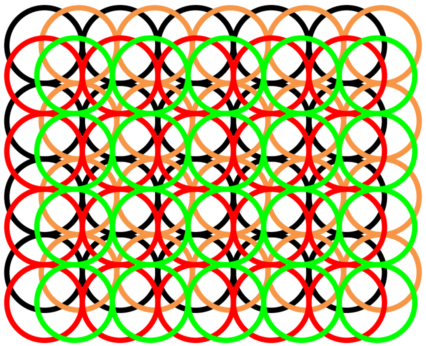




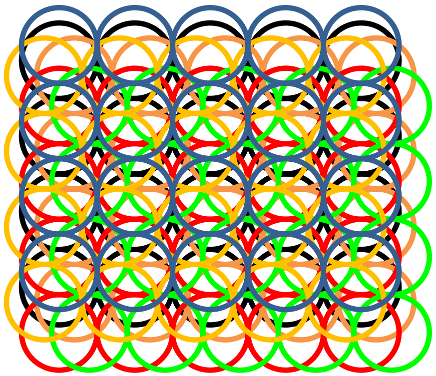
120 mW, 300 kHz, 1 µm pitch, 100 slices

Scan strategy

Fix defined start positions



Random distribution of the start positions

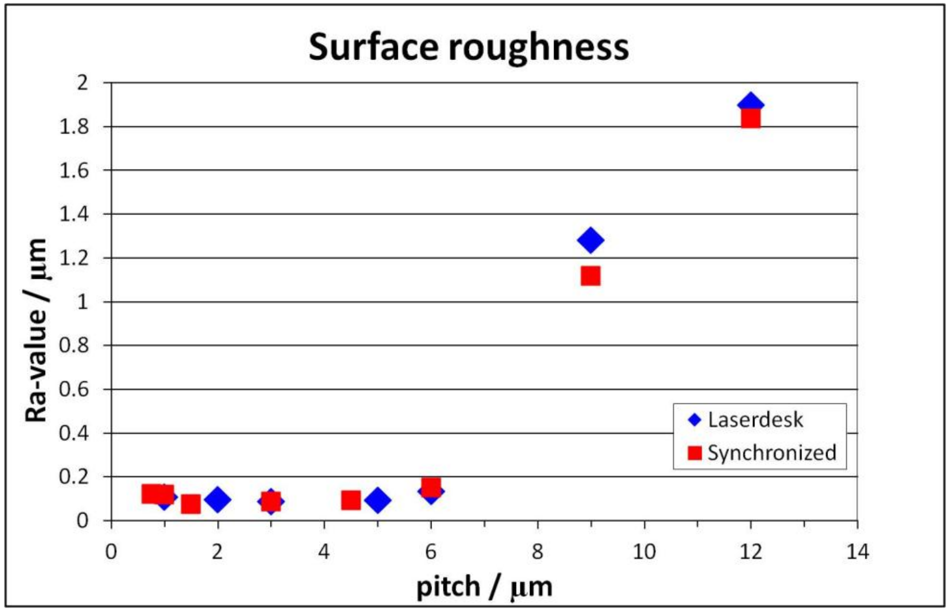


Random distribution

- Uniform random distribution
- Normal random distribution

Best strategy: Start positions determined by a normal random distribution, with μ= 0, σ= pitch/4

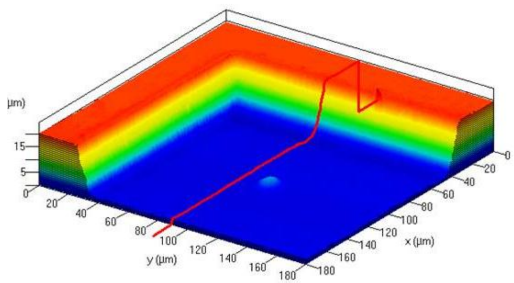
Minimal surface roughness

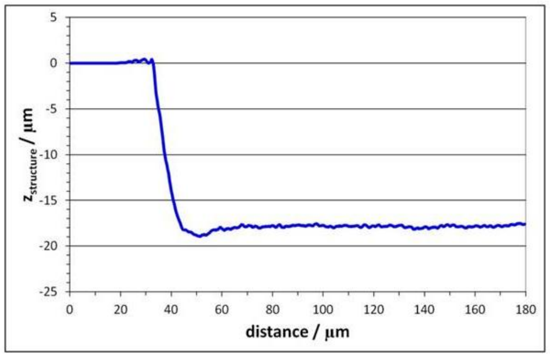


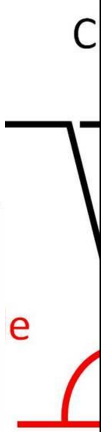
pitch / µm	# slices
1	13
3	120
12	1920

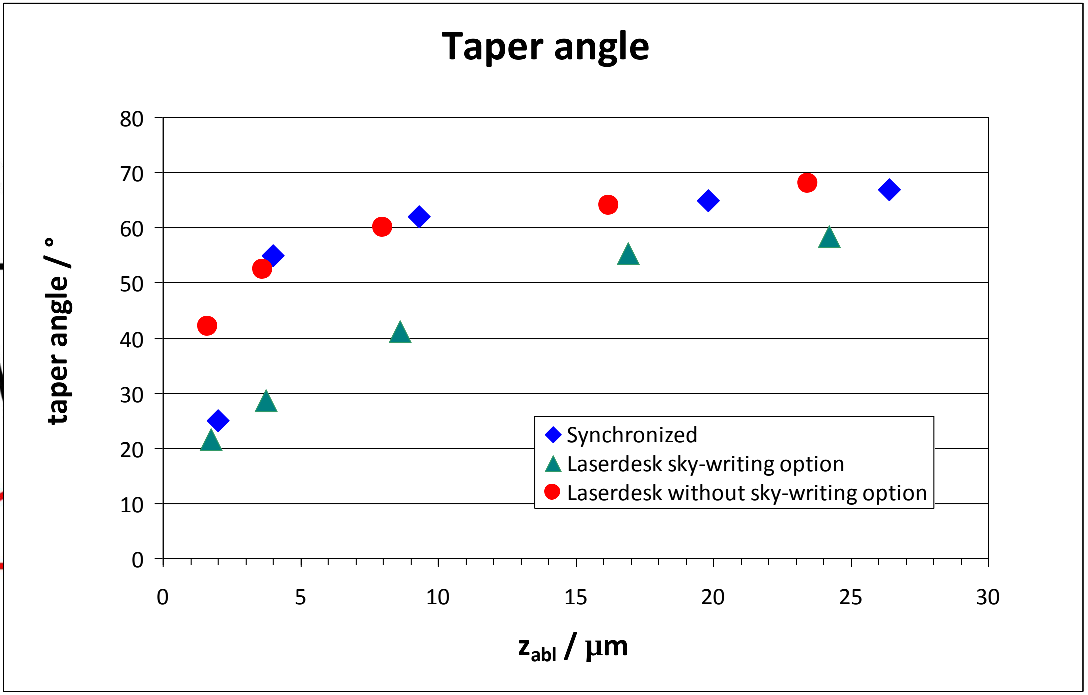
Minimal surface roughness is about 90 nm and produced with a pitch of half of the spot radius.

Steepness of wall / taper angle





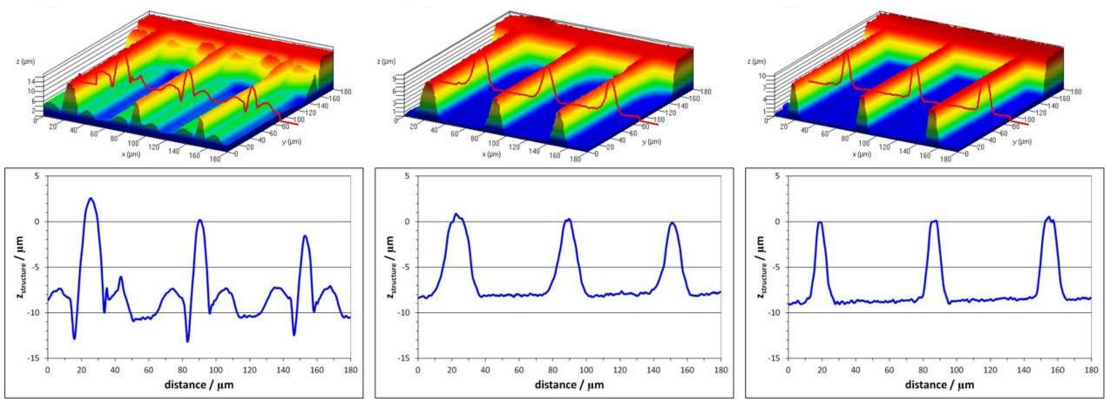




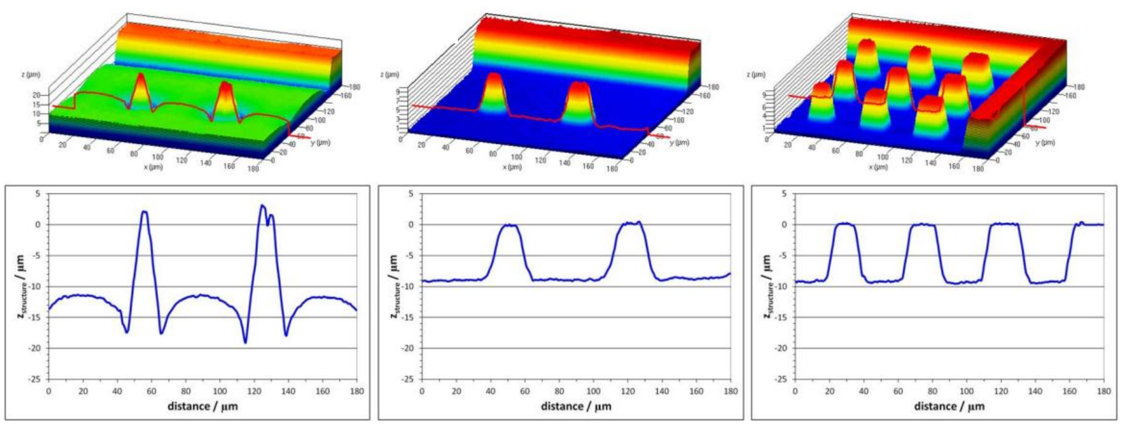
Controlling	Steep taper angle	No deep marks
Laserdesk No Sky-Writing	x	
Laserdesk Sky-Writing		x
Synchronized System	x	x

Minimal structures

Laserdesk Without sky-writing; With sky-writing; Synchronized



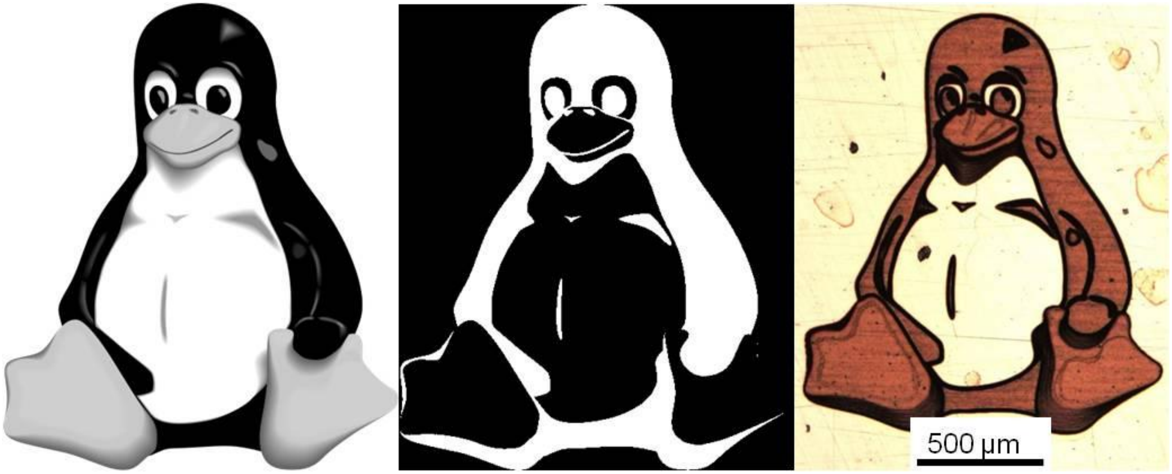
120 mW, 300 kHz, 1 μm pitch, 60 slices



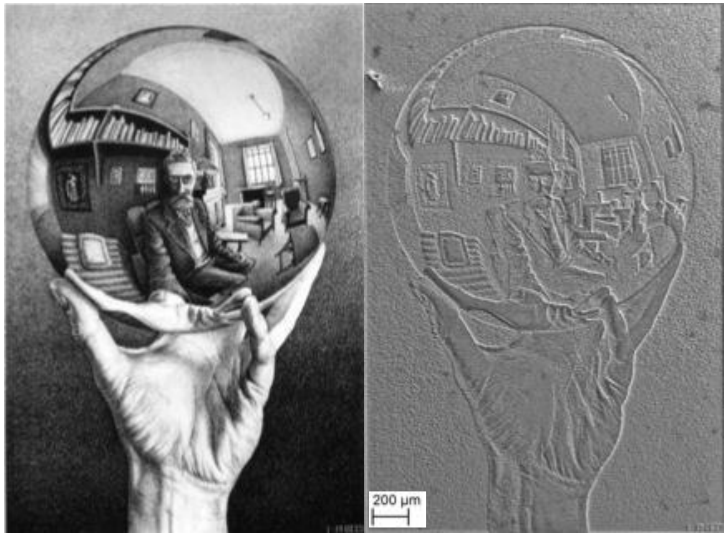
120 mW, 300 kHz, 3 μm pitch, 60 slices

- Minimal web width: 3-5 μm (~ $w_0/2$)
- Minimal side length: 6 μm (~ w_0)

Surface Structuring: Working with gray scale bitmaps

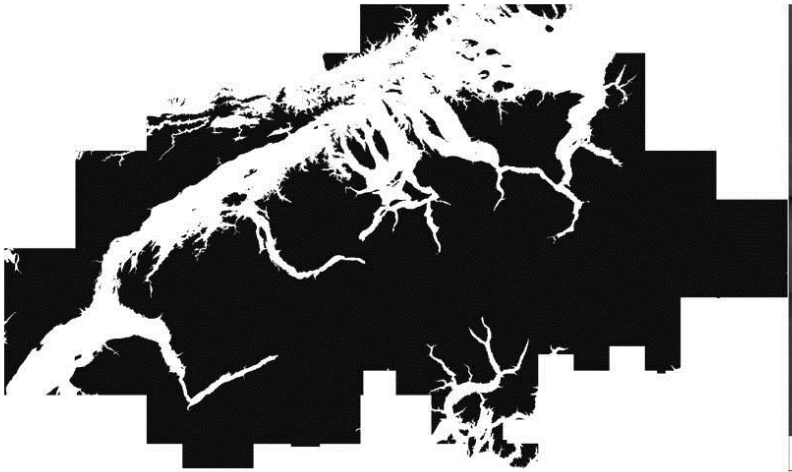


120 mW, 300 kHz, 3 µm pitch, 100 slices

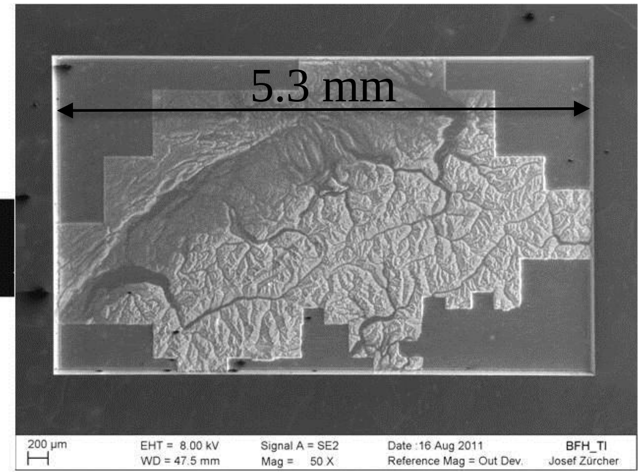


[1]: http://en.wikipedia.org/wiki/File:Tux.svg
[2]: http://brettworks.com/2012/04/26/on-the-musicality-of-m-c-escher/

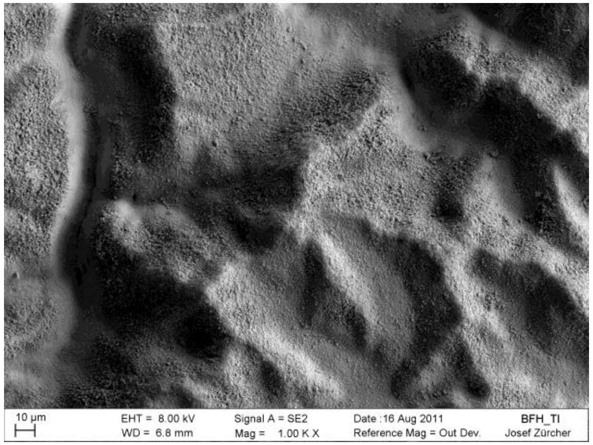
Surface Structuring: converting 3D data in bitmaps



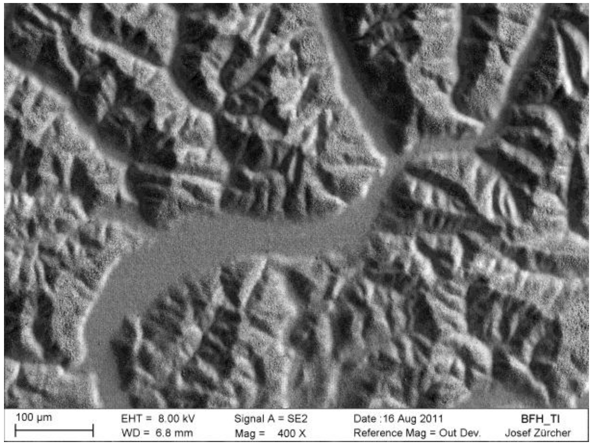
[3]:http://www.swisstopo.admin.ch/internet/swisstopo/de/home.html



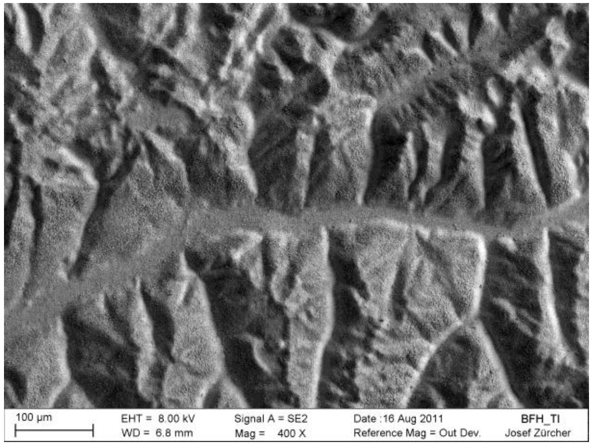
120 mW, 300 kHz, 3 µm pitch, 447 slices



Eiger, Mönch and Jungfrau



Ticino

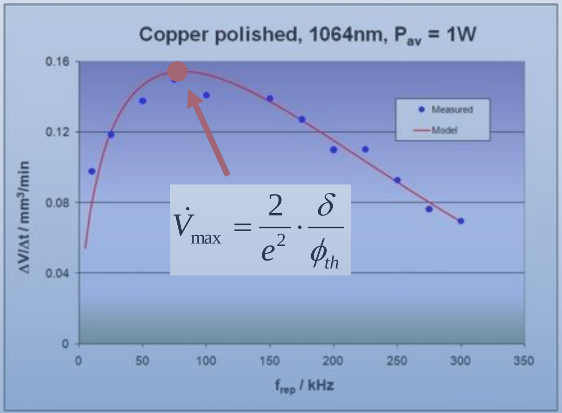


Valais

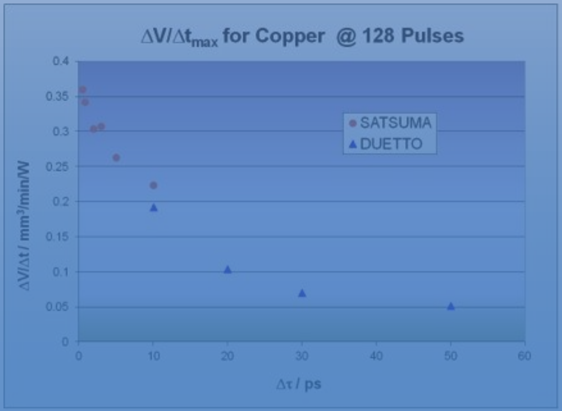
Optimization tasks

Efficiency

Maximize process efficiency

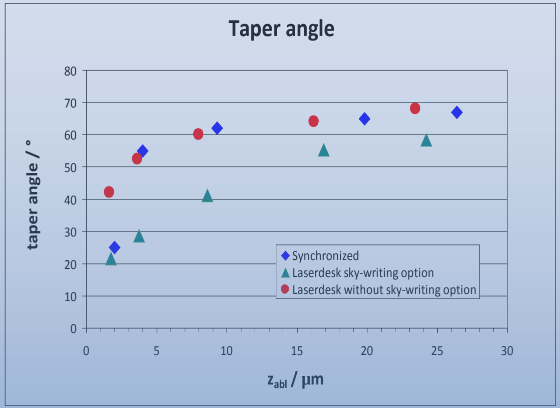


and use best suited pulse duration



Strategy

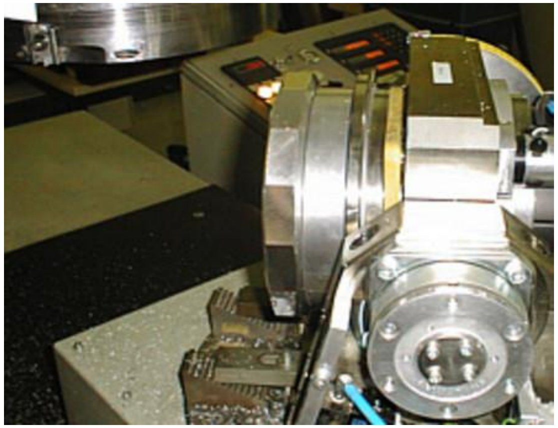
Optimize the structuring strategy



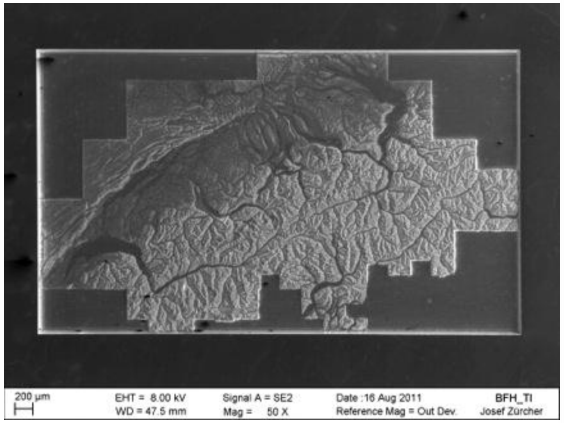
and synchronize axes with the laser

Throughput

Use fast moving axes

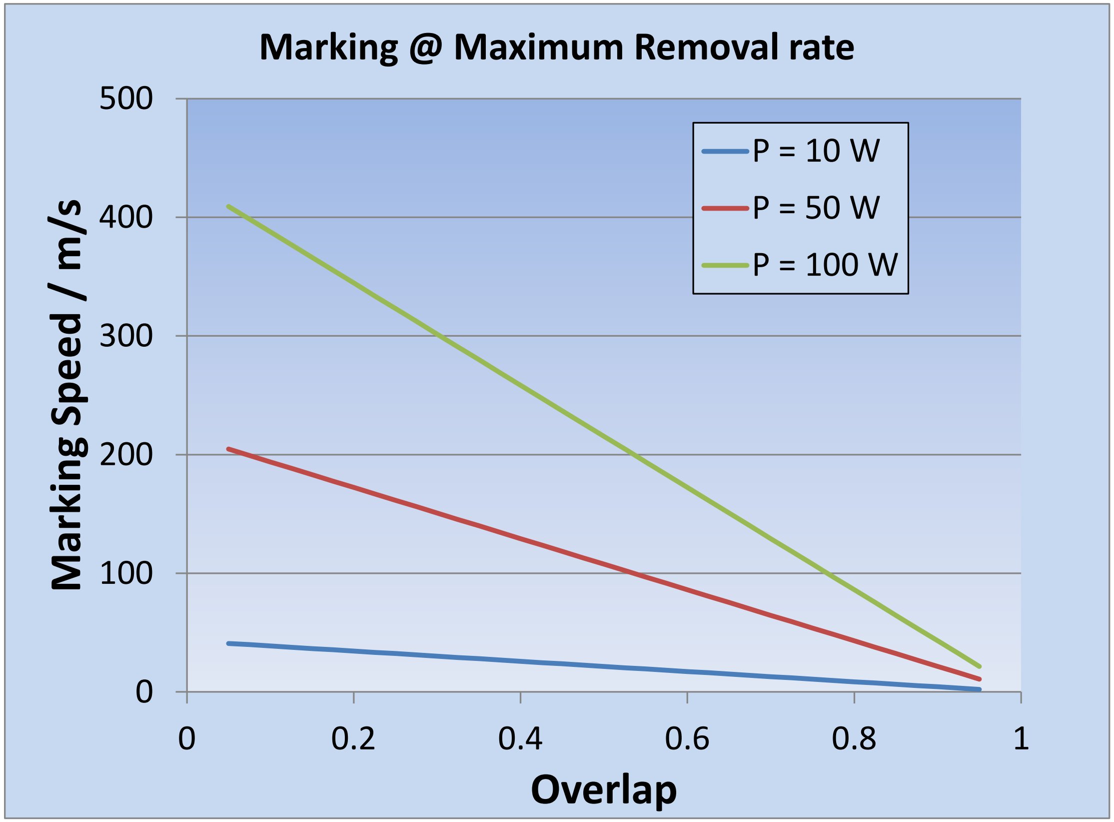


to obtain high throughput



Example: Lines (50 µm width) in stainless steel 1.4301

Parameters: $\phi_{th} = 0.08\ J/cm^2\ ,\quad \delta = 6\ nm$ Spot radius: w_0 = 25 µm



$$\frac{\dot{V}_{max}}{P_{av}} = 0.12 \frac{mm^3}{min \cdot W}$$

$$f_{opt} = 1.7\ MHz\ @\ 10W$$

$$f_{opt} = 4.3\ MHz\ @\ 25W \quad (\surd)$$

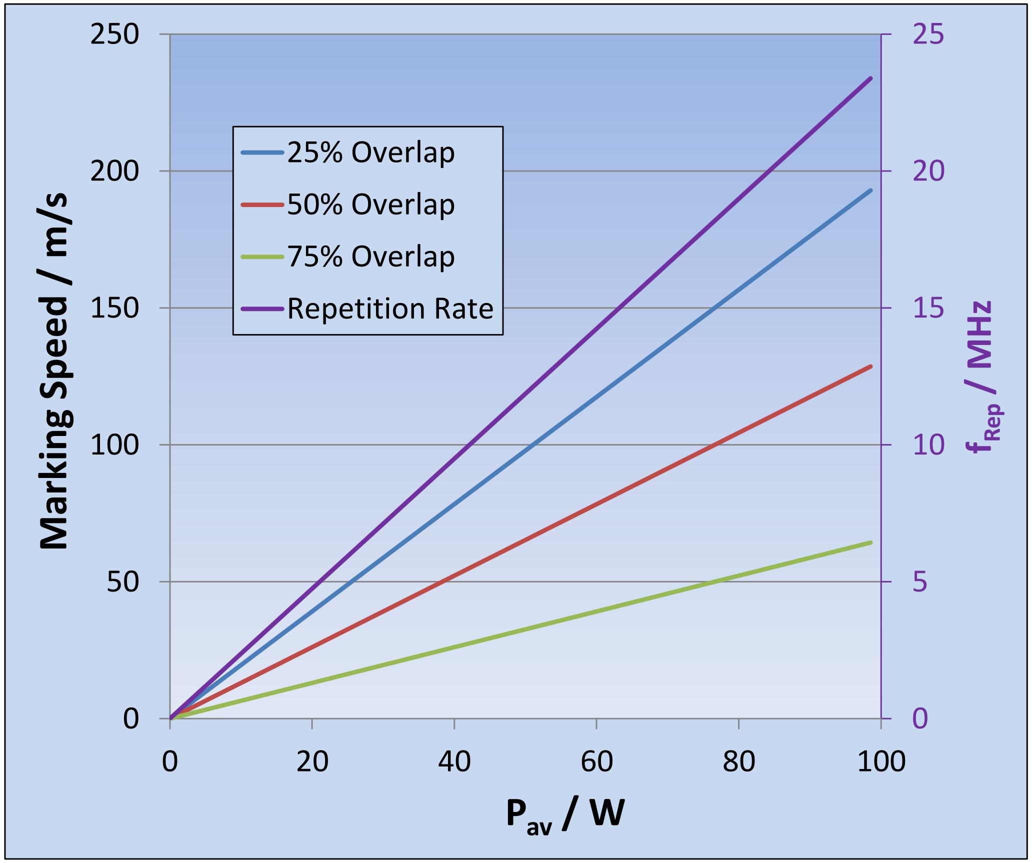
$$f_{opt} = 8.6\ MHz\ @\ 50W$$

Marking speeds from a few 10 m/s up to the speed of sound are required. $(\surd)$

Example: 3d-structures in Copper

Parameters: $\phi_{th} = 0.3\ J/cm^2\ ,\quad \delta = 38\ nm$

Spot radius: w_0 = 11 µm



$$\frac{\dot{V}_{\max}}{P_{av}} = 0.2\frac{mm^3}{min \cdot W}$$

For a spot diameter of $22\ \mu m$, a scanner optics of $f = 100\ mm$ has to be used.

For a marking speed of $1\ m/s$ the average power is in the range of $500\ mW - 1.5\ W$

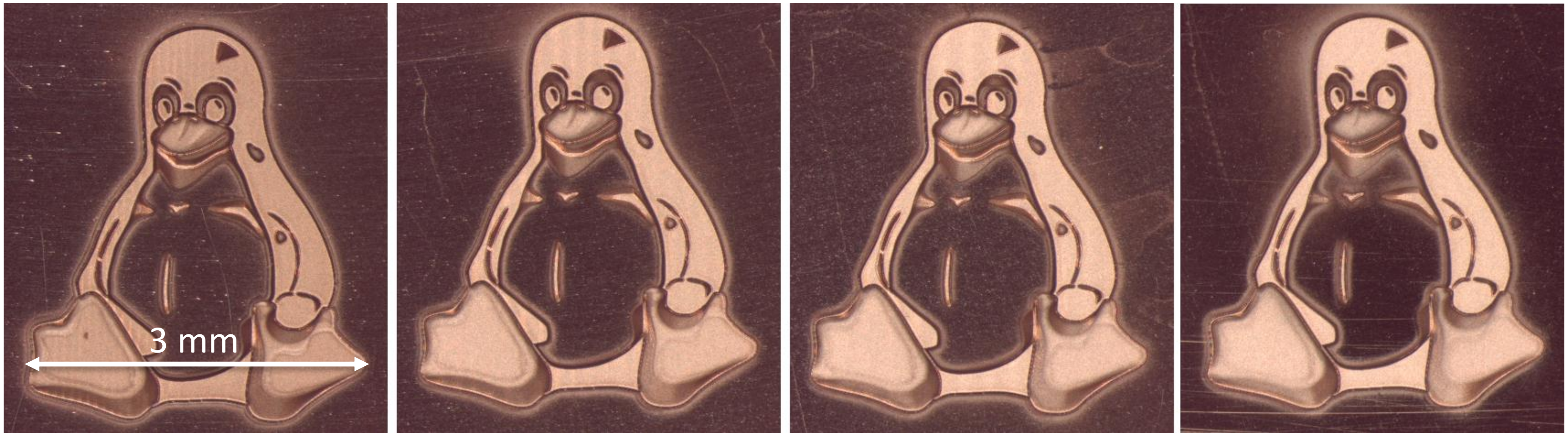
For average powers of $10W$ and more the marking speeds exceeds $10\ m/s$.

There is absolutely no scanning system on the market which can achieve these speeds with a resolution in the µm range i.e. one is not able to work at the optimum point with maximum ablation rates for average powers higher than a few Watts.

Scaleability

$\lambda = 1064\,nm$; $\phi_{th} = 0.3\,J/cm^2$; $\delta = 31.8\,nm$; $f_{obj} = 160\,mm$; $w_0 = 16.3\,\mu m$; $p = 8\,\mu m$;

$f_{rep} = 100\,kHz$	$f_{rep} = 200\,kHz$	$f_{rep} = 300\,kHz$	$f_{rep} = 600\,kHz$
$P_{av} = 925\,mW$	$P_{av} = 1.85\,W$	$P_{av} = 2.76\,mW$	$P_{av} = 5.56\,W$
$v = 0.8\,m/s$	$v = 1.6\,m/s$	$v = 2.4\,m/s$	$v = 4.8\,m/s$



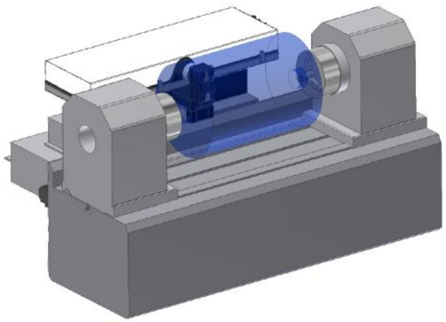
No significant difference is observed -> the process is scalable

Next step:

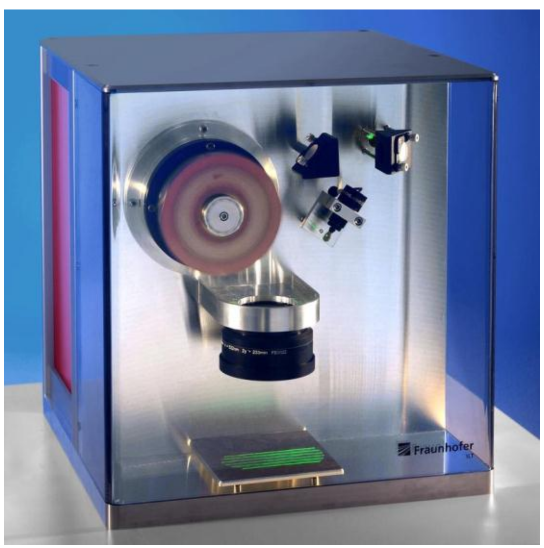
- Higher maximum scanner speed with new tuning
  -> f_{rep} > 1.8 MHz and P_{av} > 17W @ 1064nm

Alternative technologies

Fast rotating mechanical axes:

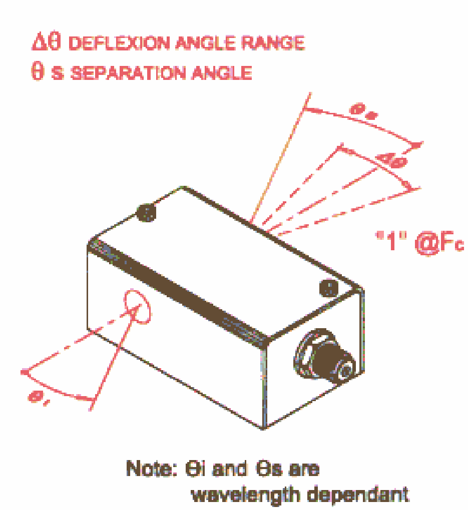


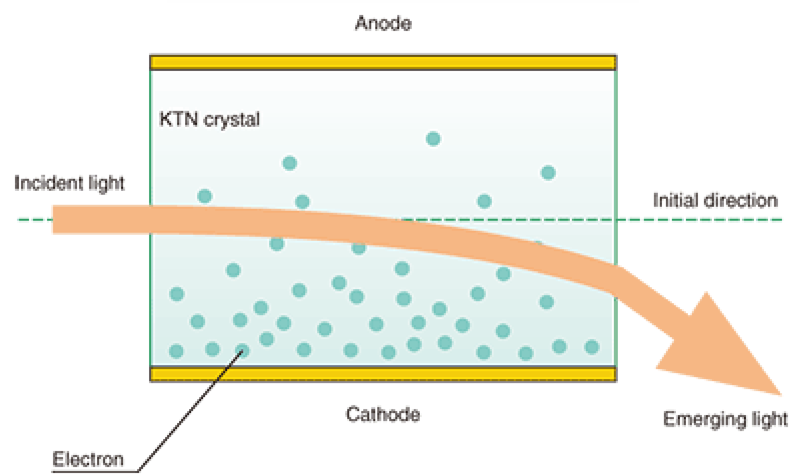
S. Brüning, G.Hennig, S. Eiffel, A.Gillner ; Proc. LIM 2011, Physics Procedia, Elsevier (2011)



http://idw-online.de/pages/de/news467826

Accousto- and Electrooptic- Deflectors:

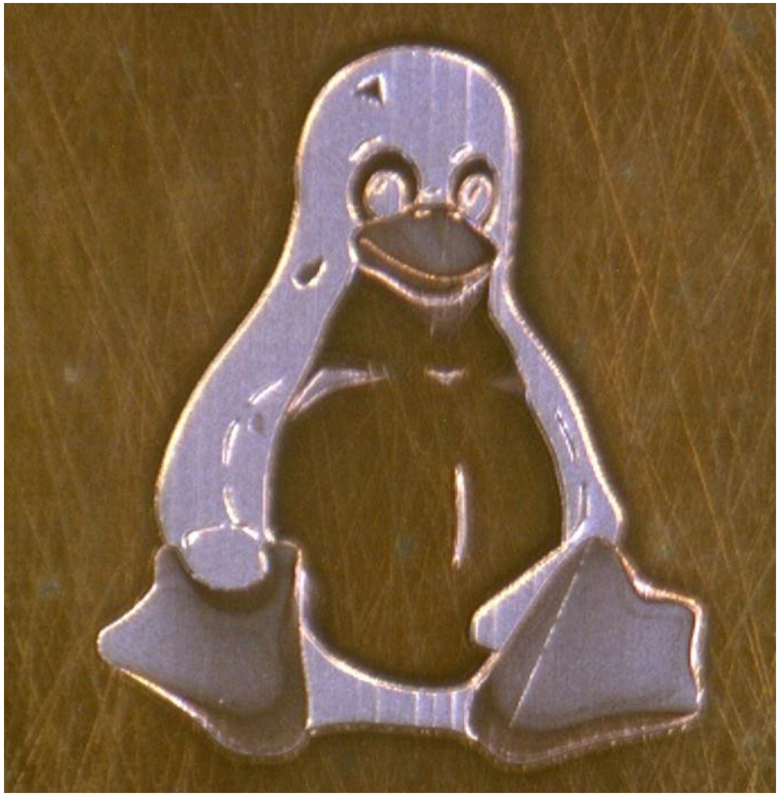




Fast rotating cylinder

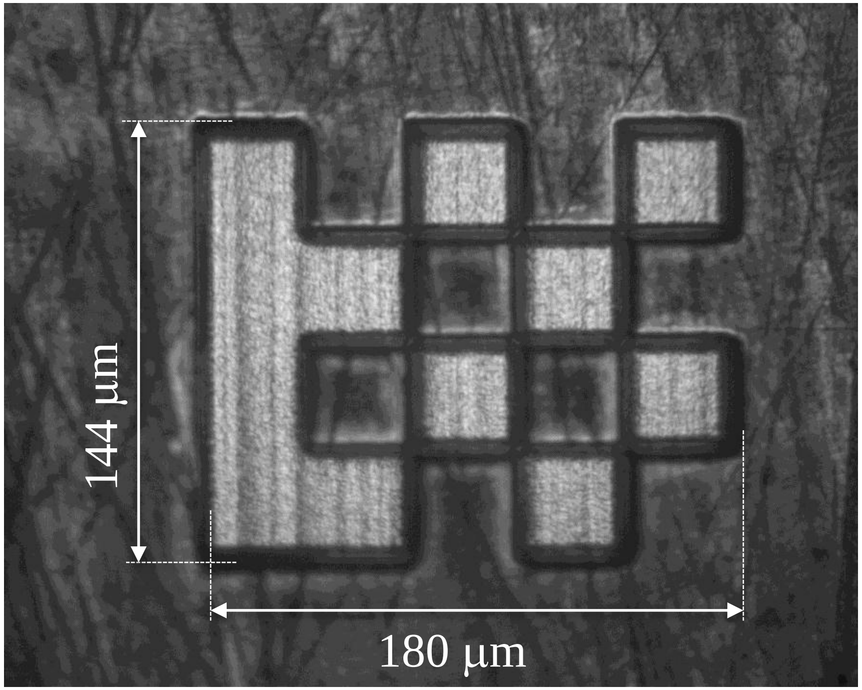
Rose: 1.1 x 1.25 mm

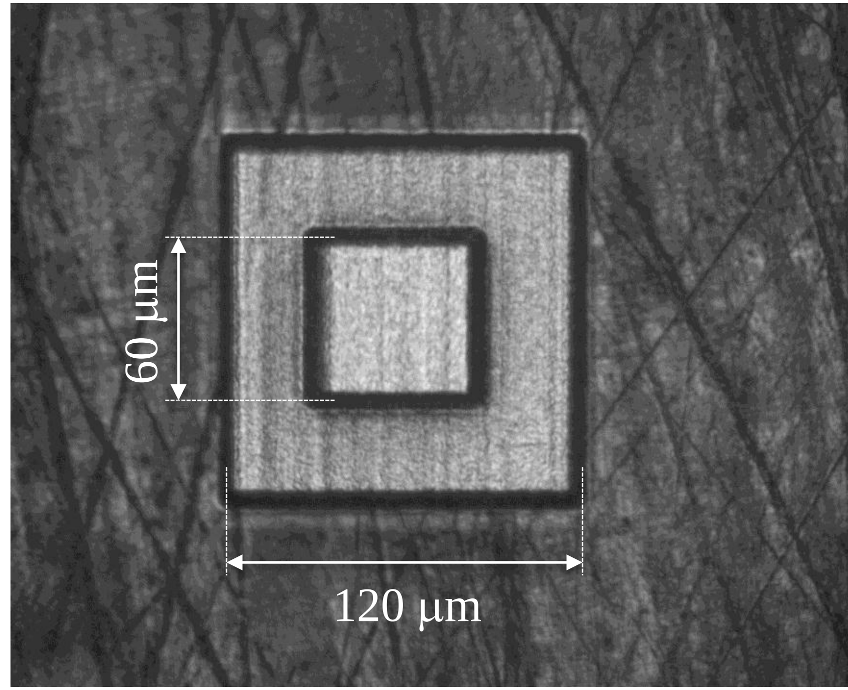
TUX: 0.93 x 1.1 mm



$$\lambda = 532\,nm; \quad w_0 = 4\,\mu m; \quad p = 2\,\mu m; \quad f_{Rep} = 3\,MHz; \quad P_{av} = 0.9\,W$$

Fast rotating cylinder



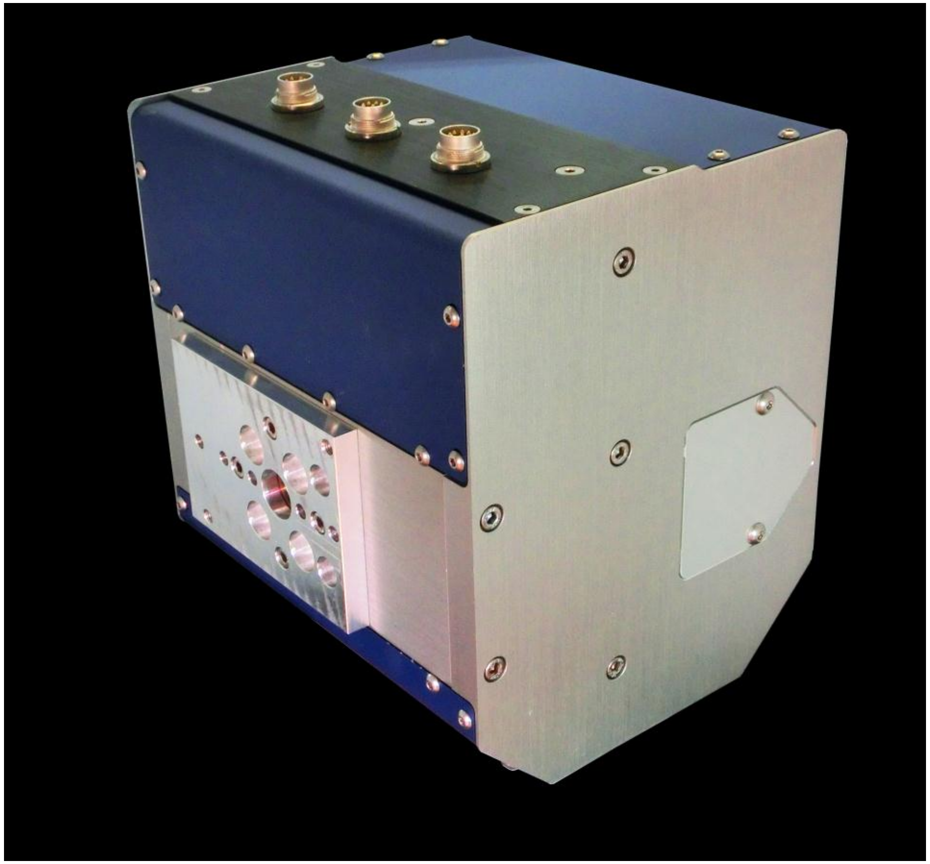


$$\lambda = 532\,nm; \quad w_0 = 4\,\mu m; \quad p = 2\,\mu m; \quad f_{Rep} = 2\,MHz; \quad P_{av} = 0.6\,W$$

Next steps:

- Go to IR and bigger spot radius
  -> f_{rep} up to 3 MHz and P_{av} up to 40W

Polygon Scanner



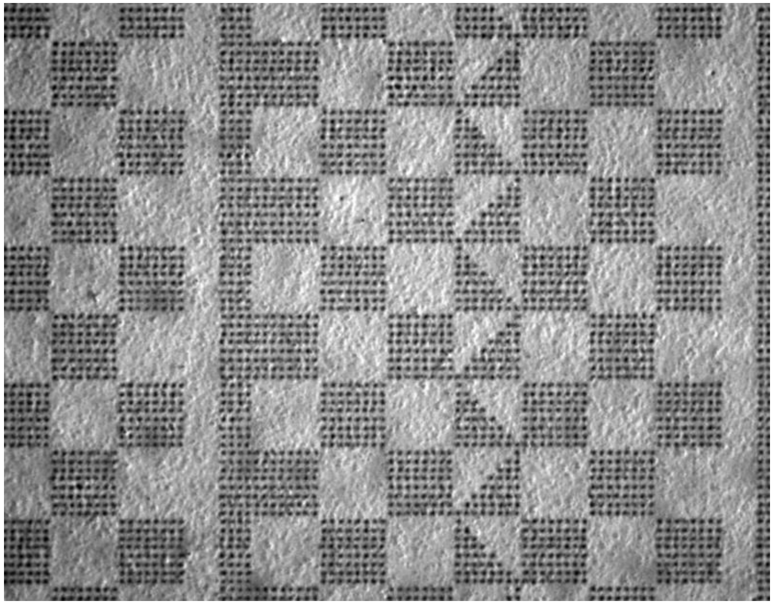
next scan technology (Belgium)

$$w_0 = 11\ \mu m \quad @ \quad \lambda = 532\ nm$$

$$w_0 = 22\ \mu m \quad @ \quad \lambda = 1064\ nm$$

$$\ell_{scan} = 170\ mm$$

$$v_{\max} = 100\ m/s$$



Synchronized with FUEGO from Time-Bandwidth Products AG

Conclusions

The efficiency of the ablation process shows an optimum for a certain applied fluence. At this point the maximum removal rate is obtained its value depend on the threshold fluence ϕ_{th} and the penetration energy penetration depth δ.

Both measures depend on the pulse duration; shorter pulses lead to higher removal rates (metals and non metals).

Mostly the optimum point is obtained at low fluencies i.e. at low pulse energies. High repetition rates are therefore needed at high average powers.

Synchronization of the mechanical axes with the laser pulse train and optimizing the scan strategy lead to an increased accuracy.

High throughput can only be obtained when high marking speeds are possible. For this, new concepts have to be discussed and are under development.

Kilowatt laser micro processing with ultra short pulses is not so far away (see also next talk).

Acknowledgement:
Parts of this work were supported by the Swiss Commission for Technology and Innovation CTI.