Berner Fachhochschule
Haute école spécialisée bernoise
Bern University of Applied Sciences

High Efficient and High Quality Surface Structuring of Metals

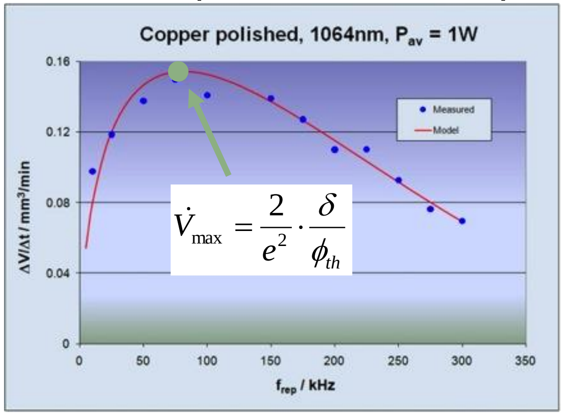
B. Neuenschwander, B. Jaeggi, M. Zimmermann, Th. Kramer,
M. Schmid, B. Lauer, P. Cam, Y. Zhang, M. Muralt, St. Remund

- Institute for Applied Laser, Photronics and Surface Technologies ALPS

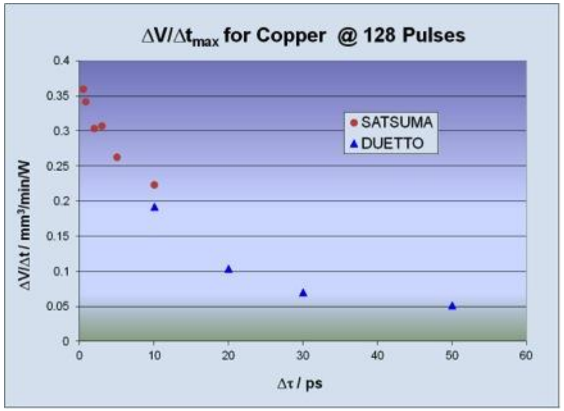
Optimization Tasks

Efficiency

Maximize process efficiency

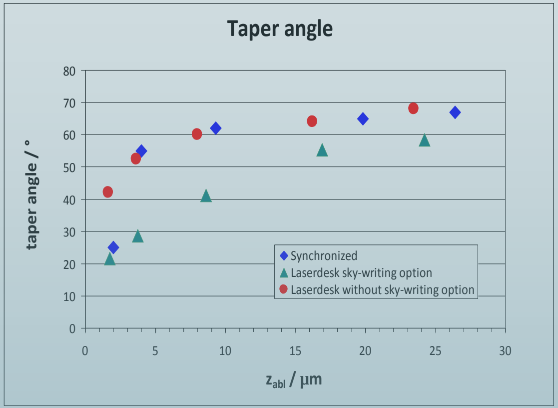


use best suited pulse duration

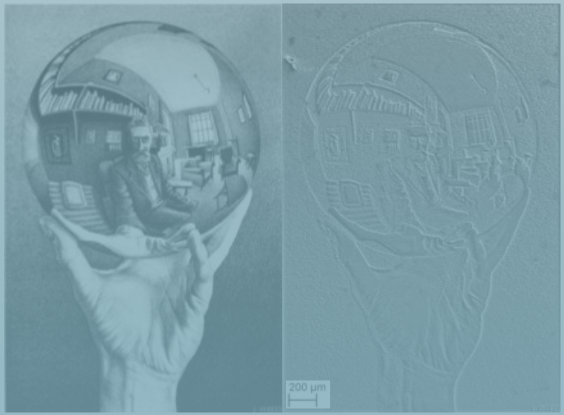


Strategy

Optimize the structuring

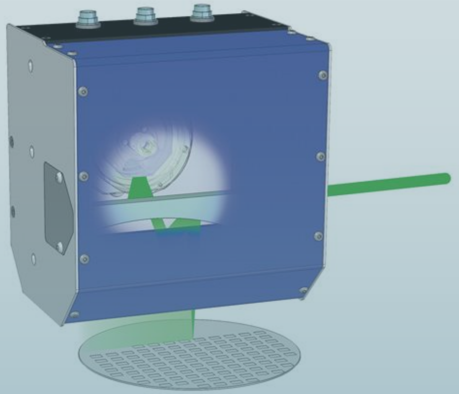


synchronize axes with the laser

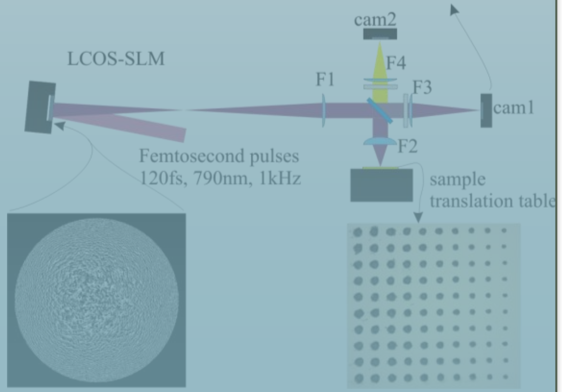


Throughput

Use fast moving axes

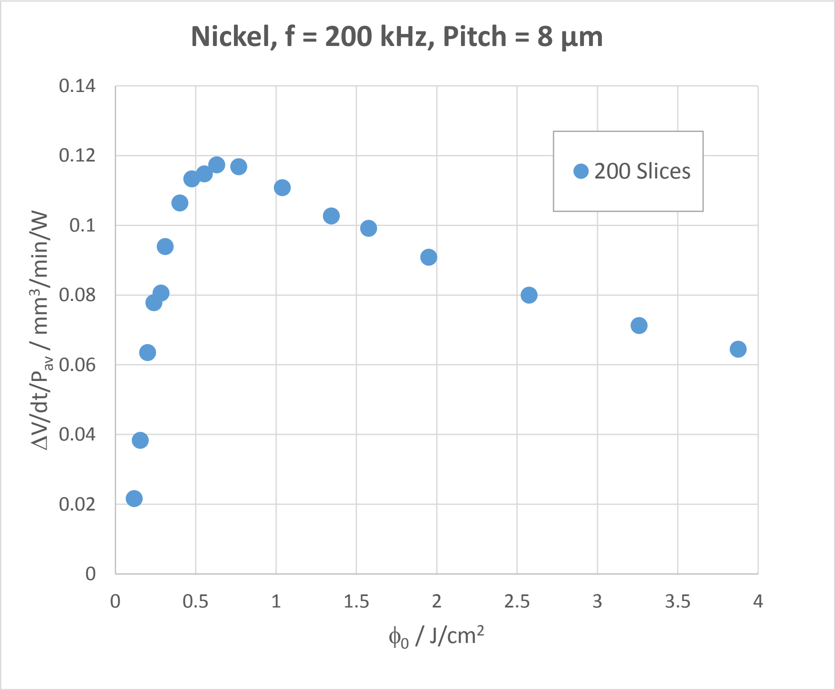


or parallel processes



Specific Removal Rate of a Gaussian Beam

- Deduce specific removal rate by machining squares



Specific Removal Rate of a Gaussian Beam

- Deduce specific removal rate by machining squares
- Theoretical Model [1]:

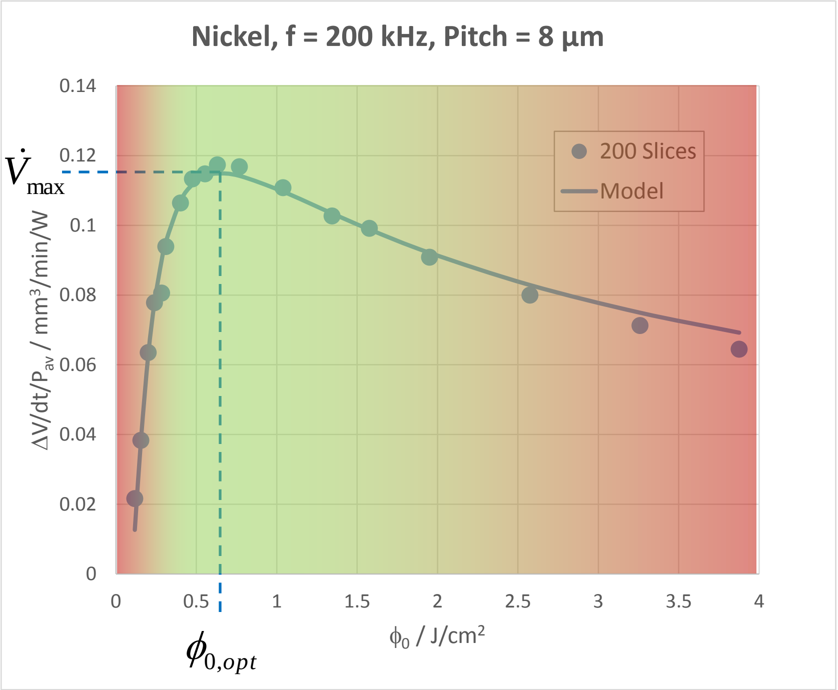
$$\frac{\dot{V}}{P_{av}} = \frac{1}{2} \cdot \frac{\delta}{\phi_{th}} \cdot ln^2\left(\frac{\phi_0}{\phi_{th}}\right)$$

With:
ϕ_{th}: Threshold fluence
δ : Energy penetration depth
ϕ_0: Peak fluence

- Optimum Point / Maximum rate

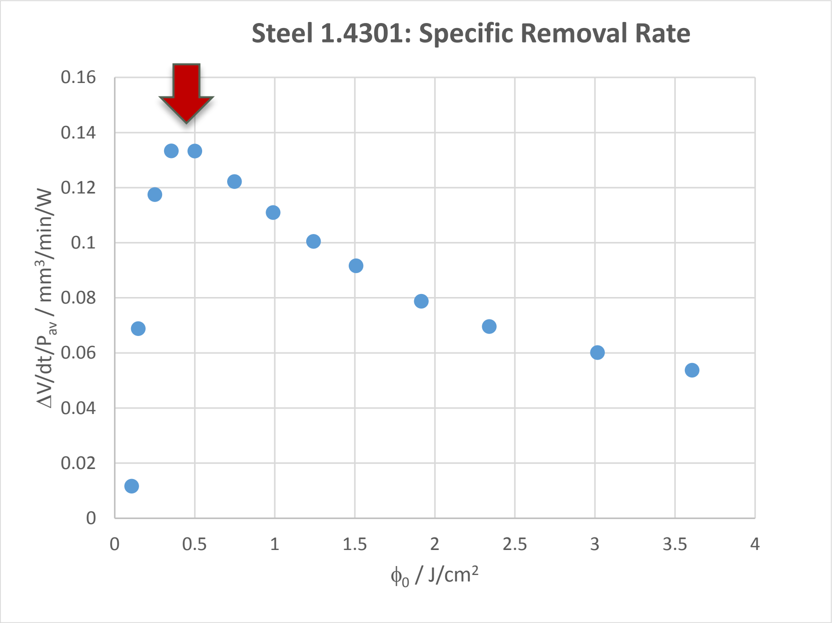
$$\phi_{0,opt} = e^2 \cdot \phi_{th} \, , \qquad \frac{\dot{V}_{max}}{P_{av}} = \frac{2}{e^2} \cdot \frac{\delta}{\phi_{th}}$$

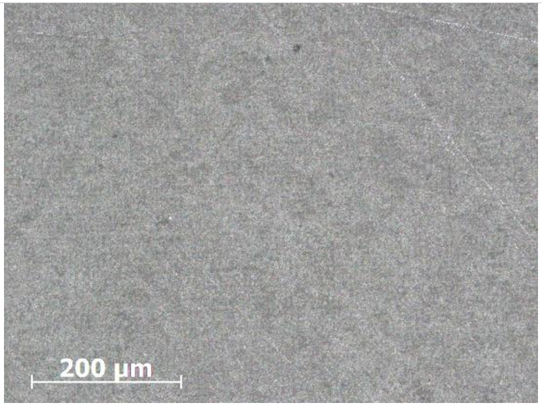
- Shorter Pulses -> Higher rates
- Process window defined by efficiency (copper, nickel, ?)



[1]: B. Neuenschwander et al, „From fs to sub-ns: Dependence of the Material Removal Rate on the Pulse Duration for Metals", Physics Procedia Vol. 41, pp. 787-794 (2013)

Steel 1.4301: Pulse energy





Squares machined with galvo:

- f_r = 200kHz, w_0 = 16 µm, pitch = 8 µm
- ϕ_0 = 0.3-0.6 J/cm² (near optimum) High surface quality

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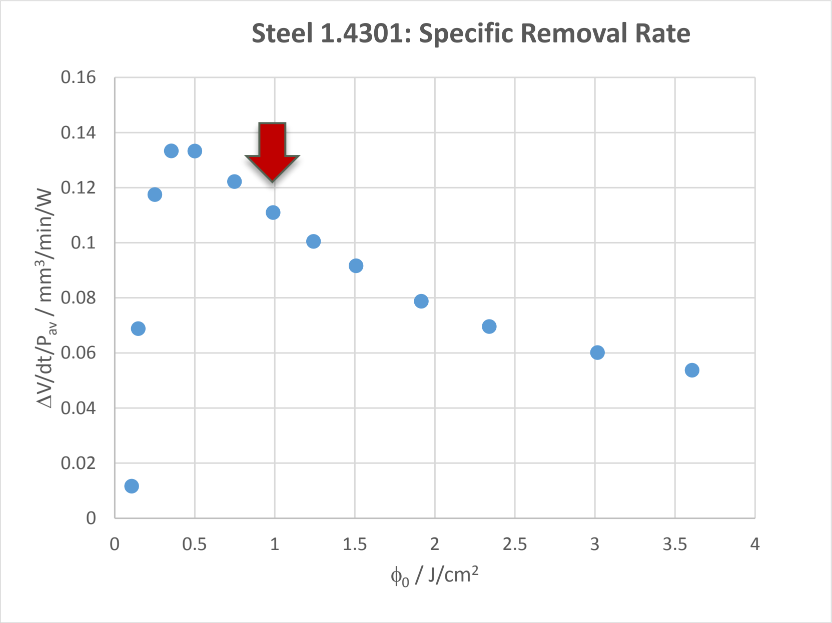

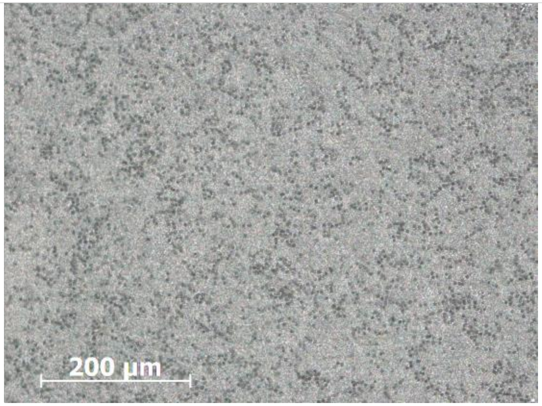

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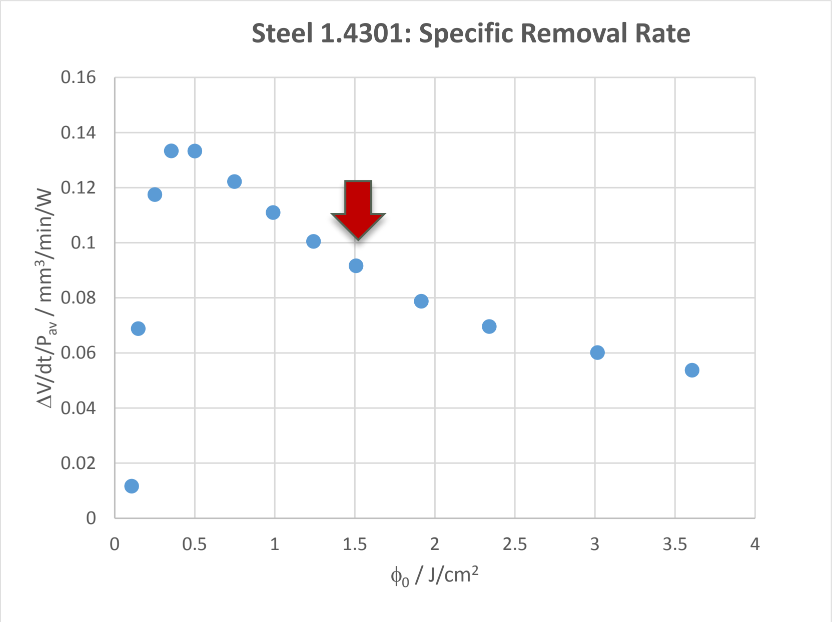

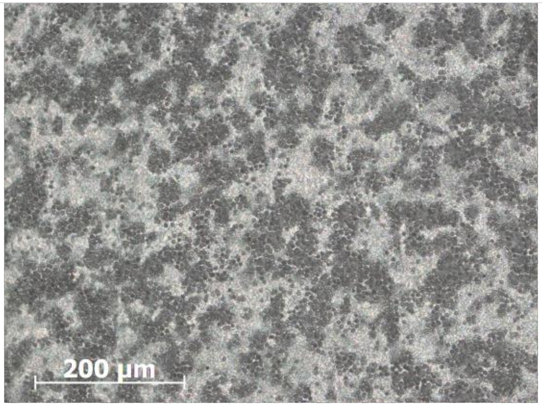

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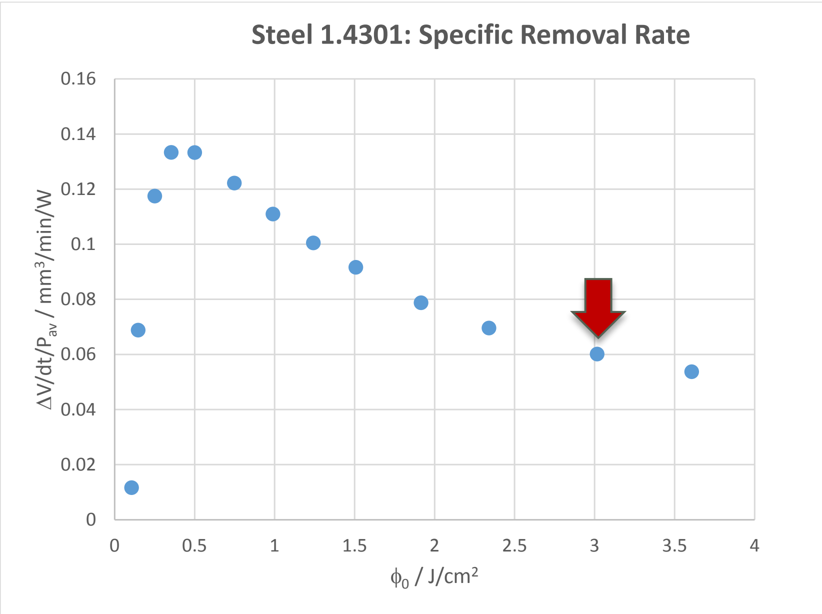

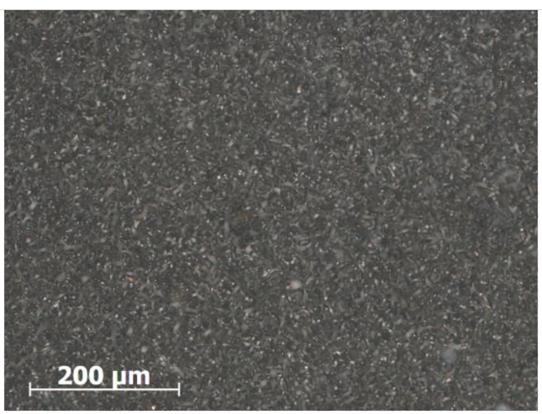

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- Not exactly following model function

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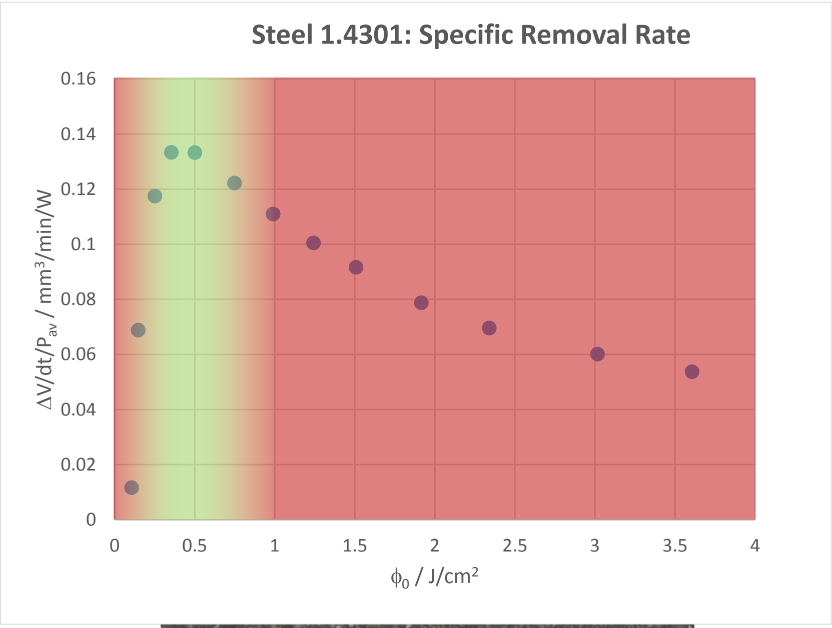

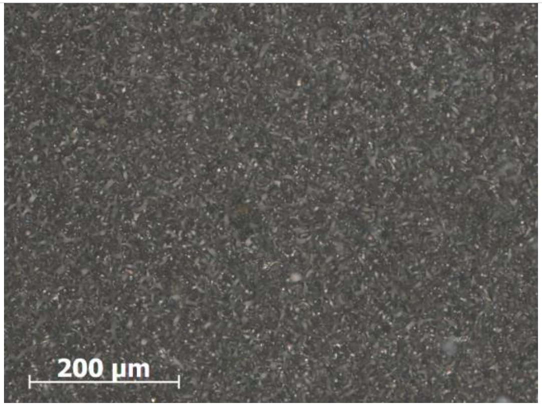

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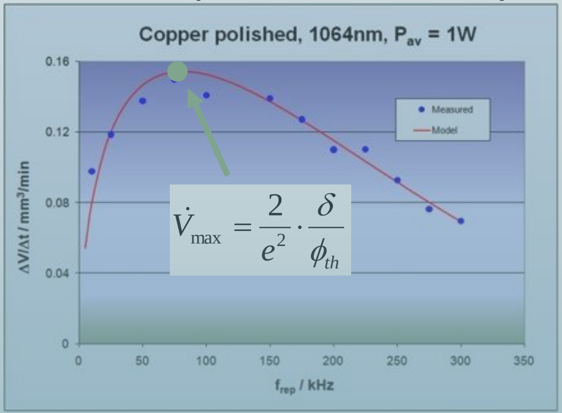
- Not exactly following model function
- Limited process window (also for other steel grades)

Optimization Tasks

Efficiency

Maximize process efficiency



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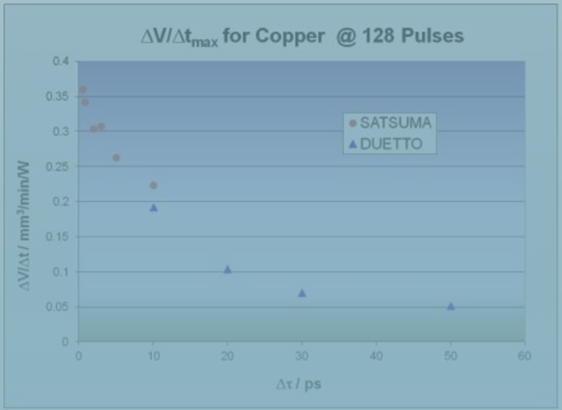
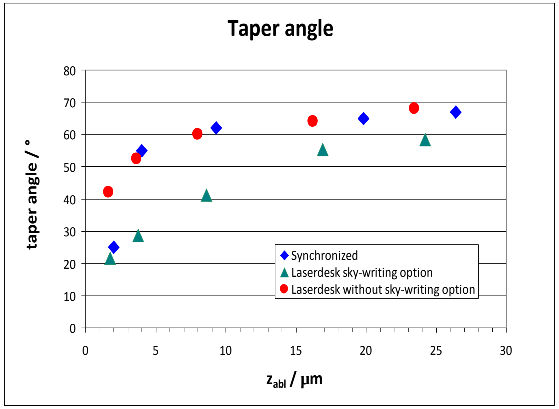
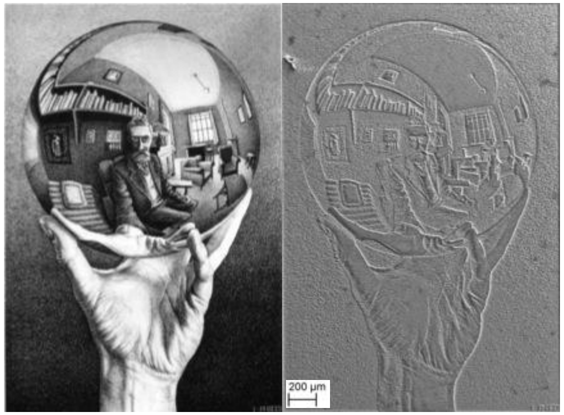


Strategy

Optimize the structuring

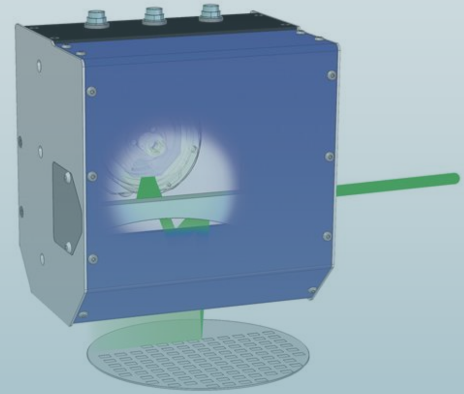


synchronize axes with the laser

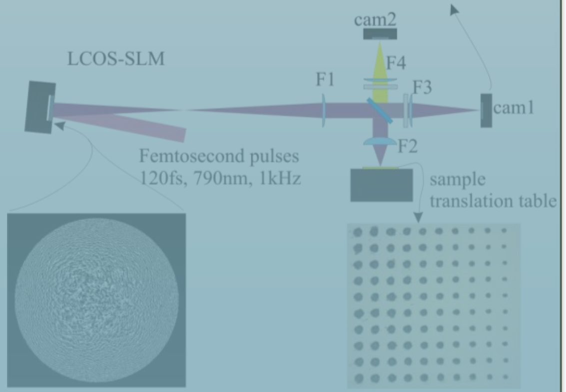


Throughput

Use fast moving axes

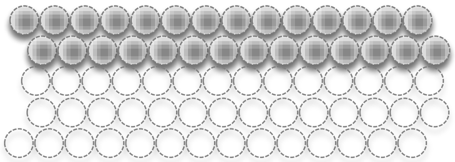


or parallel processes



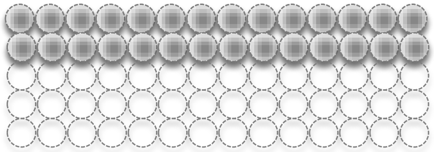
Synchronized marking

Unsynchronized



- jitter of the starting position of each line

Synchronized

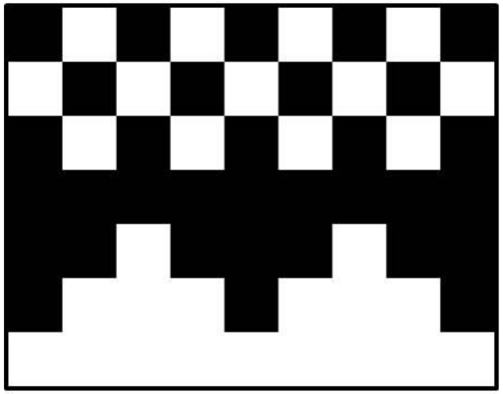


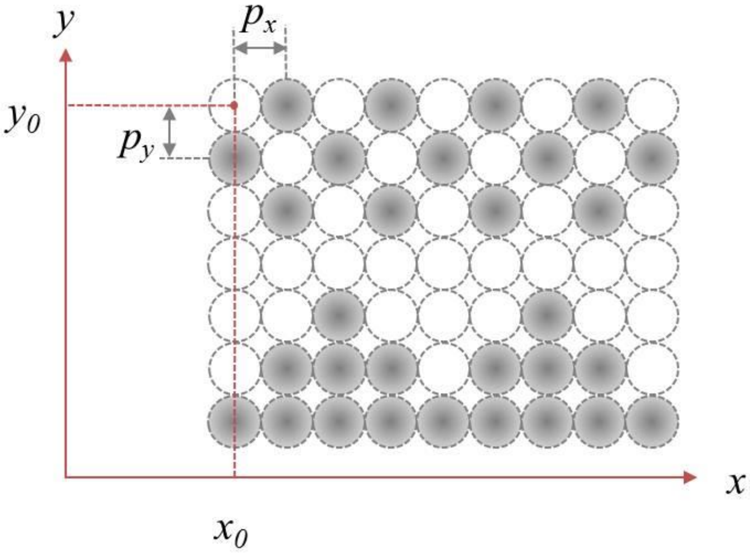
- well defined marking positions

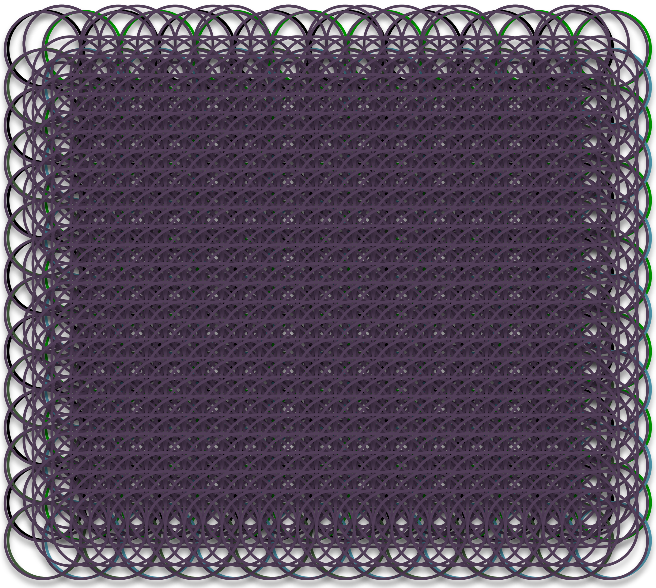
- Synchronized marking leads to highest precision [2]

[2]: Jaeggi B., Neuenschwander B. et al., "Ultra-high-precision surface structuring by synchronizing a galvo scanner with an ultra-short-pulsed laser system in MOPA arrangement," Proc. SPIE 8243, (2012)

Synchronized marking





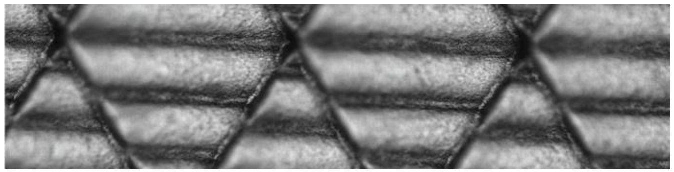


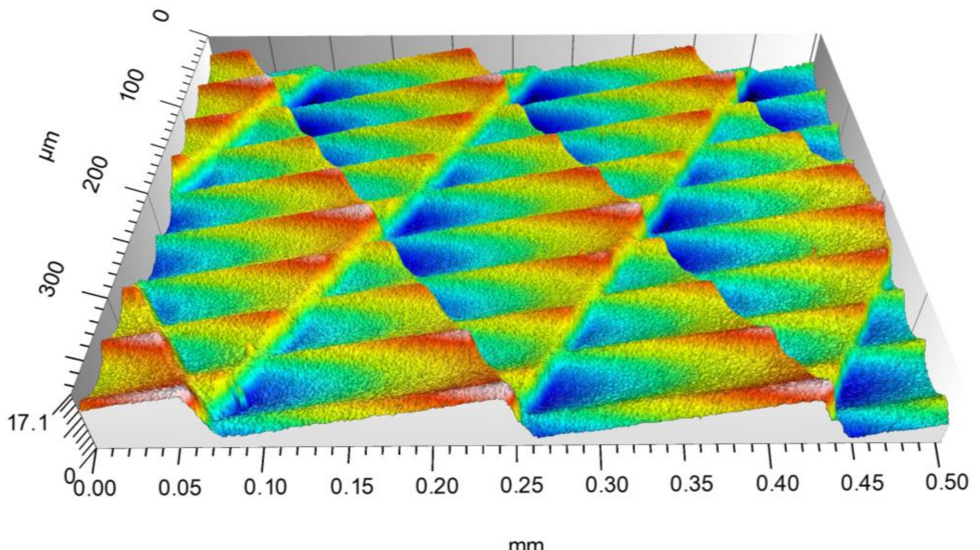
- Synchronized marking leads to highest precision
- Structuring information described in b/w-bitmap
- Definition of the start positions (upper left corner of bitmap)
- Clever distribution of the starting points
- Choose right pitch for best surface quality and roughness
- Best pitch is about half of a spot radius w_0

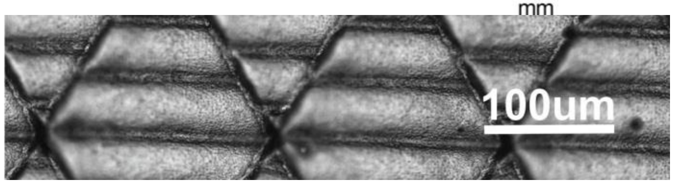
[2]: Jaeggi B., Neuenschwander B. et al., "Ultra-high-precision surface structuring by synchronizing a galvo scanner with an ultra-short-pulsed laser system in MOPA arrangement," Proc. SPIE 8243, (2012)

Examples with synchronized Galvo Scanner

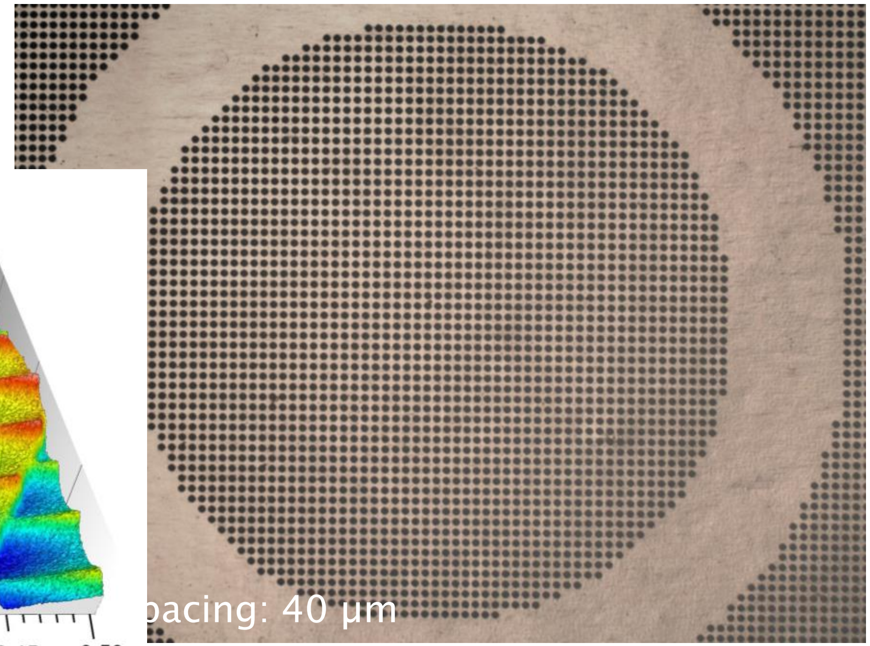
Large area shark skin structure







Multi-pulse drilling on the fly



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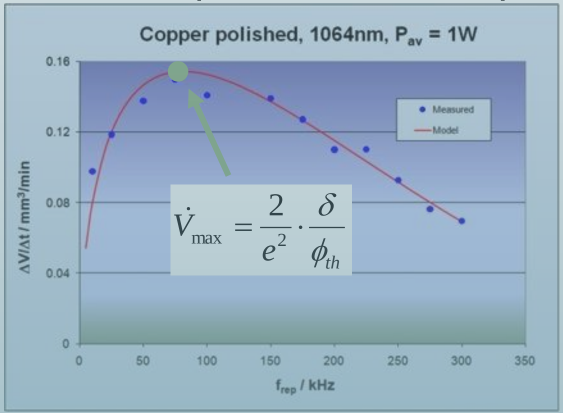
Efficiency

Maximize process efficiency



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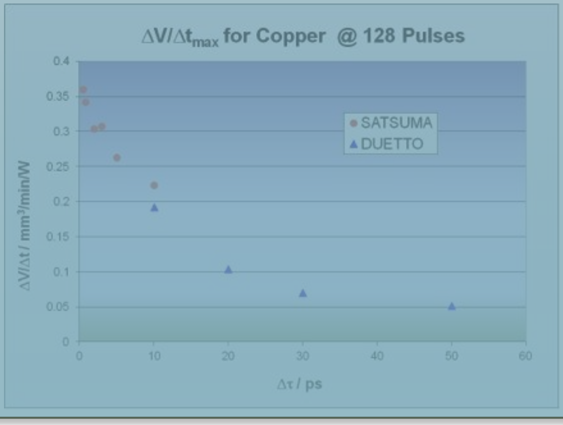
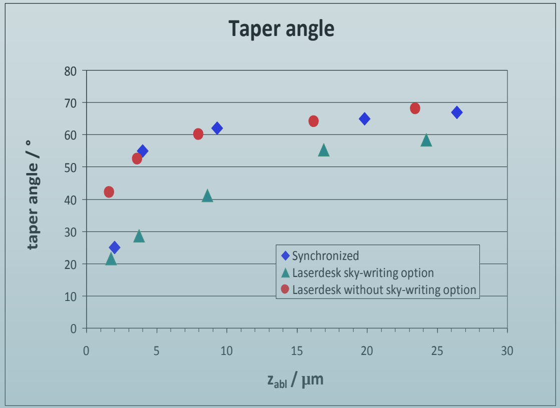
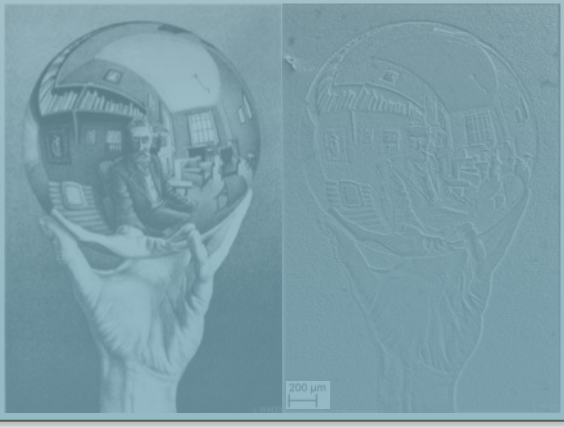


Strategy

Optimize the structuring

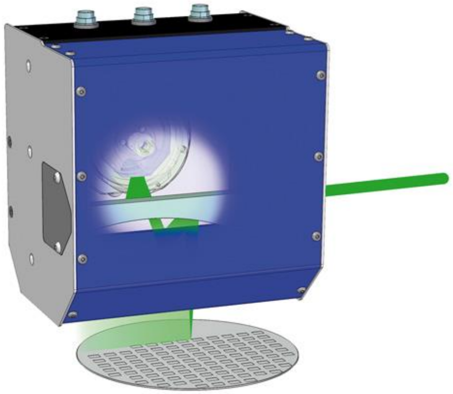


synchronize axes with the laser



Throughput

Use fast moving axes



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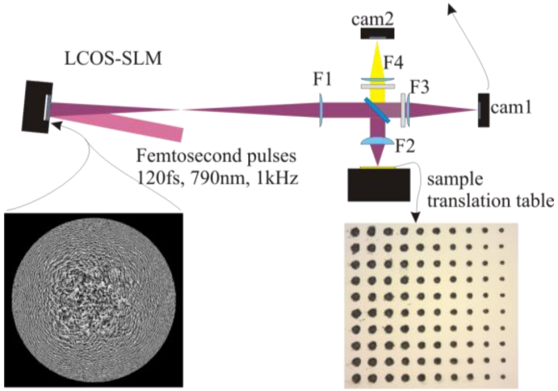
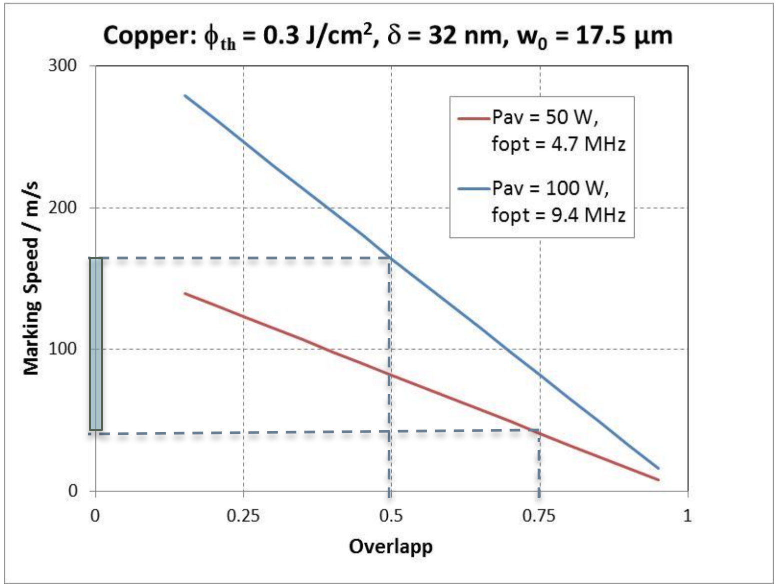
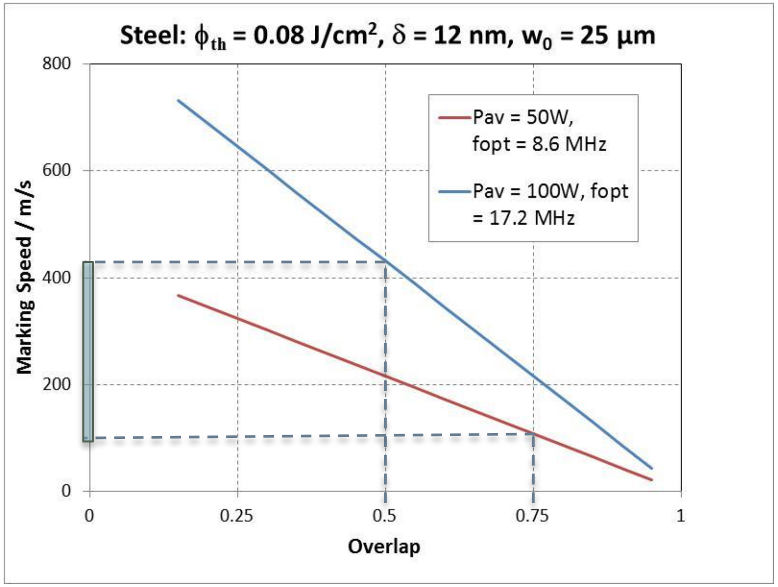


Marking Speed

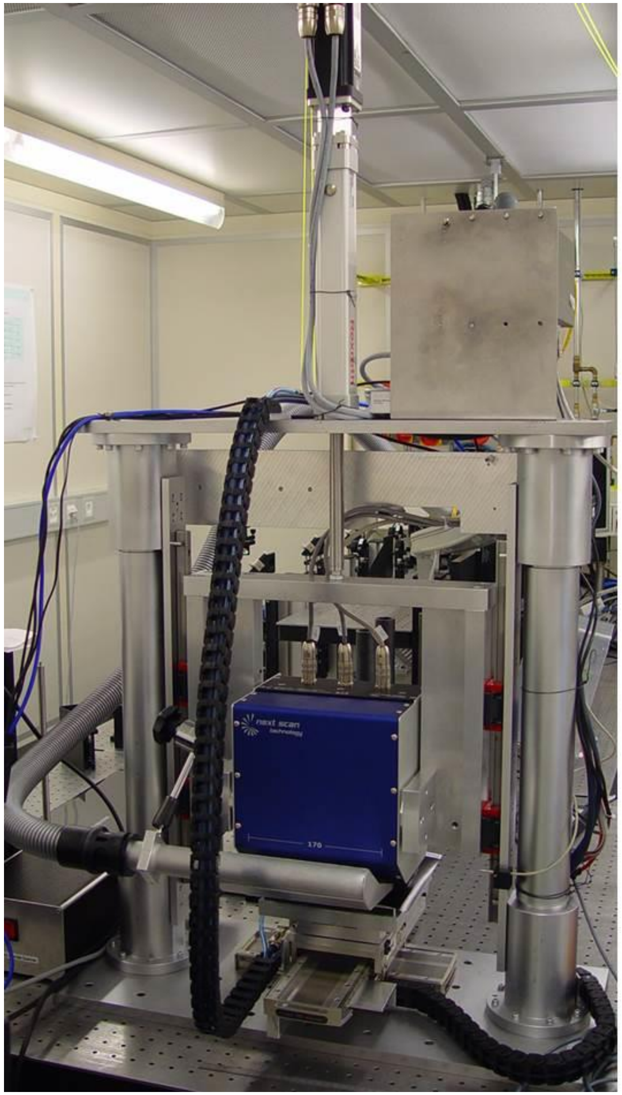
- A short calculation leads to: $v_{mark} = \frac{4}{\pi \cdot e^2} \cdot \frac{(1-o) \cdot P_{av}}{w_0 \cdot \phi_{th}}$ o: Overlap (50% - 75%)





- Working near the optimum point with a few 10W of average power demands:
  - High marking speeds of 100m/s and more (not accessible with galvo scanners).
  - Single pulse switching at repetition rates of a few MHz to about 20MHz.

Polygon 1: Experimental set – up



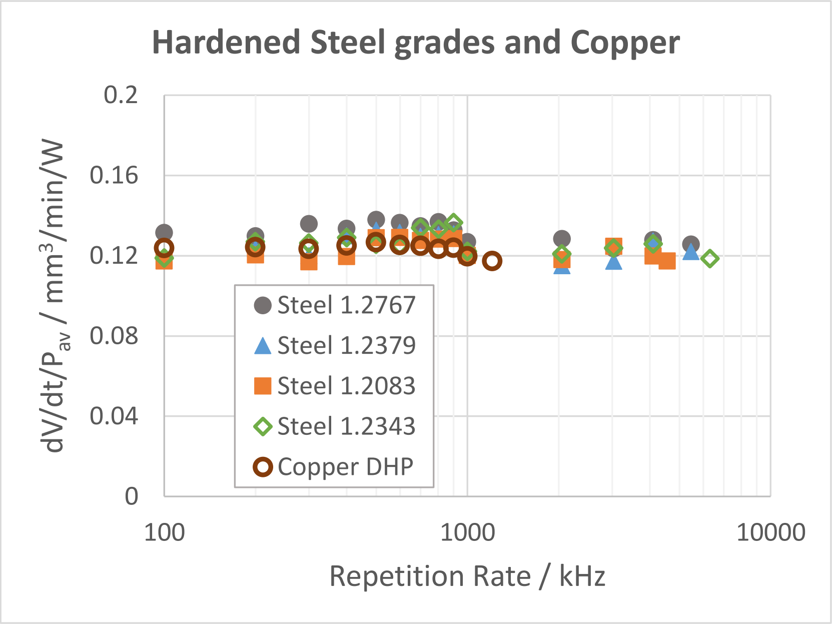
Characteristics:

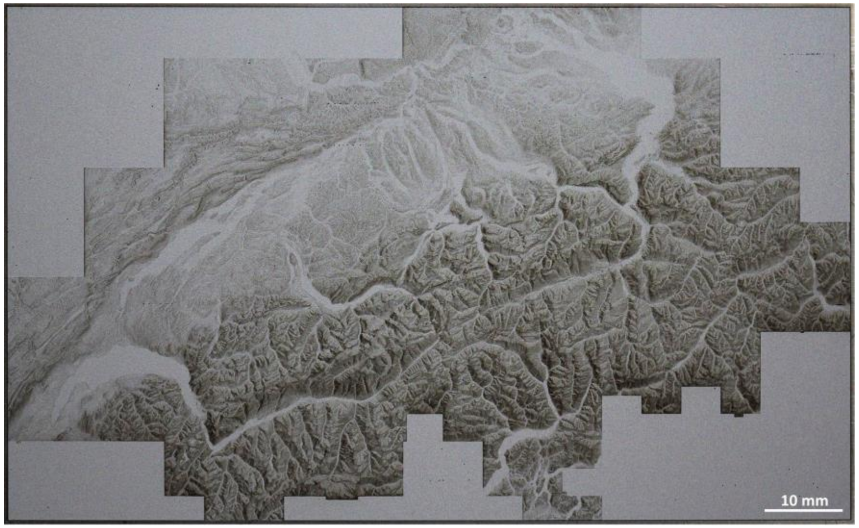
- Spot radius
  - Set up1: w_0 = 28.9 μm
  - Set up2: w_0 = 22.6 μm
- Circular polarization by using a $\lambda/4$-waveplate
- Focal position on the sample surface

Laser System:

- Synchronized via SuperSync™ technology
- FUEGO from Lumentum,
  $\Delta\tau$ = 10 ps, 50W, 1064nm, $M^2 \leq 1.2$
- Max 43 W on the workpiece

Scale up to 43 W with 10ps pulses



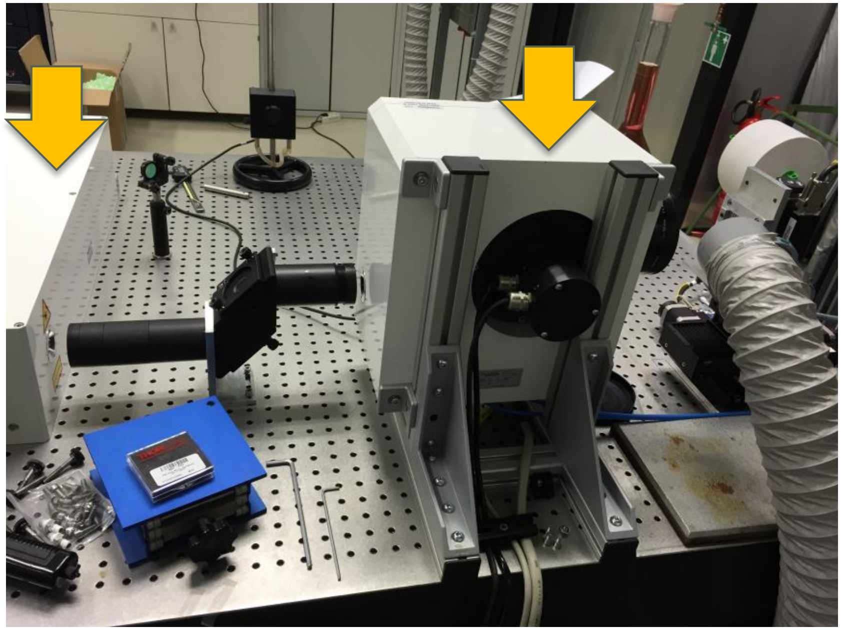


- The process is scalable into the 50W regime with several MHz repetition rate

- f_{rep}: 4.1MHz
- P_m: 25.6W
- Pitch: 14.5µm → v_{scan}: 59.5m/s
- No. of Layers: 2233

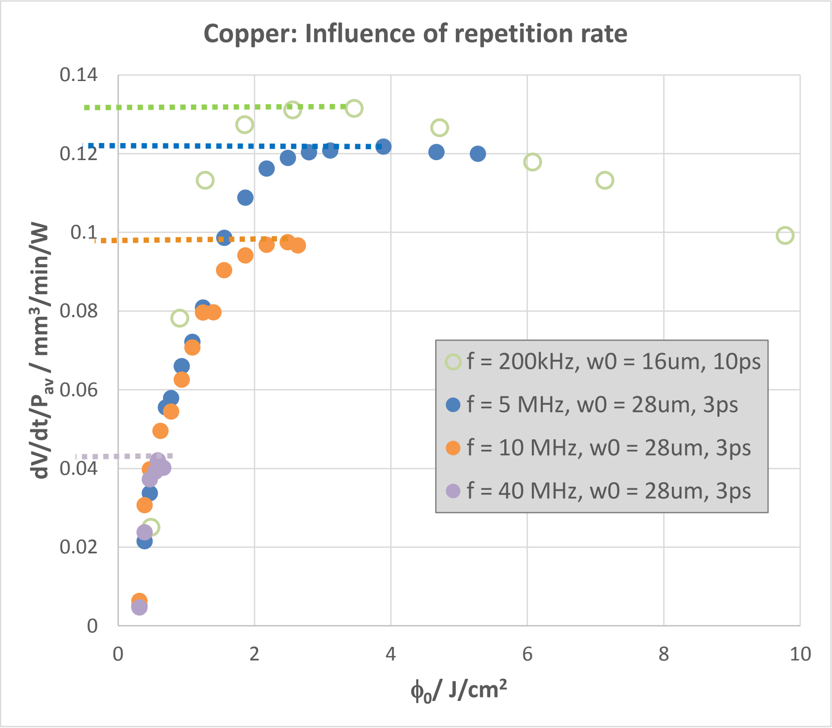
Is a further scale up above100W possible?

Polygon 2: Set – up



- Amphos High Power Laser
  - $P_{av,max}$ = 350W
  - $\Delta\tau$ = 500 fs .. 5 ps (used 3ps)
  - λ = 1030 nm
  - Linearly polarized
- High speed Polygon
  - Not synchronized
  - 1 integrated galvo
  - 12 facets
  - f_{Obj} = 100 mm
  - $v_{mark,max}$ = 480 m/s

Copper: Influence of the Repetition Rate



- Maximum specific removal rate strongly depends on repetition rate
- Points to a "shielding" effect

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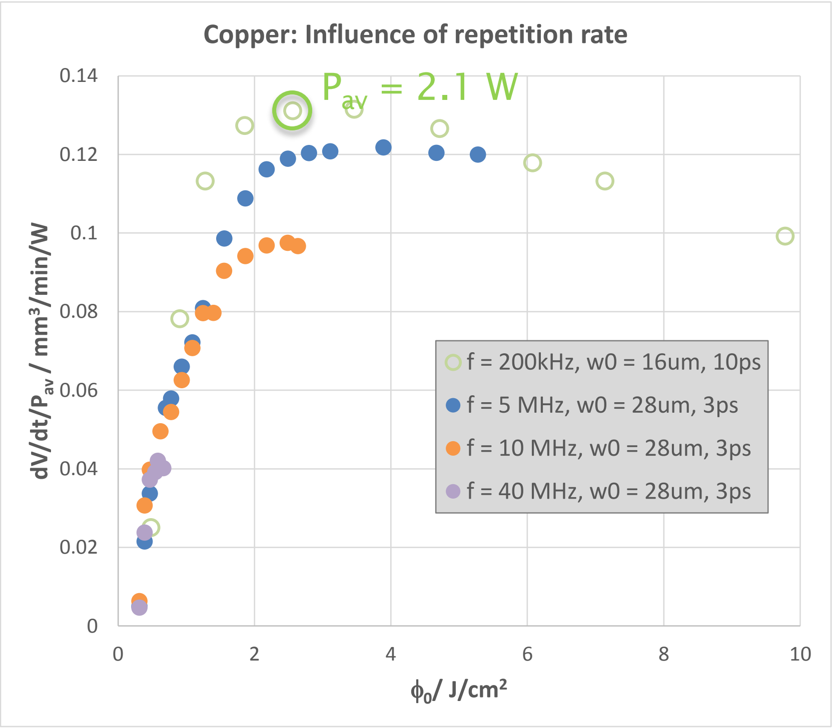

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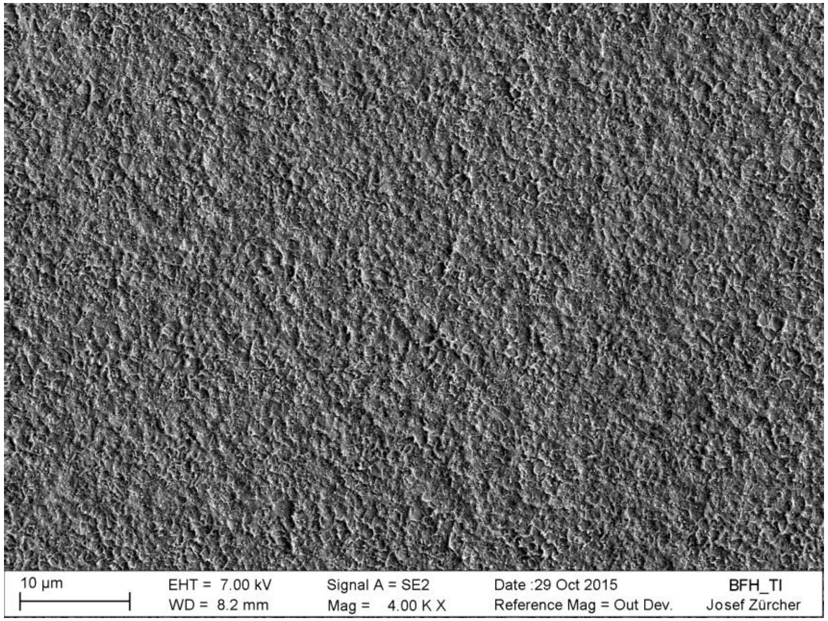

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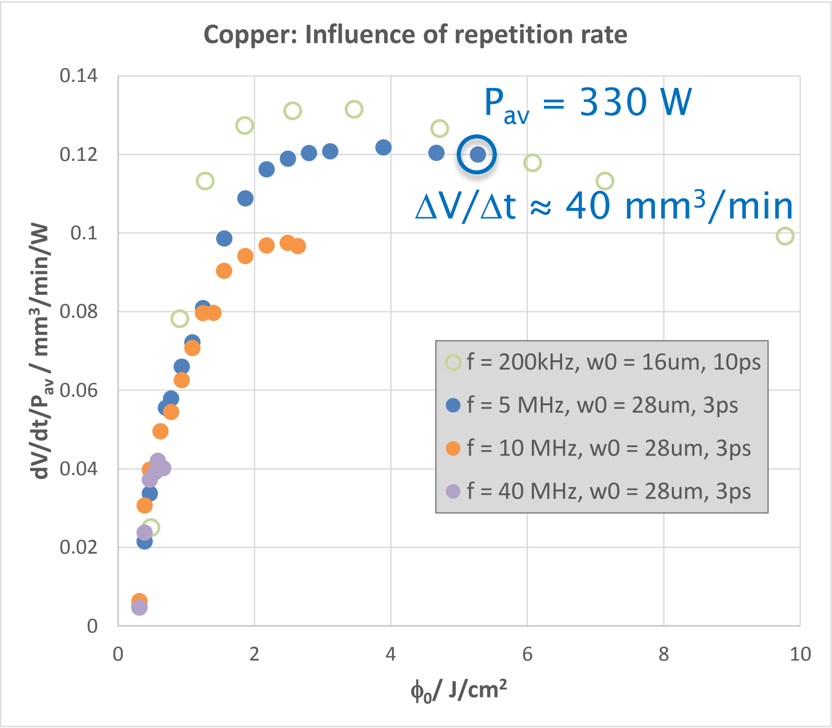

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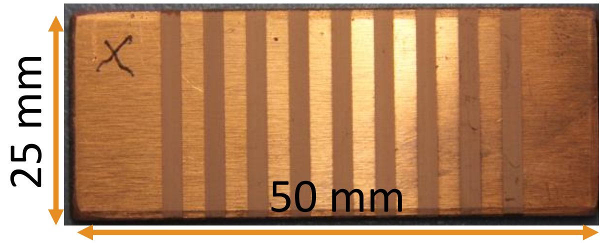
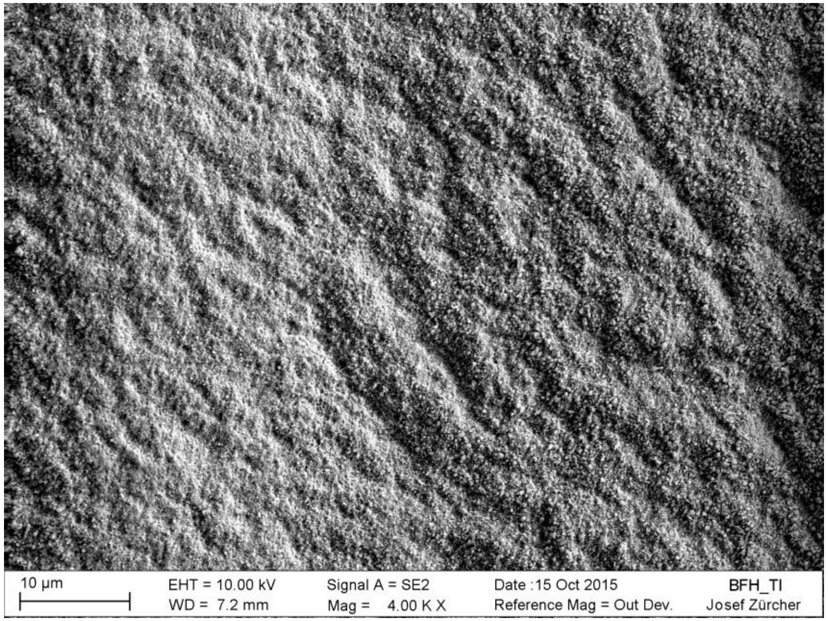


≈ 1h for 2mm thick sample



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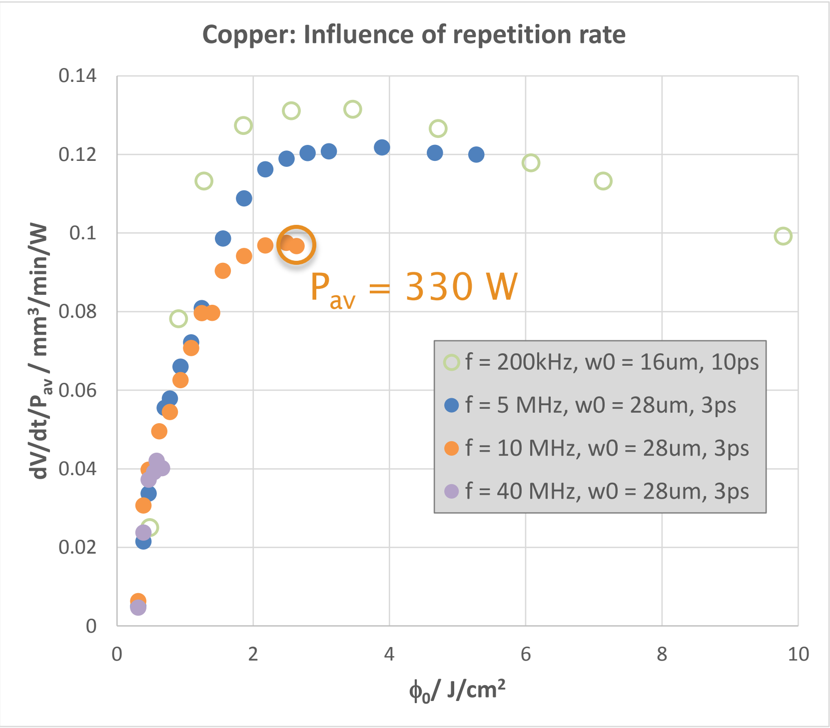

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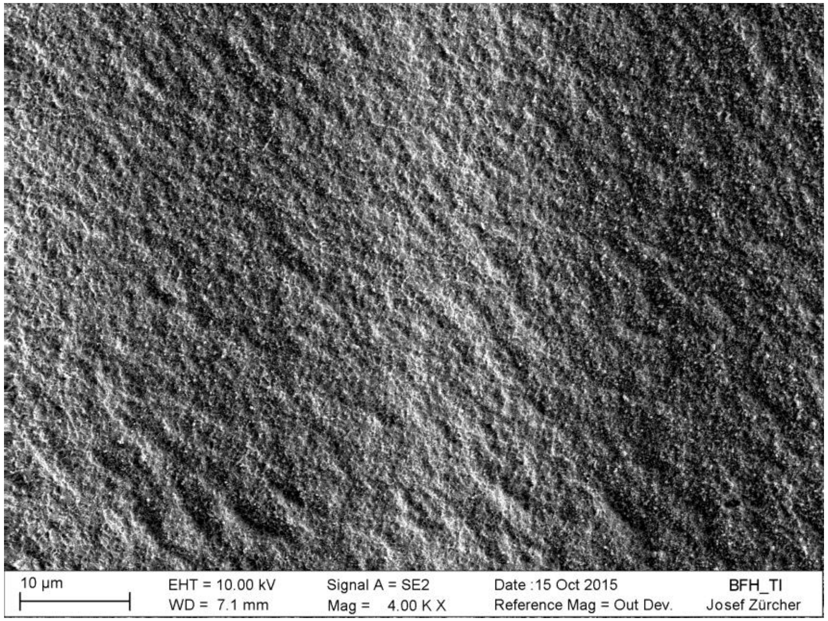

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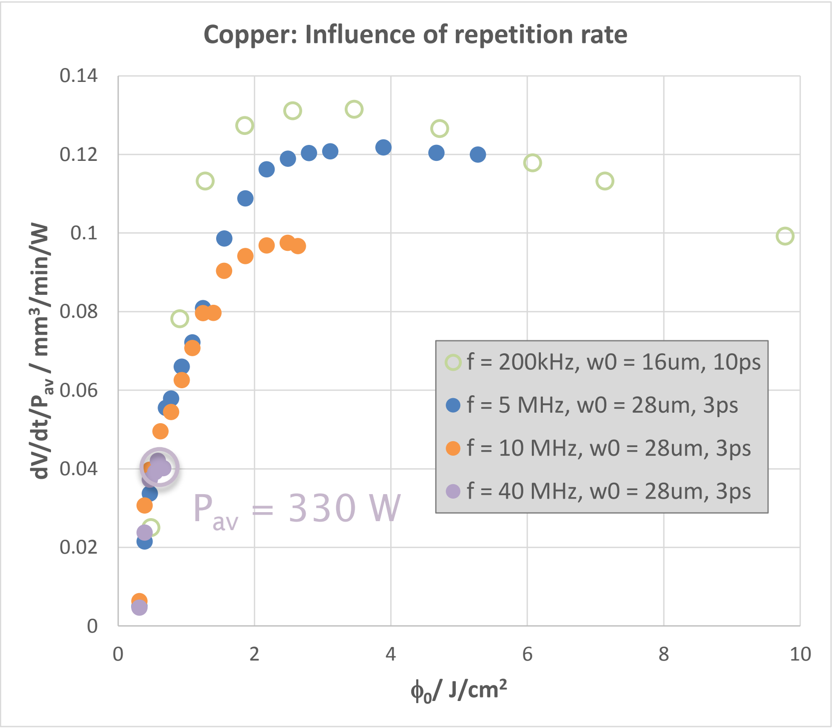

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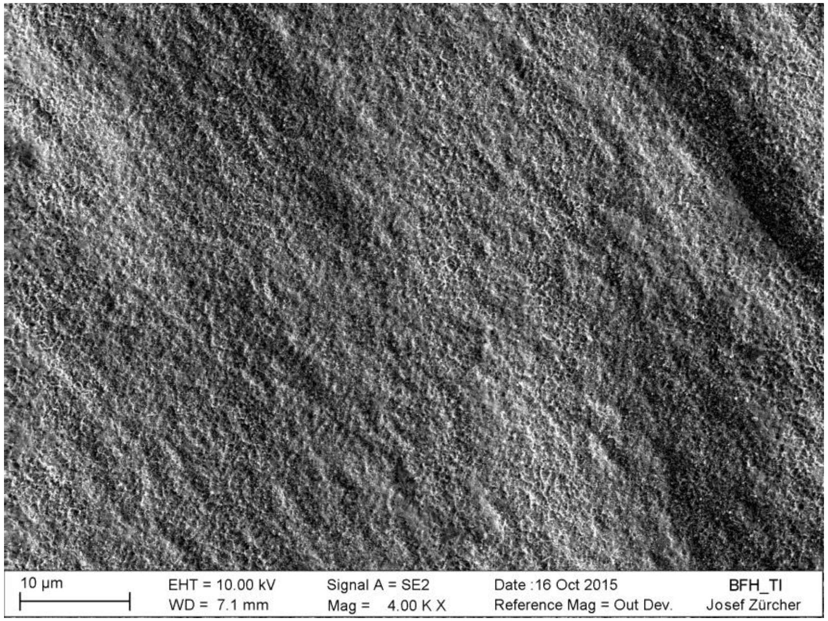

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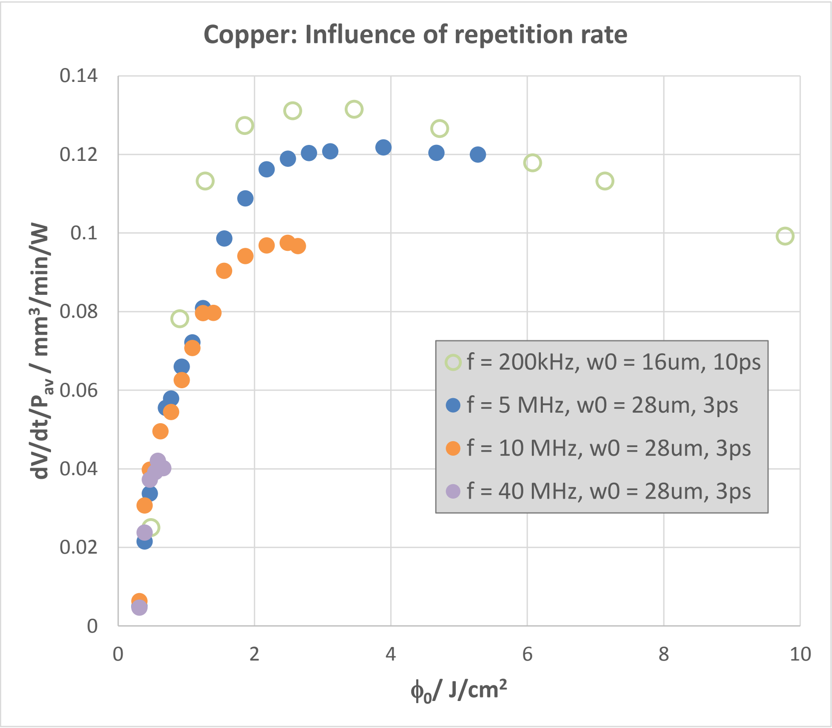
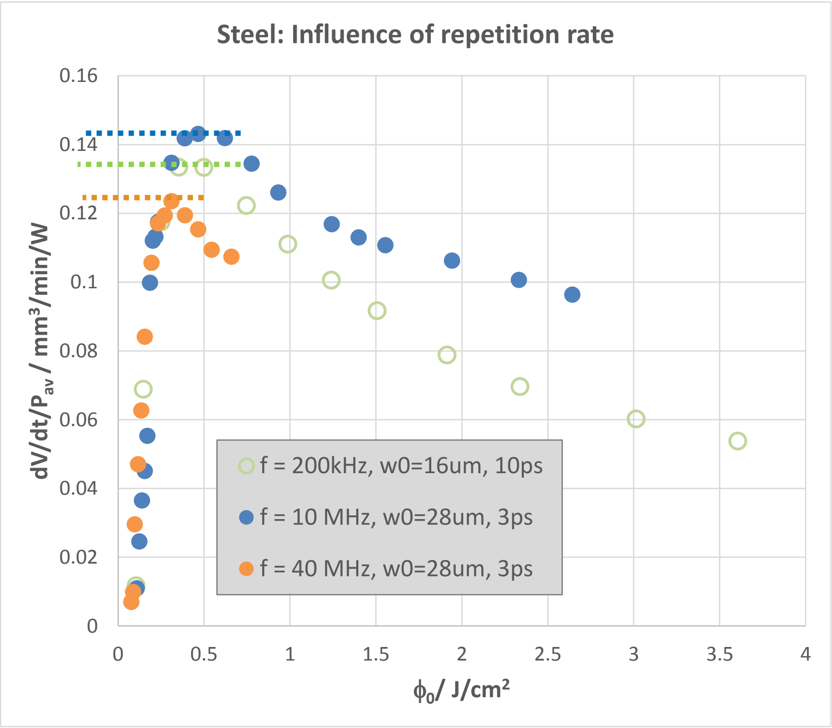


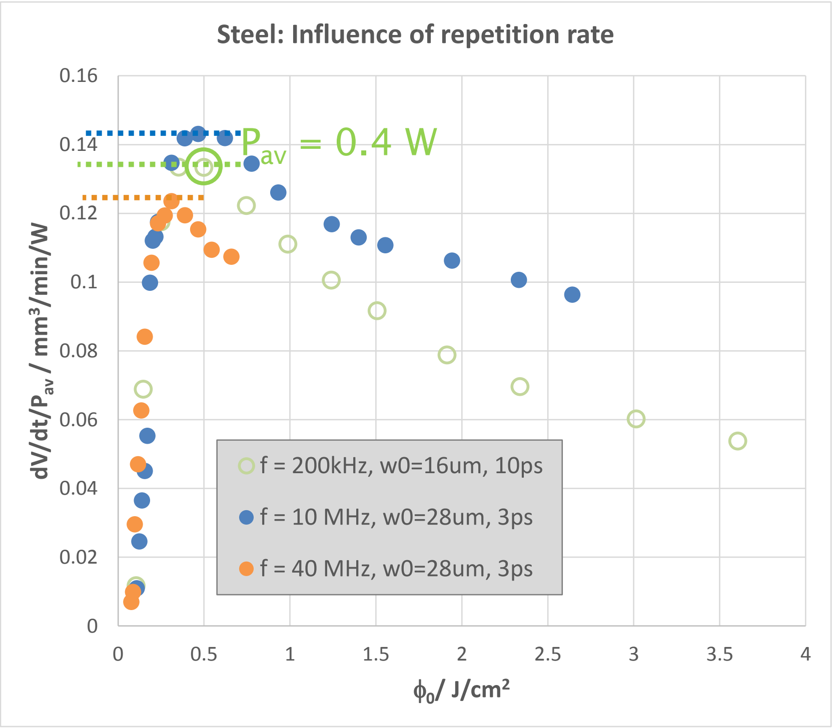
- Maximum specific removal rate strongly depends on repetition rate
- Points to a "shielding" effect
- Good surface quality up to maximum average power of 330W
  - Maximum removal rate 40mm^3/min @ 5MHz
  - Small melting effects for 40MHz repetition rate

Steel: Influence of the Repetition Rate

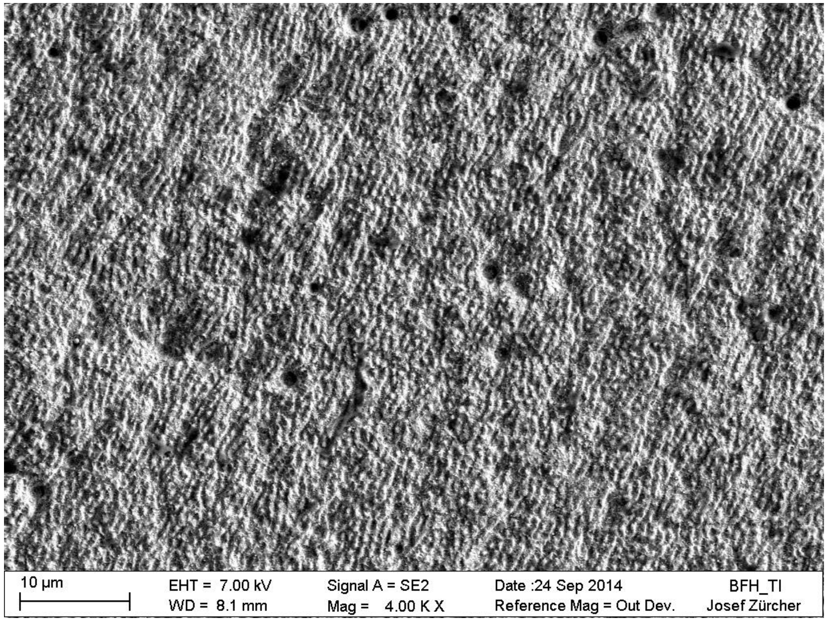


- Repetition rate has only a small influence onto the maximum specific removal rate

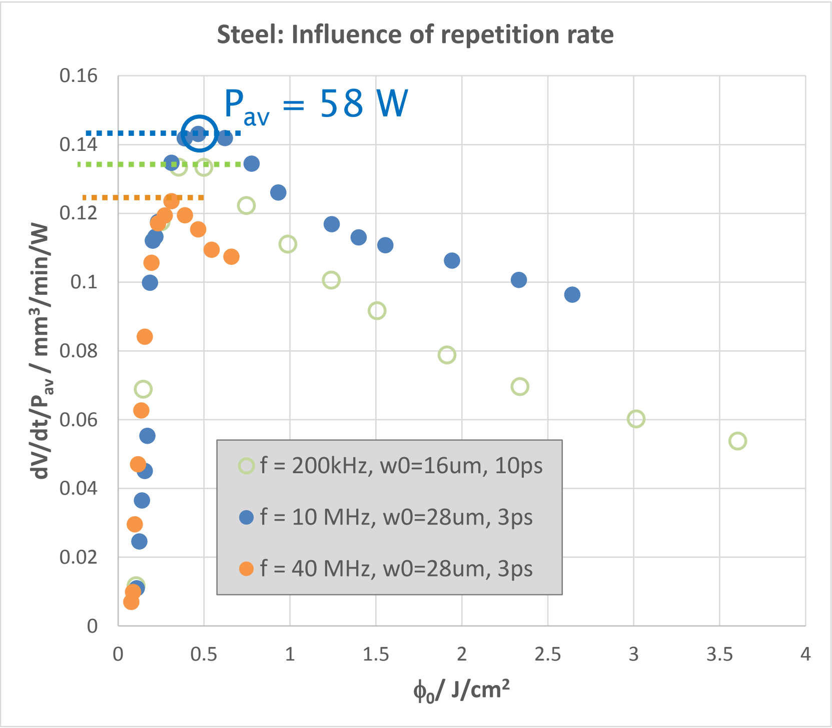
Steel: Influence of the Repetition Rate



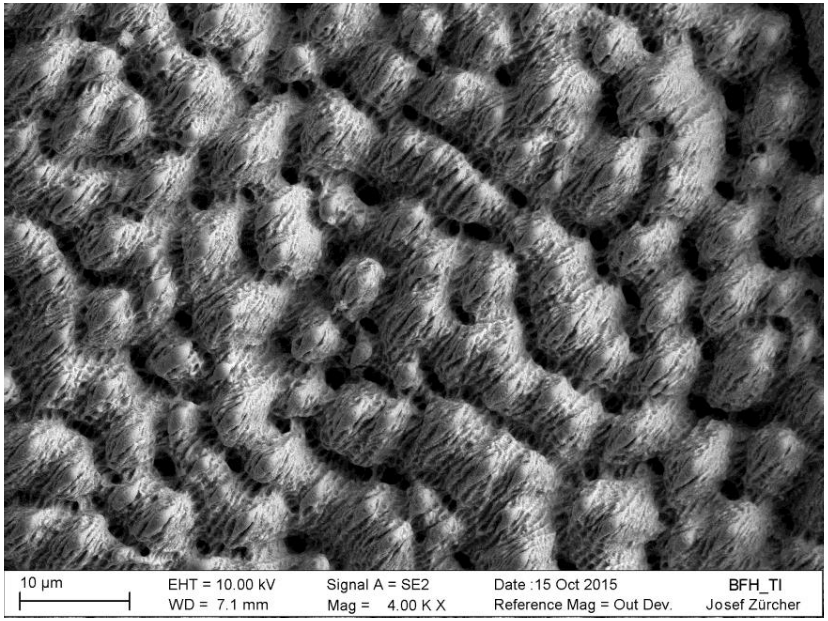
- Repetition rate has only a small influence onto the maximum specific removal rate
- Smooth surface, good quality



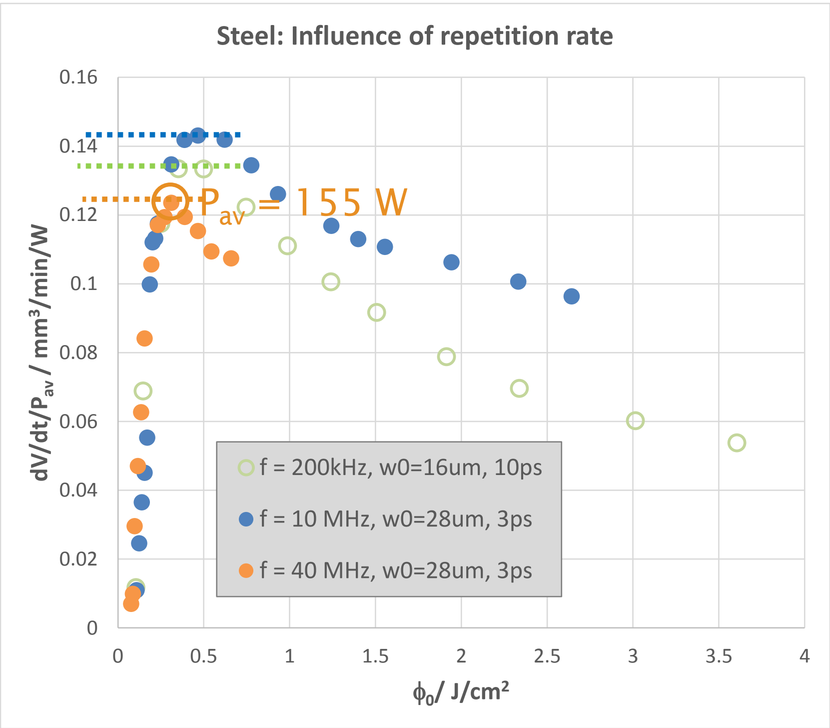
Steel: Influence of the Repetition Rate



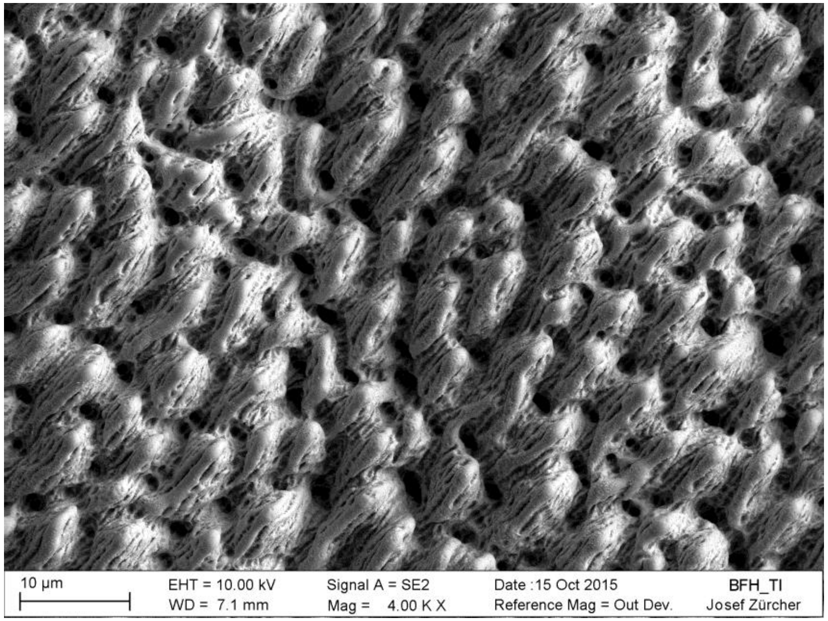
- Repetition rate has only a small influence onto the maximum specific removal rate
- Bumpy surface at highest spec. removal rate for 10 MHz



Steel: Influence of the Repetition Rate



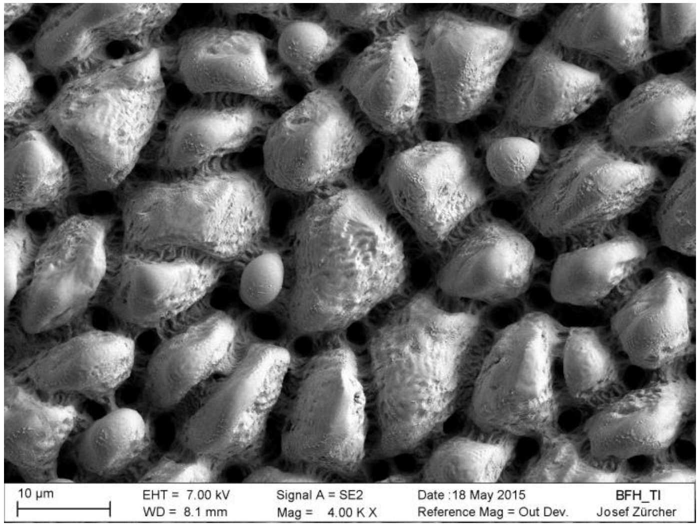
- Repetition rate has only a small influence onto the maximum specific removal rate
- More pronounced at higher average power and repetition rate



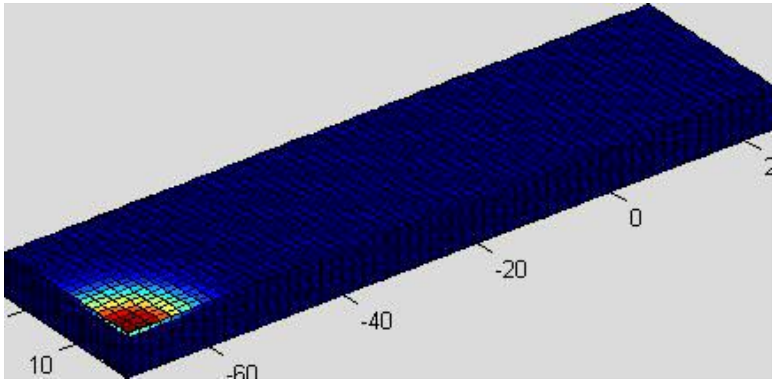
Steel: Heat accumulation

Finding of [3]:

- A part of the incoming energy is always converted to heat (38-40% for steel 1.4301)
- If ΔT_{max} > 610 ºC (just before the next pulse strikes on the surface) bumpy surface is supposed to appear

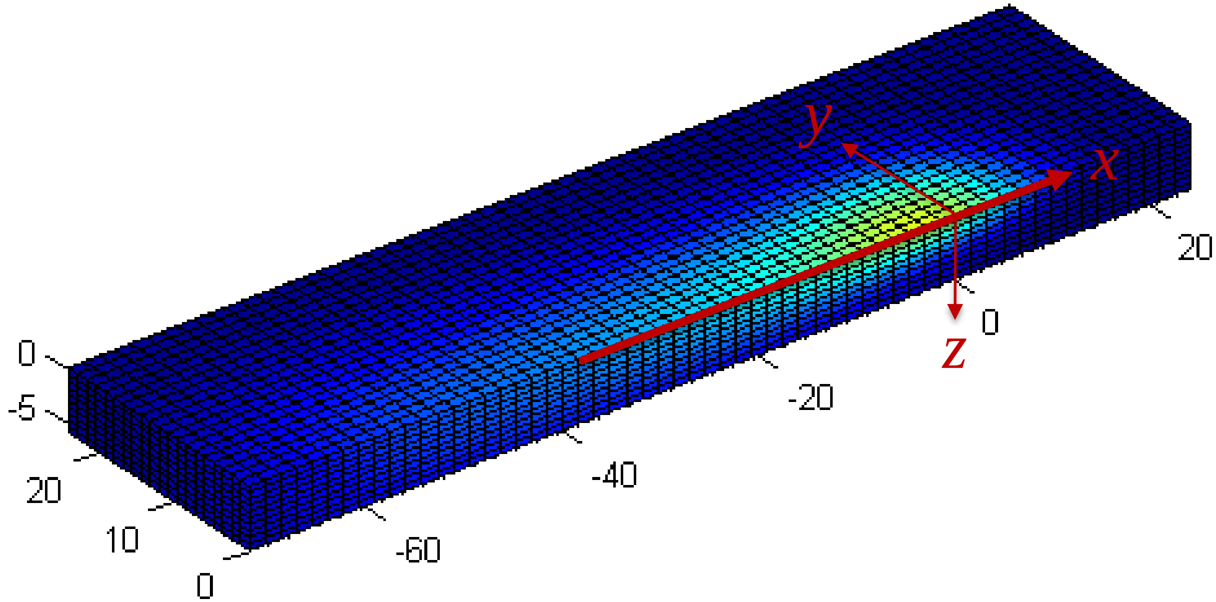


- Analytical expression: $T(x, y, z, t)$
- Pulsed beam along straight line



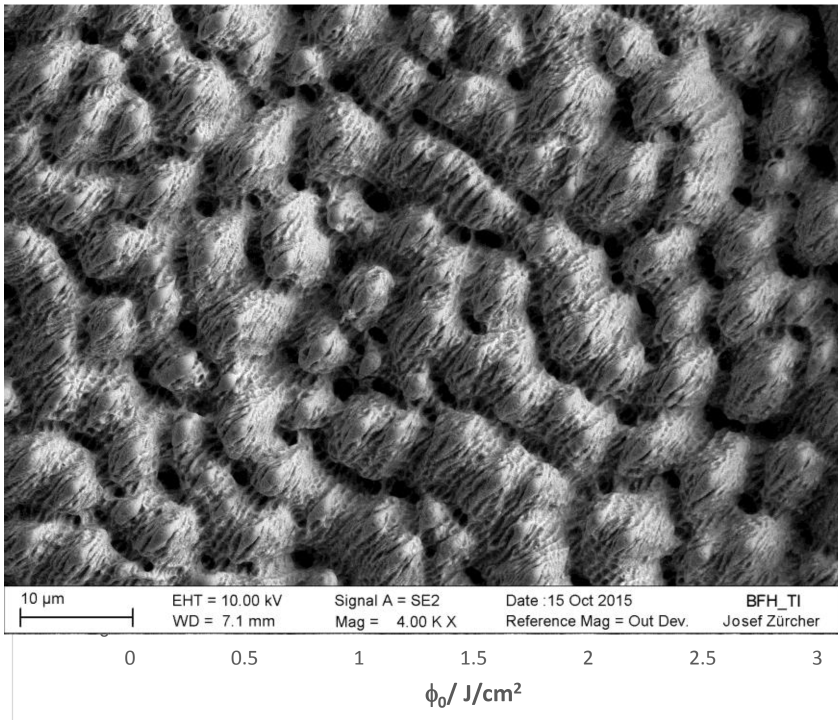
[3] F. Bauer et al., " Heat accumulation in ultra-short pulsed laser processing of metals", Opt. Expr., 23, 1035 – 1043 (2015)

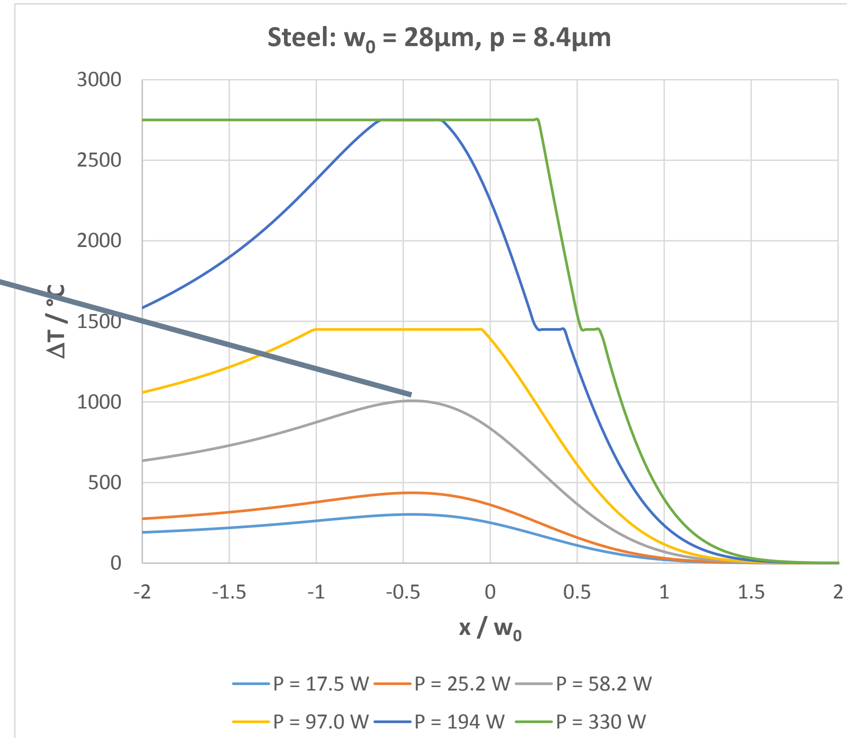
Temperature along a Scan Line



- Shown is the temperature along the scan line (x-axis) just before the next pulse strikes on the surface
- The previous pulse is located at x = 0

Steel: Temperature estimations

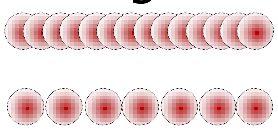




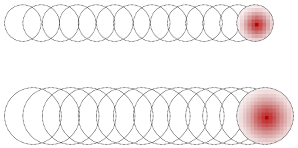
Alternative strategies

Single Spot:

- Enlarge the pitch:

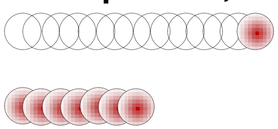


- Increase spot size:

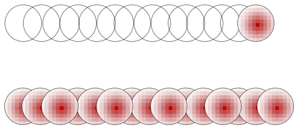


Multi Spot:

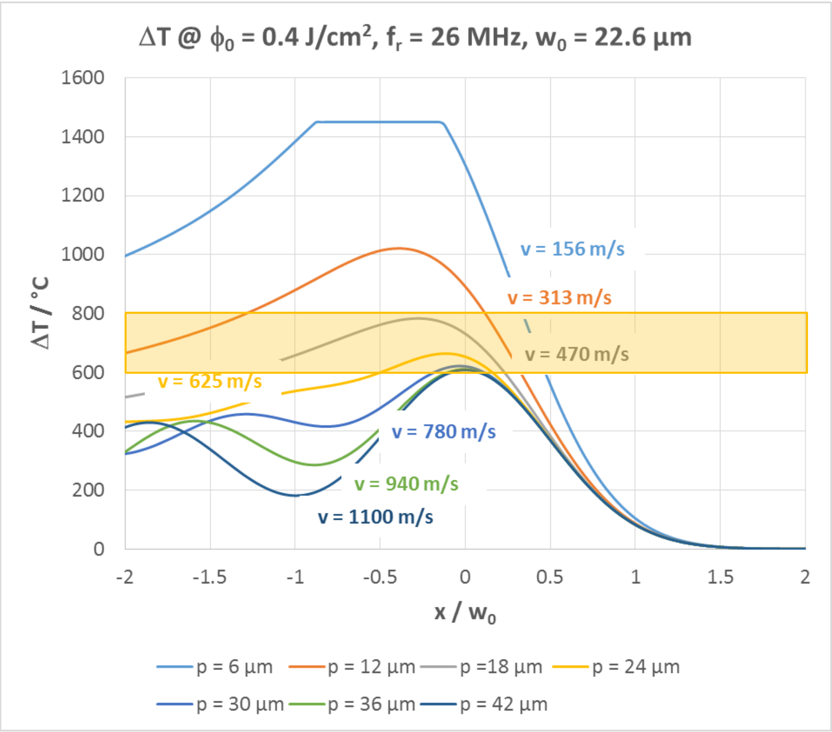
- Temporal, Bursts:



- Spatial:



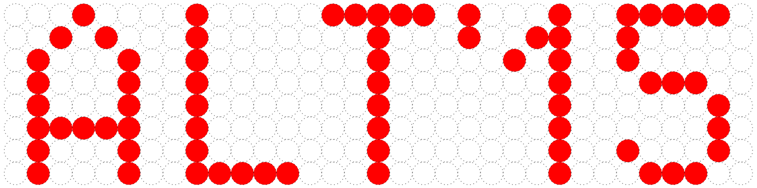
Scale – up to P_{av} = 100W: Enlarge pitch



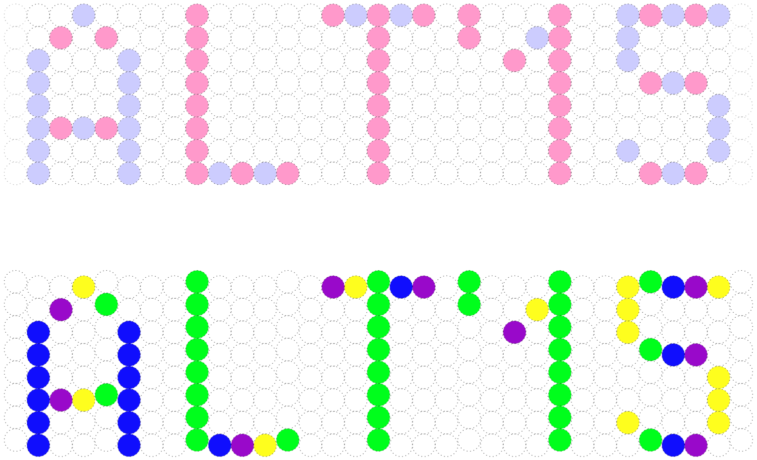
- Pitch varied from 6 to 42 µm
- needed pitch ≥ 24 µm (≥ w_0)
- v_{mark} > 600 m/s

"Interlaced" Mode

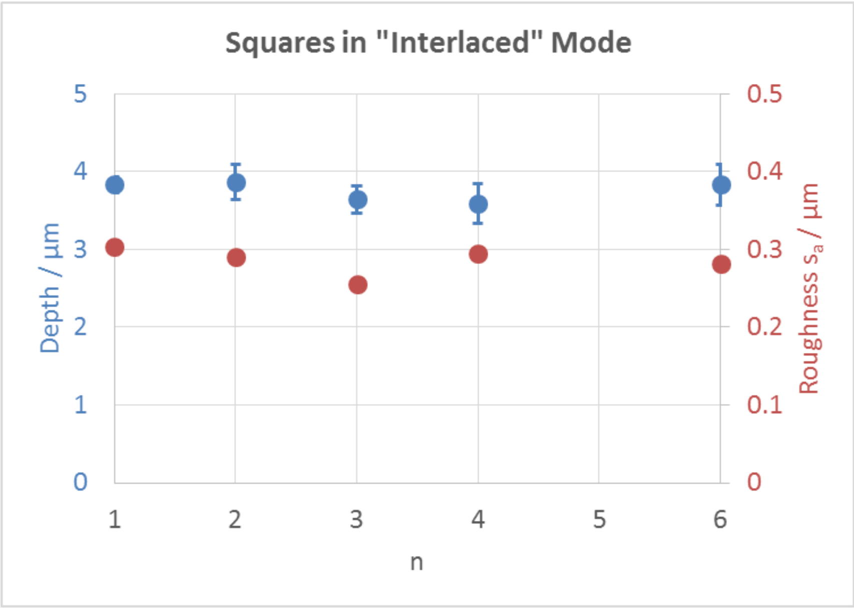
- A given spot pattern can also be machined



- in n passes (pitch n times)

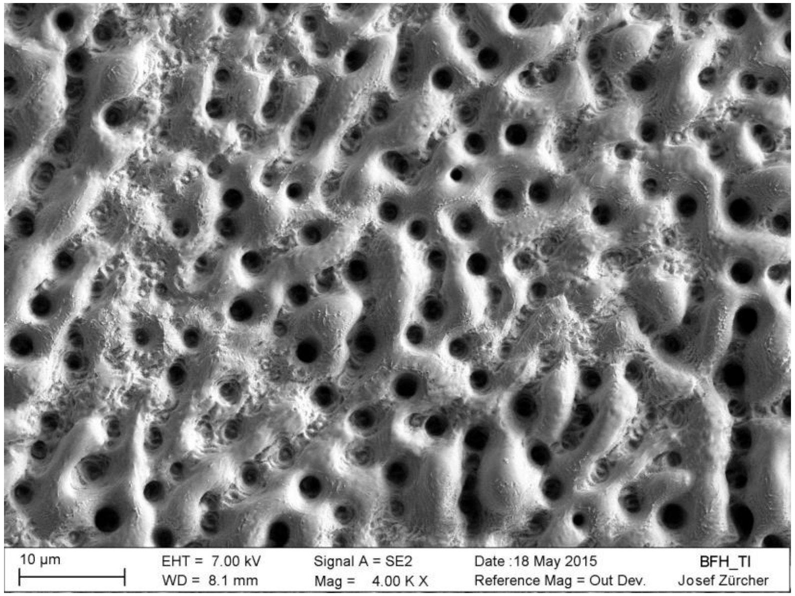


- Squares machined with galvo scanner:
  w_0 = 15.5 µm, p = 8 µm, 0.5 MHz
  ϕ_0 = 0.51J/cm², 50 slices

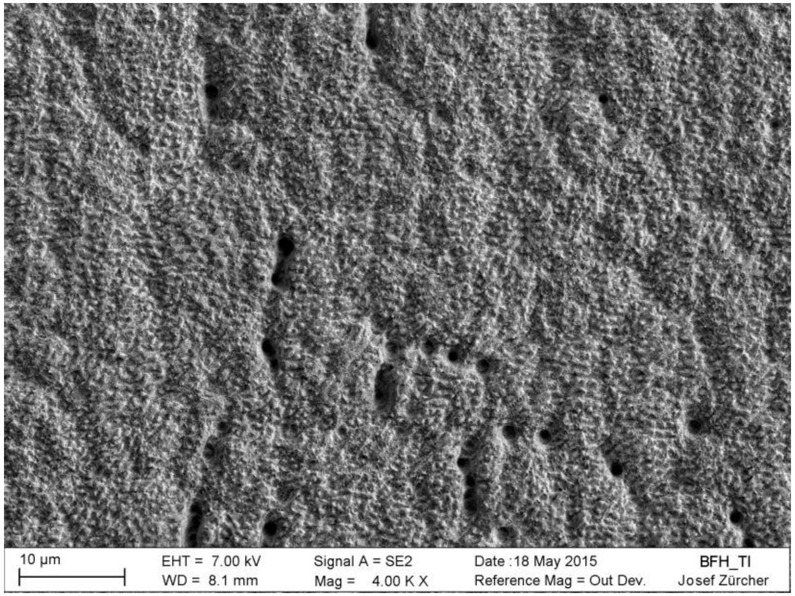


Test of "Interlaced Mode" with Polygon Scanner

- P_{av} = 42.8W, f = 8.2 MHz, ϕ_o = 0.51 J/cm^2



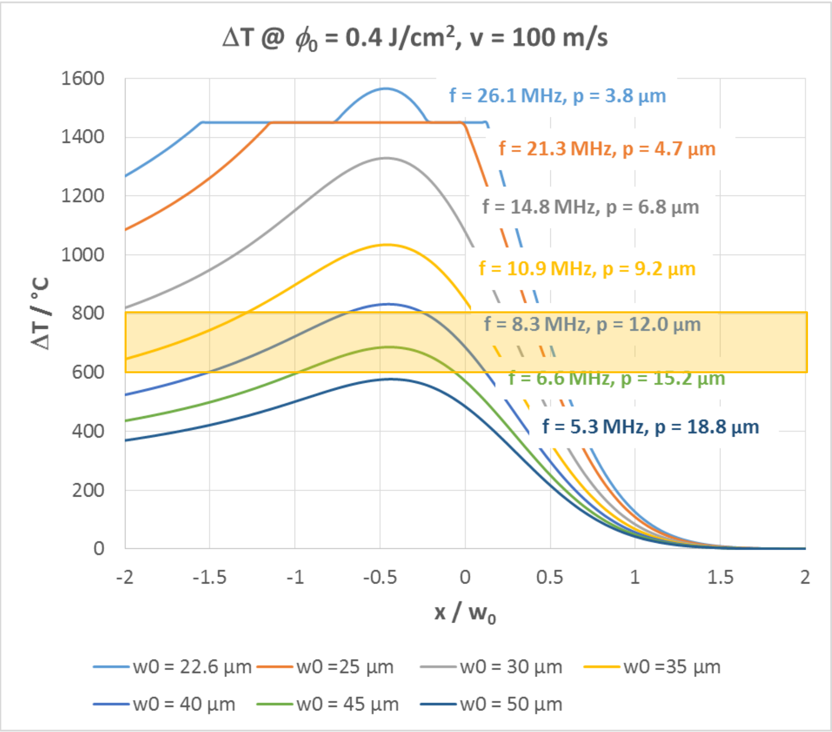
v = 25 m/s, p = 3.1 µm, 30 slices



v = 100 m/s, p = 12.2 µm, 120 slices

- High pitch with interlaced mode works (√)
  - Very high marking speeds (> 600 m/s), synchronized **(?)**
  - High repetition rate (26 MHz) and single pulse switching **(?)**

Scale – up to P_{av} = 100W: Enlarge Spot Size



- Spot radius w_0: 22.6 µm – 50 µm
- v_{mark} = 100 m/s √
- Result:
  - $w_0 \geq$ 45 µm (√)
  - f $\leq$ 6.6 MHz √
- Will work with our polygon 1
- Limitations in precision and minimum structures size

Conclusions

- Metals show an optimum fluence with maximum specific removal rate
- Process window (pulse energy) limited by efficiency and/or quality
- Synchronization is a key for precise machining
- Power scale up to 50W was demonstrated for copper and steel
- Further scale up can be limited
  - Heat accumulation (e.g. steel)
  - "shielding" effects (e.g. copper) ?
- Demonstrated up to 330W and 40mm^3/min for copper
- For steel interlaced mode with high marking speeds, synchronization and single pulse switching or bigger spot sizes will be needed

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- Special thanks to
  - Joseph Zürcher for the SEM-pictures
  - Urs Hunziker for all his work in the mechanical workshop
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