Berner Fachhochschule
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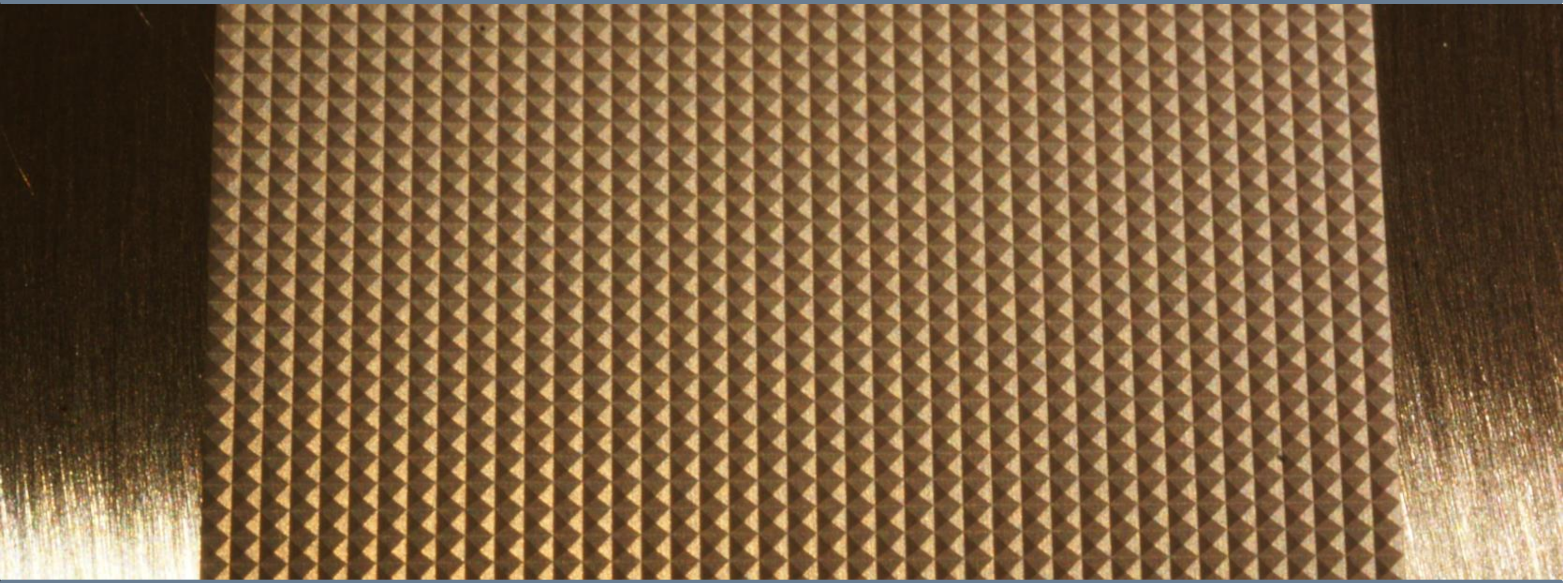


Ultra Short Laser Pulses: A Versatile Tool for Applications in Watch Industry and Jewelry

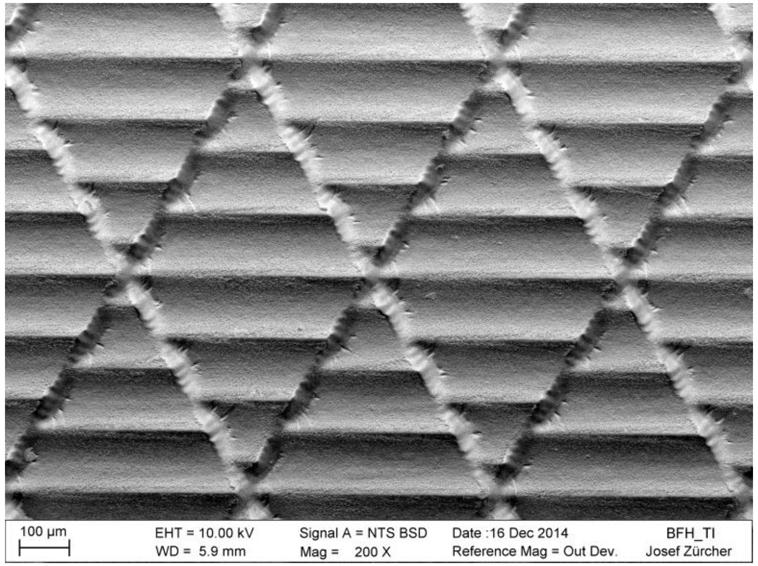
T. Kramer, B. Jäggi, St. Remund, M. Schmid, B. Neuenschwander

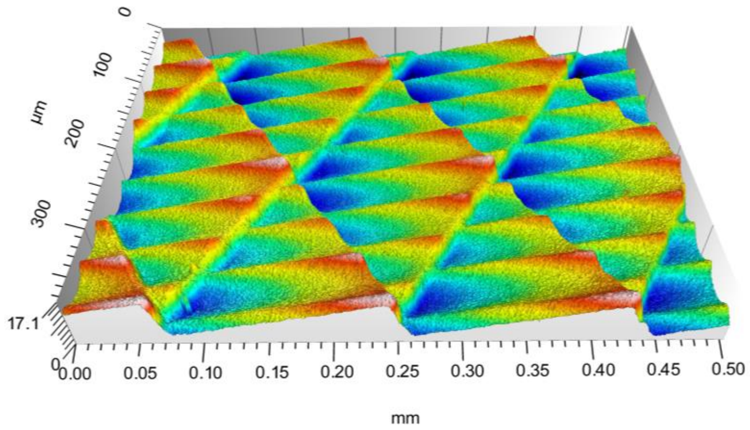
- Bern University of Applied Sciences / Institute for Applied Laser, Photonics and Surface Technologies

EPMT: Booth E126

Motivation

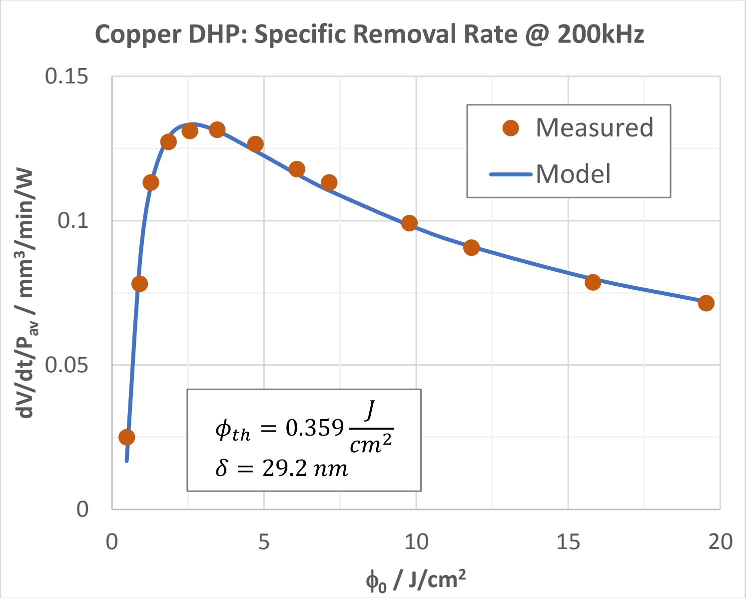
3D Shark Skin Structure





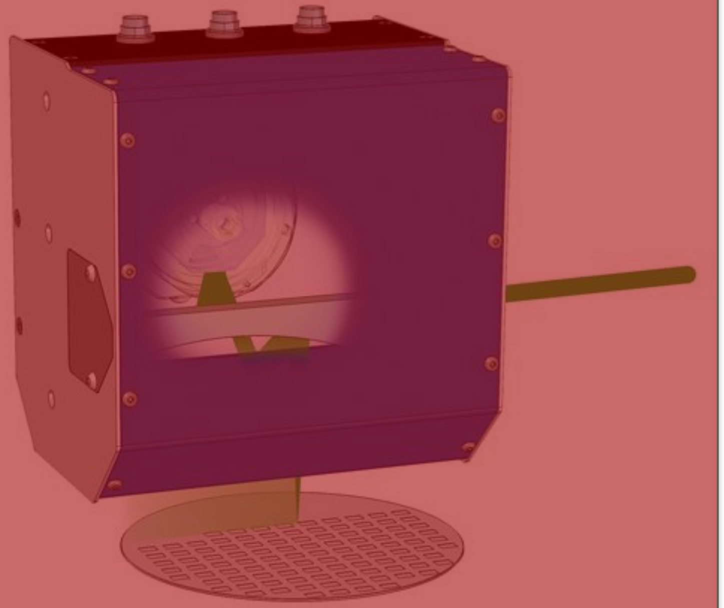
Optimization Tasks

Efficiency:



Strategy:

Throughput:



State of the Art: Ablation model Gaussian Beam

- Specific removal rate [1]:

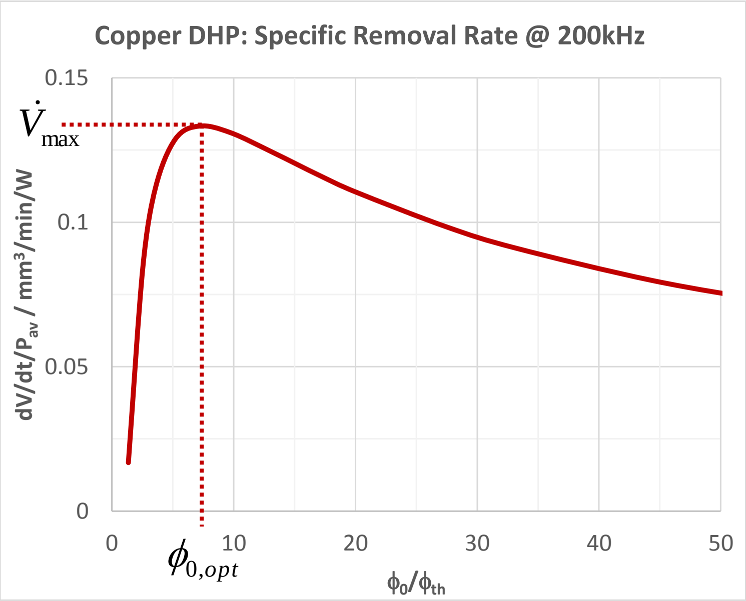
$$\frac{\dot{V}}{P_{av}} = \frac{dV}{dE} = \frac{1}{2}\cdot\frac{\delta}{\phi_0}\cdot\ln^2\left(\frac{\phi_0}{\phi_{th}}\right)$$

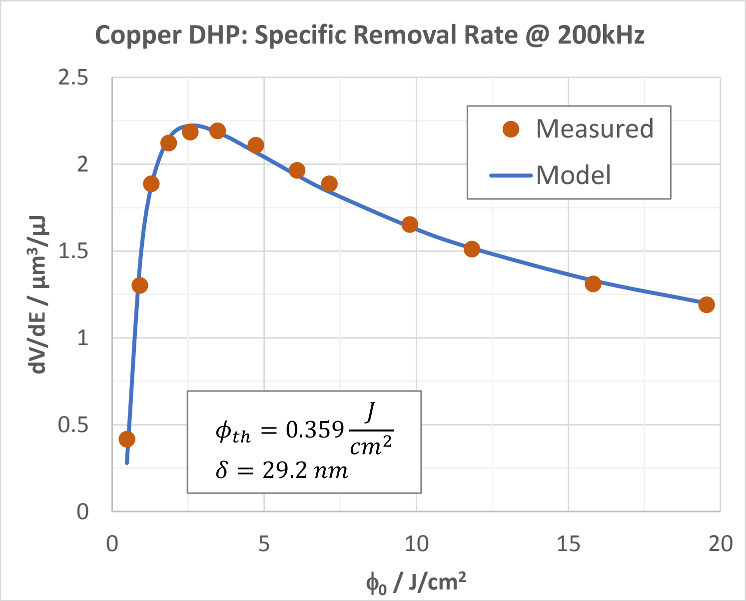
with:
ϕ_{th}: Threshold fluence
δ : Energy penetration depth
ϕ_0: Peak fluence

- Optimum Point / Maximum removal rate

$$\phi_{0,opt} = e^2\cdot\phi_{th} \qquad \frac{\dot{V}_{\max}}{P_{av}} = \left.\frac{dV}{dE}\right|_{\max} = \frac{2}{e^2}\cdot\frac{\delta}{\phi_{th}}$$

- Shorter Pulses -> higher removal rates



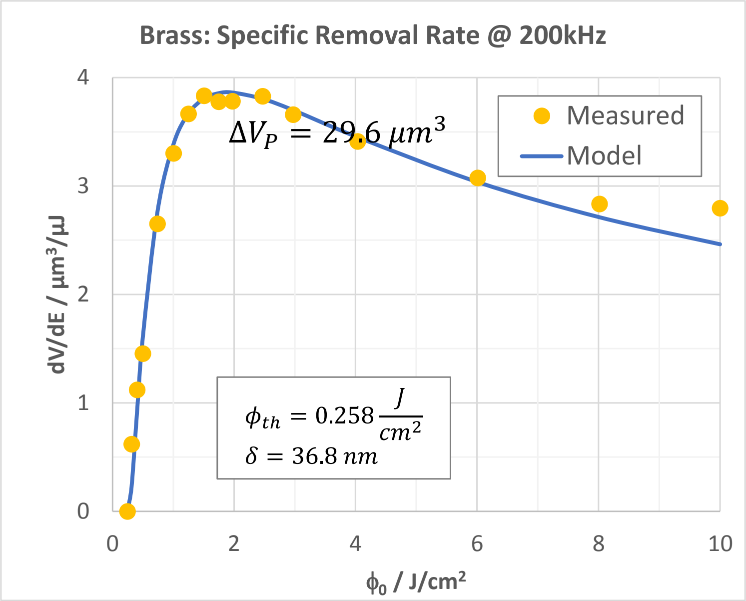


[1]: B. Neuenschwander et al, „From fs to sub-ns: Dependence of the Material Removal Rate on the Pulse Duration for Metals", Physics Procedia Vol. 41, pp. 787-794 (2013)

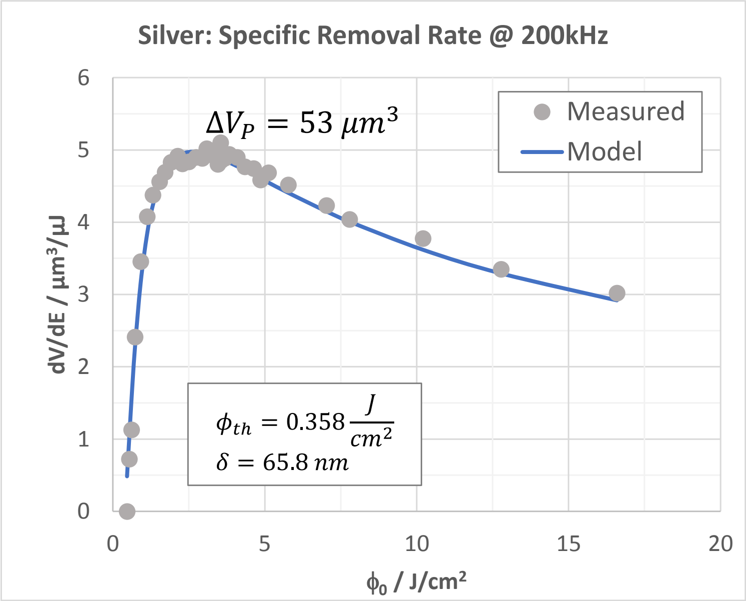
$$\left.\frac{\dot{V}}{P_{av}}\right|_{max} = \left.\frac{dV}{dE}\right|_{max} = 0.133\ \frac{mm^3}{min\cdot W} = 2.22\ \frac{\mu m^3}{\mu J}$$

State of the Art: Ablation model Gaussian Beam

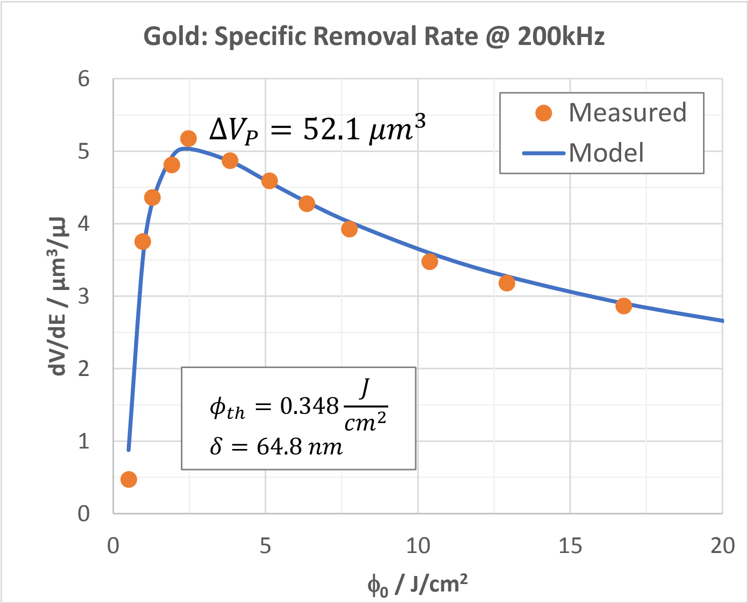
- Brass: $\Delta\tau$ = 10 ps, w_0 = 16 µm



- Silver: $\Delta\tau$ = 10 ps, w_0 = 16 µm



- Gold: $\Delta\tau$ = 10 ps, w_0 = 16 µm

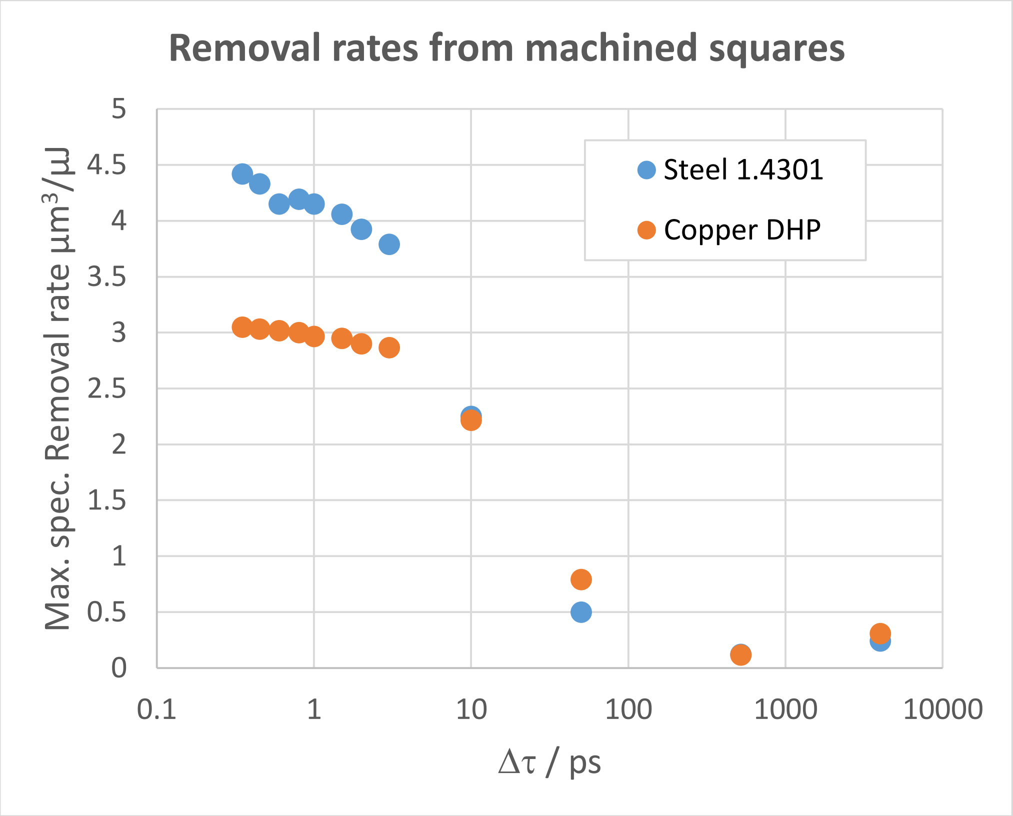


$$\left.\frac{\dot{V}}{P_{av}}\right|_{max} = 0.232\ \frac{mm^3}{min \cdot W} = 3.86\ \frac{\mu m^3}{\mu J}$$

$$\left.\frac{\dot{V}}{P_{av}}\right|_{max} = 0.299\ \frac{mm^3}{min \cdot W} = 4.98\ \frac{\mu m^3}{\mu J}$$

$$\left.\frac{\dot{V}}{P_{av}}\right|_{max} = 0.302\ \frac{mm^3}{min \cdot W} = 5.03\ \frac{\mu m^3}{\mu J}$$

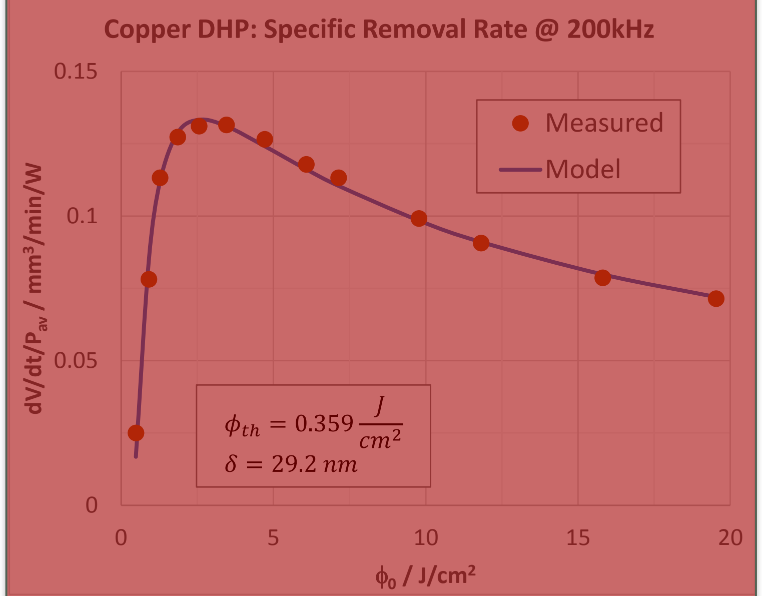
Influence of the Pulse Duration



- Shorter pulses lead to higher spec. removal rates
- Gain depends on the material
- Strong drop between 3ps and 50ps
- Mainly caused by change of energy penetration depth
- Low rates for pulse durations between 50ps and 4ns

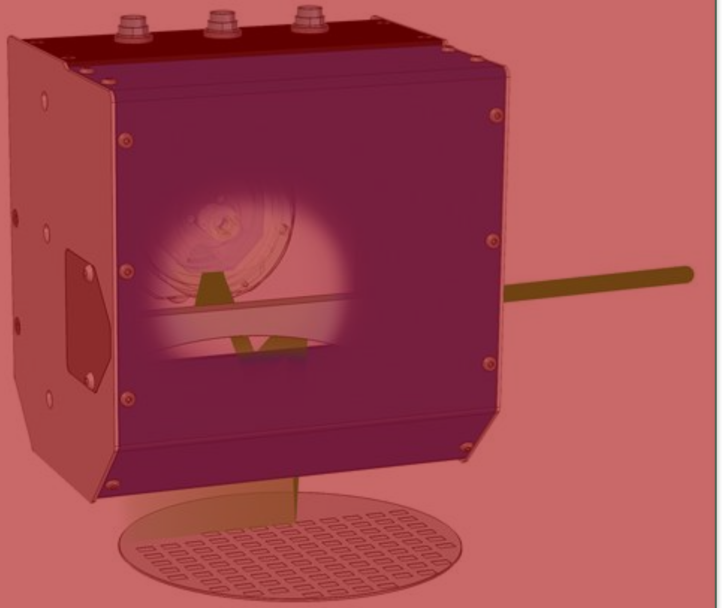
Optimization Tasks

Efficiency:



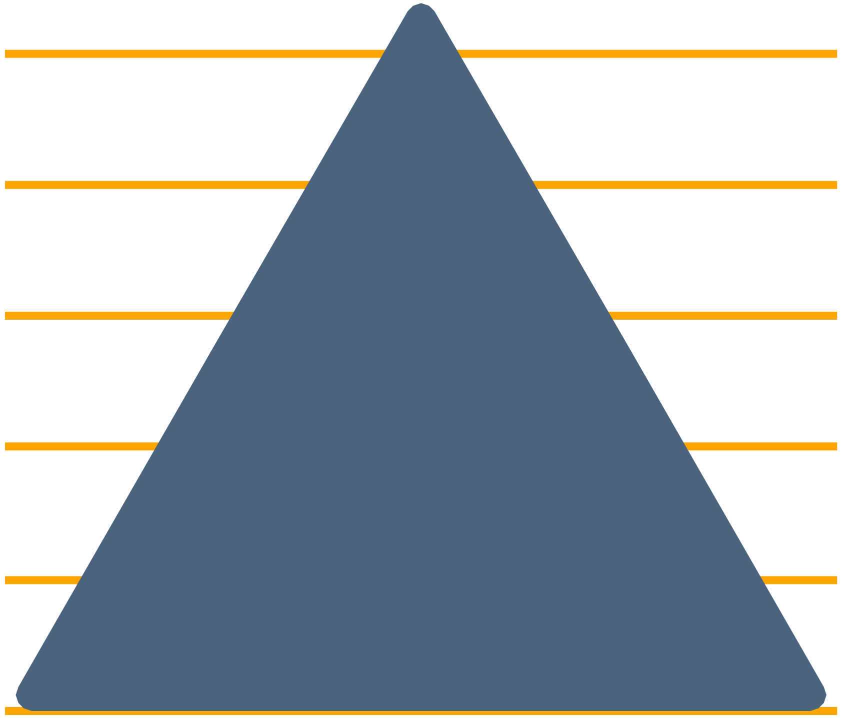
Strategy:

Throughput:

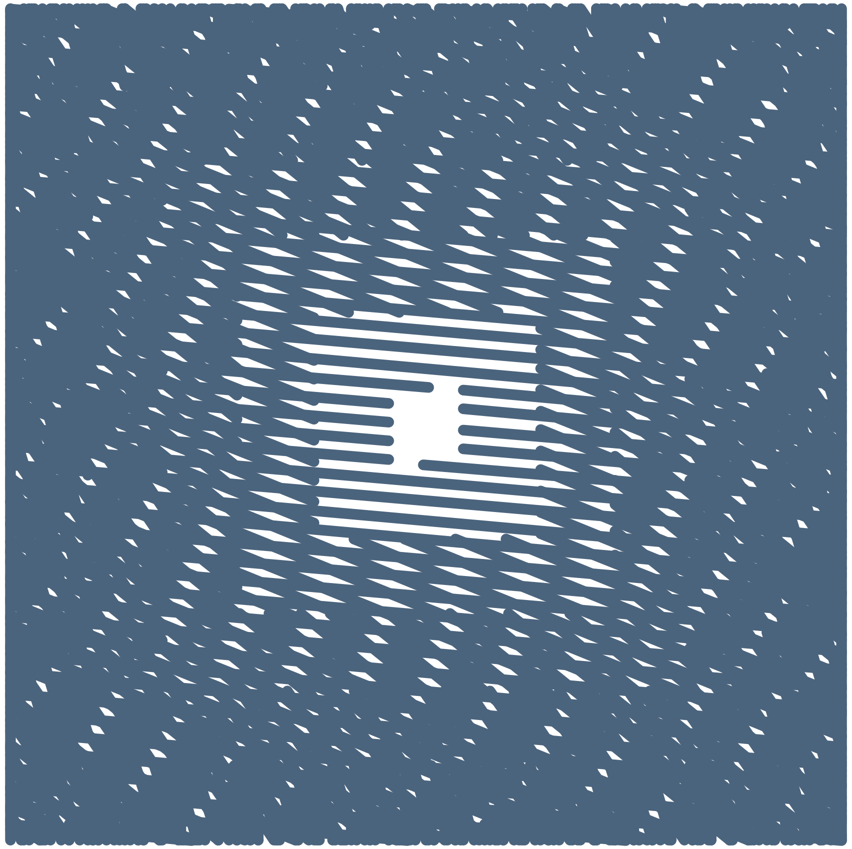


Introduction

Conventional Processing



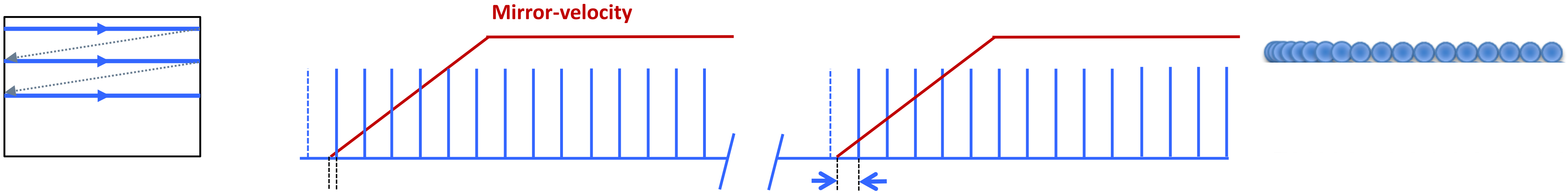
- 2.5D / 3D structure is sliced
- generation of layers
- typical layer thickness 0.1 µm



- Each layer is filled with hatch pattern

Standard Modes

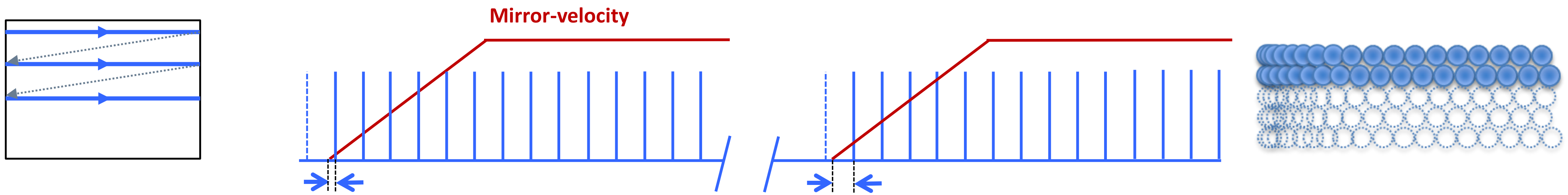
Standard approach, start at the boundary of the structure



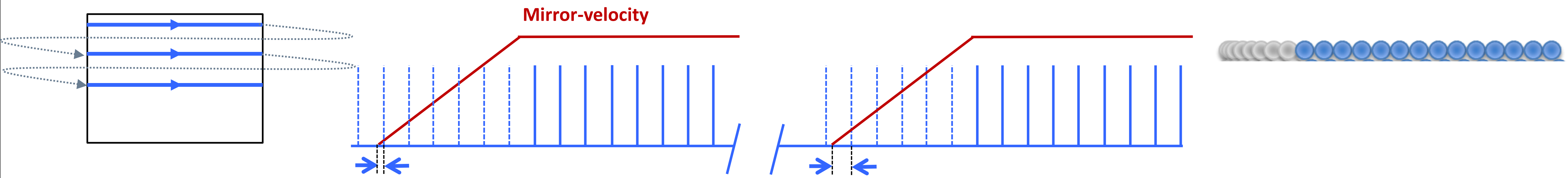
- «Acceleration problem»
- Deep marking at the border
- Well defined border
- Steep walls

Standard Modes

Standard approach, start at the boundary of the structure



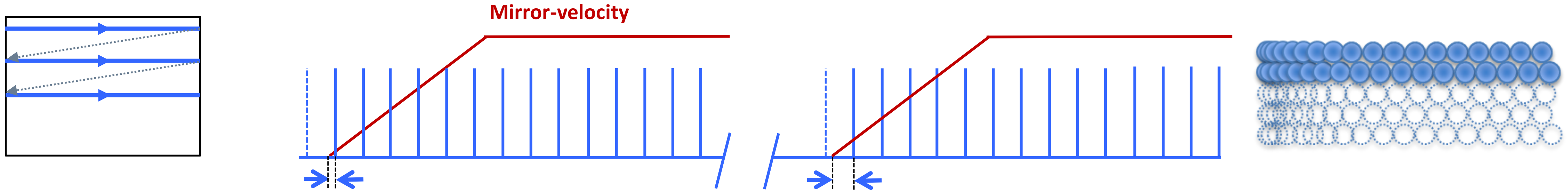
Marking with Skywriting



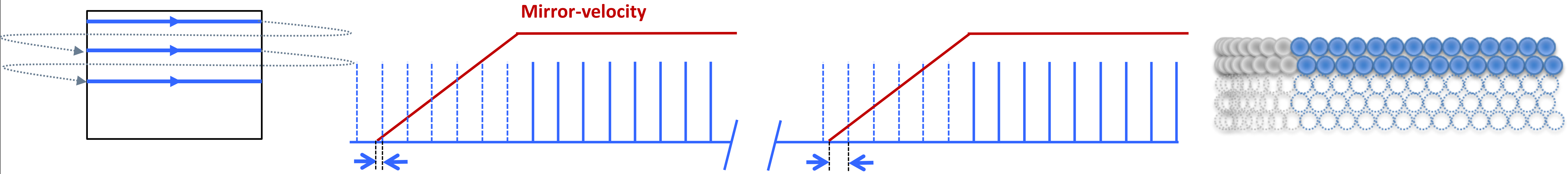
- No deep marking
- Diffuse border
- Less steep walls

Standard Modes

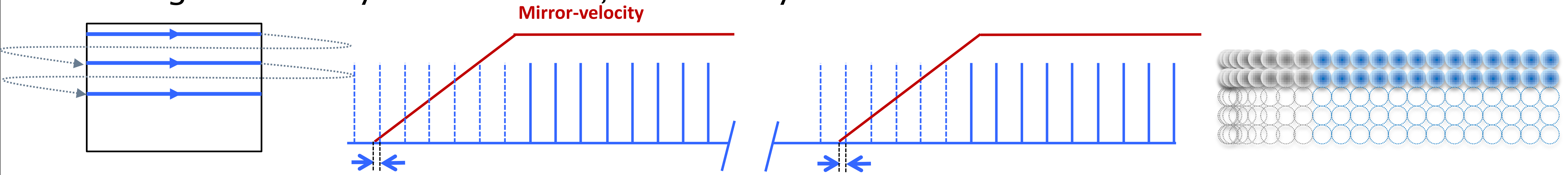
Standard approach, start at the boundary of the structure



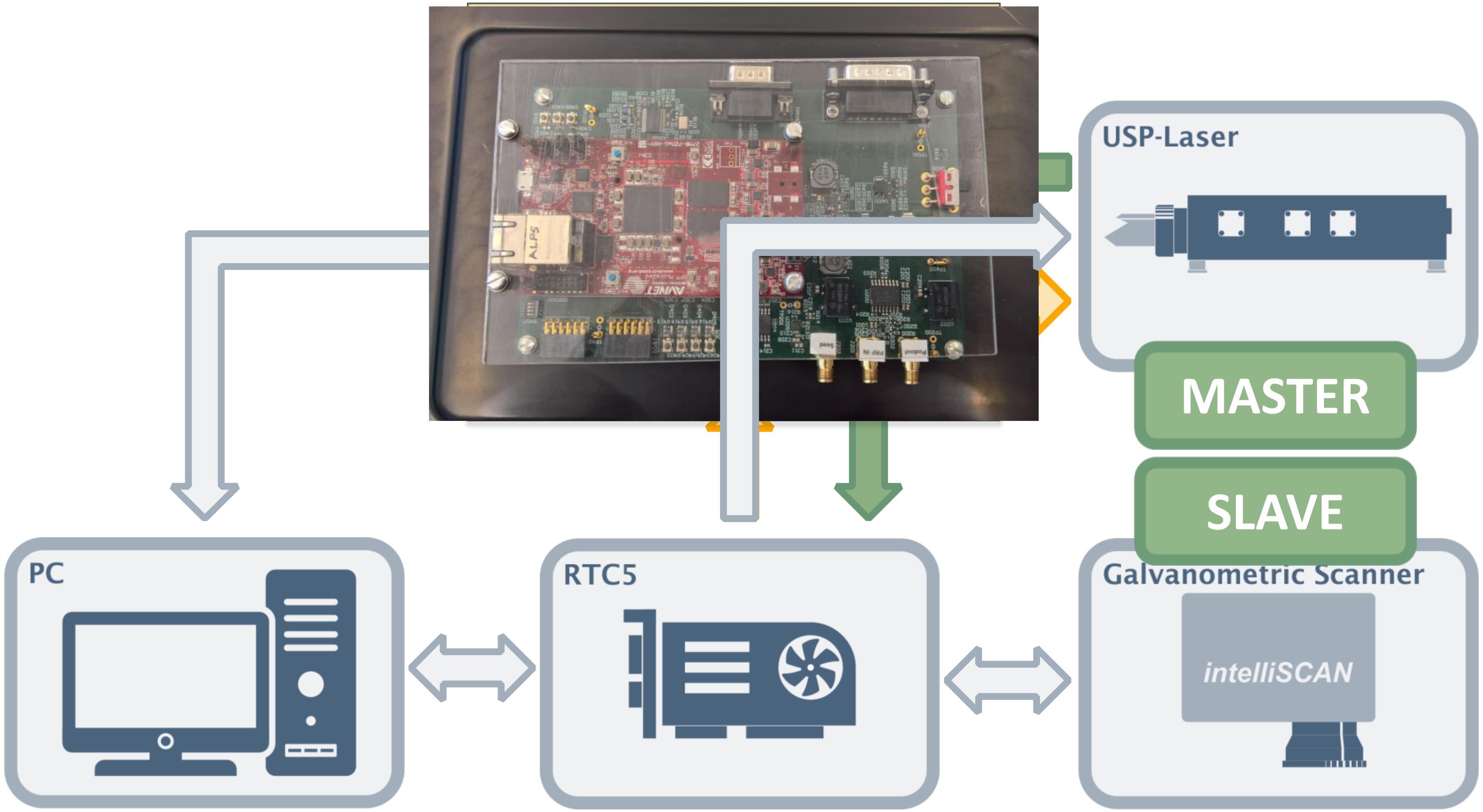
Marking with Skywriting



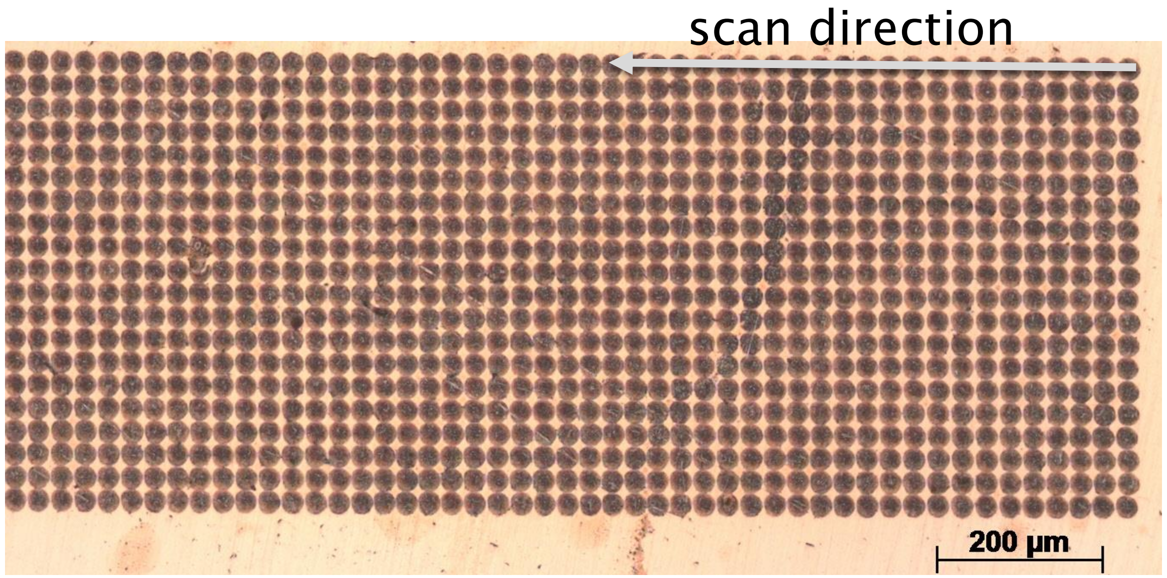
Marking with full Synchronization, start always at the border of the structure

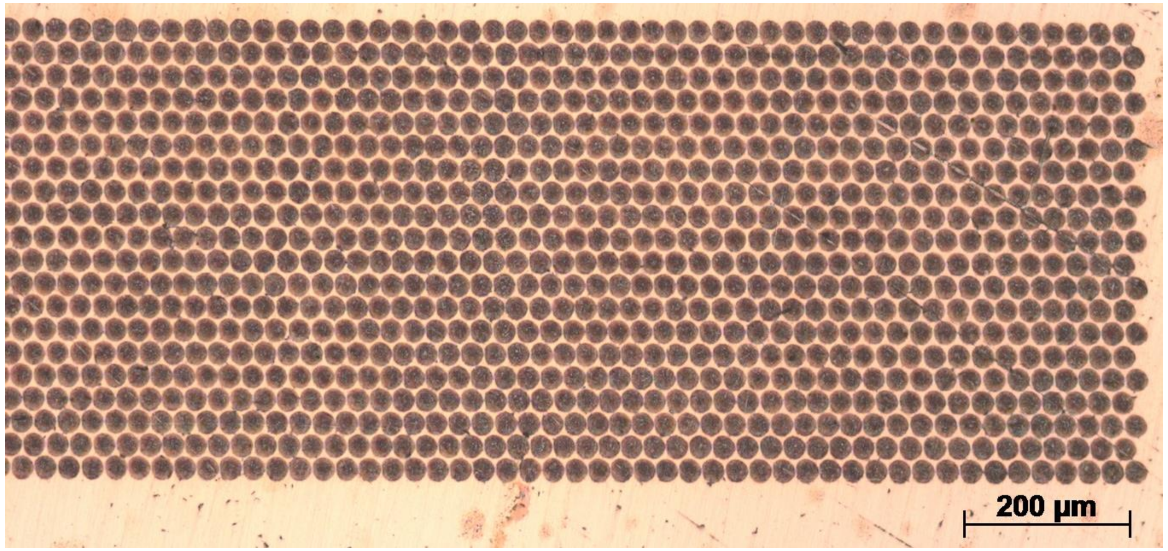


Fully synchronized Galvo-Scanner Set – Up



Fully Synchronized Scanning: Unidirectional Scanning

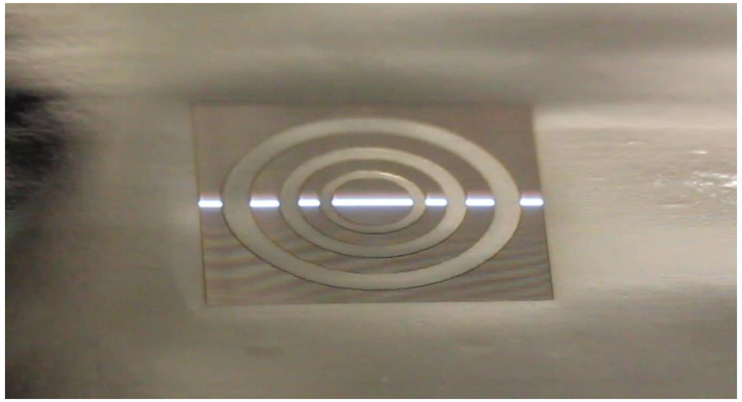




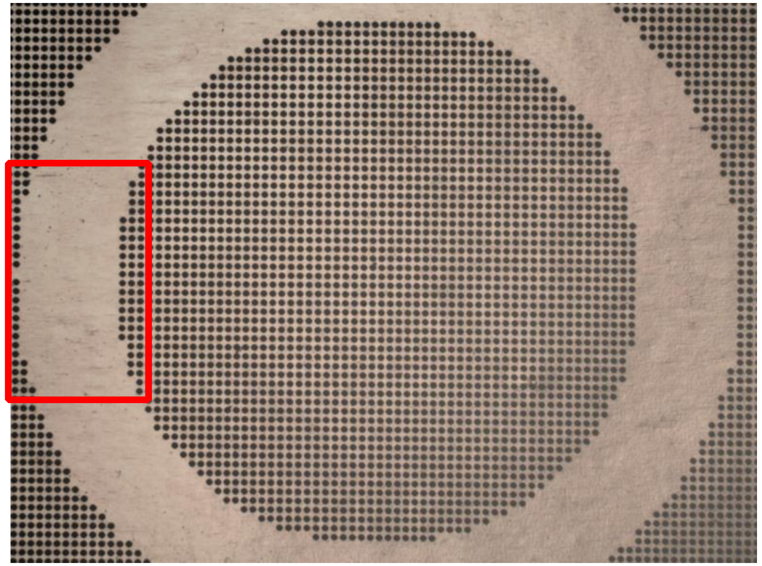
- Equal starting points in x-direction
- Matrix pattern

- Systematic change in x-direction
- Regular pattern
  - e.g. densest sphere packing

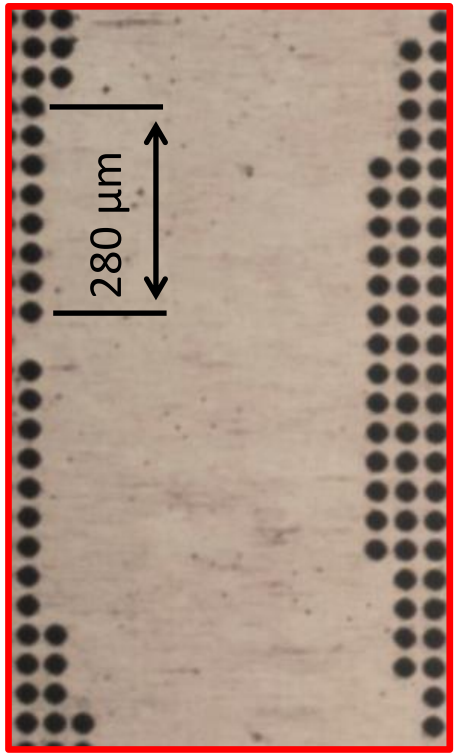
Application 1: Multipulse Drilling on the Fly



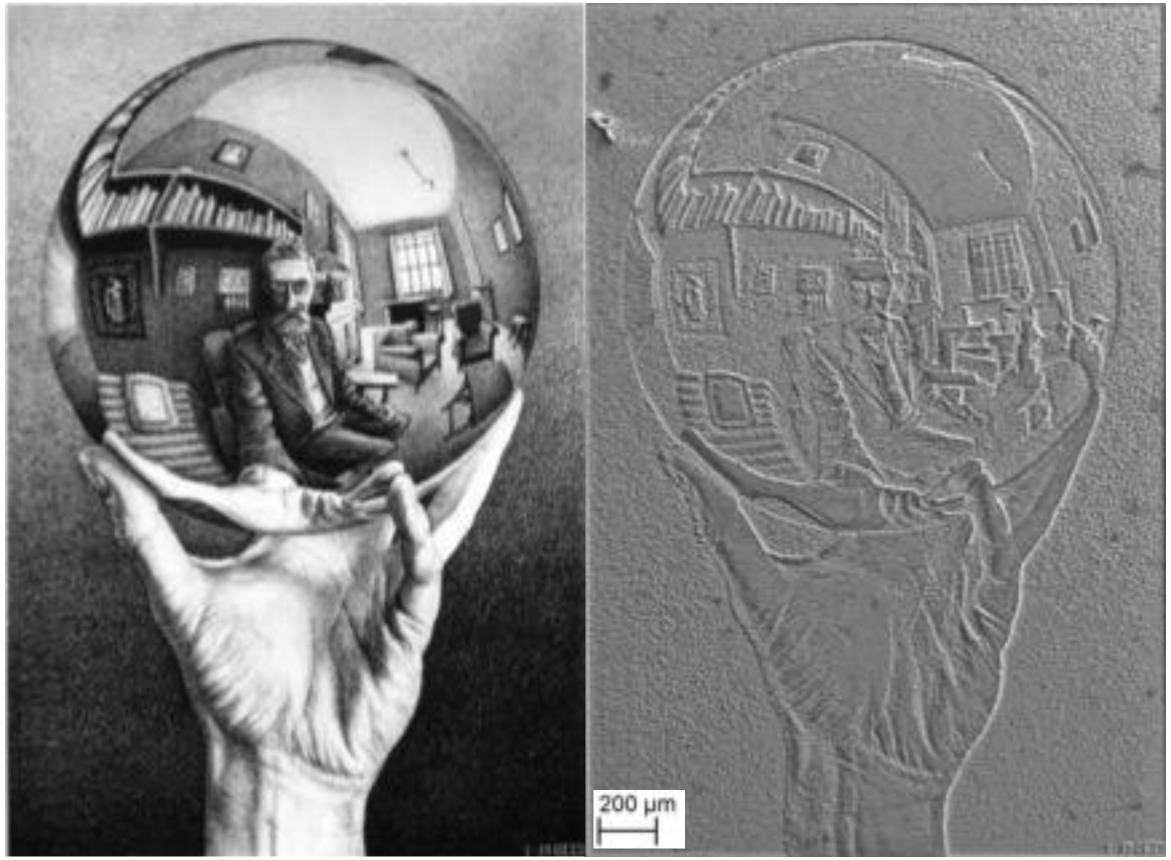
- Repetition rate f_{rep} 0.2 MHz
- Average Power P_{ave} 1.8 W
- Pitch: 40.0 µm
- Scan speed v_{scan} 8.0 m/s
- Picture size 250 x 250 pixel
- Repeats 900



- Each whole corresponds to a pixel with laser on
- No coloring or deformation of the foil due to heat accumulation



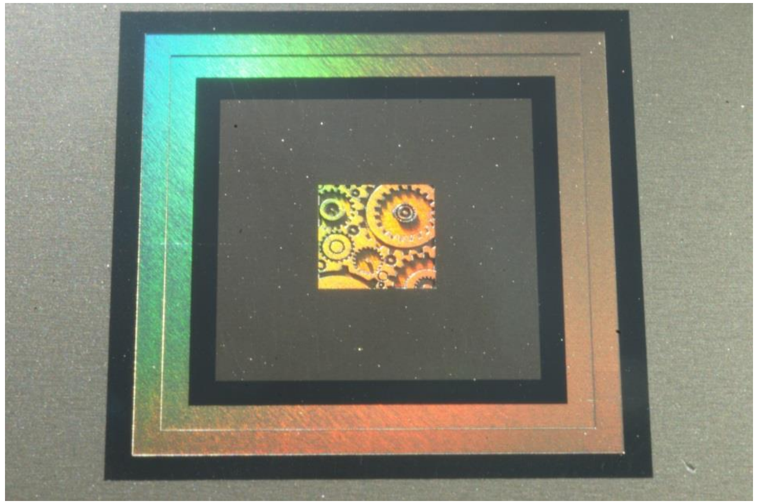
Application 2: Machining of Grey-Scale Bitmaps



http://brettworks.com/2012/04/26/on-the-musicality-of-m-c-escher/

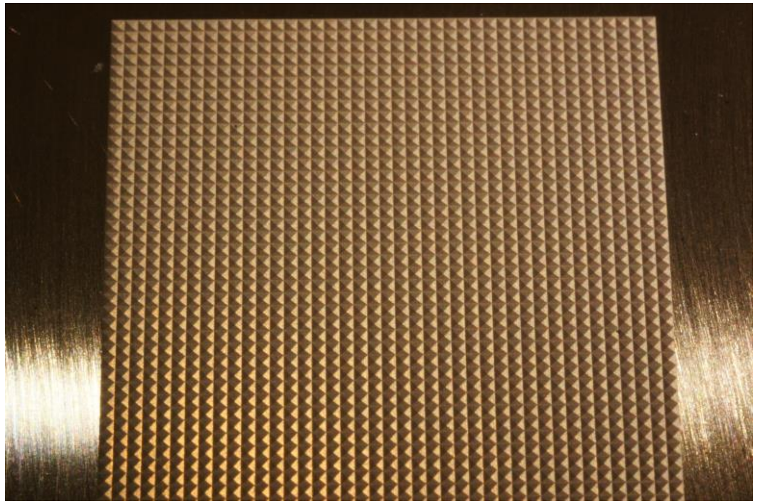
Application 3: 3D Surface Structuring

Structuring of Steel 1.4301



20 mm

Pyramids in Copper

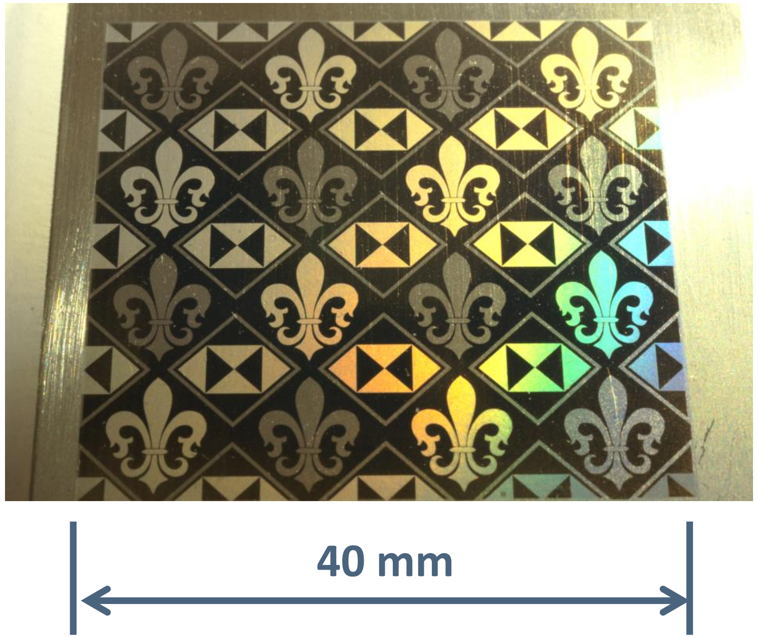


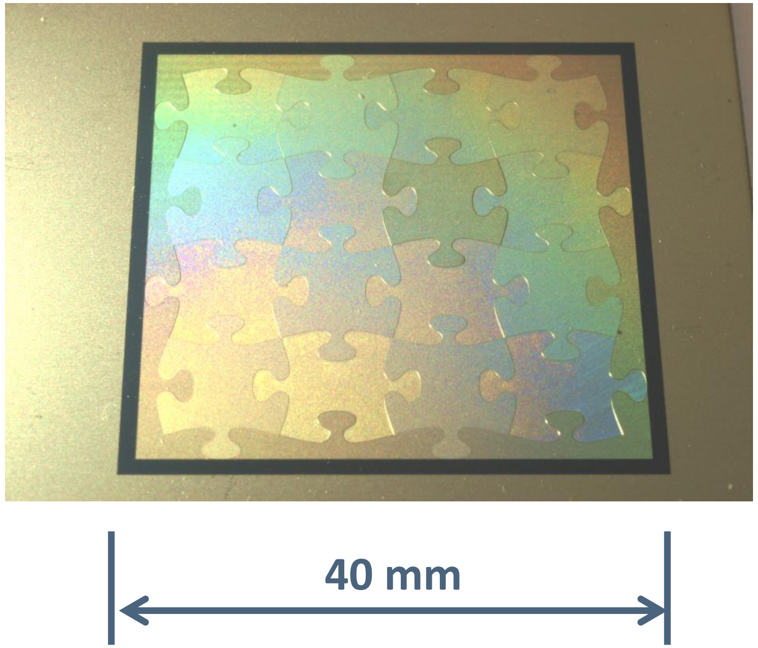
20 mm

Shark Skin Structure in Copper

20 mm

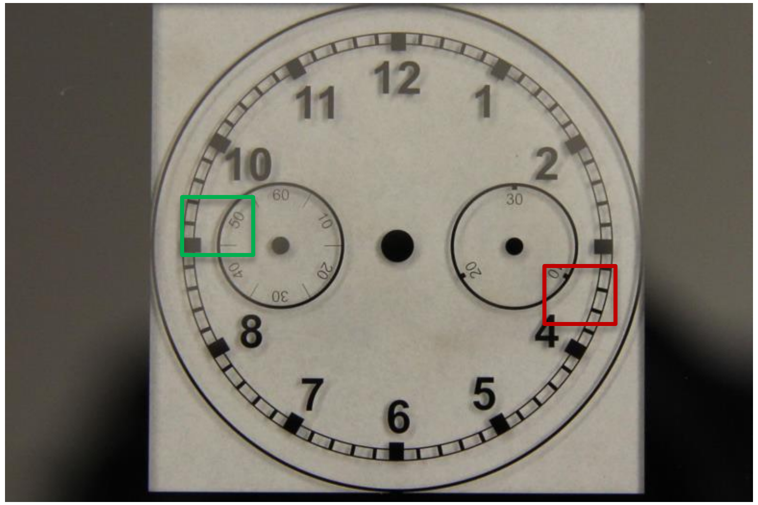
Application 4: Coloring and Polishing





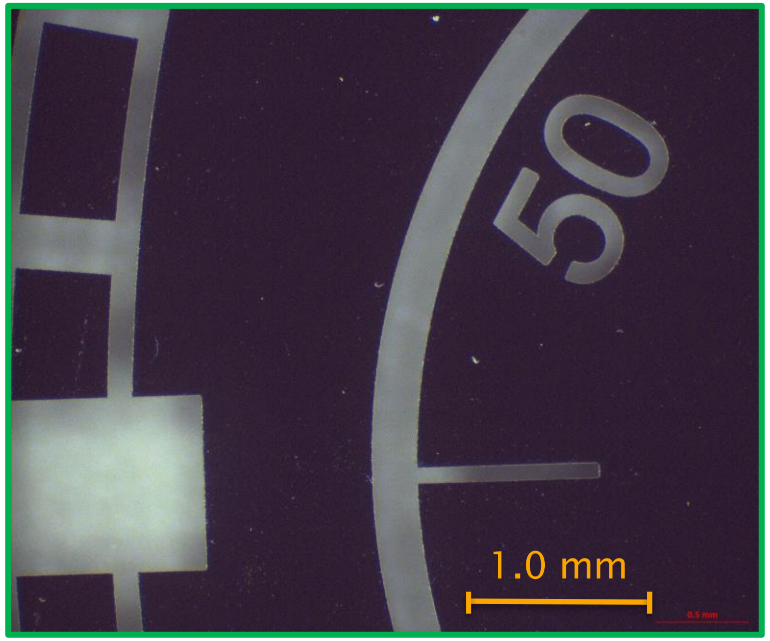
Application 5: De-Coating

Removed Chromium Layer



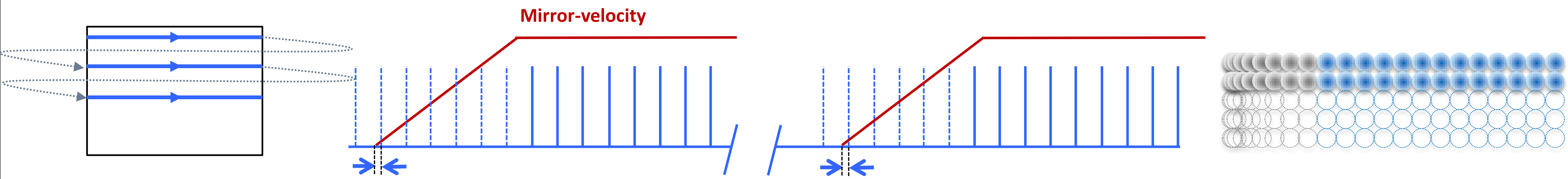
Detail

Detail (negative pattern)



Limits with Galvo Scanner

Marking with full Synchronization, start always at the border of the structure



Todays speed limit given by the galvo scanner

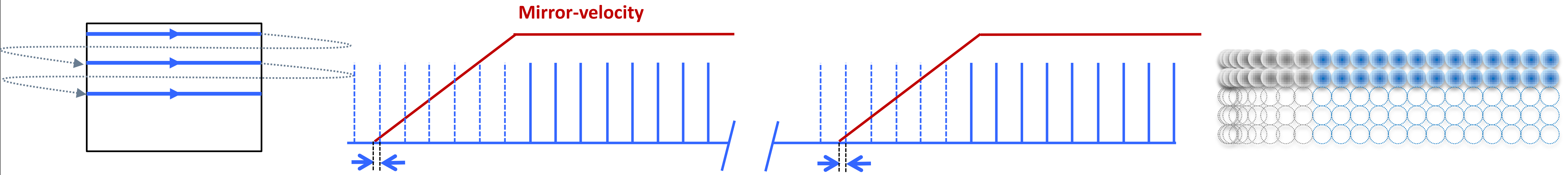
- 60 m/s with $w_0 \approx 35\ \mu m$ (255mm objective)
- 40 m/s with $w_0 \approx 22\ \mu m$ (160mm objective)
- 25 m/s with $w_0 \approx 14\ \mu m$ (100mm objective)

Technical limit, hard to improve

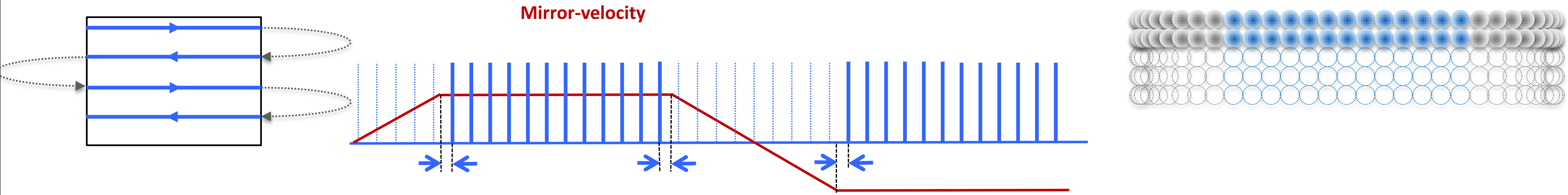
Optimum speed also depends on the line length

Future Steps

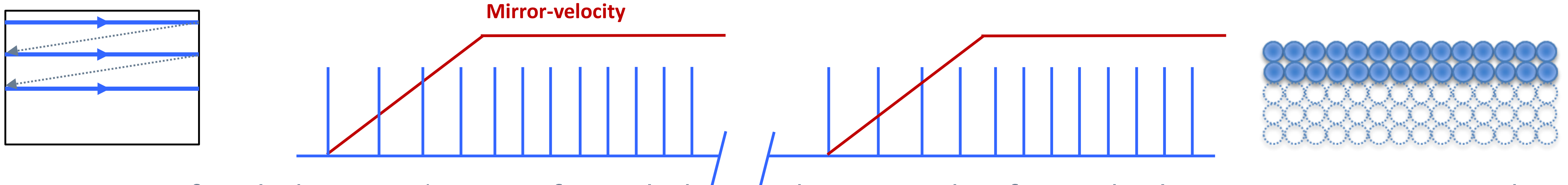
Marking with full Synchronization, start always at the border of the structure



Bidirectional marking (twice as fast), already realized

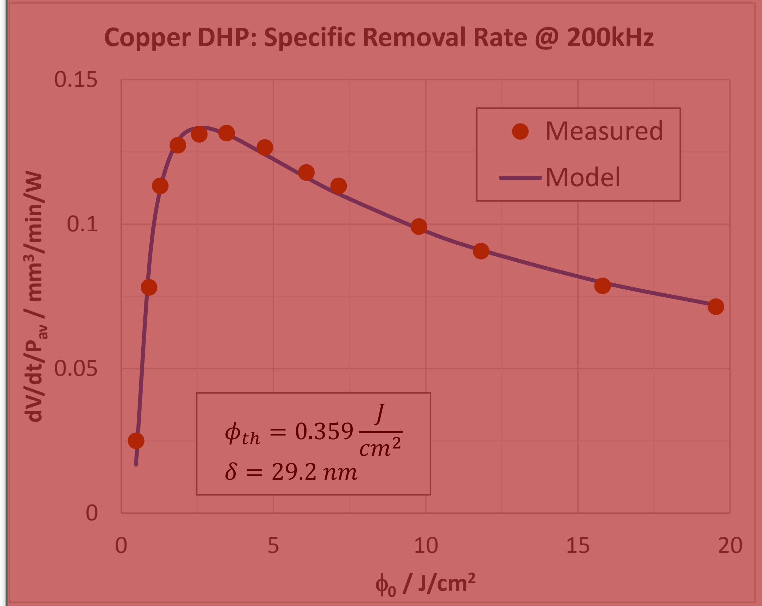


Speed-dependent laser control, starting at the edge of the geometry (gain max. 30%)



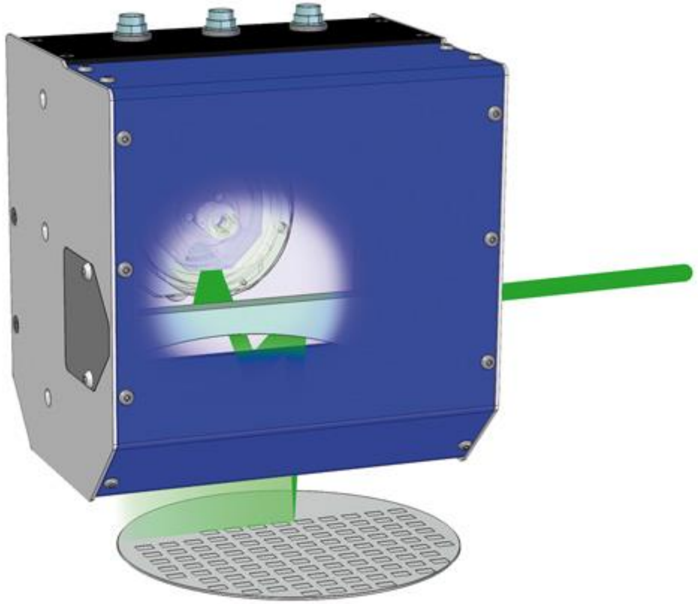
Optimization Tasks

Efficiency:



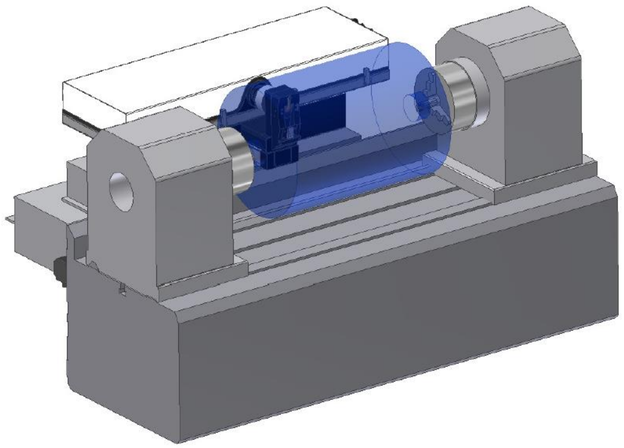
Strategy:

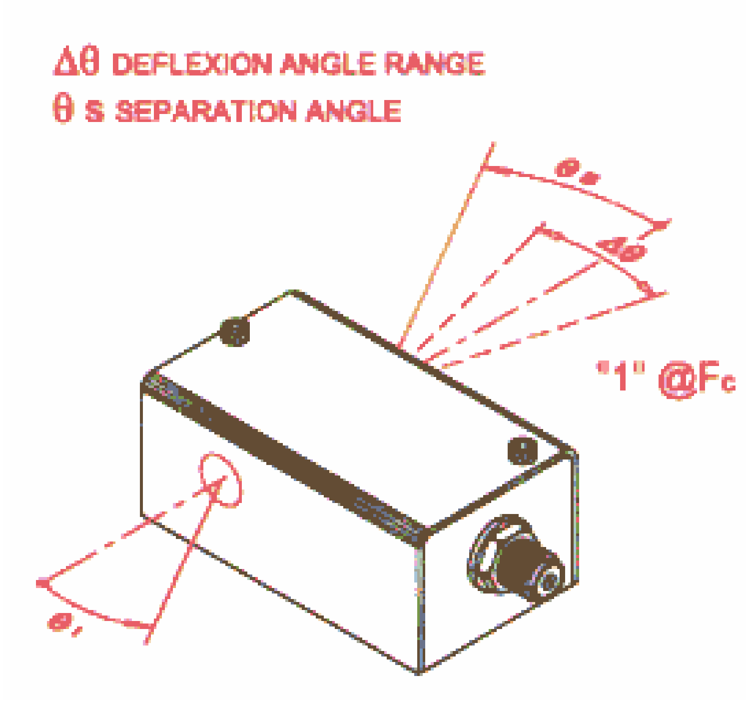
Throughput:

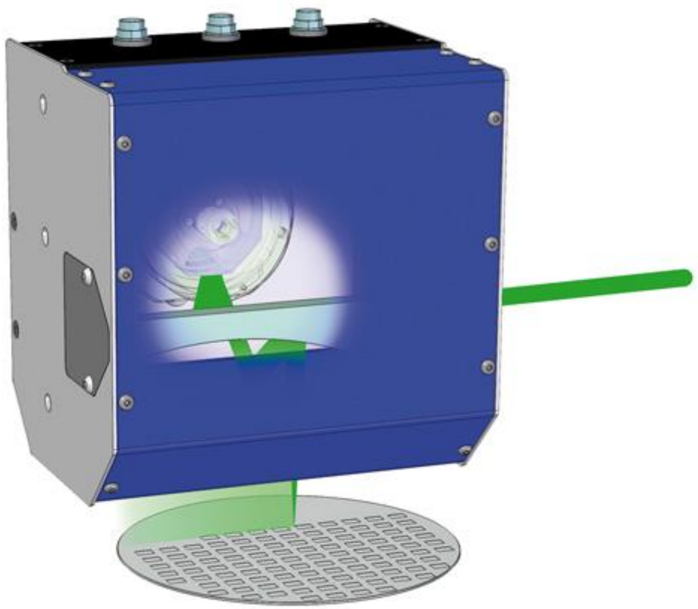


Scale-Up: Technologies

- Fast Rotating Cylinders
- AO- or EO- Deflectors
- Polygon Line Scanner



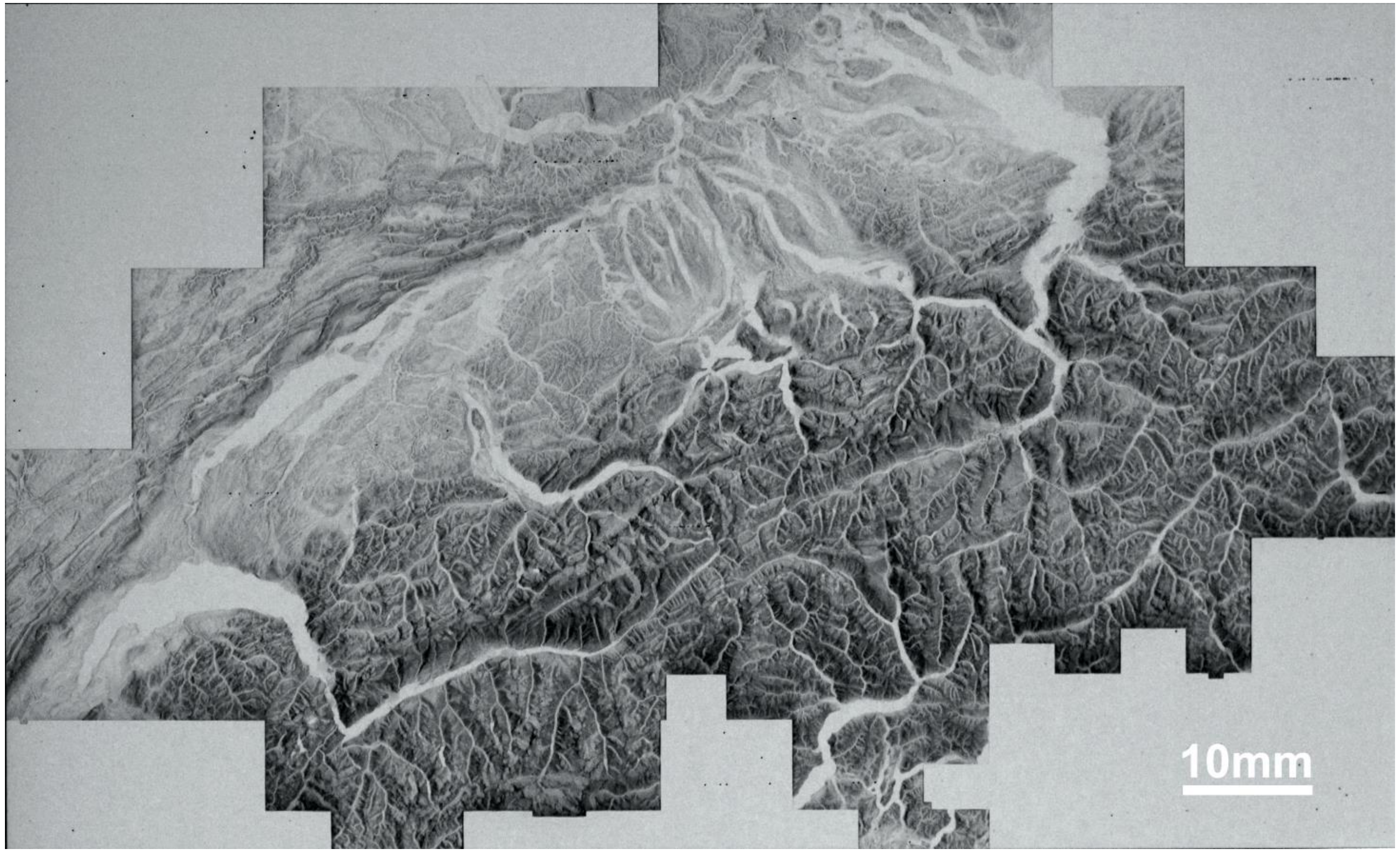




[3] S. Brüning, G.Hennig, S. Eiffel, A.Gillner ; Proc. LIM 2011, Physics Procedia, Elsevier (2011)

[4] B. Jäggi et al., "High Throughput and High Precision Laser micromachining with ps-Pulses in Synchronized Mode with a fast Polygon Line Scanner", SPIE 8967-25 (2014)

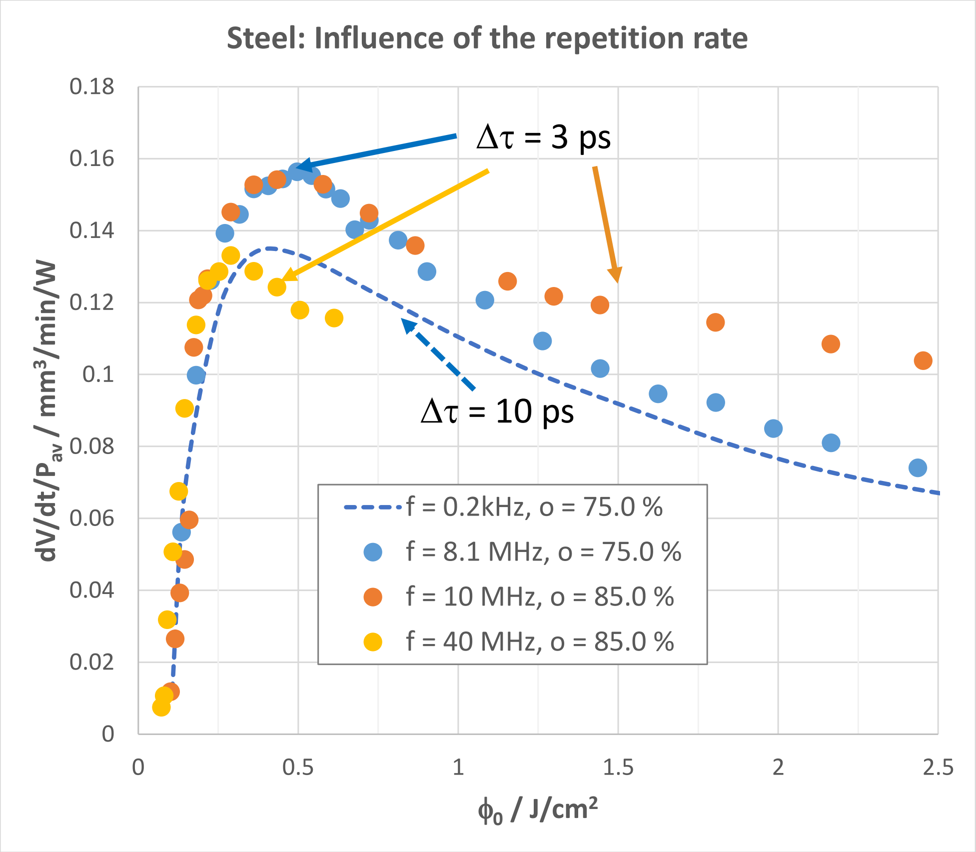
Polygon: Line Scanner for Scale-Up of Steel 1.4301



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

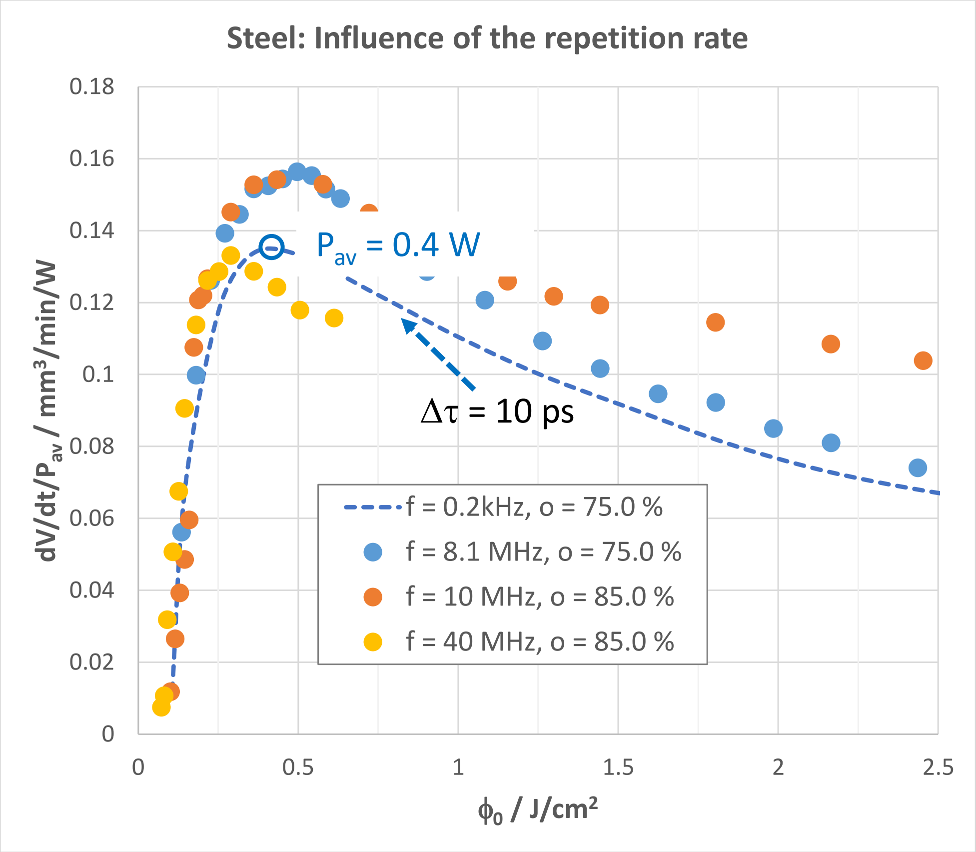
- **Is a further scale up above the 100W regime possible?**

Steel: Influence of the Repetition Rate

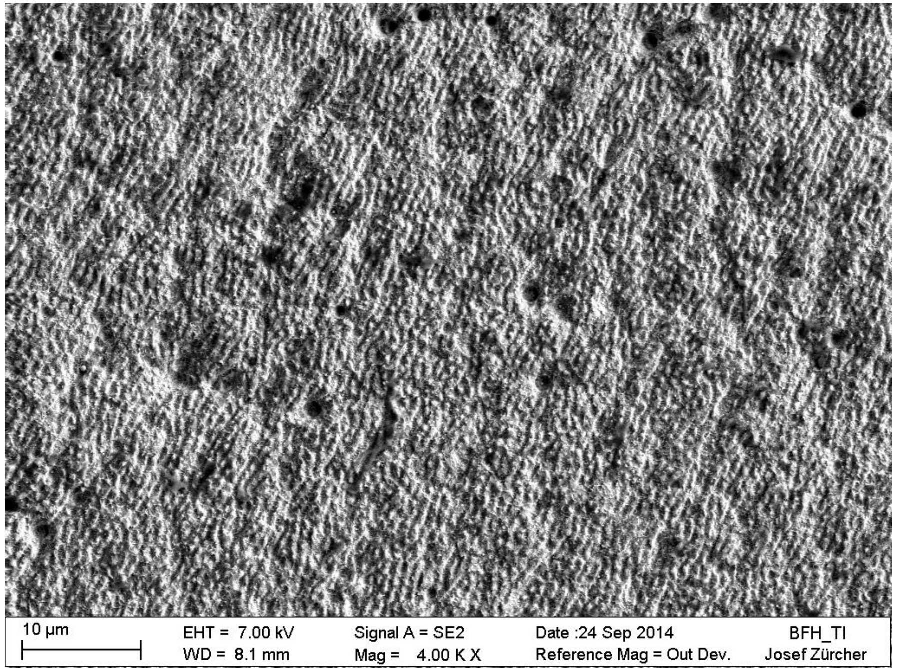


- Equal for f = 8.1MHz and 10MHz (shorter pulses -> higher rates)
- Drop of about 15% for 40MHz

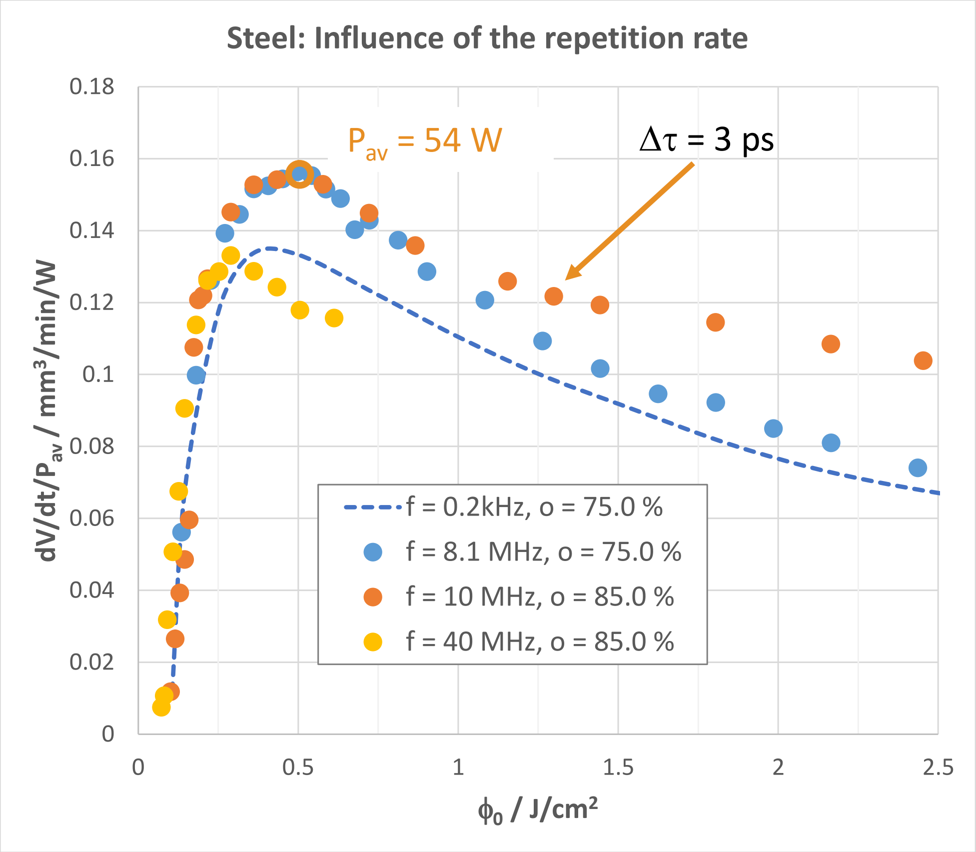
Steel: Influence of the Repetition Rate



- Equal for f = 8.1MHz and 10MHz (shorter pulses -> higher rates)
- Drop of about 15% for 40MHz
- Smooth surface, good quality

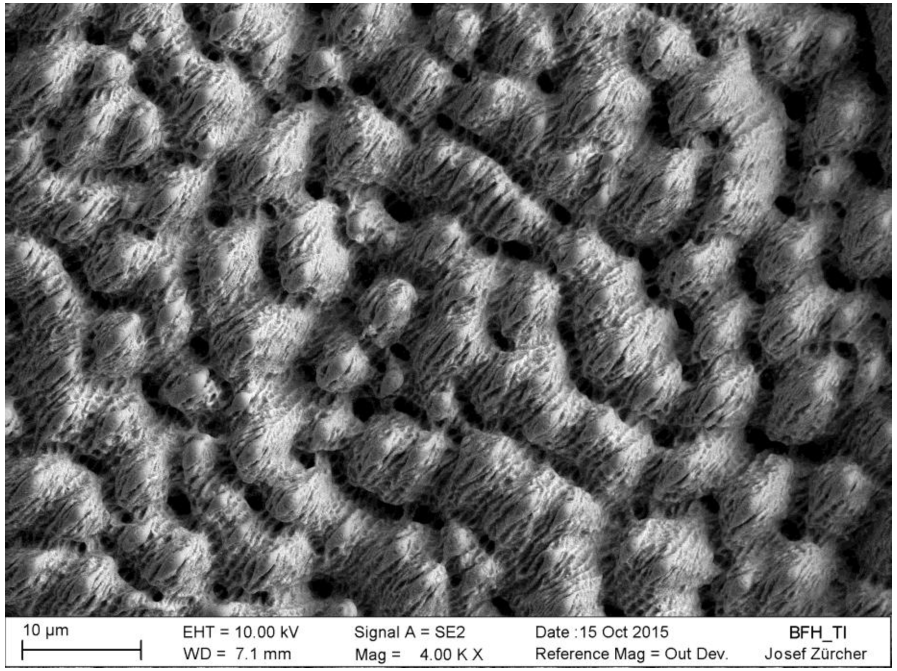


Steel: Influence of the Repetition Rate

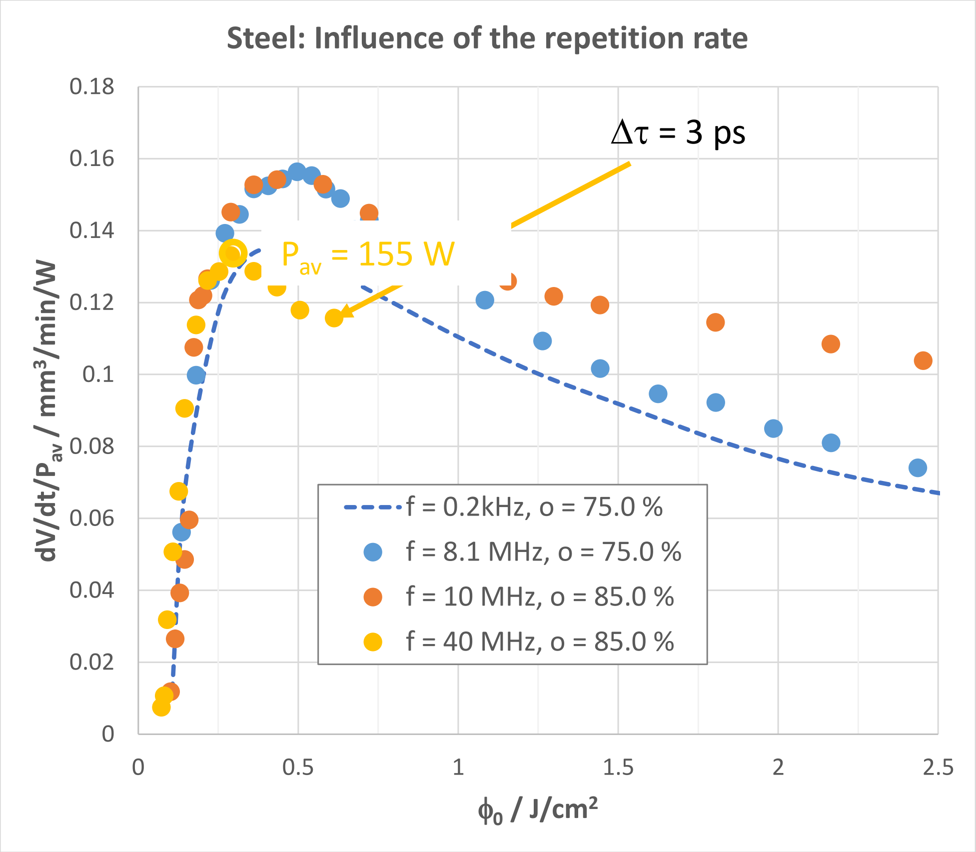


- Equal for f = 8.1MHz and 10MHz (shorter pulses -> higher rates)
- Drop of about 15% for 40MHz

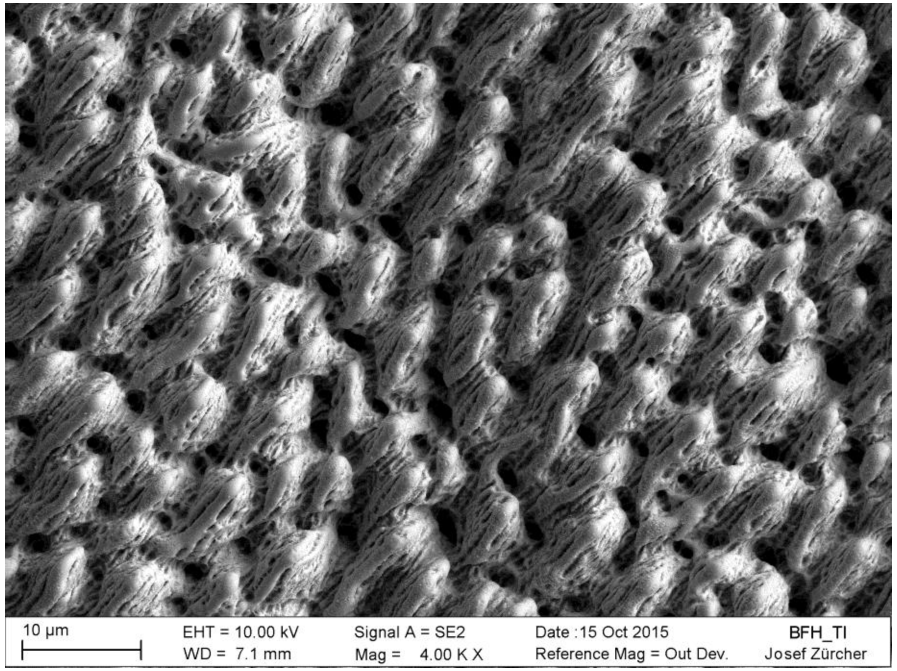
- Bumpy surface for f = 10MHz



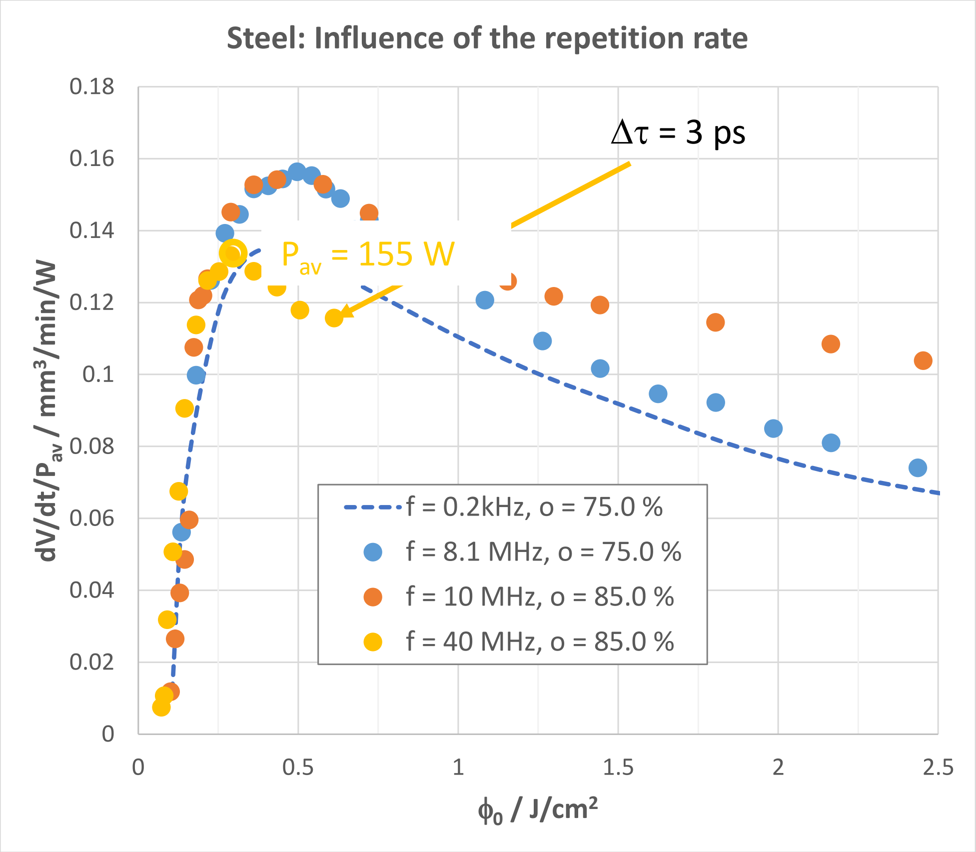
Steel: Influence of the Repetition Rate



- Equal for f = 8.1MHz and 10MHz (shorter pulses -> higher rates)
- Drop of about 15% for 40MHz
- More pronounced for f = 40MHz



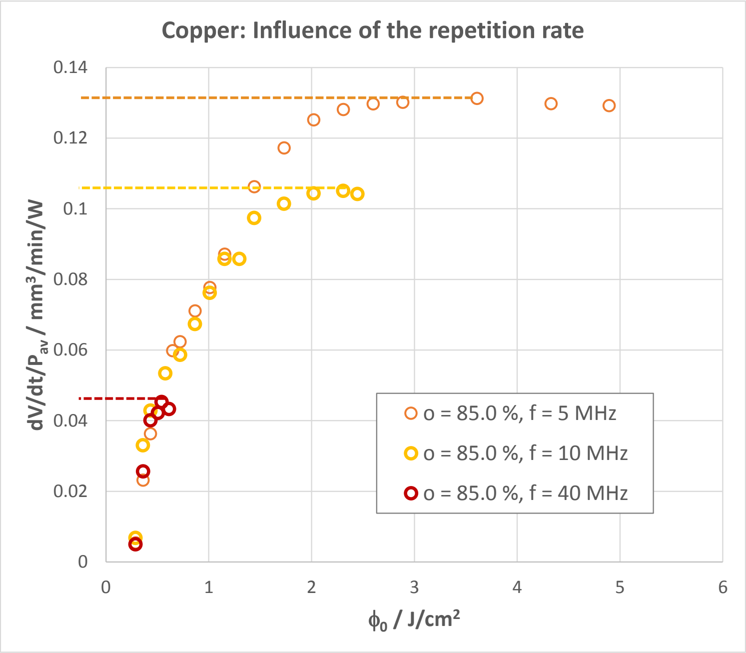
Steel: Influence of the Repetition Rate



- Equal for f = 8.1MHz and 10MHz (shorter pulses -> higher rates)
- Drop of about 15% for 40MHz
- More pronounced for f = 40MHz
- Bumpy surface are caused by heat accumulation [5]

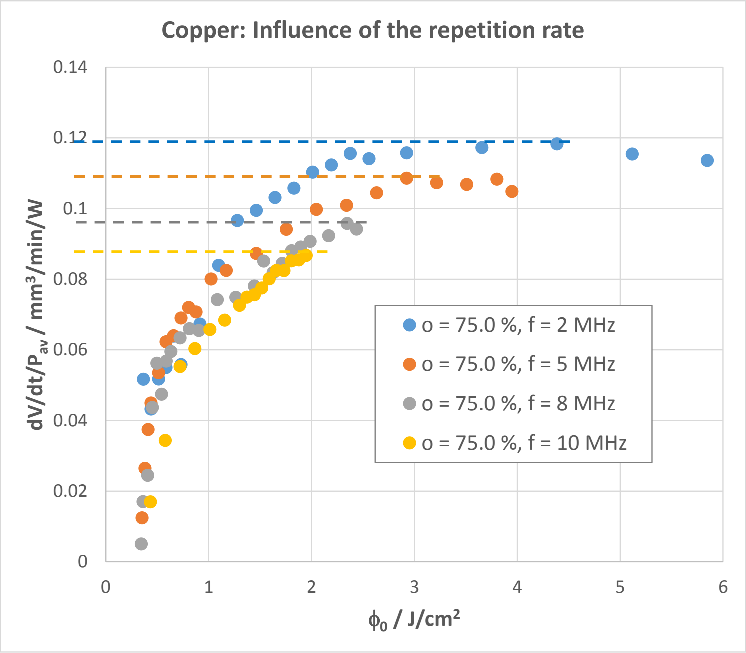
[5] F. Bauer et al., " Heat accumulation in ultra-short pulsed laser processing of metals", Opt. Expr., 23, 1035 – 1043 (2015)

Copper and Brass: Influence of the Repetition Rate

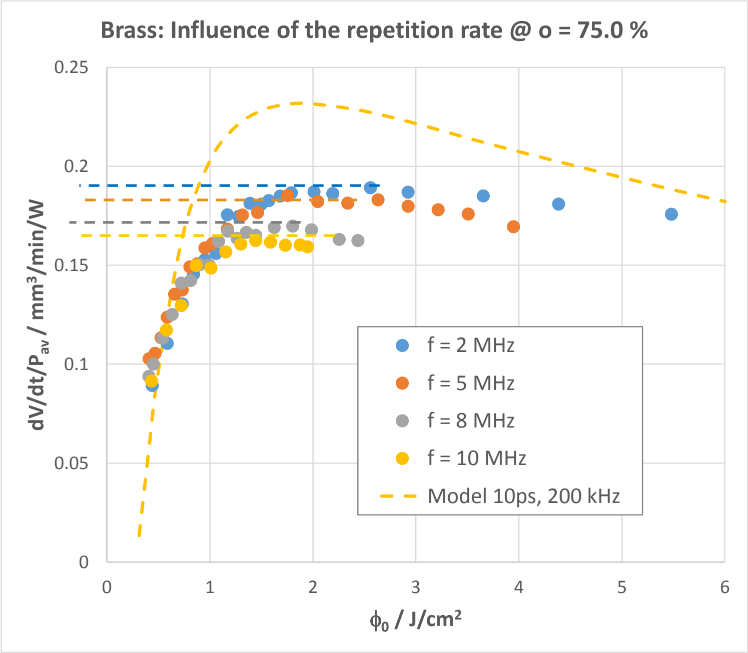


- For a fixed overlap a strong decrease of the specific removal rate is observed for higher repetition rates

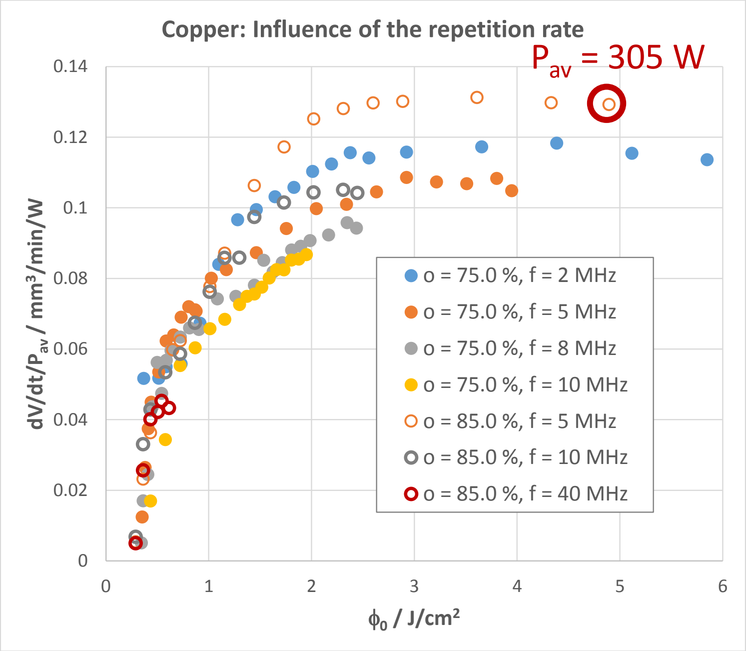
Copper and Brass: Influence of the Repetition Rate



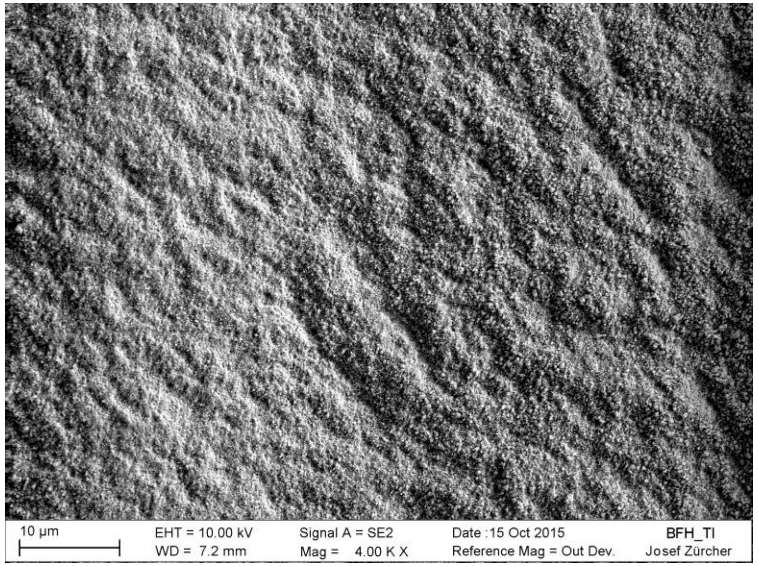
- For a fixed overlap a strong decrease of the specific removal rate is observed for higher repetition rates
- Drop already from 2 MHz
- Similar behavior for brass
- Particle/Plasma Shielding



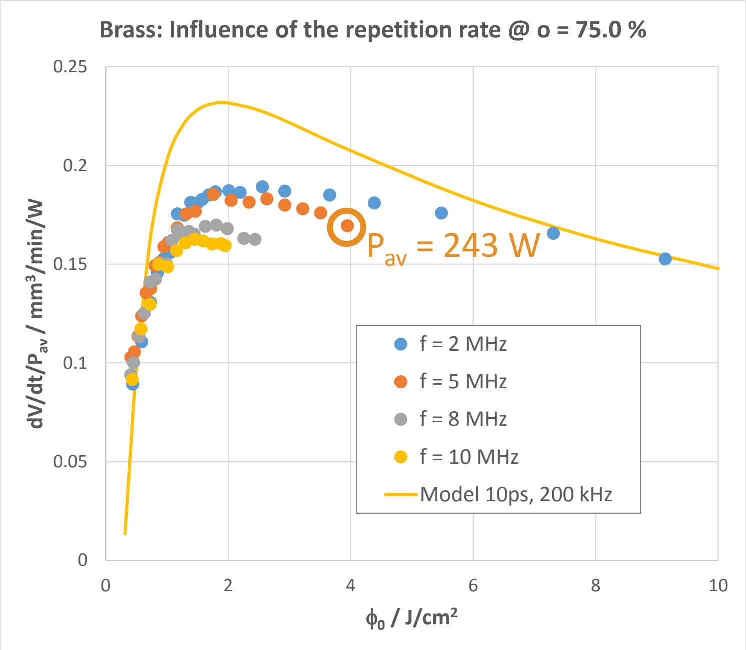
Copper and Brass: Surface Quality at high Average Powers



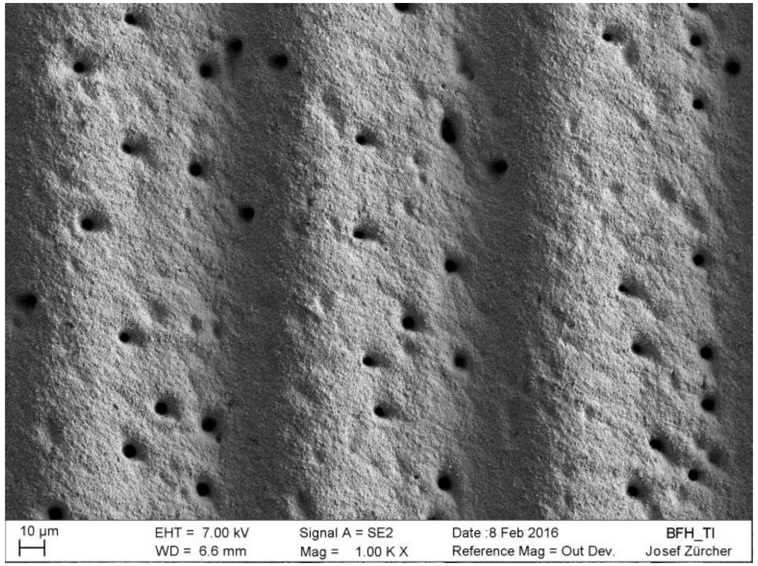
- Copper @ 5 MHz
  - Quite good surface quality at highest peak fluence
  - $\frac{dV}{dt} \approx 40\,\frac{mm^3}{min}$



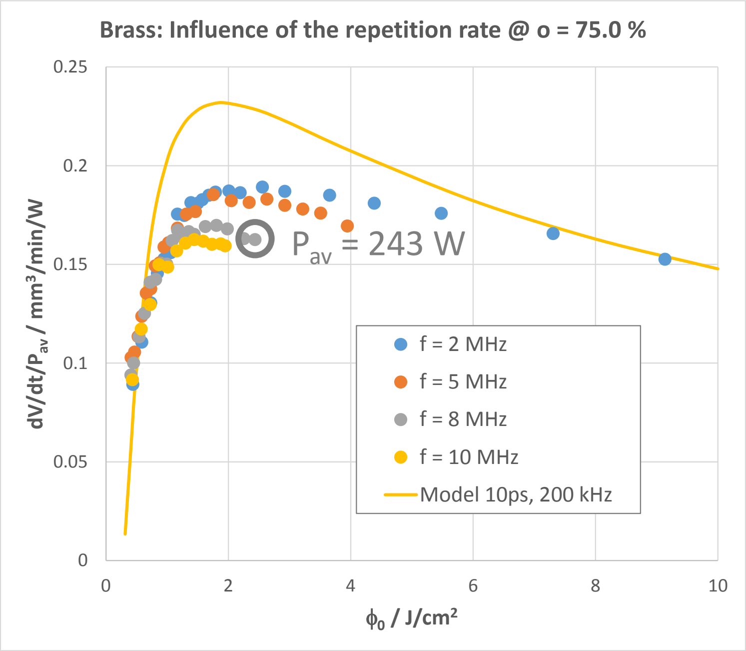
Copper and Brass: Surface Quality at high Average Powers



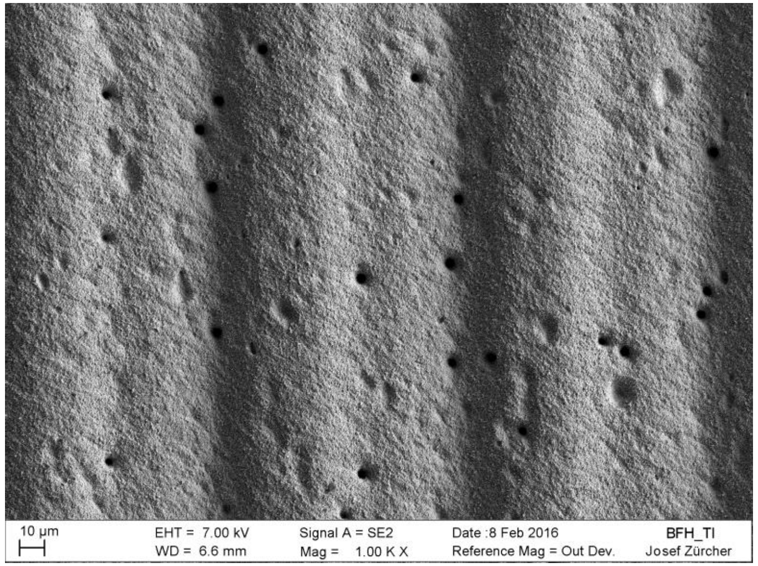
- Copper @ 5 MHz
  - Quite good surface quality at highest peak fluence
  - $\frac{dV}{dt} \approx 40 \frac{mm^3}{min}$
- Brass @ 5 MHz:
  - Good Surface Quality
  - $\frac{dV}{dt} \approx 41 \frac{mm^3}{min}$
  - Cavities due to lead inclusions?



Copper and Brass: Surface Quality at high Average Powers



- Copper @ 5 MHz
  - Quite good surface quality at highest peak fluence
  - $\frac{dV}{dt} \approx 40 \frac{mm^3}{min}$
- Brass @ 5 MHz:
  - Good Surface Quality
  - $\frac{dV}{dt} \approx 41 \frac{mm^3}{min}$
  - Cavities due to lead inclusions?
- Brass @ 10 MHz:
  - Surface quality improved
  - $\frac{dV}{dt} \approx 40 \frac{mm^3}{min}$



Conclusion / Outlook

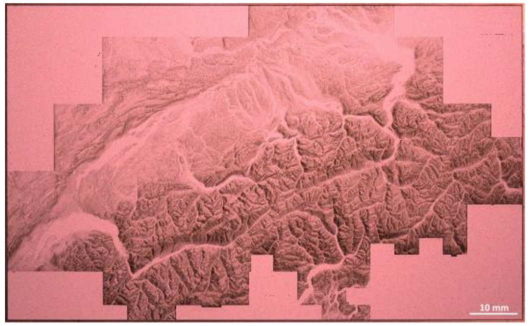
- Metals show an optimum fluence going with highest efficiency i.e. spec. removal rate
- Its value depends on the pulse duration. In general shorter pulses are advantageous

- Synchronization is a key factor for precise and fast micromachining
- Marking speeds up to 40m/s with high end galvo scanner by maintaining the high precision demonstrated

- Power scale – up into the 300 W regime was demonstrated
  - Heat accumulation represents a serious issue for steel
  - Shielding appears even for "low" repetition rates of 2MHz
  - Both effects can be reduced by higher marking speed
  - Copper / brass could be machined with good surface quality and removal rates of about $40mm^3/min$

Conclusion / Outlook

Steel 50W



Copper 300W

(√)

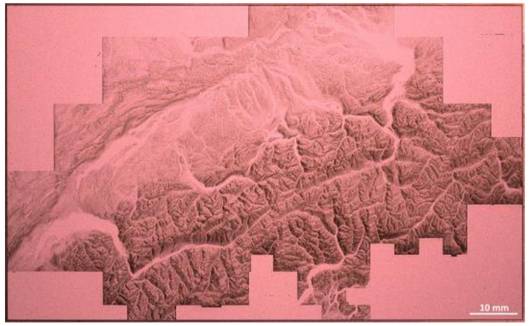
Steel 300W

(×)

v_{mark} > 1000 m/s, f_{rep} > 20 MHz, synchronized ???

Conclusion / Outlook

Steel 50W



Copper 300W

(√)

Steel 300W

(×)

New strategies needed and under development

Acknowledgement

- Special Thanks to Stefan Barcikowsi and his group from University Duisburg Essen for giving us the opportunity to work with their high power laser system

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Thank You for Your Attention