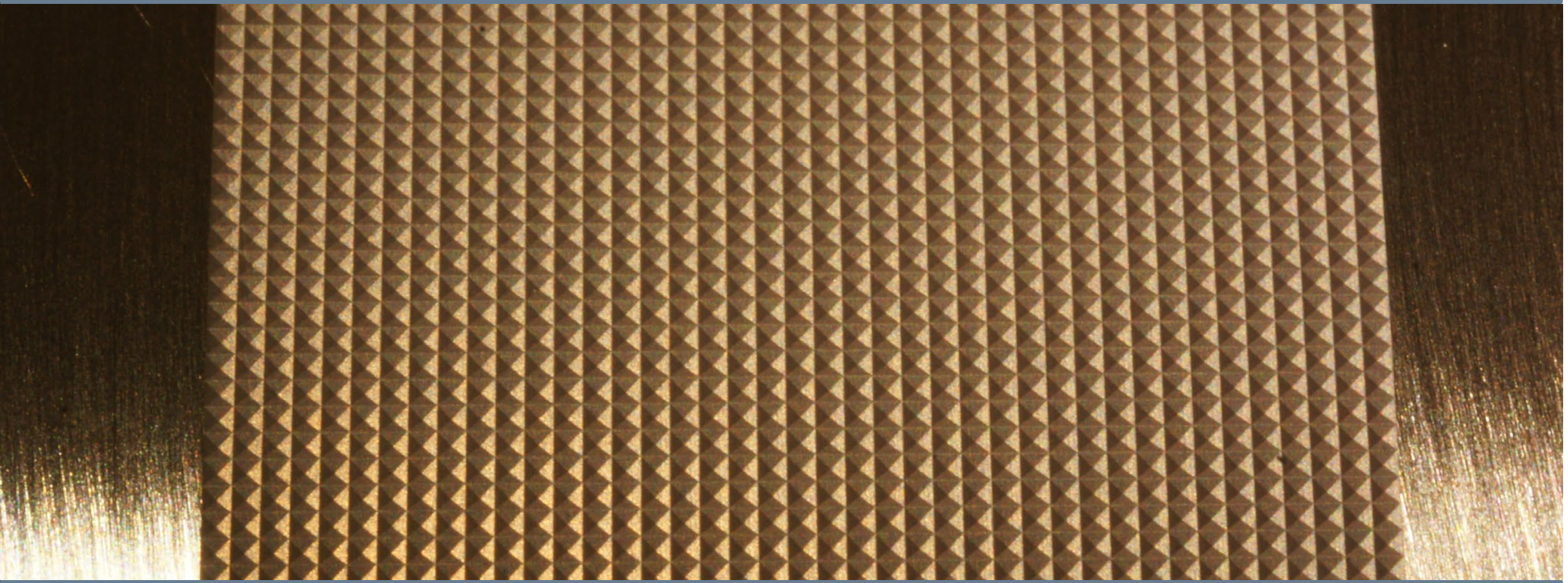
Berner Fachhochschule
Haute école spécialisée bernoise
Bern University of Applied Sciences



Entwicklungen und Trends in der Laser-Mikrobearbeitung

T. Kramer, S. Remund, B. Jäggi, M. Chaja, M. Muralt, Y. Zhang, B. Lauer,
M. Gafner, D. Zwygart, M. Schmid, T. Mähne, B. Neuenschwander

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

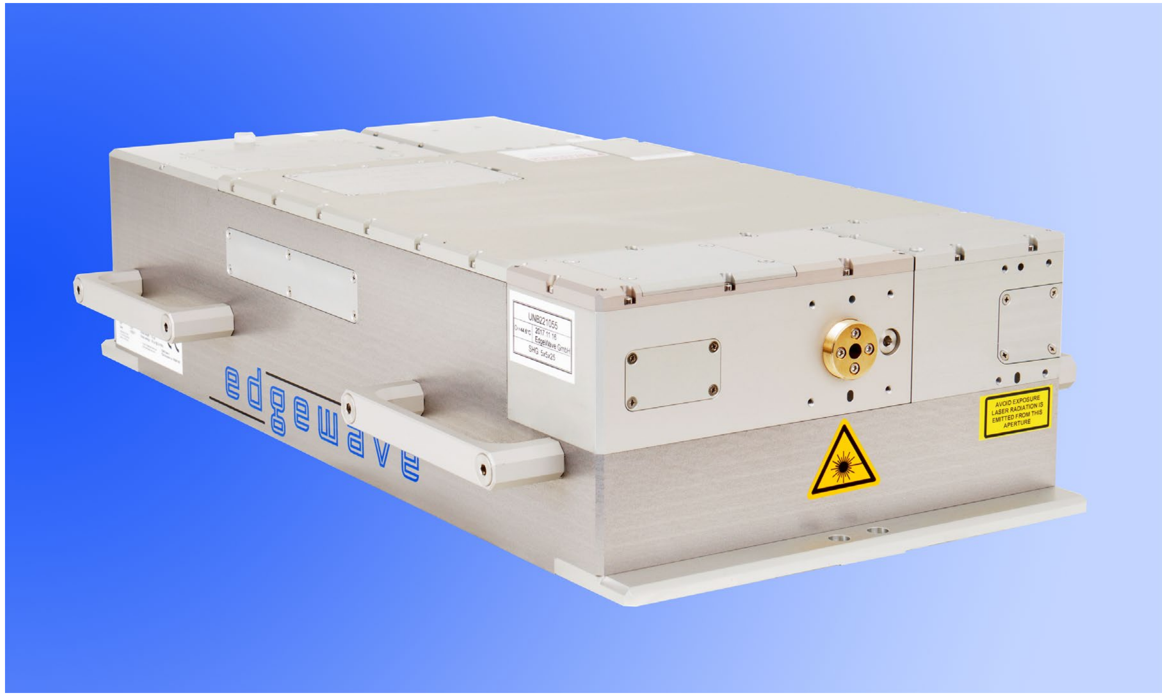
Lasers available

- Tangor
  - $P_{av} > 100W$
  - $E_p > 500\ \mu J$
  - $\Delta\tau < 500\ fs$

Lasers available

- 5080 Femto Edition
  - $P_{av} = 120W$
  - $E_p = 125\ \mu J$
  - $\Delta\tau = 900\ fs$

Lasers available

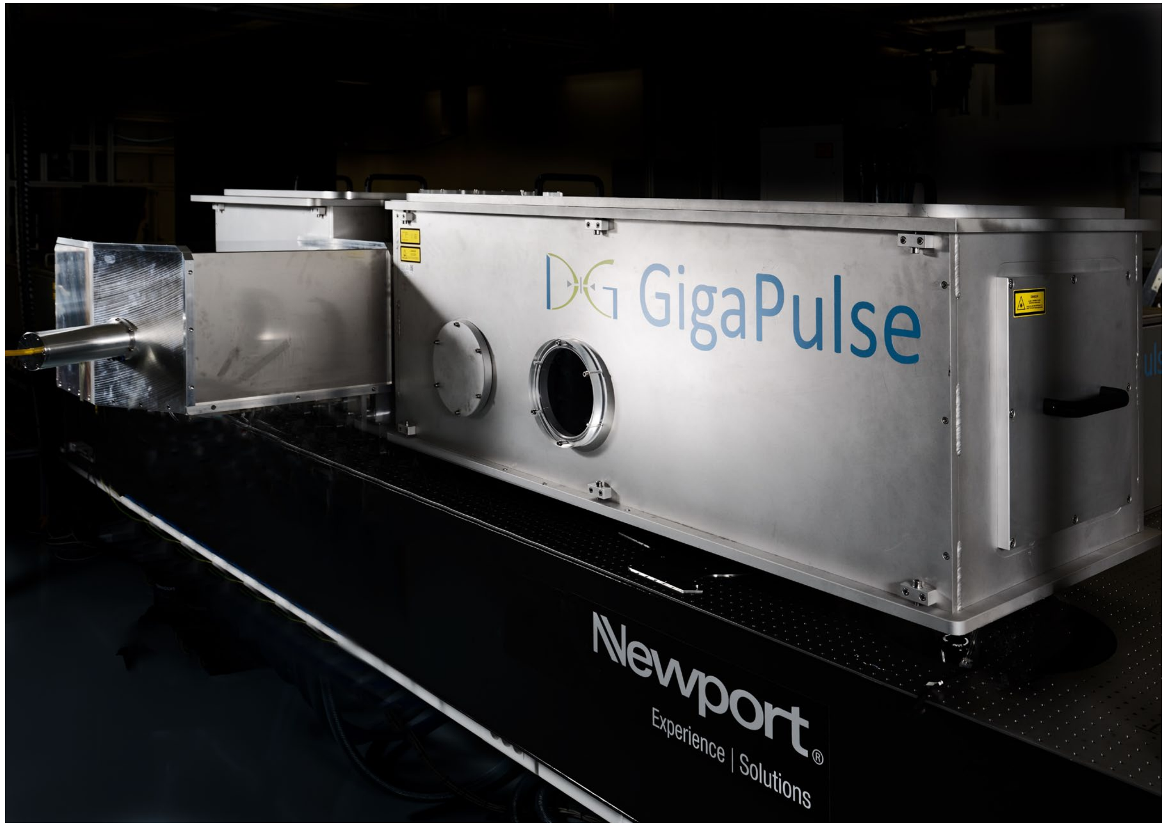


- FX Series
  - $P_{av} = 200W$
  - $E_p = 100\ \mu J$
  - $\Delta\tau = 600\ fs$

Lasers available

- Amphos 200
  - $P_{av} = 400\ W$
  - $E_p = 500\ \mu J$
  - $\Delta\tau = 1\ ps$

Lasers available



- Giga Pulse
  - $P_{av} = 1'400\ W$
  - $E_p = 1.4\ mJ$
  - $\Delta\tau \leq 3\ ps$

Lasers available

- Dira 750-5
  - $P_{av} = 750\ W$
  - $E_p = 150\ \mu J$
  - $\Delta\tau \leq 2\ ps$

Some Publications

- *J. P. Negel, A. Loescher, B. Dannecker, P. Oldorf, S. Reichel, R. Peters, M. Abdou Ahmed, Th. Graf,* **Thin Disk multipass amplifier for fs pulses delivering 400 W of average and 2.0 GW of peak power for linear polarization as well as 235 W and 1.2 GW for radial polarization**, Appl. Physics B: Lasers & Optics, 123, 156 (2017)
- *M. Müller, M. Kienel, A. Klenke, T. Gottschall, E. Shestaev, M. Plotner, J. Limpert, A. Tünnermann,* **1 kW 1 mJ eight-channel ultrafast fiber laser**, Opt. Lett. 41, 3439-3442 (2016)
- *J. P. Negel, A. Loescher, A. Voss, D. Bauer, D. Sutter, A. Killi, M. Abdou Ahmed, Th. Graf;* **Ultrafast thin-disk multipass laser amplifier delivering 1.4 kW (4.7 mJ, 1030 nm) average power converted to 820 W at 515 nm and 234 W at 343 nm,** Optics Express, 23, 21064-21077 (2015)
- *B. Gronloh, P. Russbueldt, B. Jungbluth, H.-D. Hoffmann*, **Ultrafast green laser exceeding 400 W of average power**, Proc. SPIE 9135, 91350C (2014)
- *P. Russbüldt, T. Mans, J. Weitenberg, H. D. Hoffmann, R. Poprawe*, **Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecfond amplifier**, Opt. Lett. 35, 4169-4171 (2010)

Summary

- Industry ready lasers with 100 W average power available today (also from other manufacturers)
- Multiple 100 W average power will be industry ready soon
- Up to 1 kW and more is "on the way"
- Missing average power will not be an issue in future
- **The important question will be: How to deal with it?**

Ablation model Gaussian Beam

- Specific removal :

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

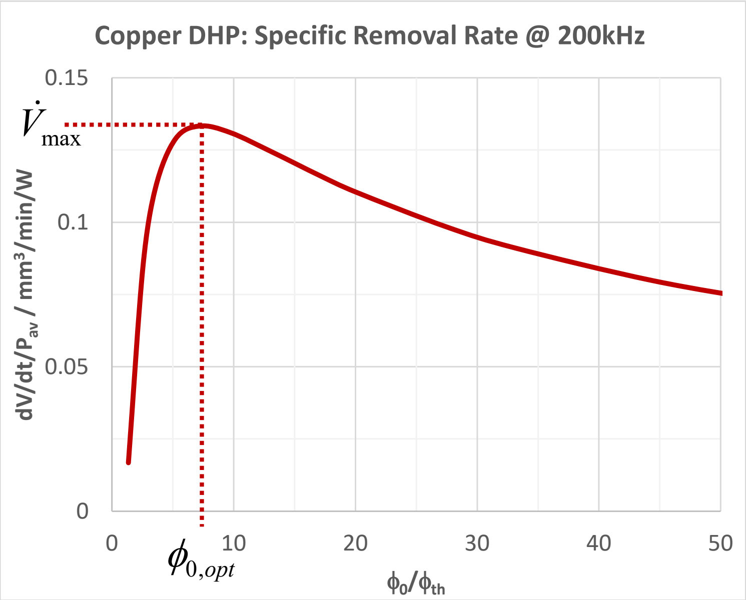
with:
ϕ_{th}: Threshold fluence
δ : Energy penetration depth
ϕ_0: Peak fluence

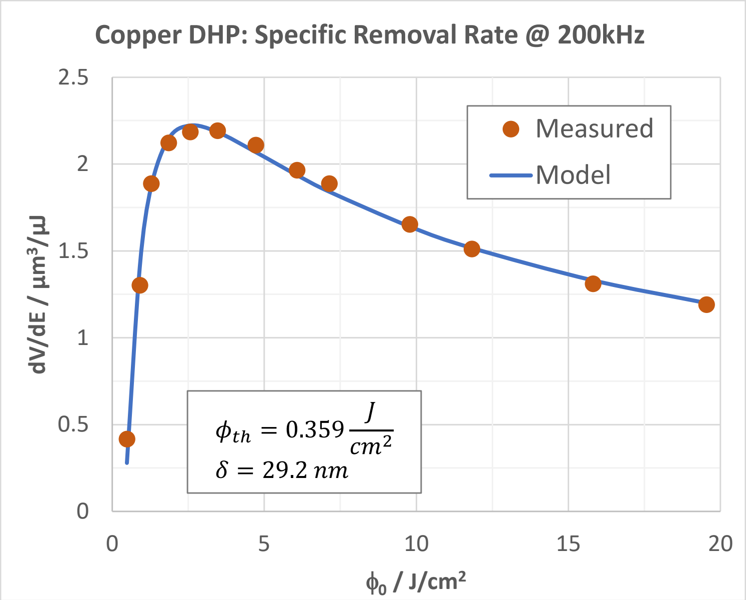
- Optimum Point / Maximum removal rate

$$\phi_{0,opt} = e^2 \cdot \phi_{th}$$

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

- Shorter Pulses -> higher removal rates

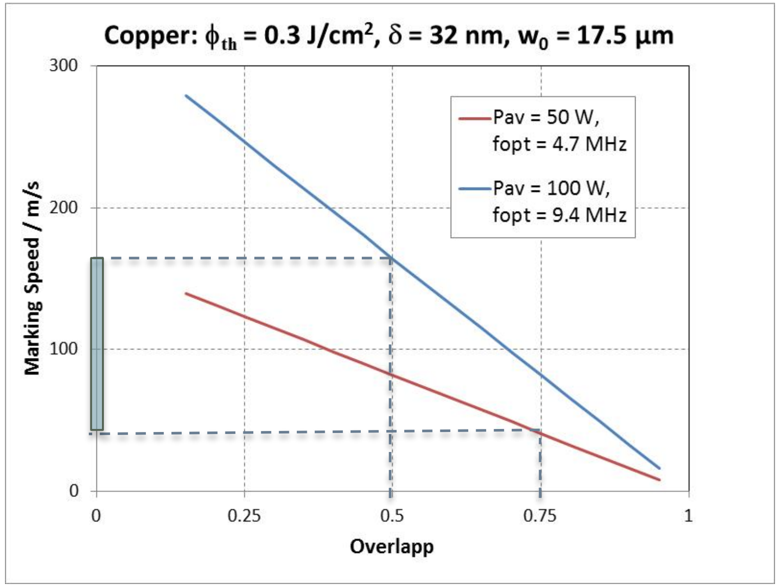


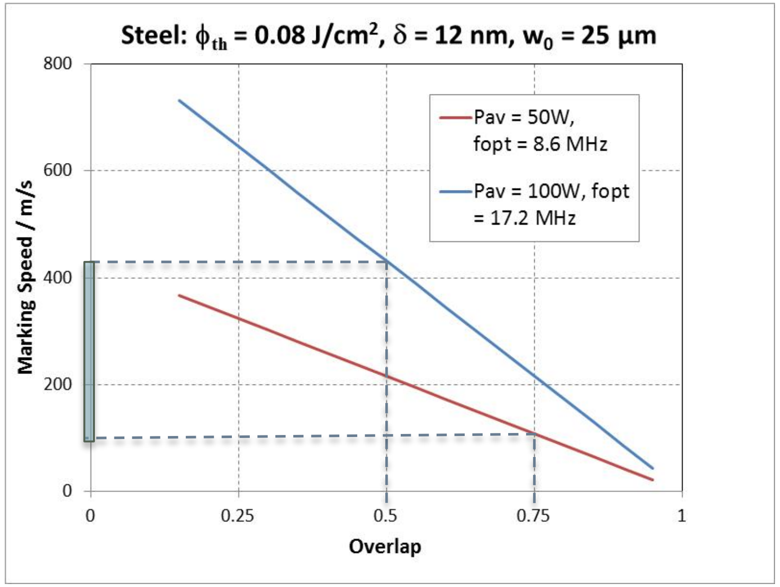


$$\left.\frac{\dot{V}}{P_{av}}\right|_{max} = 0.133 \frac{mm^3}{min \cdot W} = 2.22 \frac{\mu m^3}{\mu J}$$

Marking Speed

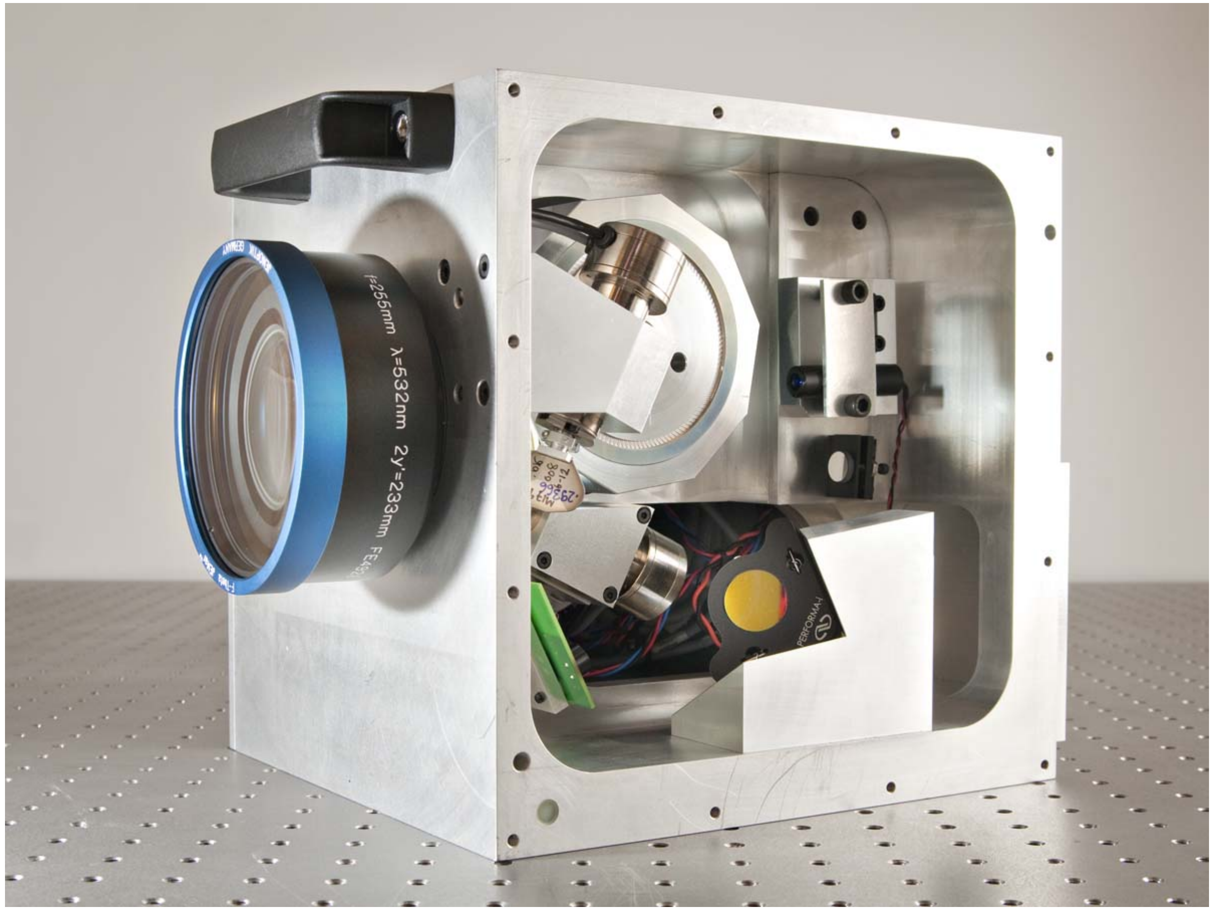
- A short calculation leads to: $v_{mark} = \frac{4}{\pi \cdot e^2} \cdot \frac{(1-o) \cdot P_{av}}{w_0 \cdot \phi_{th}}$ with o the overlap





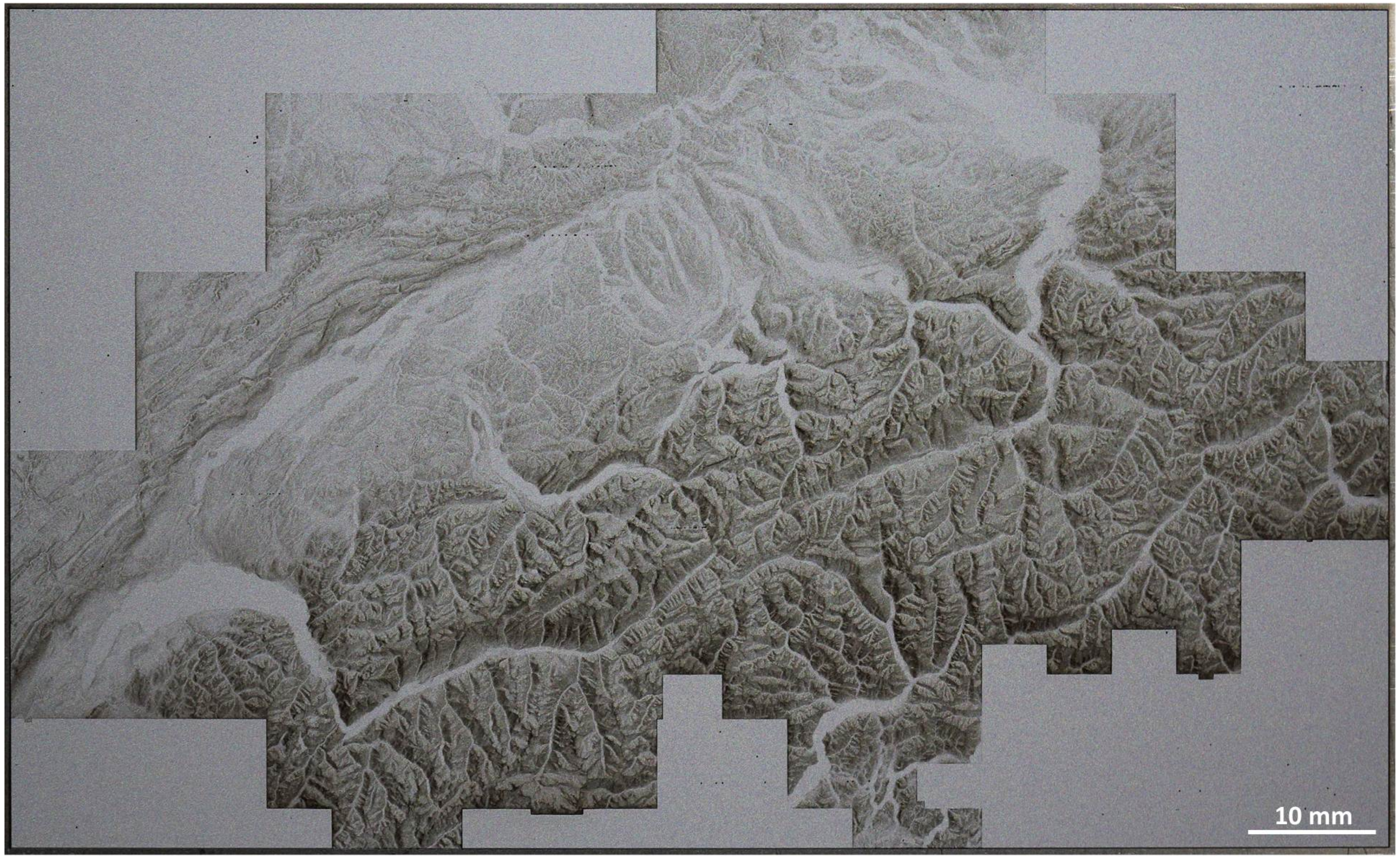
- Working near the optimum point with a few 10W of average power demands:
  - High marking speeds of 100m/s and more (not accessible with galvo scanners)
  - Single pulse switching at repetition rates of a few MHz to about 20MHz

Polygon - Scanner



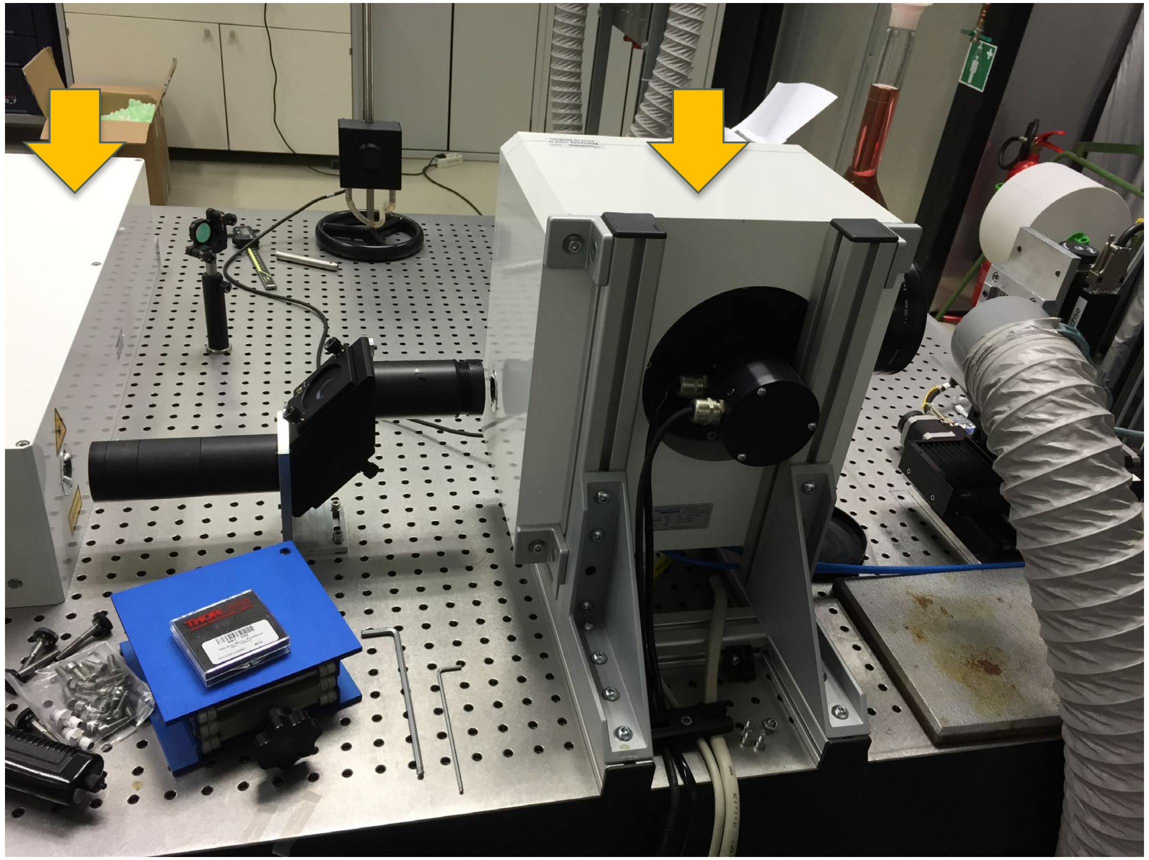
Synchronized Machining with Polygon Line Scanner LSE-170

Steel 1.4301 (AISI 304)



- **Parameters**
  - $f_r = 4.1\ MHz$
  - $P_{av} = 25.6\ W$
  - $w_0 = 29\ \mu m$
  - $v_{scan} = 60 m/s$
  - $p = 14.5 \mu m$
  - $2233\ Layers$
- **Tested up to**
  - $f_r = 6.83\ MHz$
  - $P_{av} = 42\ W$
  - No SP with PoD
- **Is a further scale up above 100W possible?**

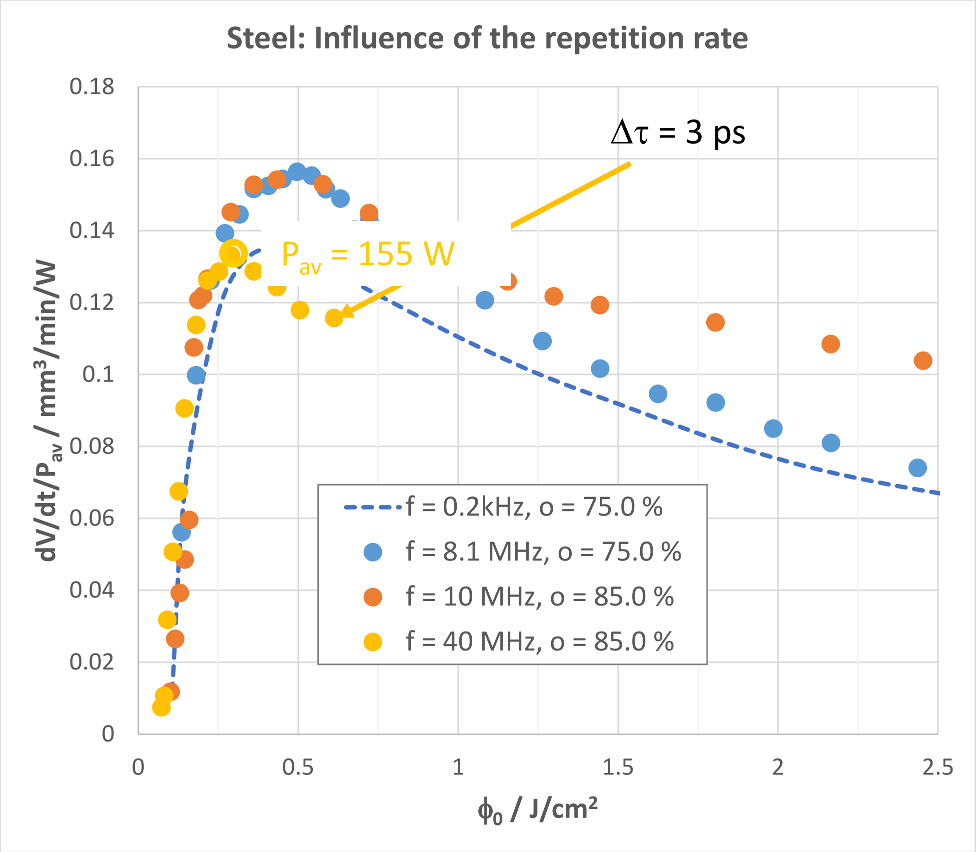
Polygon 2: Scale-Up above 100 W



- Amphos High Power Laser
  - $P_{av,max}$ = 450 W
  - $\Delta\tau$ = 900 fs .. 5 ps (used 3ps)
  - λ = 1030 nm
  - Linearly polarized

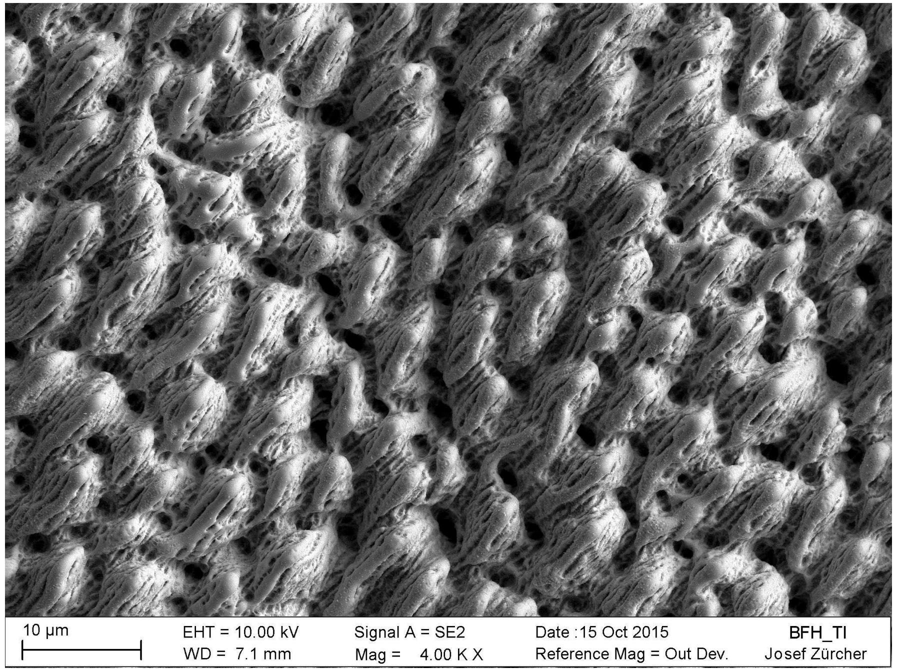
- High speed Polygon
  - Not synchronized
  - 1 integrated galvo
  - 12 facets mirror wheel
  - f_{Obj} = 100 mm (telecentric)
    w_0 = 28 µm (estimated)
  - $v_{mark,max}$ = 480 m/s

Steel: Influence of the Repetition Rate



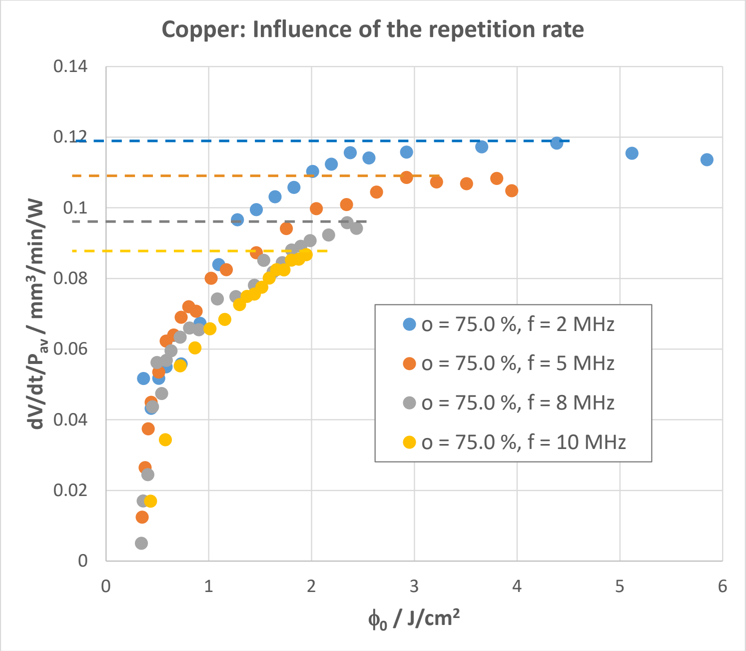
[3] F. Bauer et al., " Heat accumulation in ultra-short pulsed laser processing of metals", Opt. Expr., 23, 1035 – 1043 (2015)

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

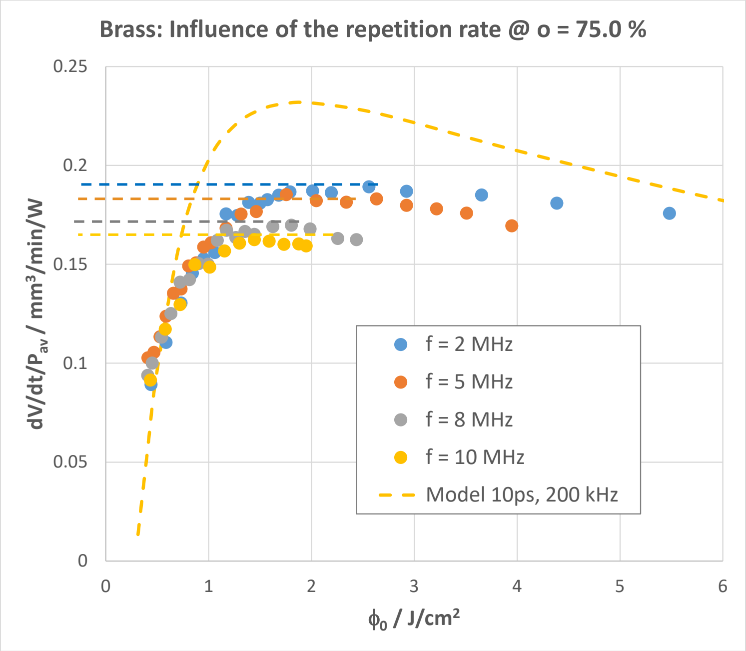


- Bumpy surface due to heat accumulation [3]

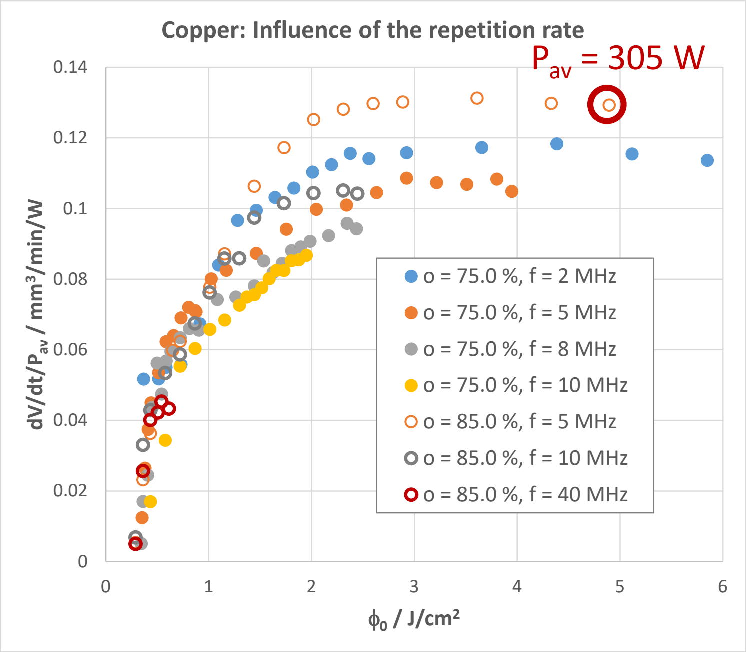
Copper and Brass: Influence of the Repetition Rate



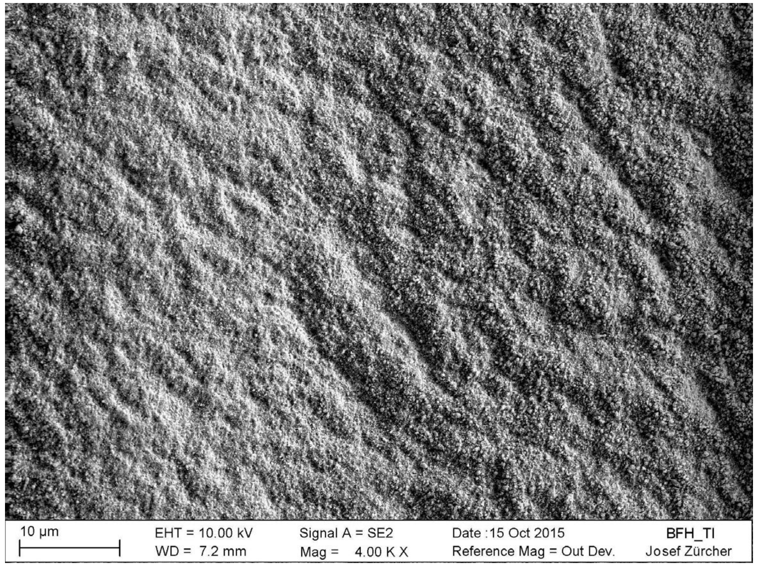
- For a fixed overlap a strong decrease of the specific removal rate is observed for higher repetition rates
- Drop already from 2 MHz
- Similar behavior for brass
- Particle or Plasma Shielding



Copper and Brass: Surface Quality at high Average Powers



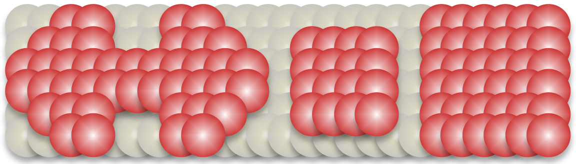
- Copper @ 5 MHz
  - Quite good surface quality at highest peak fluence
  - $\frac{dV}{dt} \approx 40 \frac{mm^3}{min}$



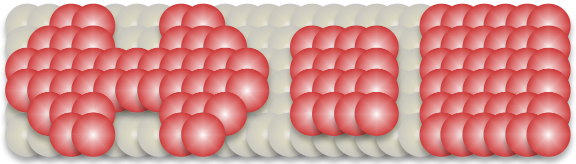
Heat accumulation and/or shielding are limiting the the power scale-up

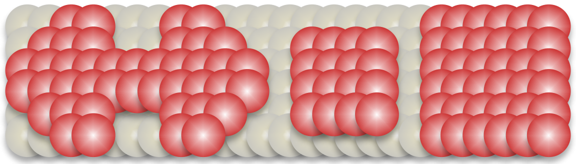
"Interlaced" Mode: Principle

- A given spot pattern can also be machined

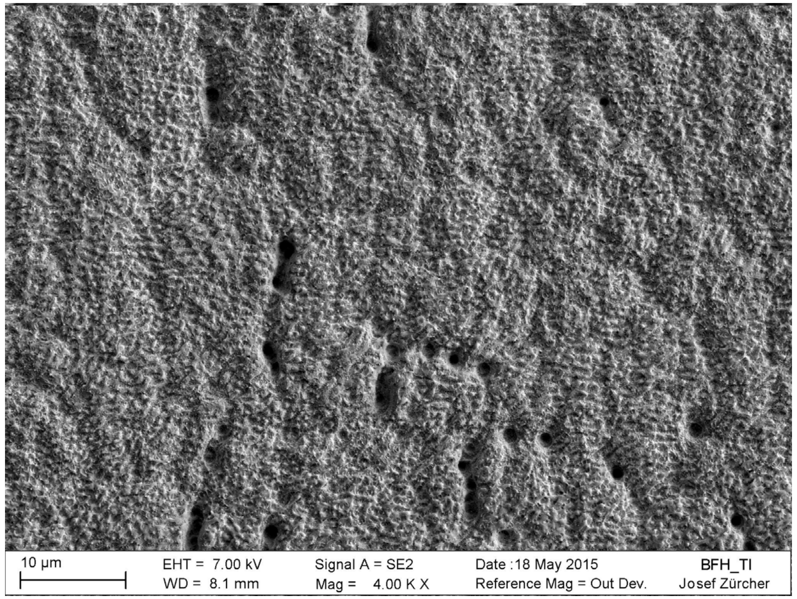


- In n passes with n times larger pulse-pulse distance:





- 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 (√)

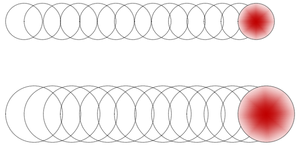
Marking Speed at optimum point

- Steel with $\phi_{th} = 0.08\ \frac{J}{cm^2}$, $w_0 = 15\ \mu m$ and an overlap of 0% (Spot diameter from pulse to pulse):
  - $P_{av} = 100W\ \rightarrow\ v_{mark} = 1640\ \frac{m}{s}\ ,\ \ f_r = 48\ MHz$
  - $P_{av} = 500W\ \rightarrow\ v_{mark} = 8200\ \frac{m}{s}\ ,\ \ f_r = 240\ MHz$
- Copper with $\phi_{th} = 0.35\ \frac{J}{cm^2}$, $w_0 = 15\ \mu m$ and an overlap of 0% (Spot diameter from pulse to pulse):
  - $P_{av} = 100W\ \rightarrow\ v_{mark} = 330\ \frac{m}{s}\ ,\ \ f_r = 11\ MHz$
  - $P_{av} = 500W\ \rightarrow\ v_{mark} = 1650\ \frac{m}{s}\ ,\ \ f_r = 55\ MHz$
- 3 times above optimum (not possible for steel):
  - $P_{av} = 100W\ \rightarrow\ v_{mark} = 110\ \frac{m}{s}\ ,\ \ f_r = 3.5\ MHz$
  - $P_{av} = 500W\ \rightarrow\ v_{mark} = 550\ \frac{m}{s}\ ,\ \ f_r = 17.5\ MHz$

- **Copper could ev. be machined with several 100 W**
- **But alternative approaches are demanded anyway**

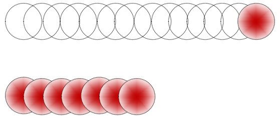
Strategies for High Pulse Energies

- Increase spot size



  - for micromachining?
  - Used for machining of CFRP

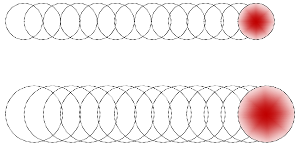
- Multi-spots: Temporal, Bursts:



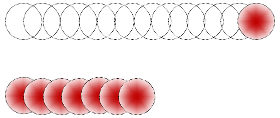
Might be a possibility but has also limitations

Strategies for High Pulse Energies

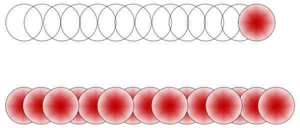
- Increase spot size



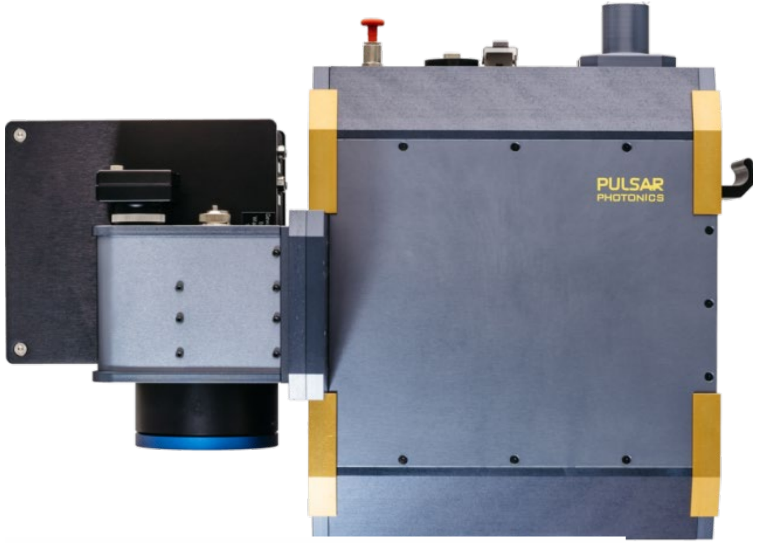
- Multi-spots: Temporal, Bursts:

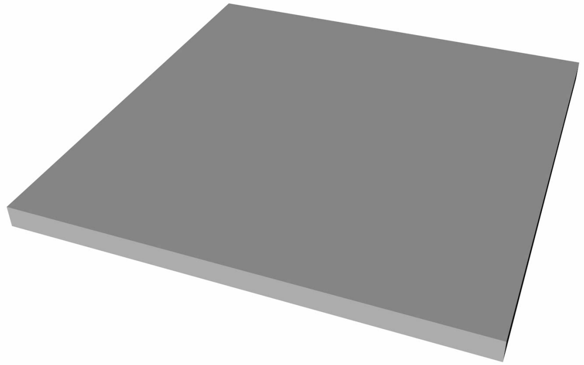


- Multi-spots: Spatial



Multispot Processing: Industrialized Solution

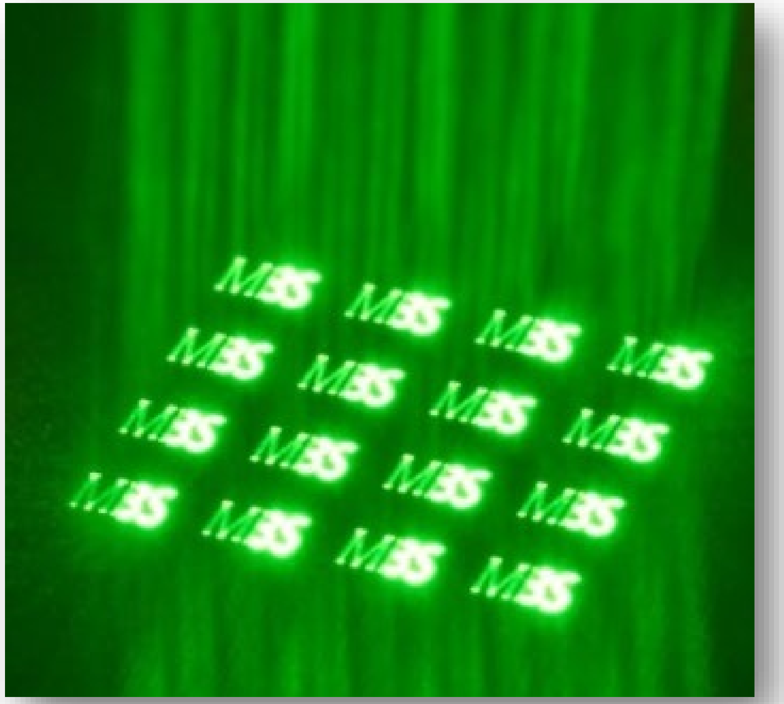




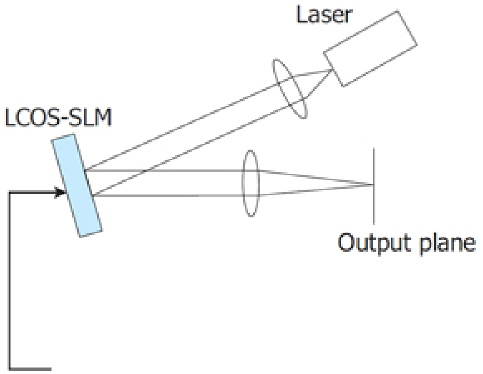
- Combination of beam splitting unit and scanning system
- Max. Power: 150 W
- 532nm or 1064nm
- Field Size: 5x5mm (f = 100 mm objective)
- Spot Position Error <3 µm

- restricted to periodical structures

- 16 parallel beams



Multispots with SLM



Picture from http://www.hamamatsu.com/jp/en/product/alpha/L/4015/index.html

- Additional phase is added to a collimated (Gaussian) beam
- Specific patterns can be produced in the output plane
- SLM is a phase-only device
- Grating structure leads to a 0^{th} order
- Some multi-spot patterns may use the 0^{th} order

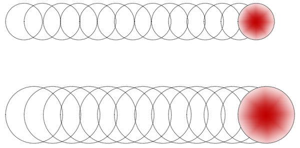
Multi-Spot Example

- Blank out single spots in a regular pattern of nxn spots
- Move target and apply different patterns

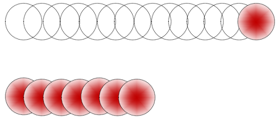
[4] K.Päiväsaari, M. Silvennoinen, J. Kaakkunen and P.i Vahimaa, “Femtosecond laser processing and spatial light modulator “, SPIE 8967-14 (2014)

Strategies for High Pulse Energies

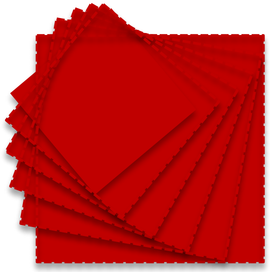
- Increase spot size



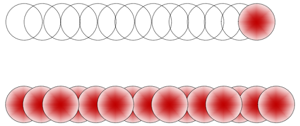
- Multi-spots: Temporal, Bursts:



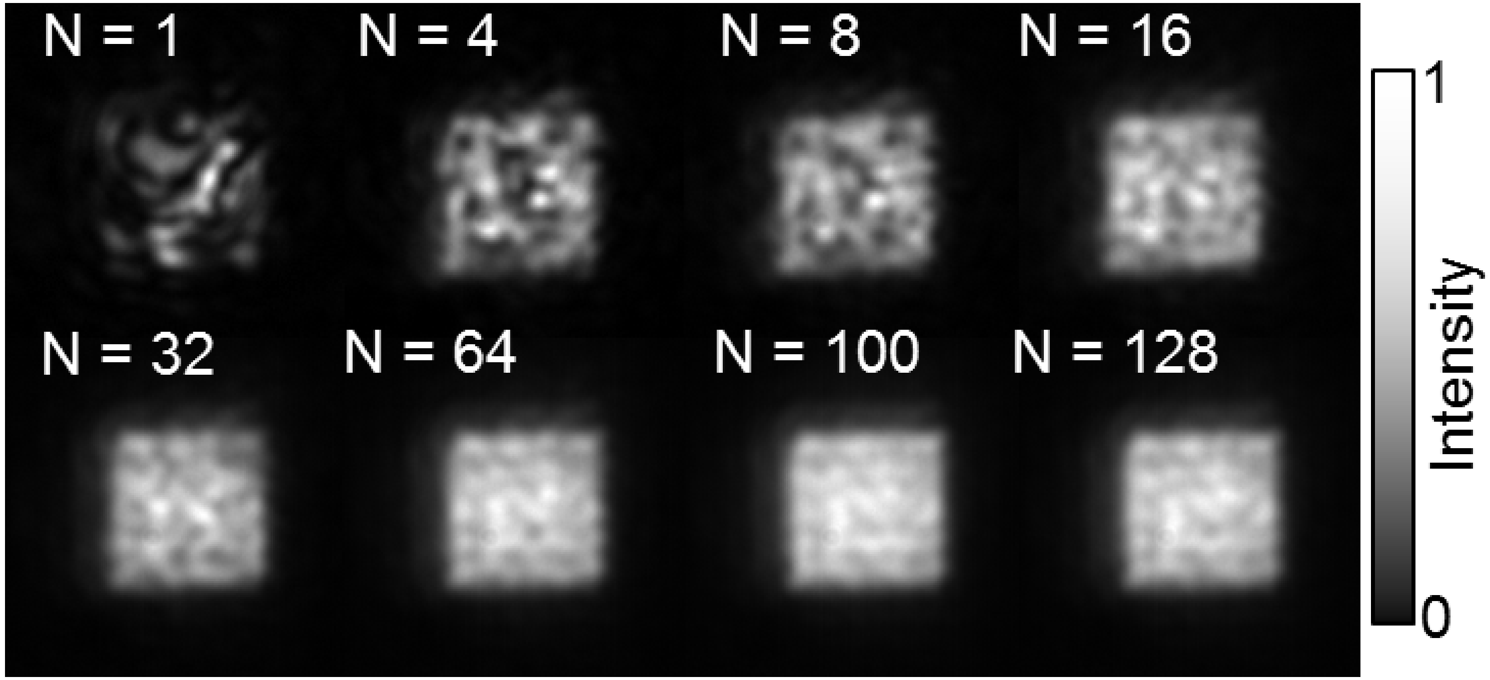
- Forming the spot



- Multi-spots: Spatial



Beam Forming Example: Speckle Reduction

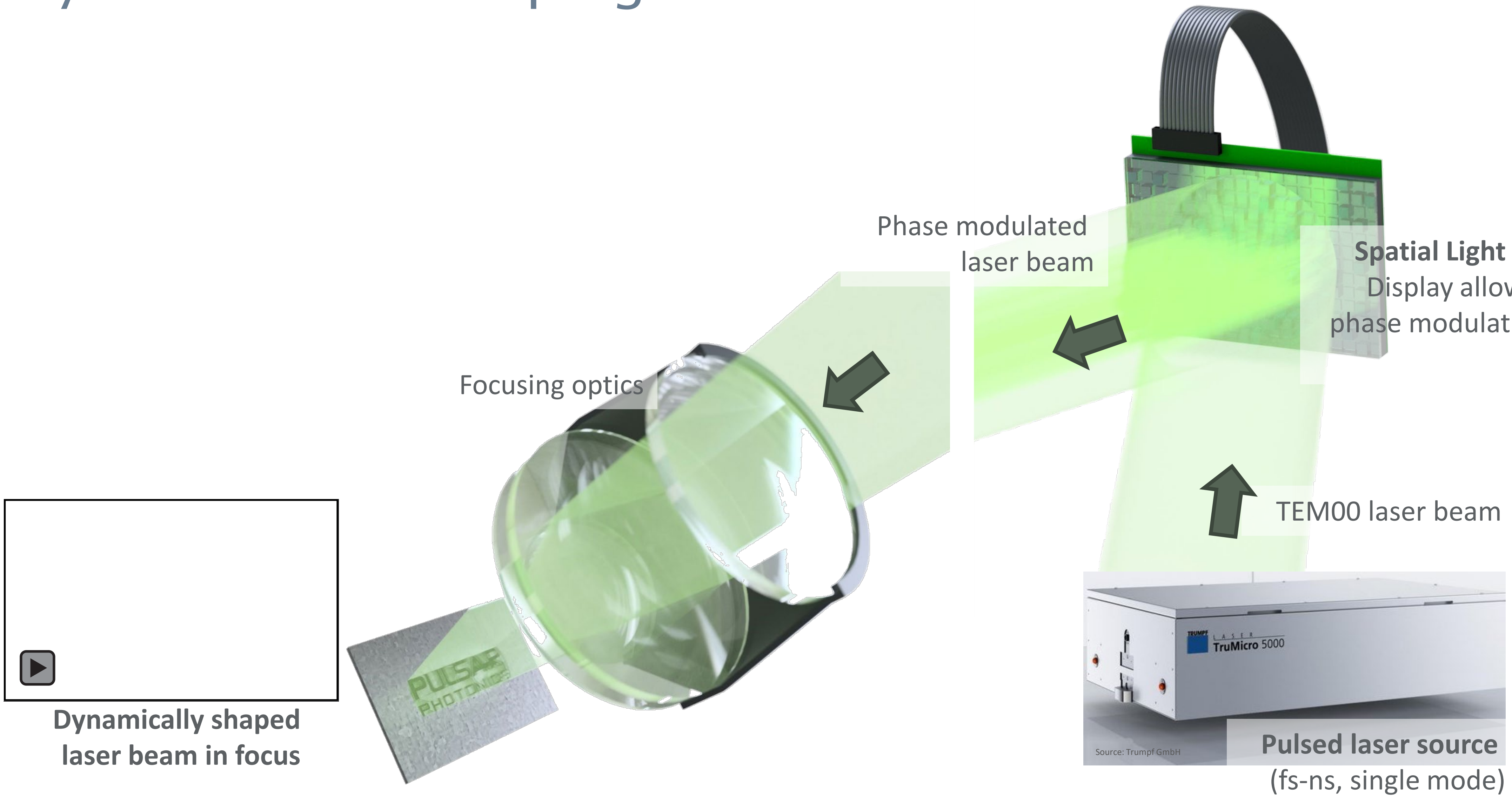


Time averaging

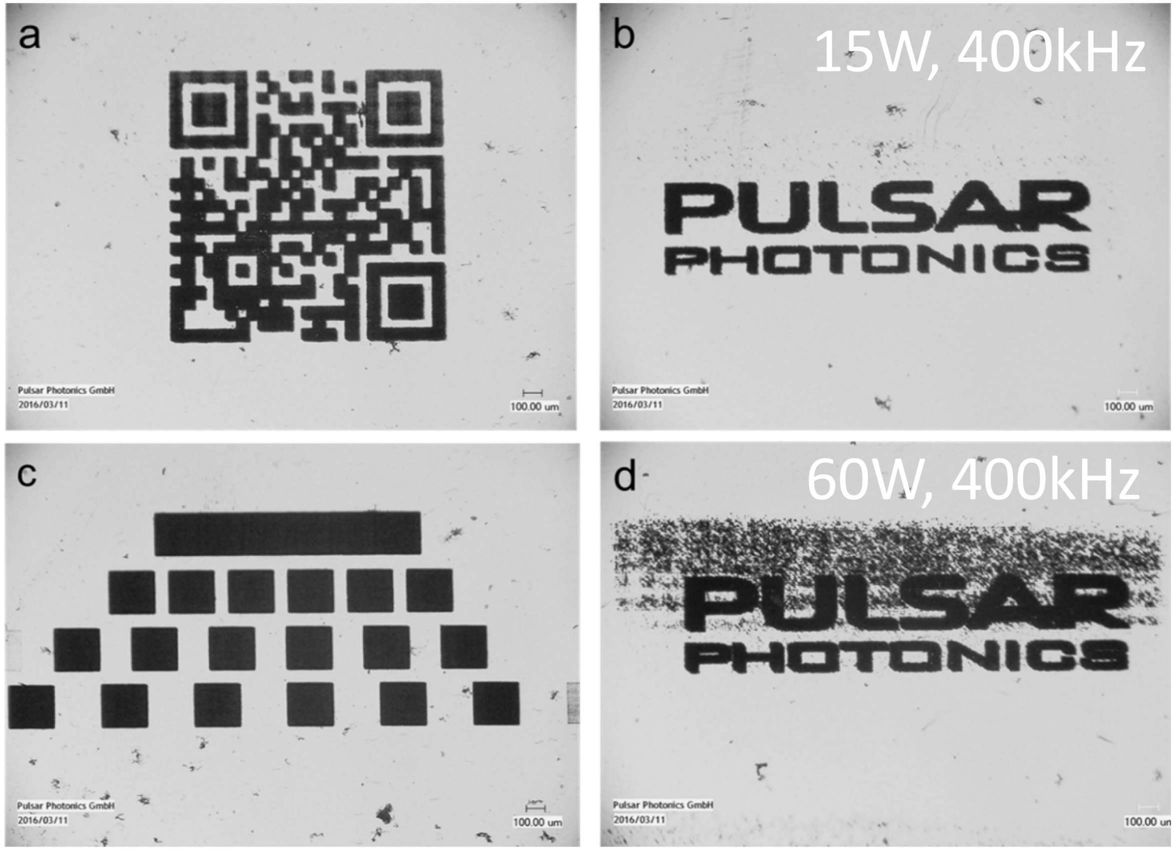
- Calculate several holograms with different random phases at start
- Play these holograms in a sequence on the SLM
- Significant speckle reduction by averaging
- N>70 is enough

[6] T. Häfner, J. Heberle, D. Holder, M. Schmidt, J. of Laser Appl., 29 (2017), 022205

Dynamic Beam Shaping with SLM



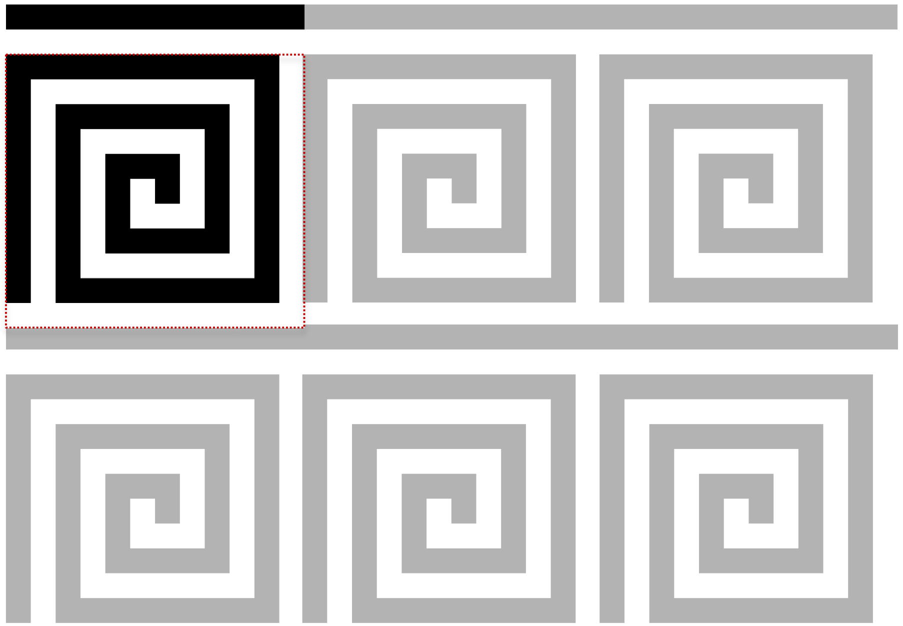
Dynamic Beam Shaping with SLM: Industrial realisation



[7] T. Klerksa, S. Eifel, 9th International Conference on Photonic Technologies LANE 2016, Industrial Paper

Diffractive Optical Element DOE

- Using only DOE and cage system to adjust correct DOE size
- Good beam quality is important (Gaussian beam) for correct structure



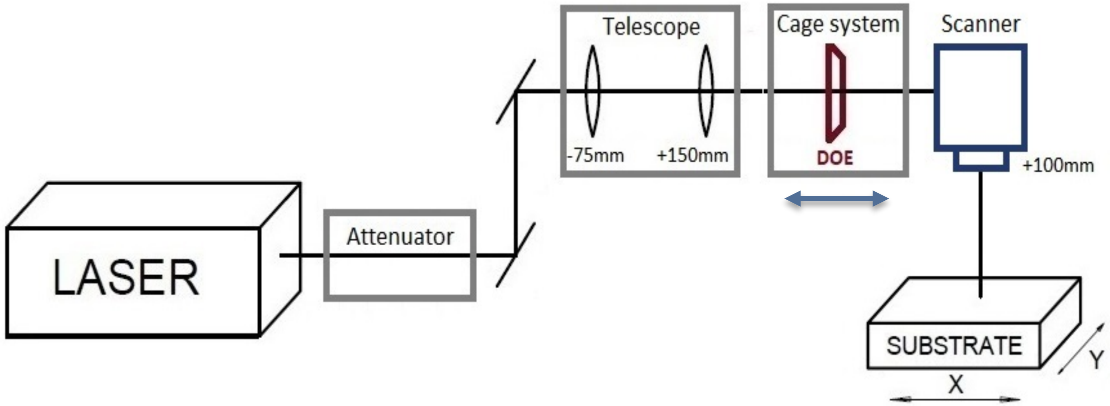
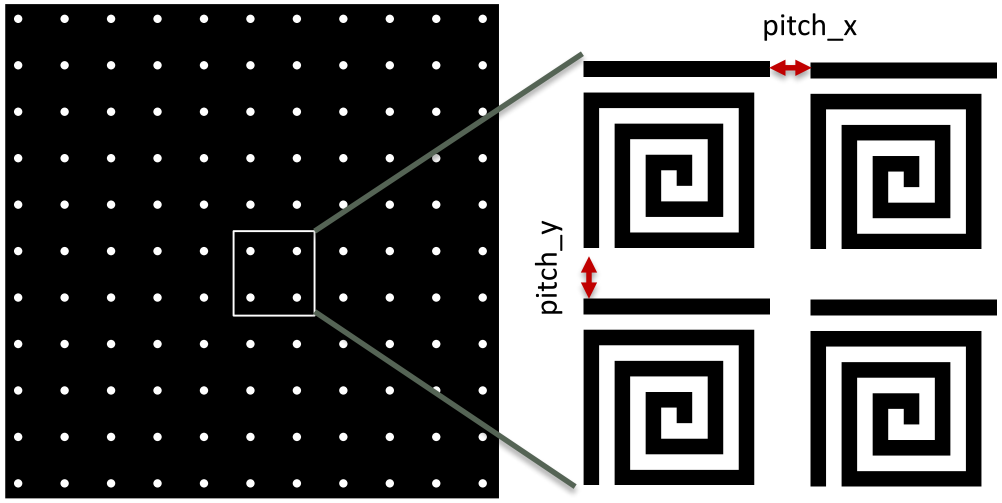
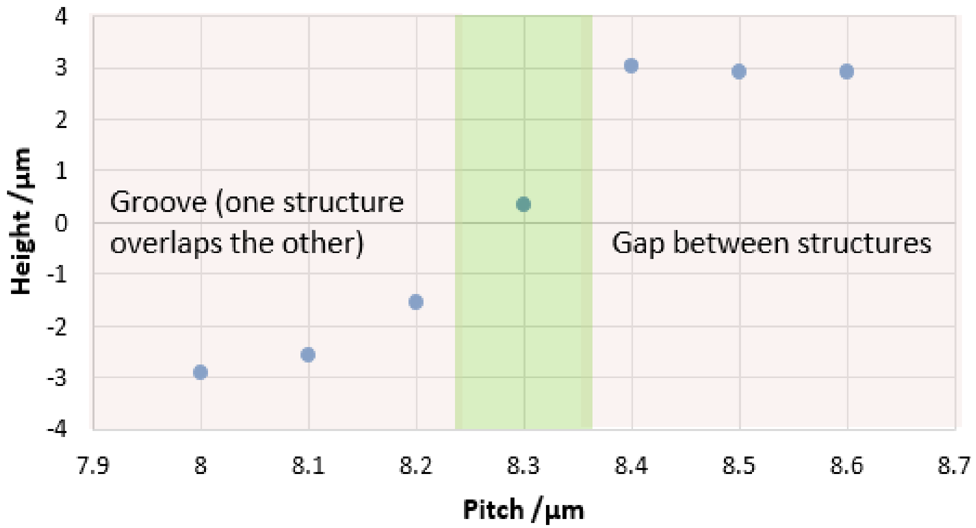


Fig 5. PicoBlade 2 setup

DOE combined with synchronized Galvo-Scanner

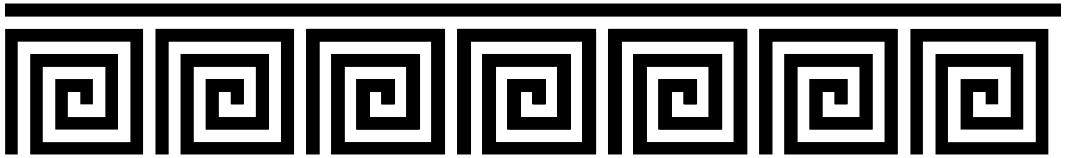
- Using only DOE and cage system to adjust correct DOE size
- Good beam quality is important (Gaussian beam) for correct structure
- Stitching with synchronized galvo scanner
- Pitch has to be adjusted in both directions

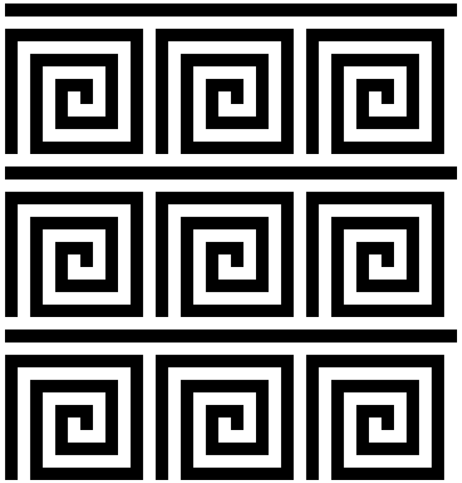




DOE combined with synchronized Galvo-Scanner

- Using only DOE and cage system to adjust correct DOE size
- Good beam quality is important (Gaussian beam) for correct structure
- Stitching with synchrinized galvo scanner
- Pitch has to be adjusted in both directions
- With correctly adjusted pitch also multiple elementary cells DOE's can be used





But: Don’t Forget the “Good Old” Galvo Scanner

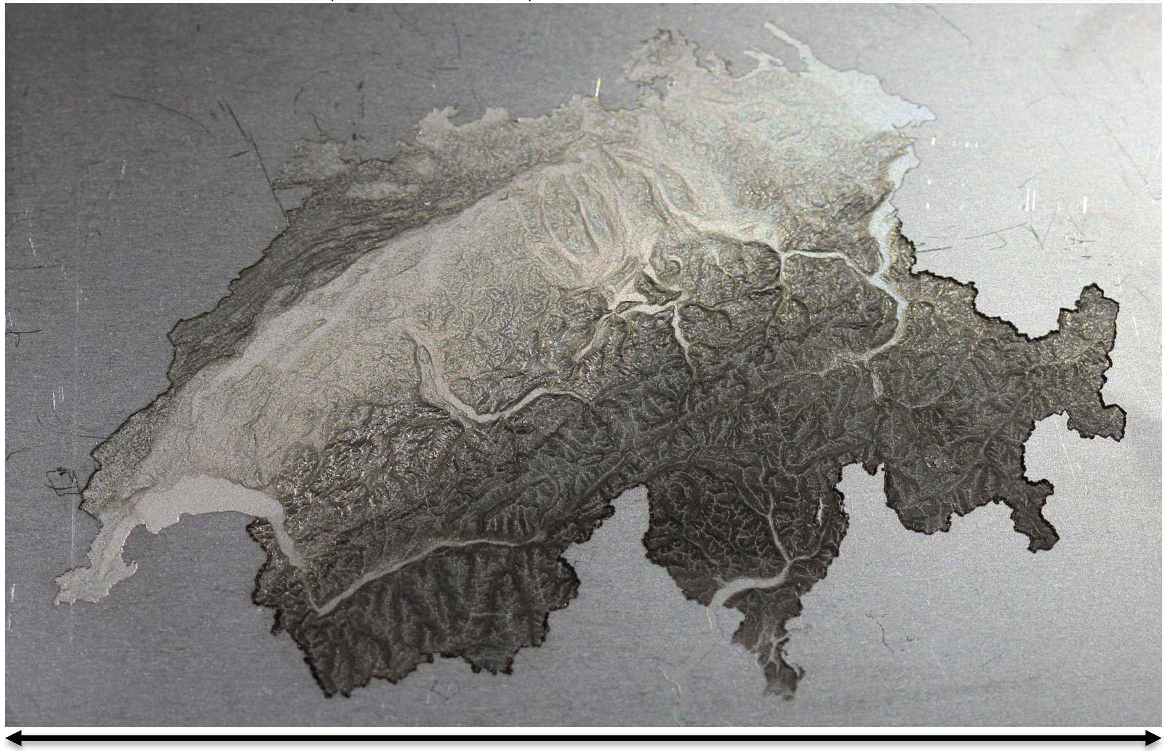
direction		Line length		trajectory	
uni	bi	const	adapt	non	opt
x		x		x	
x		x			x
x			x	x	
x			x		x
	x	x		x	
	x	x			x
	x		x	x	
	x		x		x

But: Don’t Forget the “Good Old” Galvo Scanner

direction		Line length		trajectory	
uni	bi	const	adapt	non	opt
x		x		x	
x		x			x
x			x	x	
x			x		x
	x	x		x	
	x	x			x
	x		x	x	
	x		x		x

But: Don’t Forget the “Good Old” Galvo Scanner

Steel 1.4301 (AISI 304)



48 mm

Negative structure, mountains deep

- $P_{av} = 20\,W,\ \ \Delta\tau = 10\,ps\,,\ \ \lambda = 1064\,nm$
- $f_{rep} = 2\,MHz$
- $w_0 = 20\,\mu m$
- $v_{mark} = 26\ {}^{m}/_{s}$
  - $p_x = 13\,\mu m$
  - $p_y = 13\,\mu m$
- Basic bitmap: $3500\ x\ 2361\ pixel$
- $4491\ Slices$
- $d_{max} = 400\,\mu m$
- $t_{mark,tot} = 10'000\,s = 2\,{}^{3}/_{4}\ h$
- intelli*SCAN*$_{SE}$10
- For copper $P_{av} > 100\,W$ and $t_{mark,tot} \approx {}^{1}/_{4}\ h$ should be possible

Conclusion / Outlook

- Single beams with low pulse energy
  - Polygon scanners are well suited to achieve high marking speeds
    - Limited flexibility (fixed line length, “thinking in bitmaps”)
    - Power scale – up demonstrated but limited by heat accumulation and shielding
  - Higher marking speeds with synchronization needed

- Working with high pulse energies
  - Multi – spot processing (DOE + Scanner) can be applied for periodic structures
  - More flexibility with a spatial light modulator (SLM), limited speed and laser power
  - Beam forming (DOE or SLM) allows the efficient use of high pulse energies

- The combination of beam forming elements with conventional scanning devices is a promising approach

Thank you for your Attention