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Advances in high precision and high-throughput Laser micromachining

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Outline

- Scale-Up Problem with Single Pulses
- Multi-Pulse Strategies
  - Temporal: Pulse bursts (incl. GHz)
  - Spatial: Multi – spots
- Beam forming
- Conclusions/Outlook

Ablation model Gaussian Beam

- Energy specific Volume [1]:

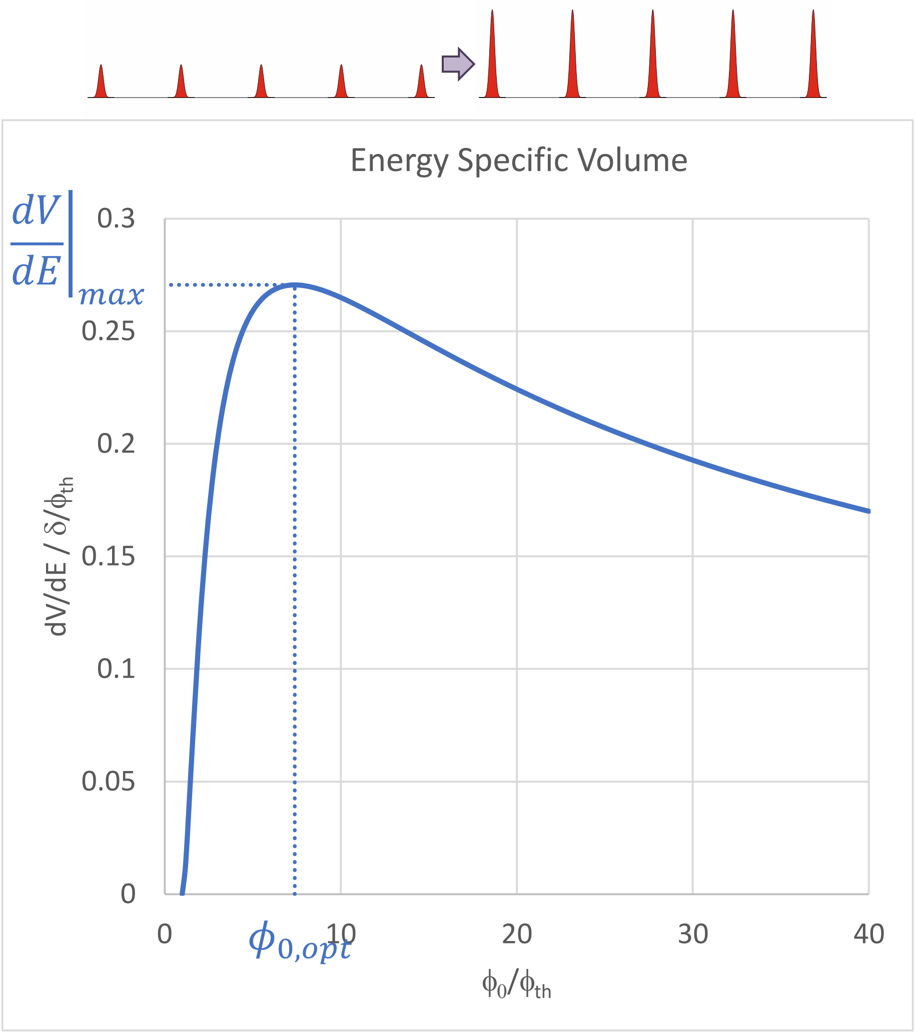
$$\frac{dV}{dE} = \frac{1}{2} \cdot \frac{\delta}{\phi_0} \cdot ln^2\left(\frac{\phi_0}{\phi_{th}}\right)$$

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

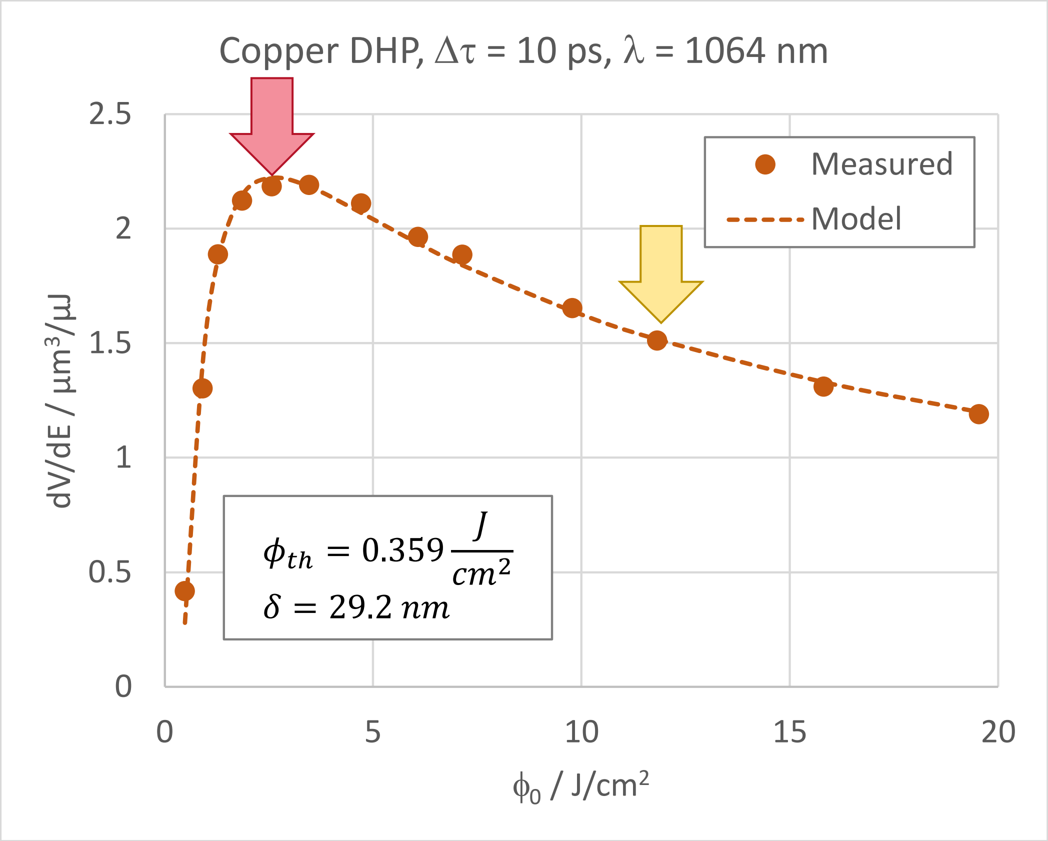
- Optimum Point / Maximum specific removal rate

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

[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)

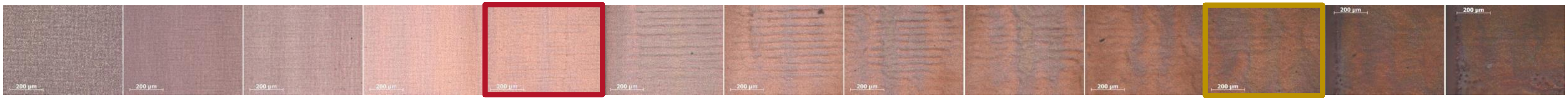


Copper DHP

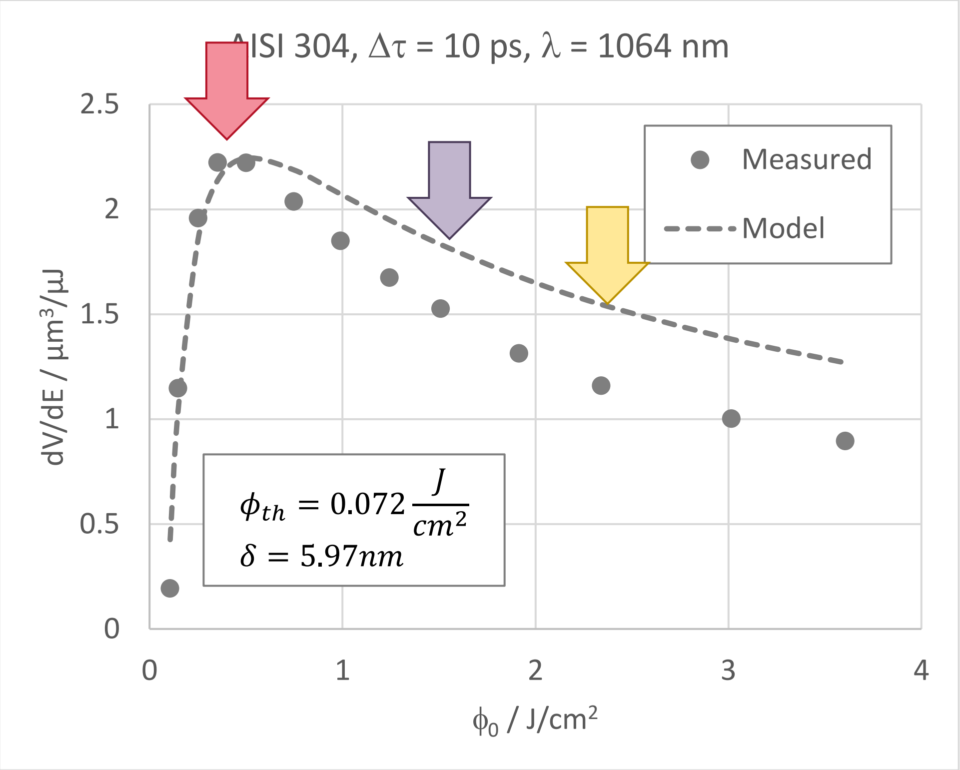


- High surface quality near optimum point
- Best strategy: Increase repetition rate
- But acceptable surface quality for higher peak fluences
- Scale up by increasing peak fluence i.e. pulse energy is also possible
- Limited repetition rate, higher fluences corresponds to higher average powers:

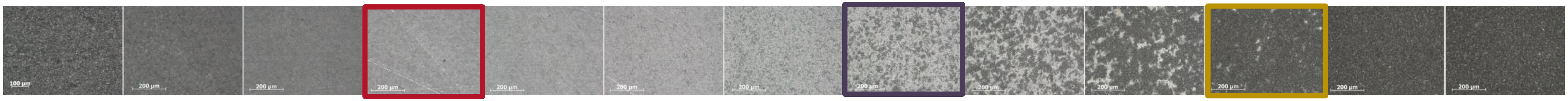
$$\dot{V}_{n\cdot\phi_{opt}} = \frac{(\ln(n)+2)^2}{4} \cdot \dot{V}_{\phi_{opt}}$$



Steel AISI 304



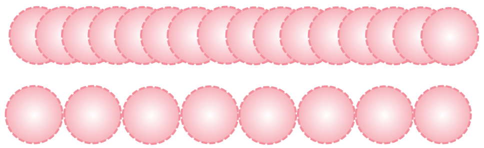
- High surface quality near optimum point
- Best strategy: Increase repetition rate
- Formation of cavities starts for peak fluences of about $E_{pulse} = 2 \cdot E_{opt}$
- For higher fluences the surface becomes fully covered by cavities (cone like protrusions CLP)
- Increasing pulse energy fails
- For several $10\ W$ average power extremely high repetition rates and marking speeds demanded



Scale-Up Strategies

Single Pulse Strategies

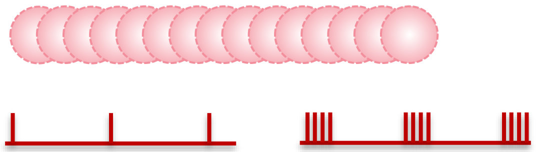
- Fast scanning



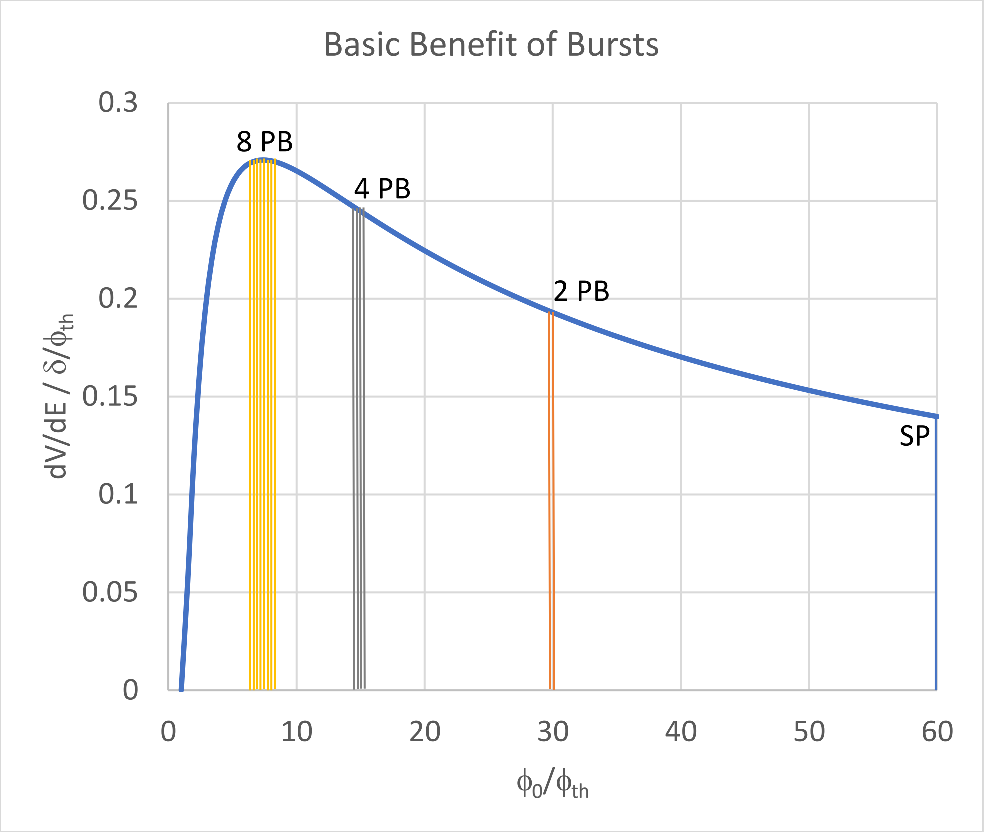
  - Just discussed

Multipulse Strategies

- Pulse Bursts:



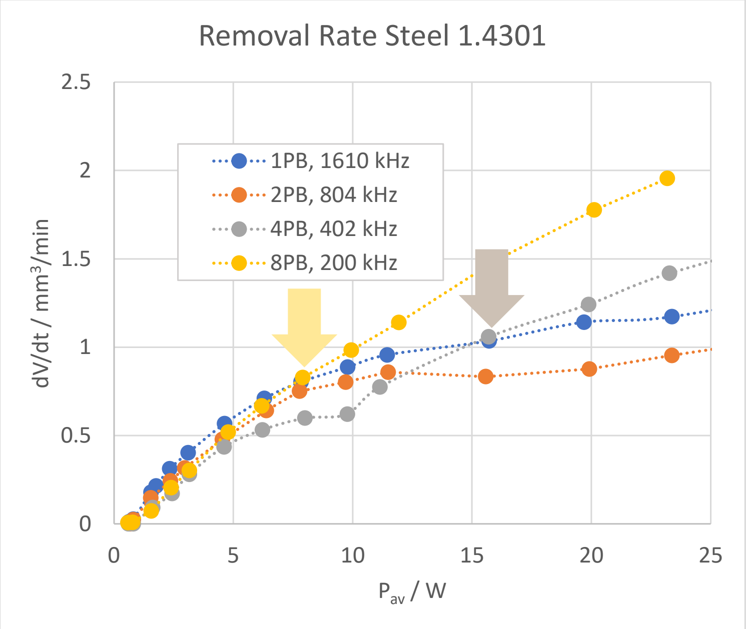
Basic Benefit of Pulse Bursts

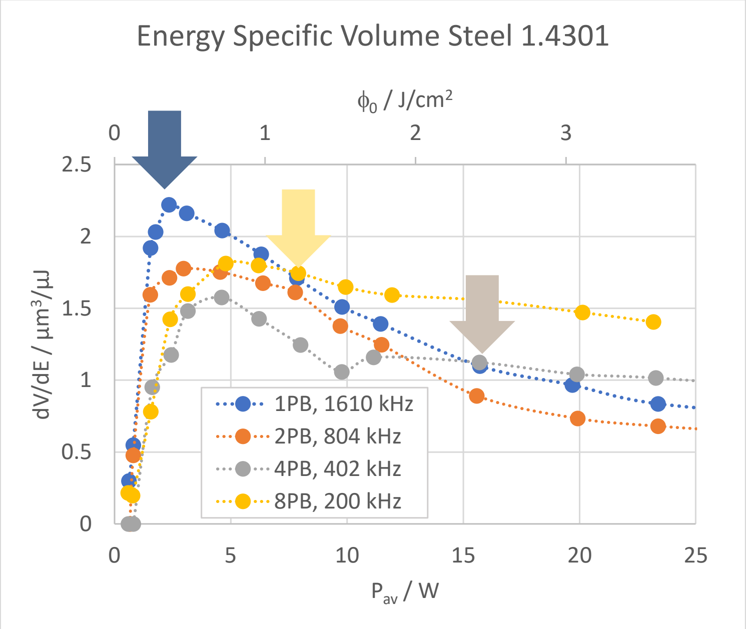


[2]: D. Förster et al, „Review on Experimental and Theoretical Investigations of Ultra-Short Pulsed Laser Ablation of Metals with Burst Pulses", Materials 14(12), 3331 (2021)

- Total energy of a pulse is distributed among different sub pulses.
- The fluence of the sub pulses converges to the optimum value
- The process becomes more efficient
- Constant average power:
  - $n_B \cdot f_{rep} = const.$

Basic Benefit of Pulse Bursts AISI 304

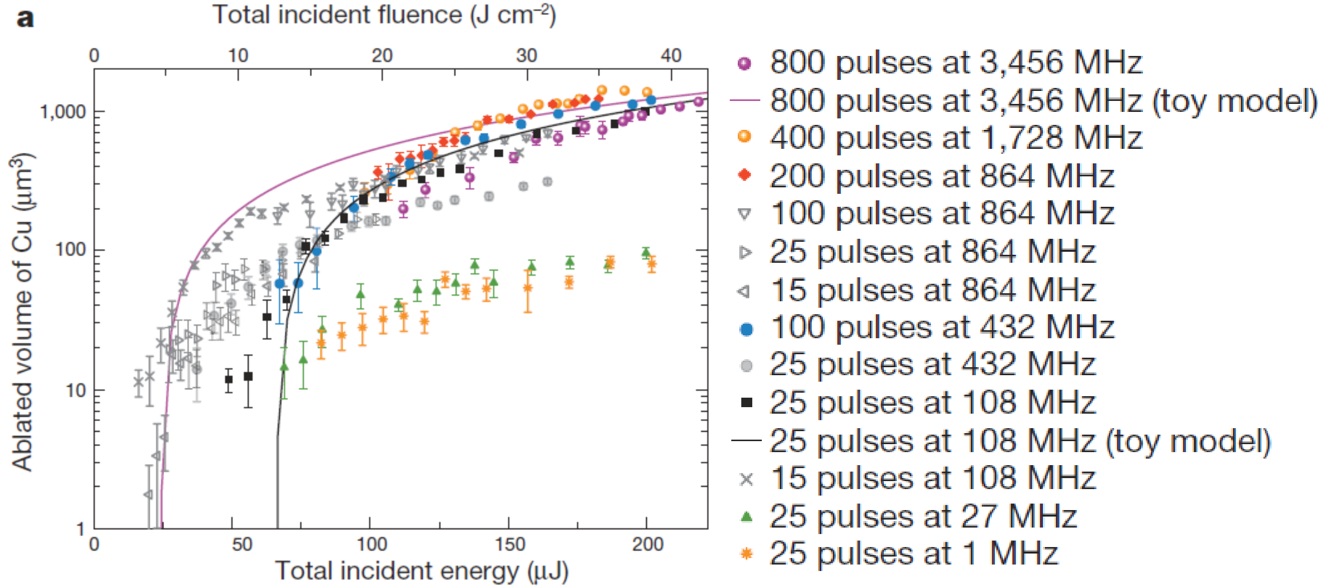


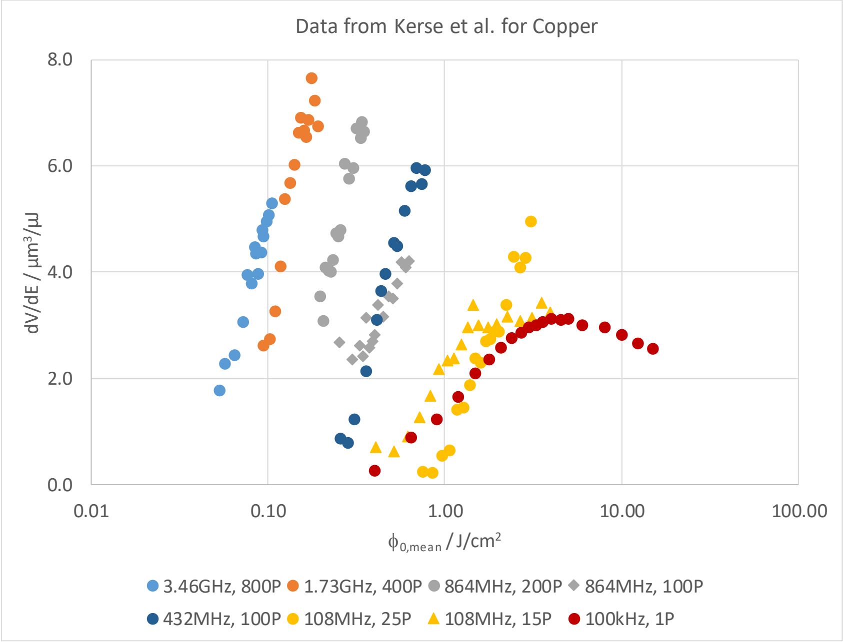


- Single pulses are most efficient
- But for higher averge powers a break even can be achieved
- From there on a burst situation can be more efficient than single pulses

GHz Burst and Ablation Cooling

- A "Nature" publication states that GHz bursts are highly efficient compared to single pulses due to the enhanced “ablation cooling” effect

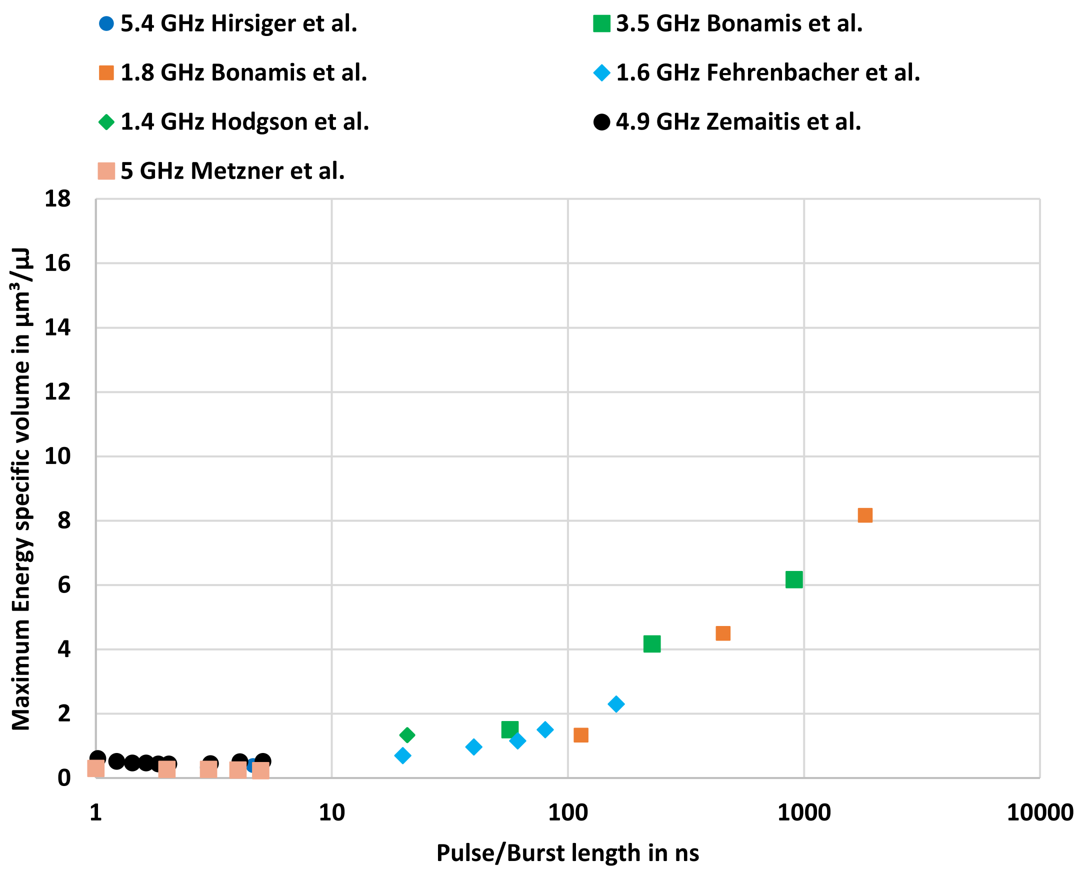




[4]: C. Kerse et al.,“Ablation-cooled material removal with ultrafast bursts of pulses” Nature **532**, 84 – 89 (2016)

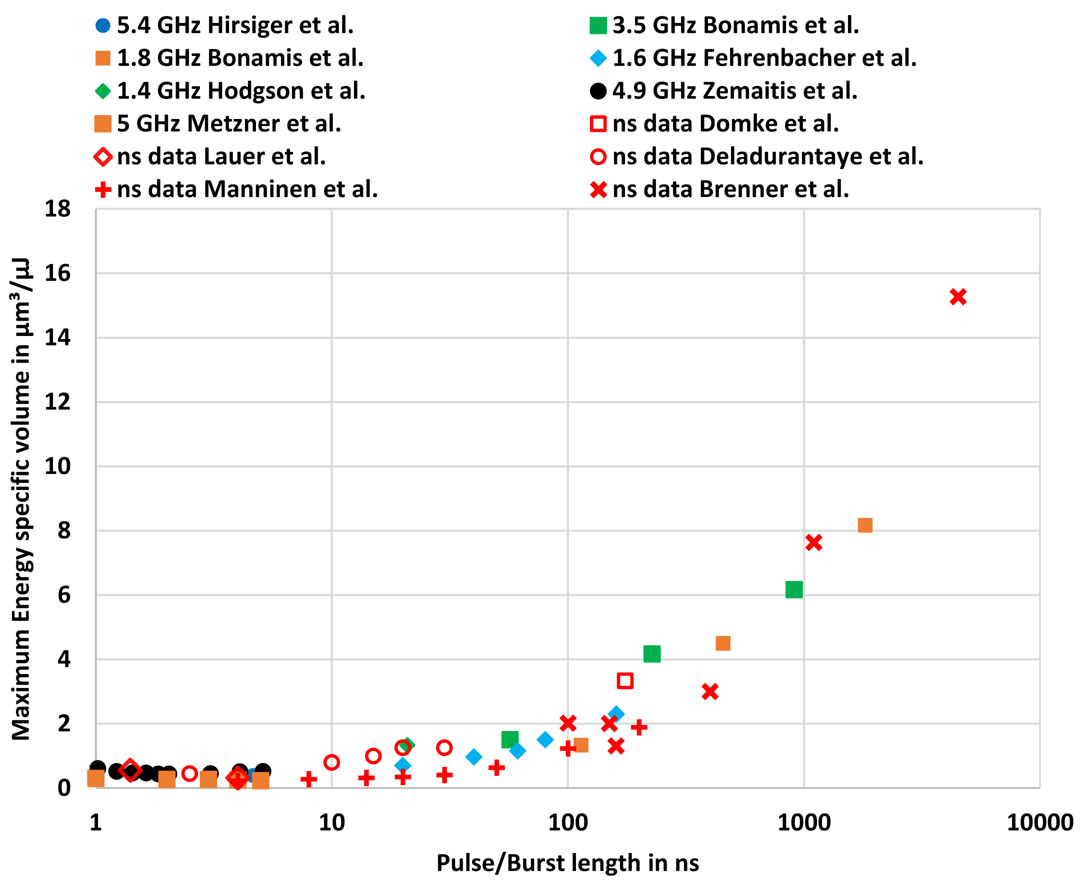
- The obtained specific removal rates are indeed above the ones for single pulses

AISI 304 GHz Bursts



- For AISI 304 high number of pulses per burst i.e. long burst lengths, lead to higher maximum energy specific volumes

AISI 304 GHz Bursts



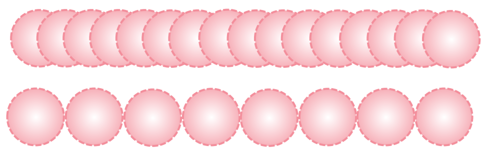
- For AISI 304 high number of pulses per burst i.e. long burst lengths, lead to higher maximum energy specific volumes
- But the trend is completely identical to the one of single pulses of corresponding pulse duration
- If ablation cooling should really exist it also identically takes place for ns pulses
- Quality aspects not considered here
- For further details we refer to [2]

[2]: D. Förster et al, „Review on Experimental and Theoretical Investigations of Ultra-Short Pulsed Laser Ablation of Metals with Burst Pulses", Materials 14(12), 3331 (2021)

Scale-Up Strategies

Single Pulse Strategies

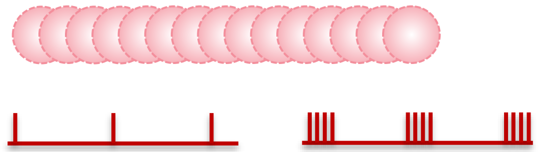
- Fast scanning



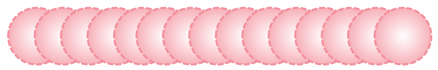
  - limits just discussed

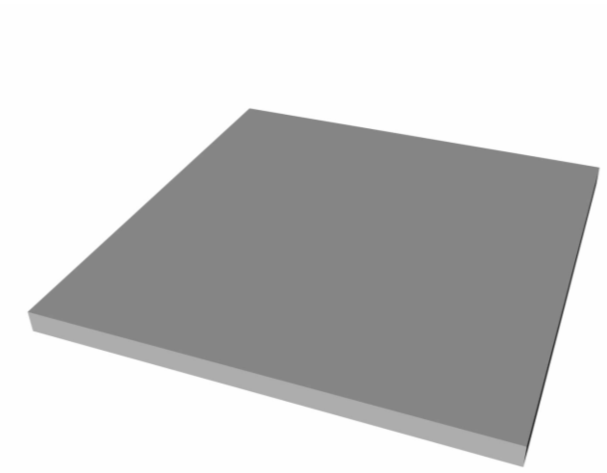
Multipulse Strategies

- Pulse Bursts:

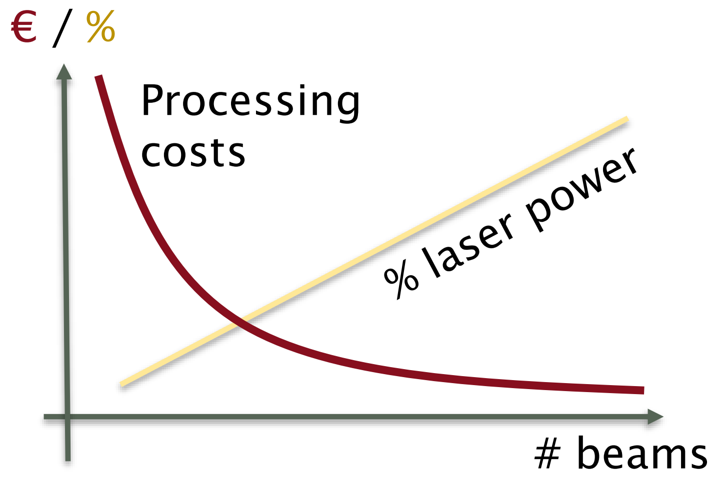


- Multispots:





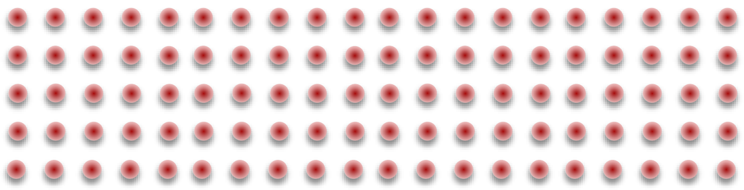
https://www.pulsar-photonics.de



- Limited to periodic structures

Multi Pulse Drilling

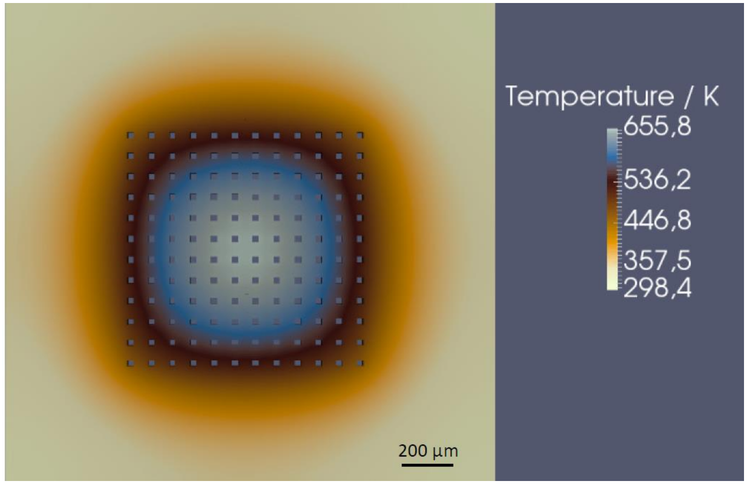
- Standard percussion drilling with $n \times n$ spots
- Change position with galvo scanner



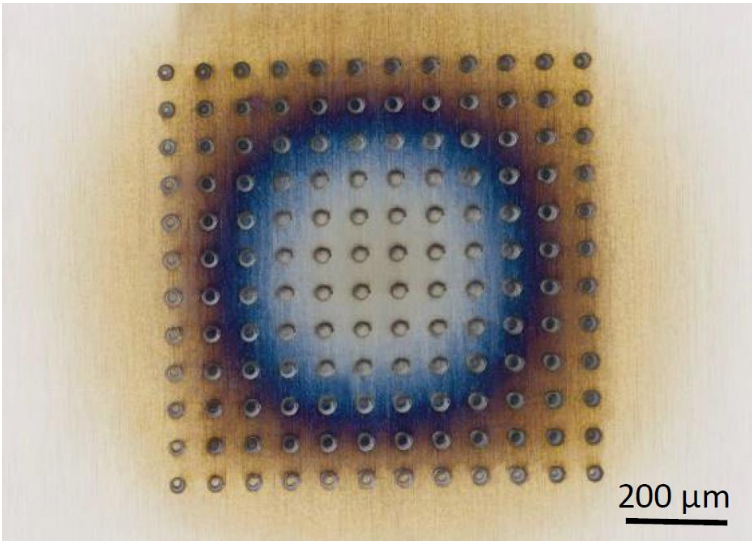
- The high total energy may lead to heat accumulation problems.

- Parallel machining with 12×12 Spots [8]

- Simulation



- Observed annealing



[8]: D. Gillner et al, „High Power Laser Processing with Ultrafast and Multi-Patallel Beams", JLMN Journal of Laser Micro/Nanoengineering 14(2), 129-137 (2019)

Optimized Galvo Scanning by Synchronization

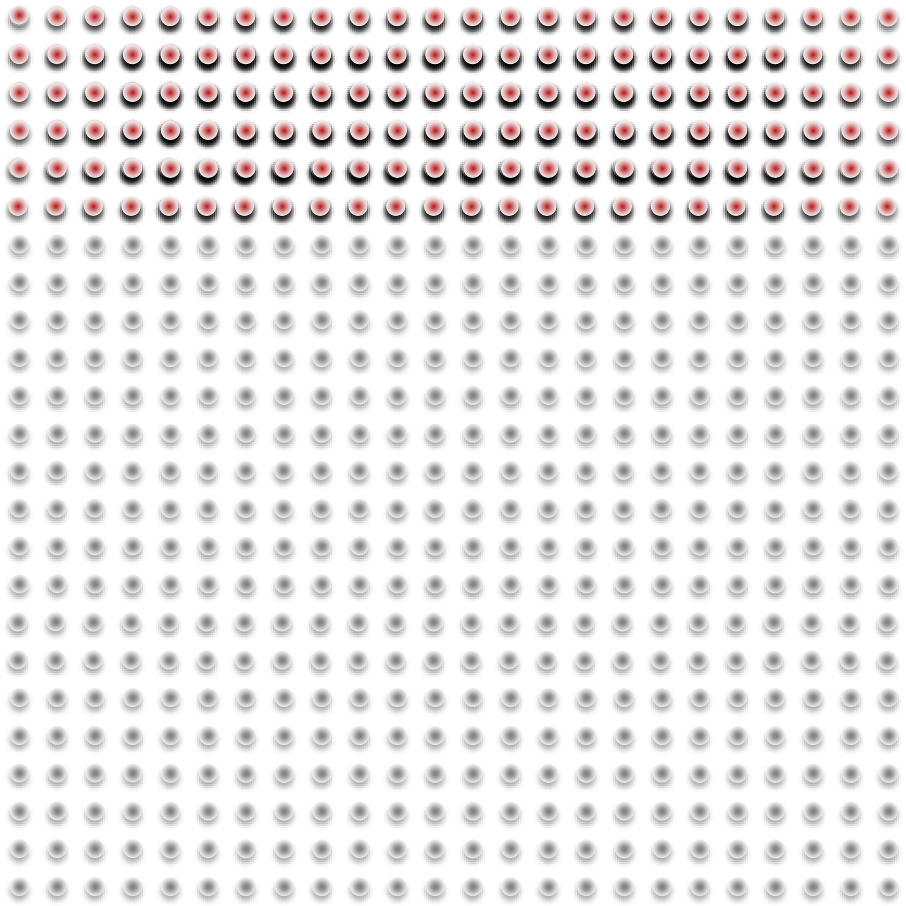
Free Running Scanner Trajectory for Bi-Directional Marking

Synchronized Scanner Trajectory for Bi-Directional Marking

- Free running
- Diffuse spot pattern
- Laser- and line-frequency do not match

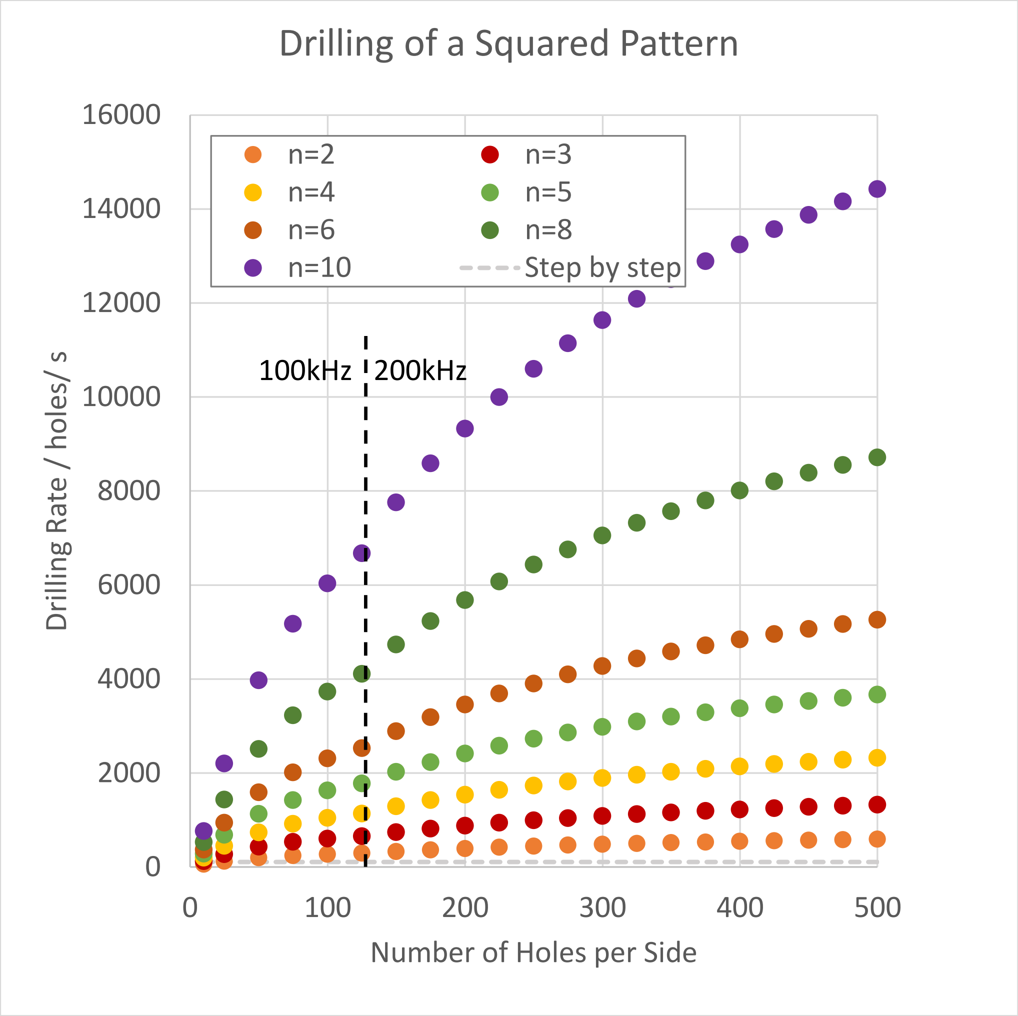
- Synchronized, laser-frequency is master
- Regular spot to spot pattern
- Fully reproducible from layer to layer

Drilling on the Fly by Multi Spot Stamping



- Stamp multi-spot pattern with nxn equally spaced spots
- Move pattern by one spot – spot distance d_x between two pulses

Drilling on the Fly by Multi Spot Stamping



- Stamp multi-spot pattern with nxn equally spaced spots
- Move pattern by one spot – spot distance d_x between two pulses
- For each point within a frame n^2 pulses are applied
  - $P_{av,n} = n^2 \cdot P_{av,1}$
  - $k_n = ceil\left(\frac{k_1}{n^2}\right)$
- For a frame with NxN spots
  - $(N + n - 2)^2$ points are marked
  - Mark length: $s_m = (N + n - 2) \cdot d_x$
- Several 1000 holes/s are achievable with minimum thermal load

Drilling on the Fly by Multi Spot Stamping

Single Spots:
675 Repetitions, P_{av} = 640 mW

- $\sim 150s$ for 100x100 holes -> $\sim 75 \frac{holes}{s}$
- for 300x300 holes $\sim 1000s$ -> $\sim 90 \frac{holes}{s}$

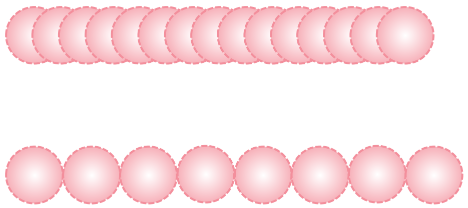
5x5 Spots with DOE:
27 Repetitions, P_{av} = 16 W

- $\sim 6s$ for 100x100 holes -> $\sim 1700 \frac{holes}{s}$
- for 300x300 holes $\sim 40s$ -> $\sim 2250 \frac{holes}{s}$

Scale-Up Strategies

Single Pulse Strategies

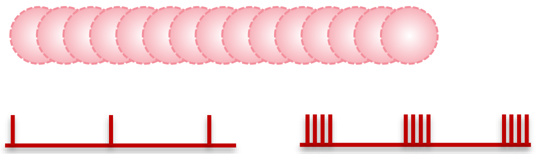
- Fast scanning



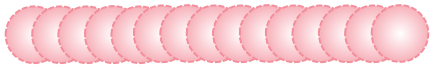
- limits already discussed

Multipulse Strategies

- Pulse Bursts:



- Multispots:

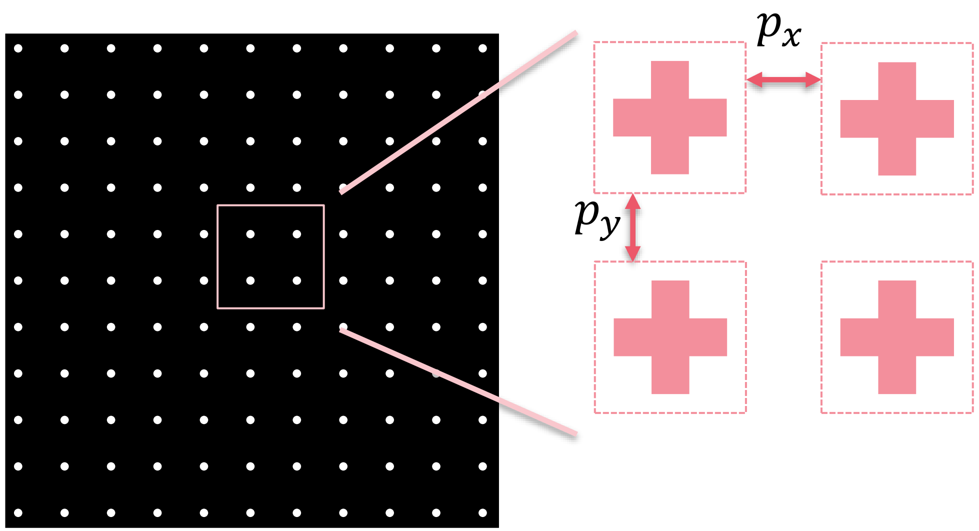


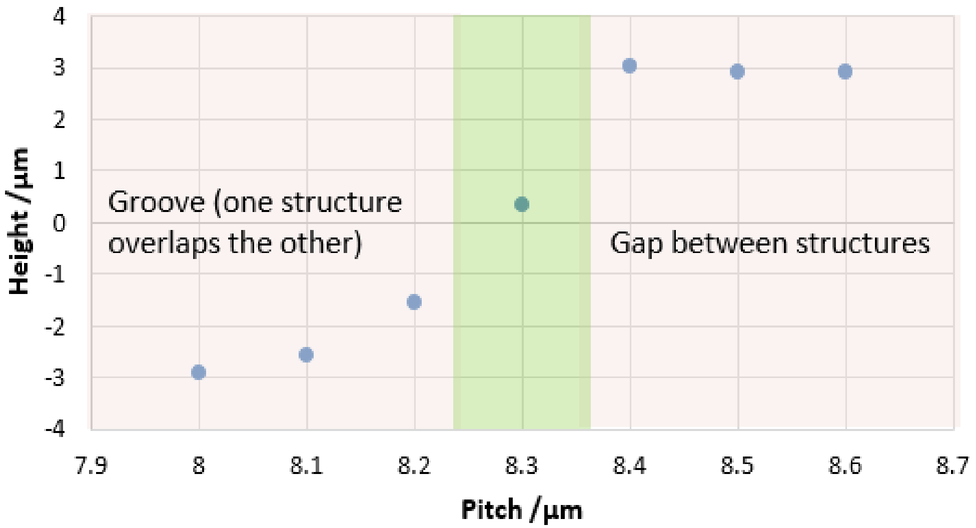
Beam Forming Strategies

- Directly forming of the desired pattern or parts of it by optical elements (DOE, SLM)

Synchronized Optical Stamping with DOE

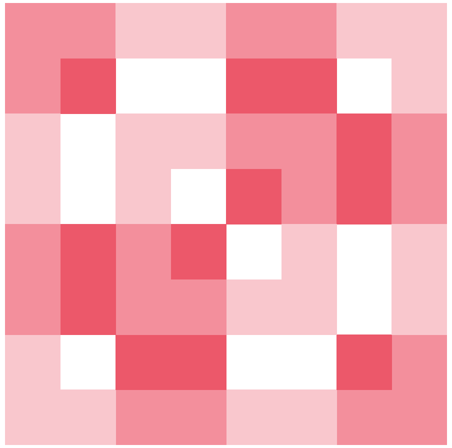
- DOE to generate an elementary cell and cage system to adjust correct pattern size
- Good beam quality is important (Gaussian beam) for correct structure
- Stitching with synchronized galvo scanner
- Pitch has to be adjusted in both directions

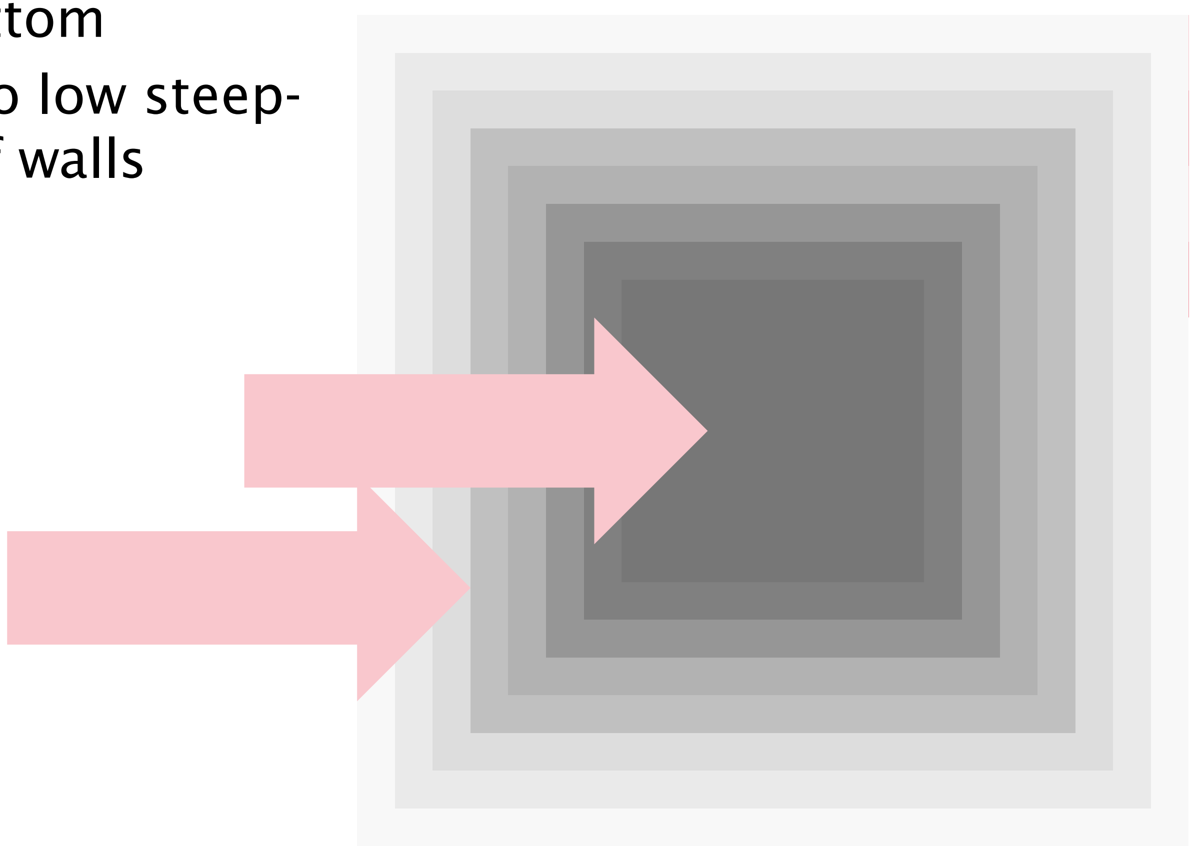




Homogeneous Ablation with 8x8 4 Level Top Hat DOE

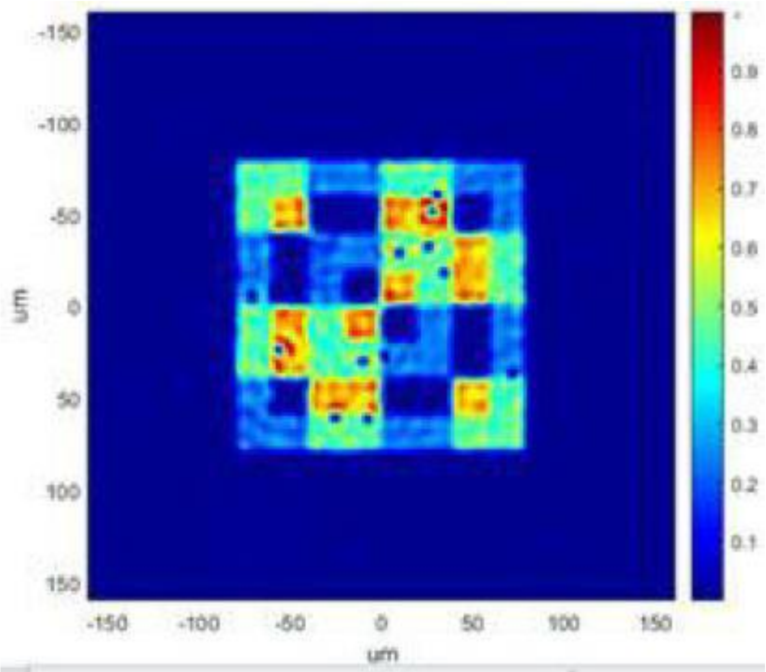
- Idea:
  - 8x8 squares of 20 µm side length
  - 4 level top hats 0%, 33%, 66%, 100%
  - Equal sum per line and row (400%)
- Synchronized scanning
- Set pulse – pulse and line – line distance to 20 µm
- Leads to homogeneous flat bottom
- But also low steep-ness of walls



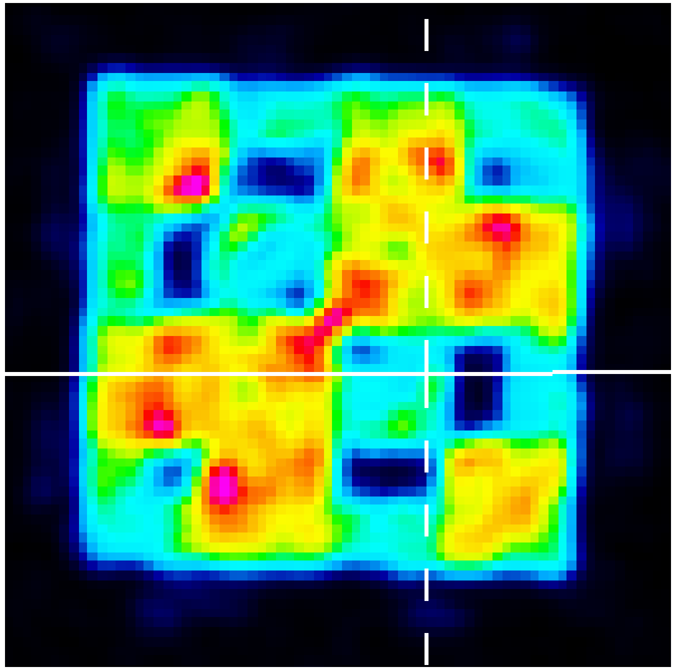


Homogeneous Ablation with 8x8 4 Level Top Hat DOE

- Calc. DOE Pattern:

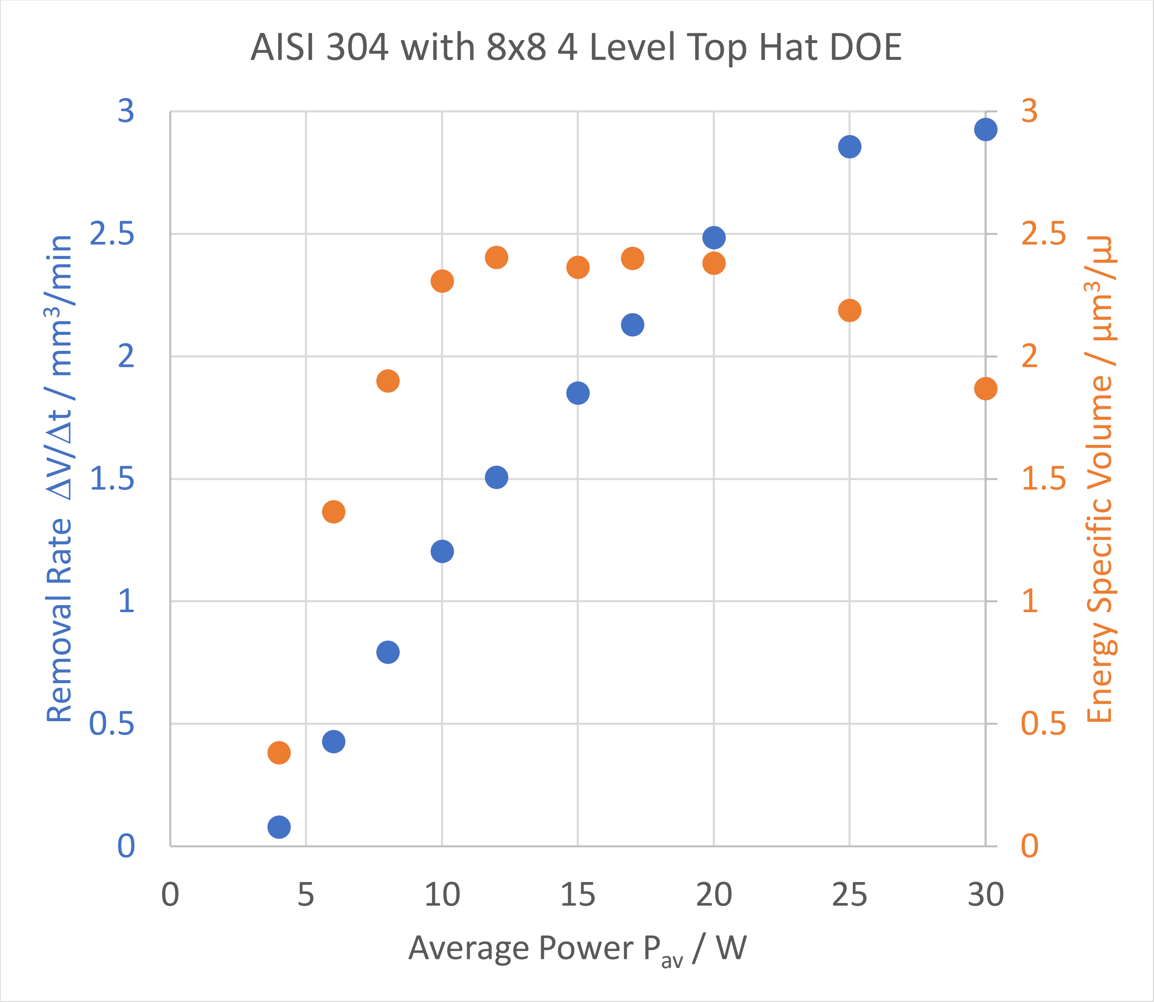


- Achieved Pattern



- Efficiency: 87%
- 14mm scanner aperture cuts higher diffraction orders
- Desired pattern not obtained
- Scanner with bigger aperture needed
- Experiments performed as planned

Homogeneous Ablation with 8x8 4 Level Top Hat DOE

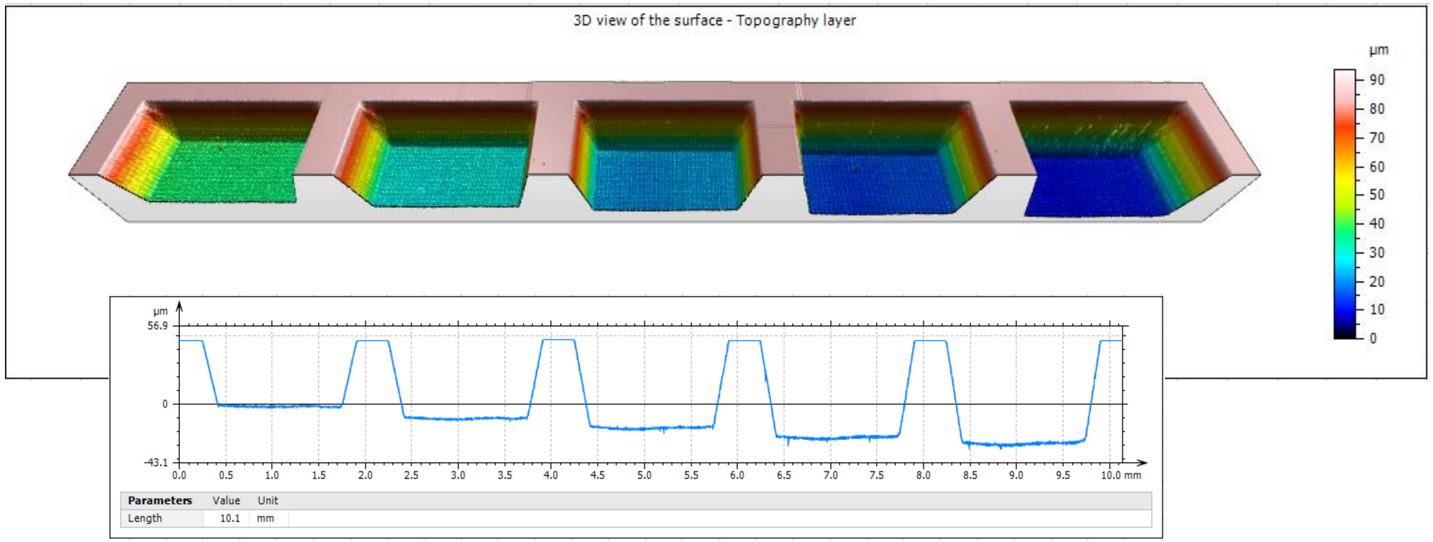


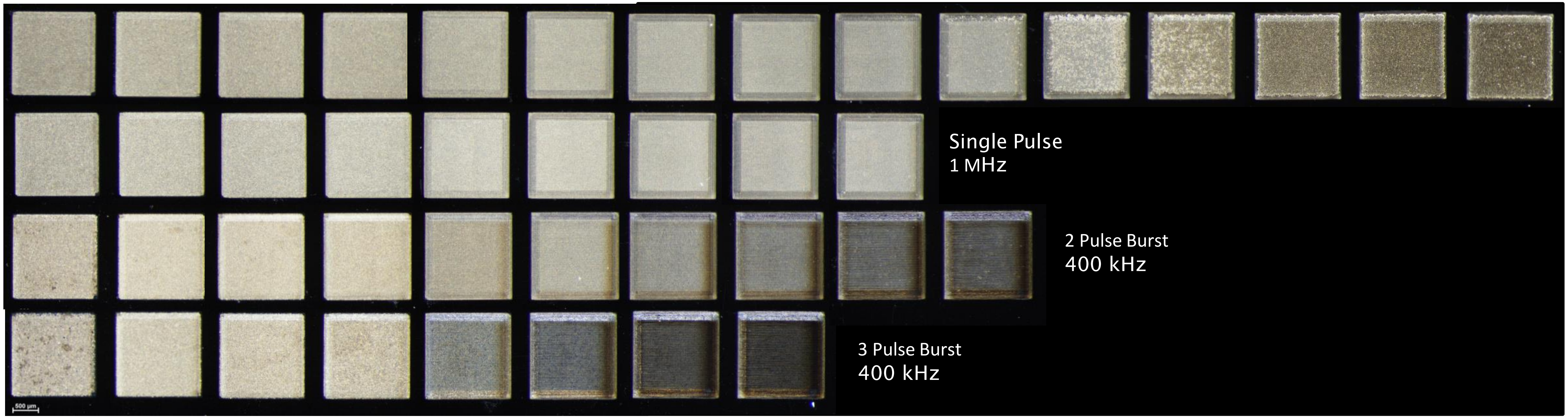
- "theoretical" maximum energy specific volume: $2.75\,\frac{\mu m^3}{\mu J}$ (top hat distribution, 4 Level DOE)
- Achieved value: $\approx 2.5\,\frac{\mu m^3}{\mu J}$
- $v_{mark,limit} = 20\,\frac{m}{s}\,, v_{mark,used} = 4\,m/s$
- Newest Results with single Pulses (@Lumentum) :

$$P_{av} = 180\,W, f_r = 1\,MHz, \frac{\Delta V}{\Delta t} \approx 16\,\frac{mm^3}{min}$$

4 Level Top Hat DOE: Stainless Steel

- homogeneous flat bottom with low walls steepness





Single Pulse
400kHz

Conclusion / Outlook

- The scale-up process of single beams with low pulse energy is limited and would demand extremely high marking speeds

- Working with high pulse energies
  - Bursts may help to distribute the energy among several sub-pulses
  - GHz bursts are like ns pulses, but can be used for hybrid processes
  - Multi – spot processing (DOE + Scanner) can be applied for periodic structuress
  - Beam forming with DOE allows the efficient use of high pulse energies and reduces the demanded repetition rate

- The combination of beam forming elements with conventional scanning devices is a promising approach to work with future 1000 W of average power.

Thank you for your kind attention