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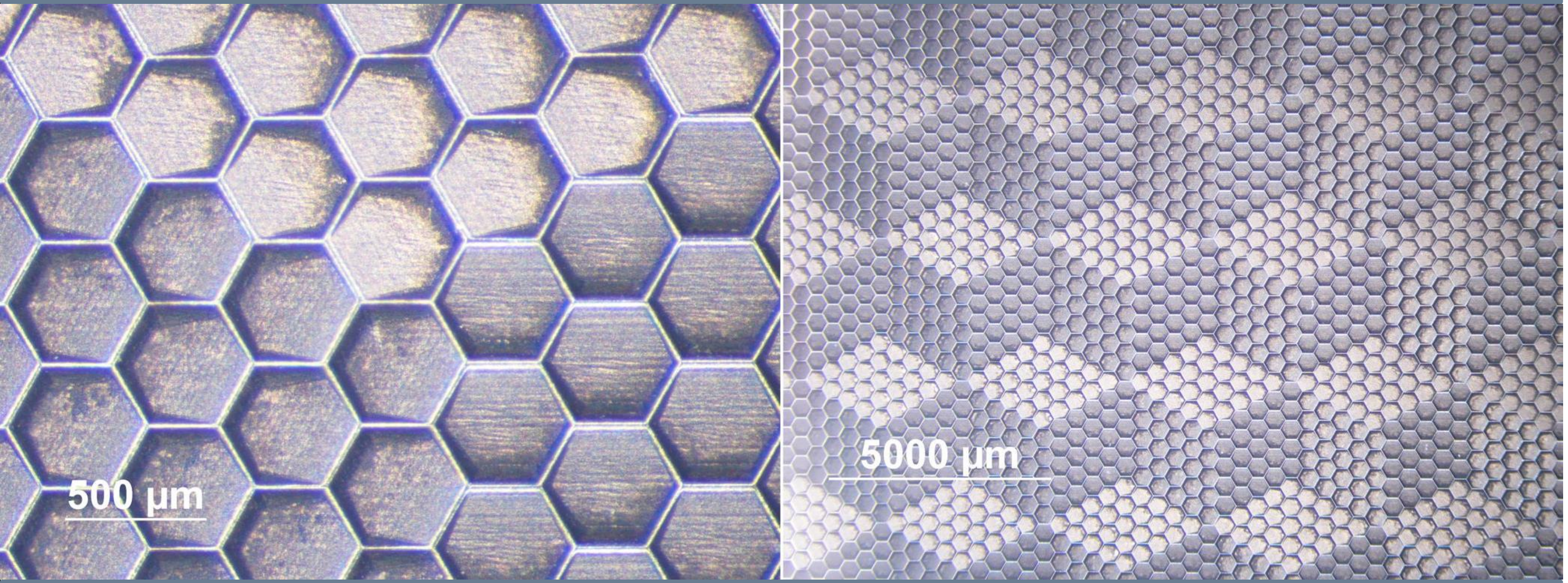

Intelligent Strategies for Smart Manufacturing

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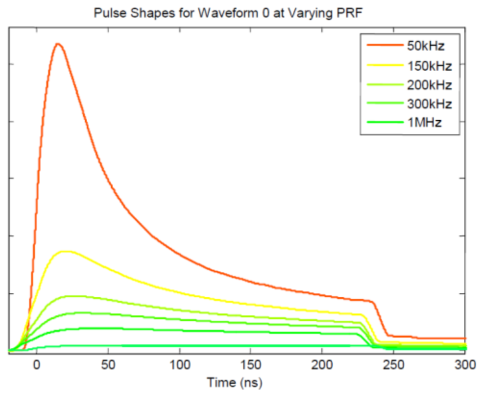
- Bern University of Applied Sciences / Institute for Applied Laser, Photonics and Surface Technologies

Outline

- Motivation
- Optimize Galvo Scanning
  - Marking on the Fly
  - Spot Size
- DOE
  - Multi-Spot
  - Combined with Synchronized Scanning
- Beam Forming with SLM
- Conclusions

Typical ns Lasers

IPG: YLPN-1-50-30-M	SPI: SP-050-P-A-EP-Z-F-Y	Coherent: AVIA NX 532-65
λ = 1064 nm	λ = 1059 - 1064 nm	λ = 532 nm
P_{av} = 30 W	P_{av} = 50 W	P_{av} = 65 W
$E_{p,max}$ = 1 mJ	$E_{p,max}$ > 1.0 mJ	$E_{p,max}$ = 433 µJ @ 150 kHz
$\Delta\tau$ = 50 ns	$\Delta\tau$ = 6 - 500 ns	$\Delta\tau$ = < 45 ns up to 150 kHz
f_{range} = 30 – 200 kHz	f_{range} = 1 kHz – 1 MHz	f_{range} = single – 300 kHz
M^2 < 2	M^2 < 1.6	M^2 < 1.3



Typical ps/fs Lasers

Lumentum: PB2

- λ = 1064 nm
- P_{av} = 50 W
- $E_{p.max}$ = 200 µJ
- $\Delta\tau$ = 10 ps
- f_{range} = single – 8 MHz
- $M^2 < 1.3$

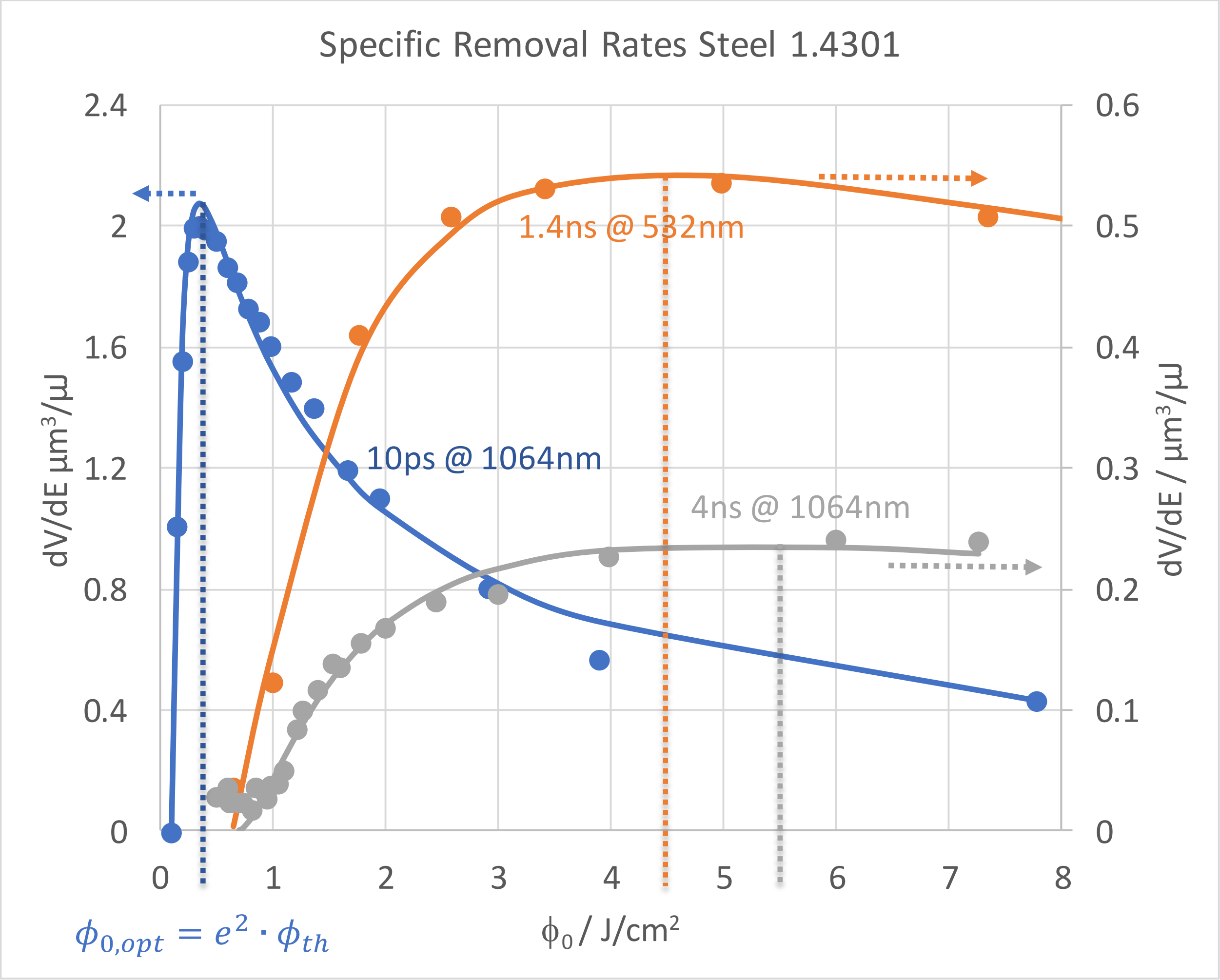
Amplitudes: Satsuma HP3

- λ = 1030 nm
- P_{av} = 50 W
- $E_{p.max}$ = 40 µJ
- $\Delta\tau$ < 350 fs
- f_{range} = single – 40 MHz
- $M^2 < 1.3$

LightConversion: PH1-20

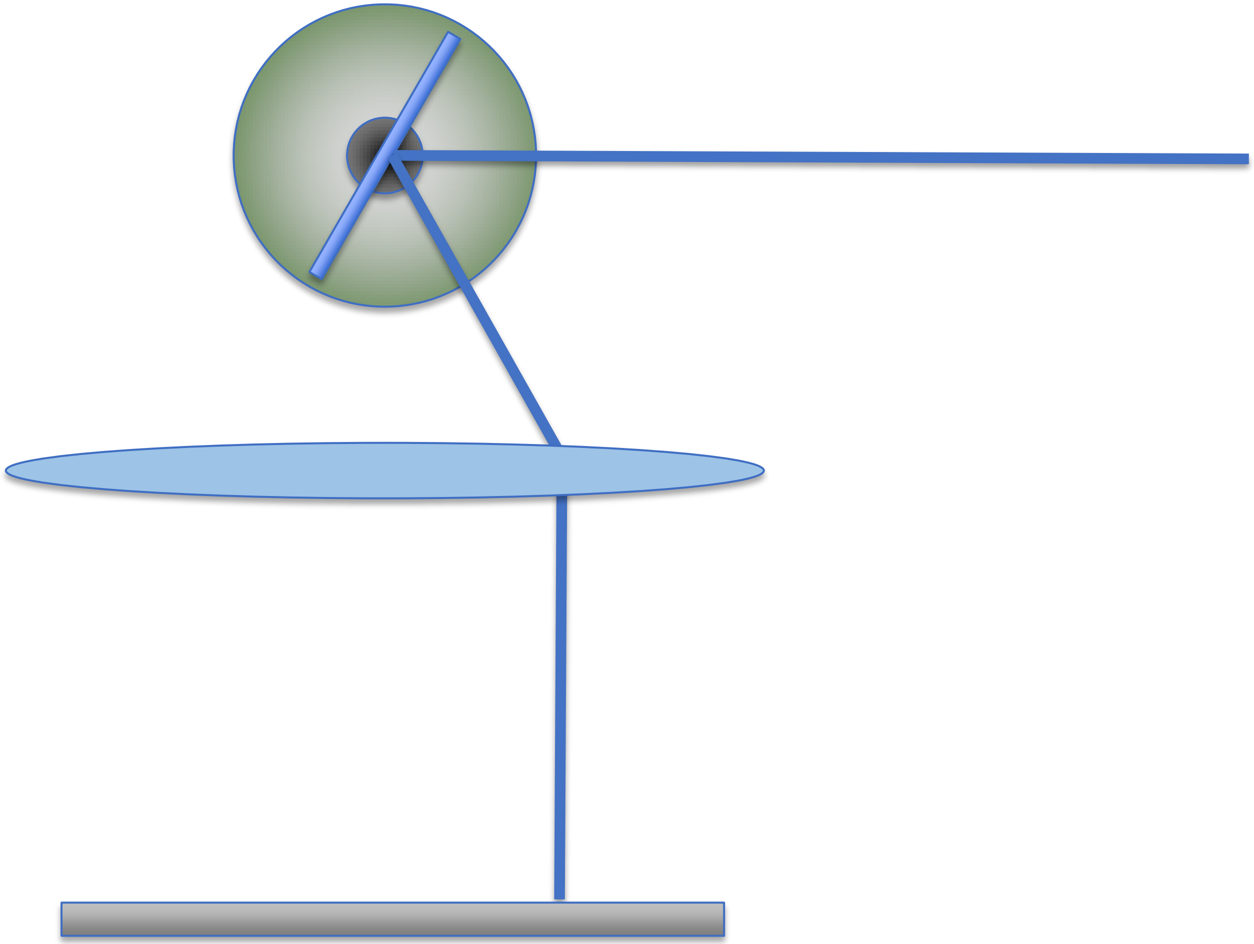
- λ = 1028 nm
- P_{av} = 20 W
- $E_{p.max}$ = 200 (400) µJ
- $\Delta\tau$ < 290 fs
- f_{range} = 1 kHz – 1 MHz
- $M^2 < 1.2$

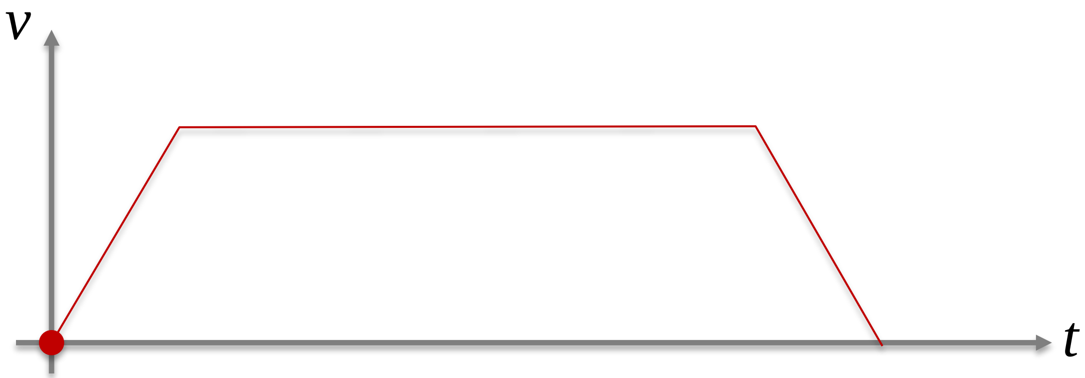
ns vs ps/fs: Processes and Systems



- Processes with ps/fs often
  - lead to better quality
  - show higher efficiency
  - need significantly lower pulse energy
- Generally USP lasers have
  - lower pulse energies
  - higher repetition rates
  - better beam quality
  - significantly higher prices
- Just replacing a ns with a ps/fs laser is not effective
- Adaption of processes and strategies is needed

Marking of a single line





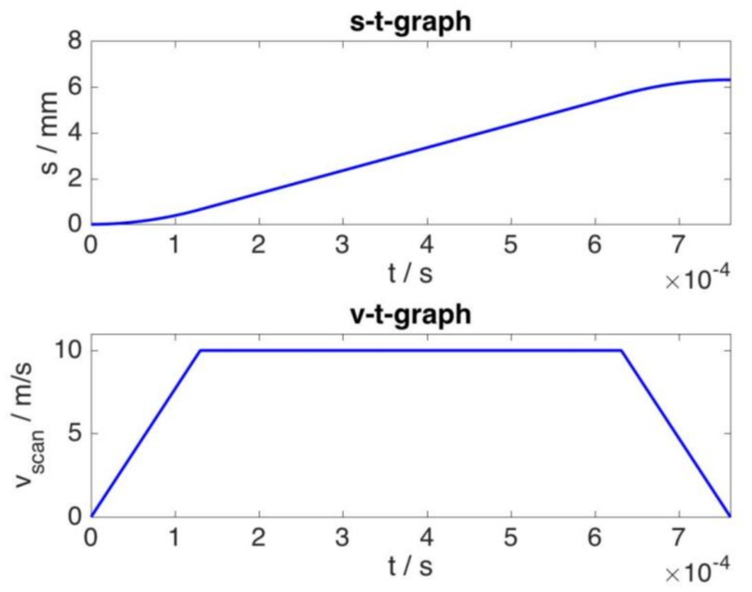
- Each line consist of
  - acceleration phase
  - phase of constant speed
  - deceleration phase

Optimization of Laser Micro Machining

- Optimizing the machining time

  - Marking of straight lines:
    - Acceleration with a_{max} (laser off)
    - Scanning at a constant velocity (laser on)
    - Deceleration with $a_{min} = -a_{max}$ (laser off)

- $t_{tot} = 2 \cdot t_a + t_v = 2 \cdot \frac{v_{scan}}{a} + \frac{s_{mark}}{v_{scan}}$



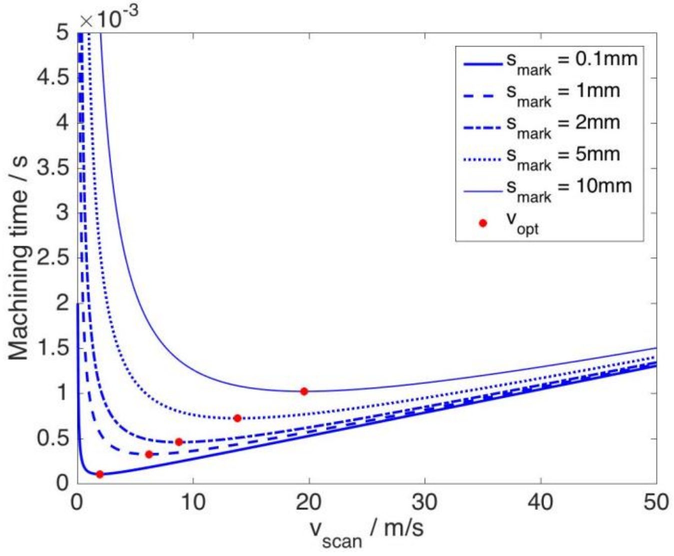
Optimization of Laser Micro Machining

- Minimum machining time observed at optimum scanning speed for a given line length
- High scan speeds even at short line lengths
- Optimum scan speed is limited by v_{max}

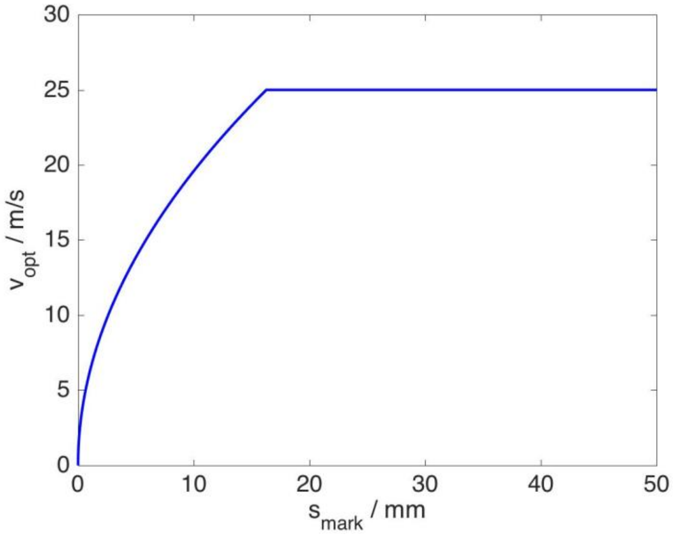
Calculations based on intelli*SCAN*$_{se}$10:

- $f_{obj} = 100\, mm$
- $\alpha_{max} = 768'000\, rad/s^2$
- $\omega_{max} = 250\, rad/s$

- Calculated marking time



- Optimum marking speed

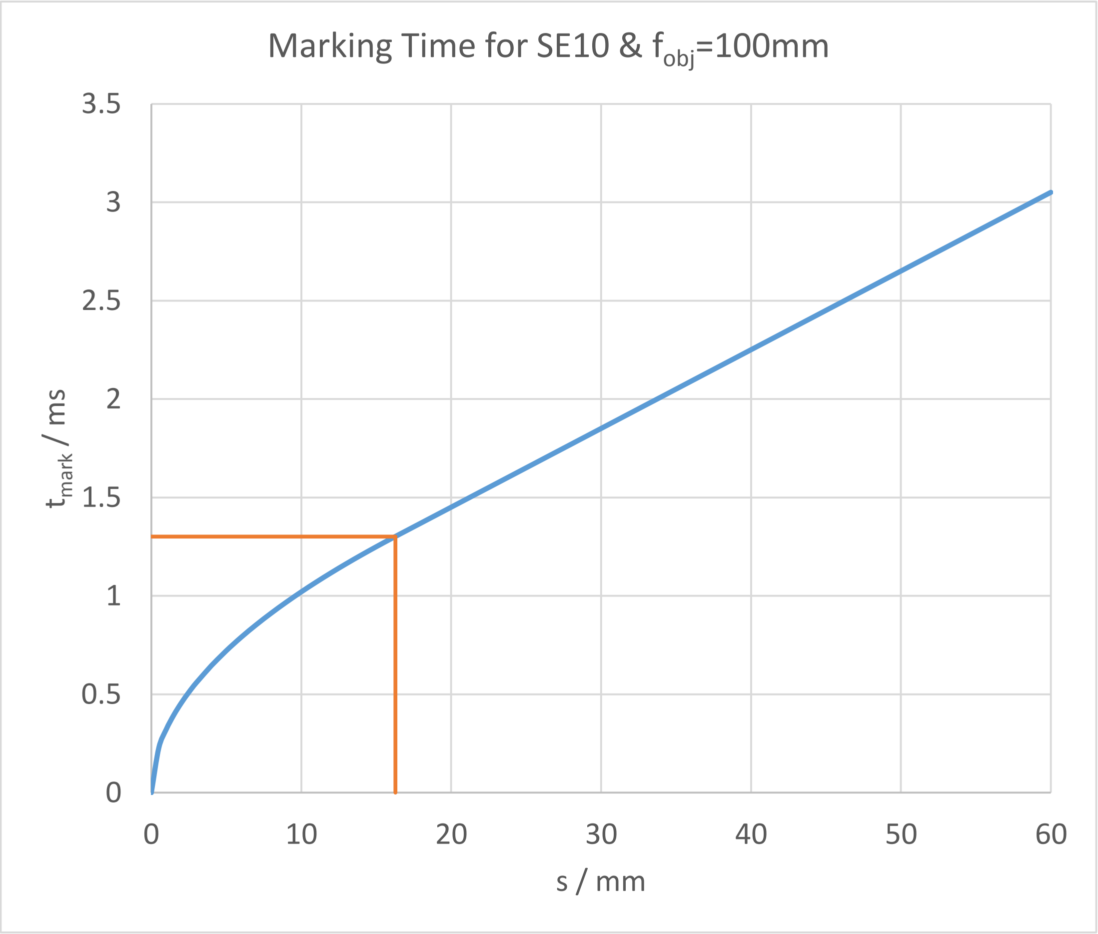


$$v_{mark} = \begin{cases} v_{opt} = \sqrt{\dfrac{s_{mark} \cdot a}{2}} \\ v_{max};\ v_{opt} > v_{max} \end{cases}$$

Line Marking Time

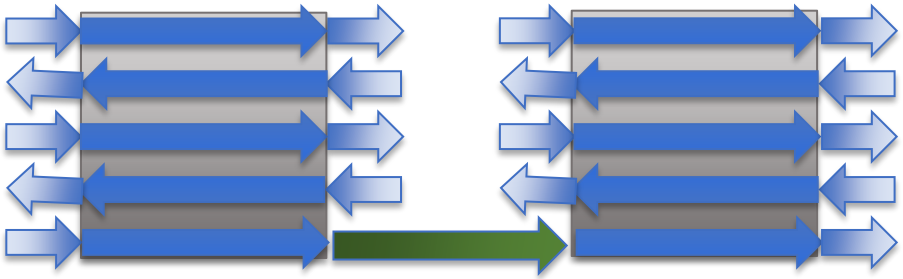
- t_{mark} depends on the line length
  - Up to $s_0 = 2 \cdot v_{max}^2 / a$ marking with v_{opt} is possible
  - Longer lines marked with v_{max}

$$t_{mark} = \begin{cases} 2 \cdot \sqrt{\frac{2 \cdot s}{a}} & s < s_0 \\ 2 \cdot \frac{v_{max}}{a} + \frac{s}{v_{max}} & s \geq s_0 \end{cases}$$

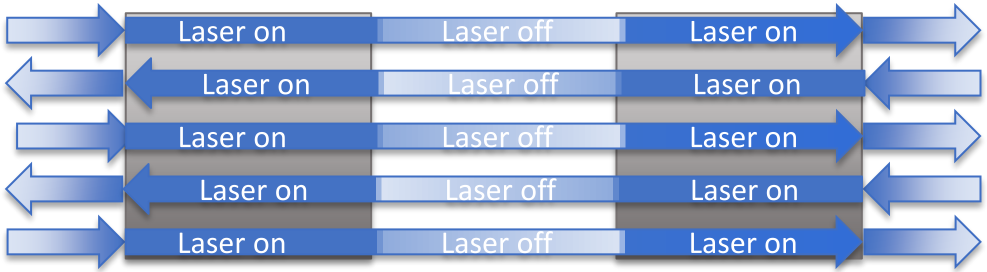


Marking on the Fly

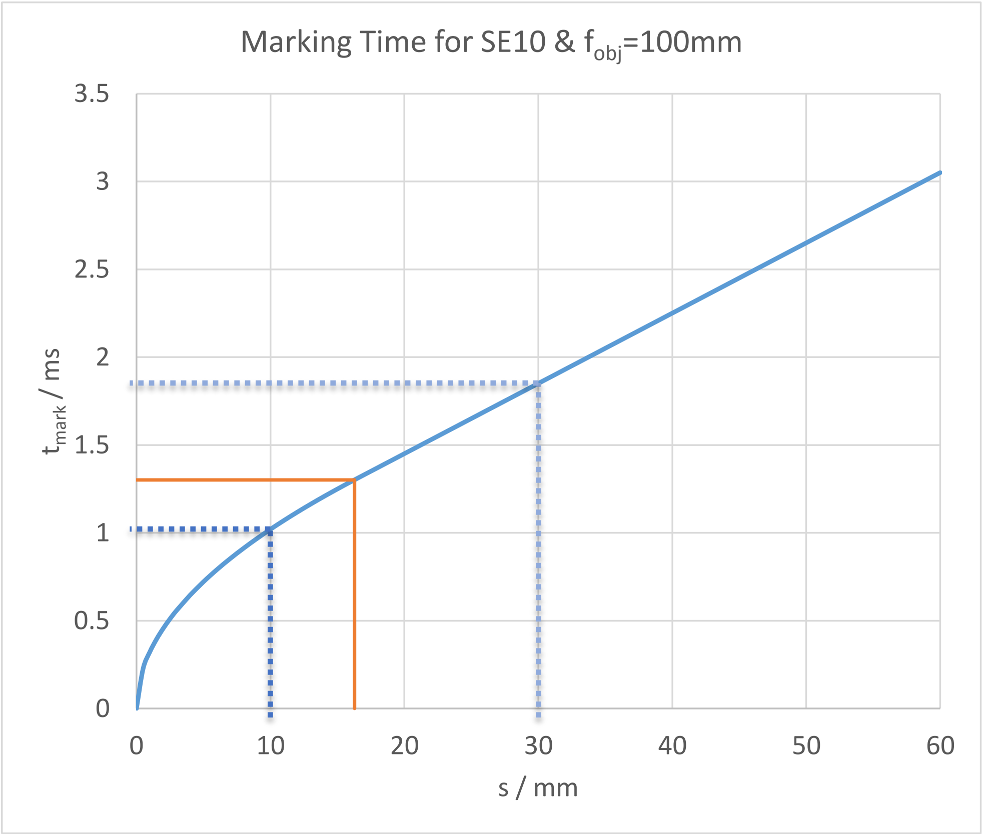
- Standard: Square by square



- On the fly

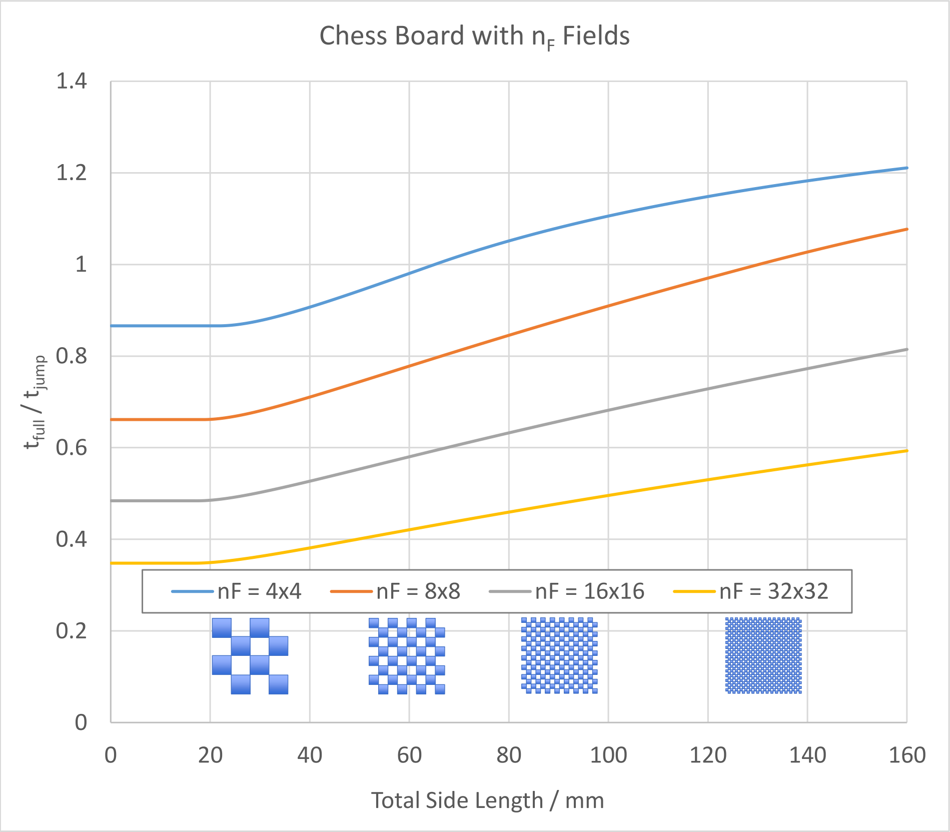


- How to mark a series of squares?
- Can on the fly marking by faster?

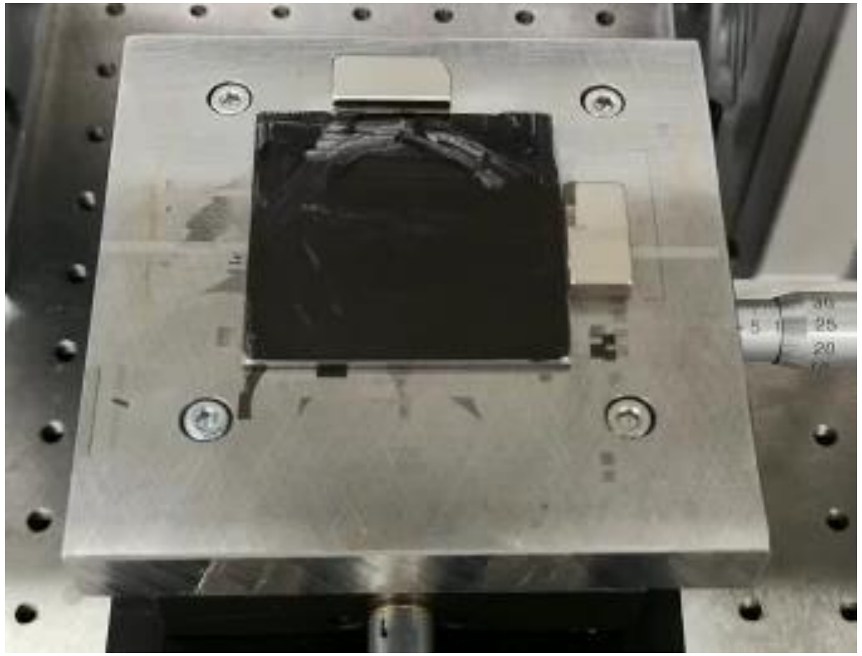


Marking on the Fly

Chess boards



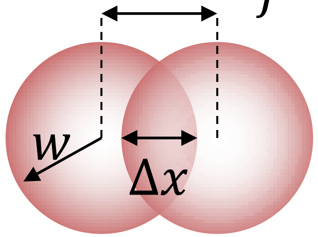
Not limited to straight lines



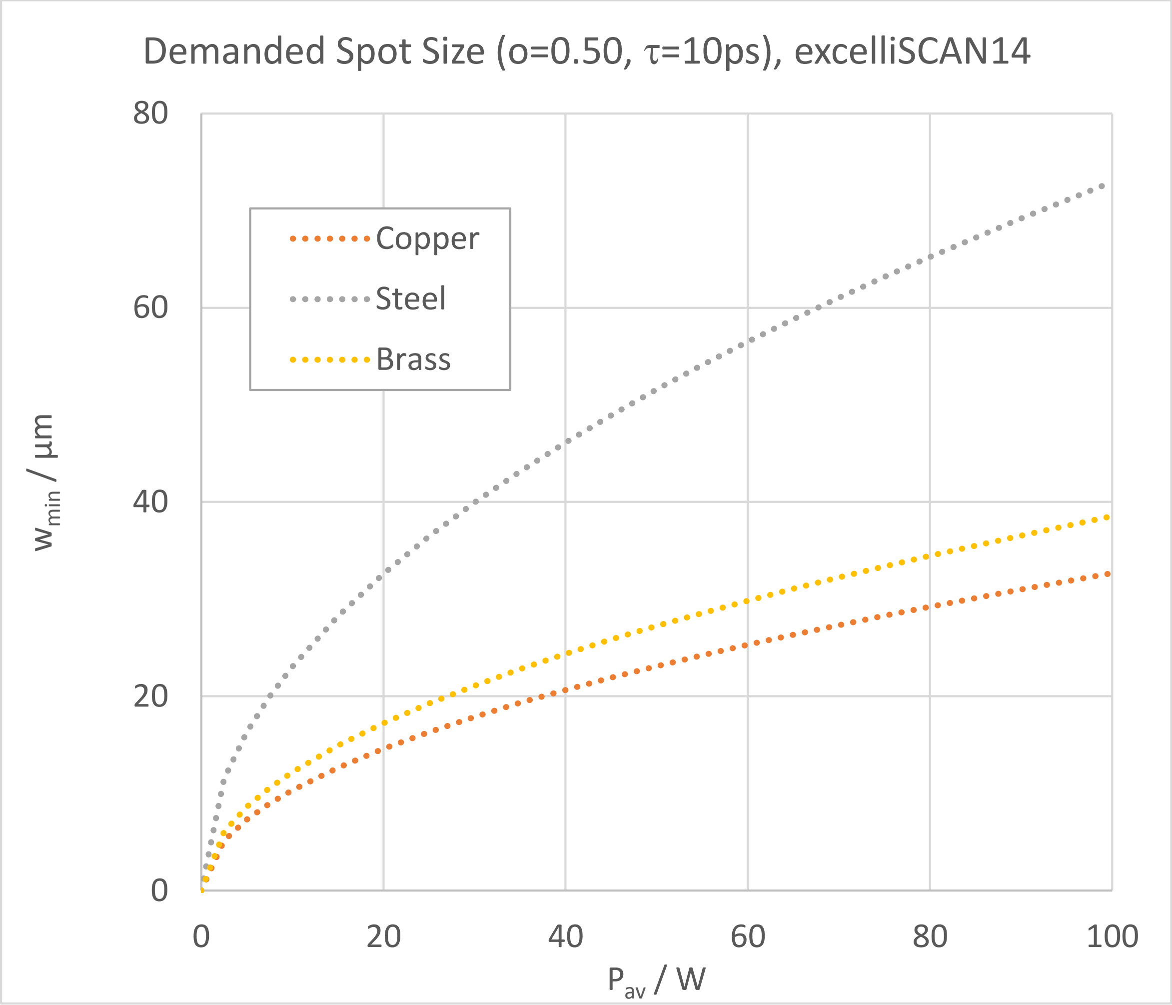
Optimized Spot Size

- $\phi_{0,opt} = e^2 \cdot \phi_{th}$
- The focal length f_{obj} directly scales with
  - Spot size w_0
  - Maximum marking speed v_{max}
- Optimized Spot size w_{min}
  - For a given overlap

$$p_x = \frac{v_{max}}{f}$$

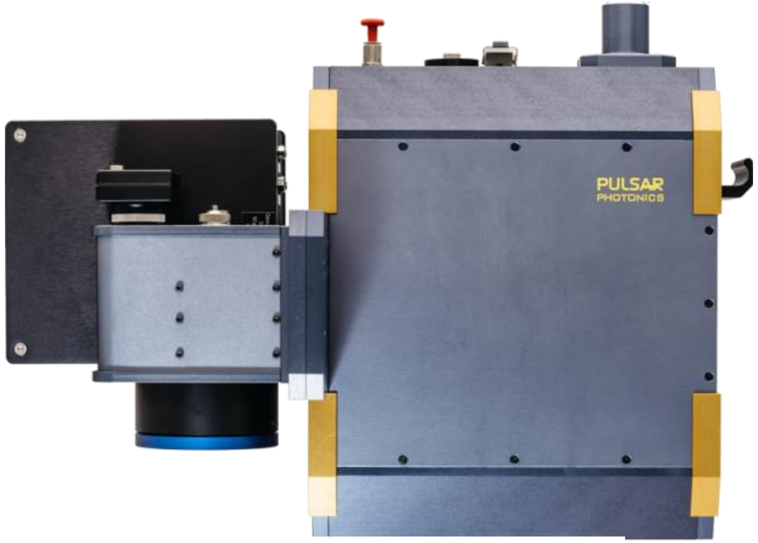


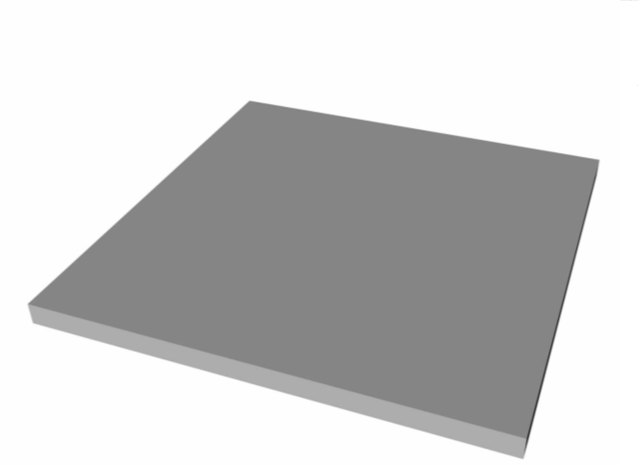
$$o = \frac{\Delta x}{2w} = 1 - \frac{p_x}{2 \cdot w}$$



Based on excelliSCAN14

Multispot Processing: Industrialized Solution

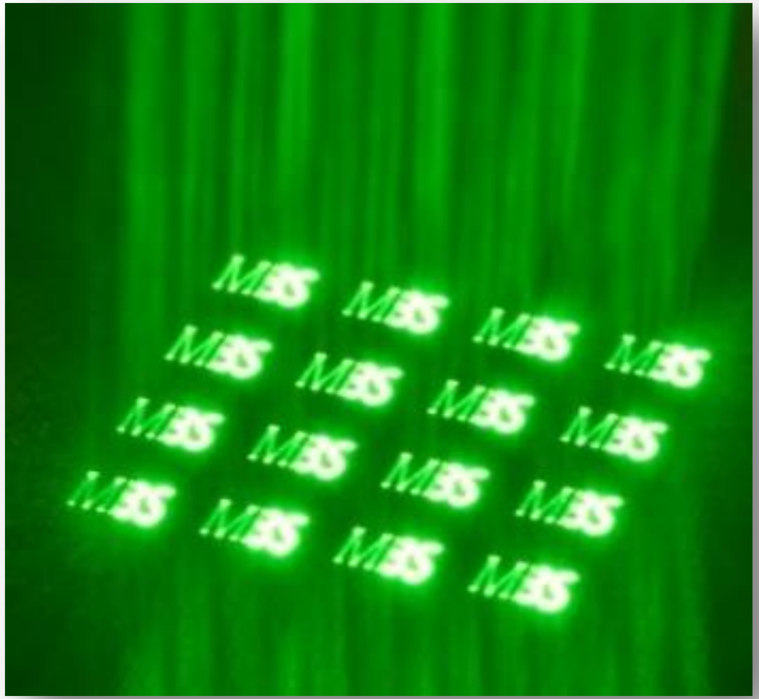




- Combination of beam splitting unit and scanning system
- Max. Power: 150 W
- 532nm or 1064nm
- Field Size: 5x5mm (f = 100 mm objective)
- Spot Position Error <3 μm

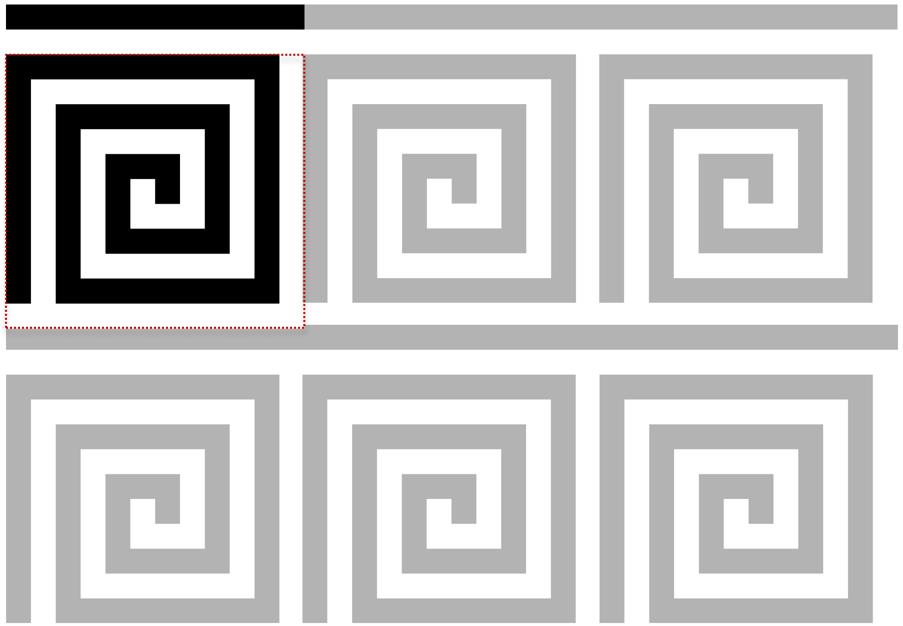
- restricted to periodical structures

- 16 parallel beams



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



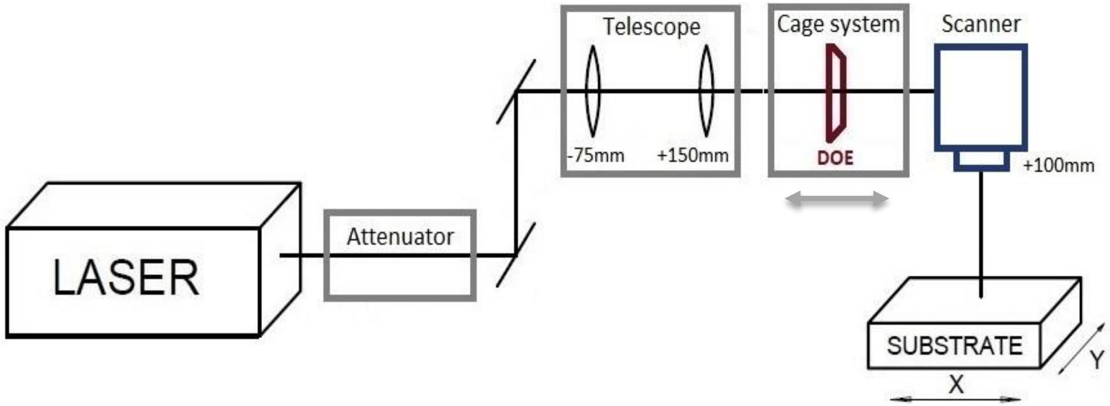
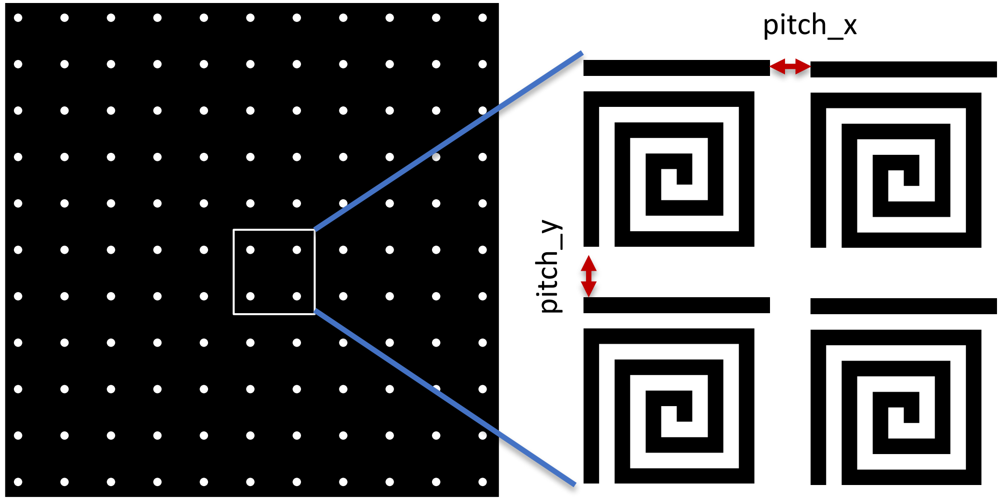
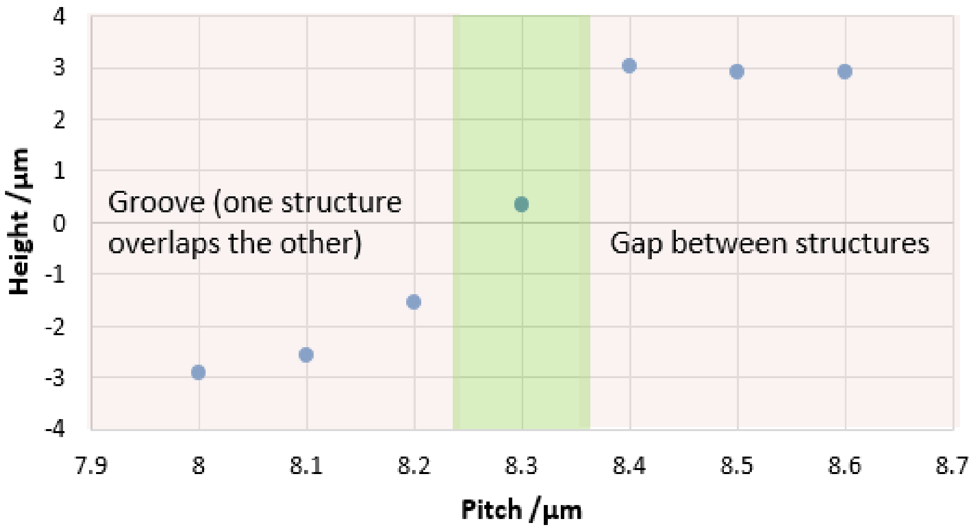


Fig 5. PicoBlade 2 setup

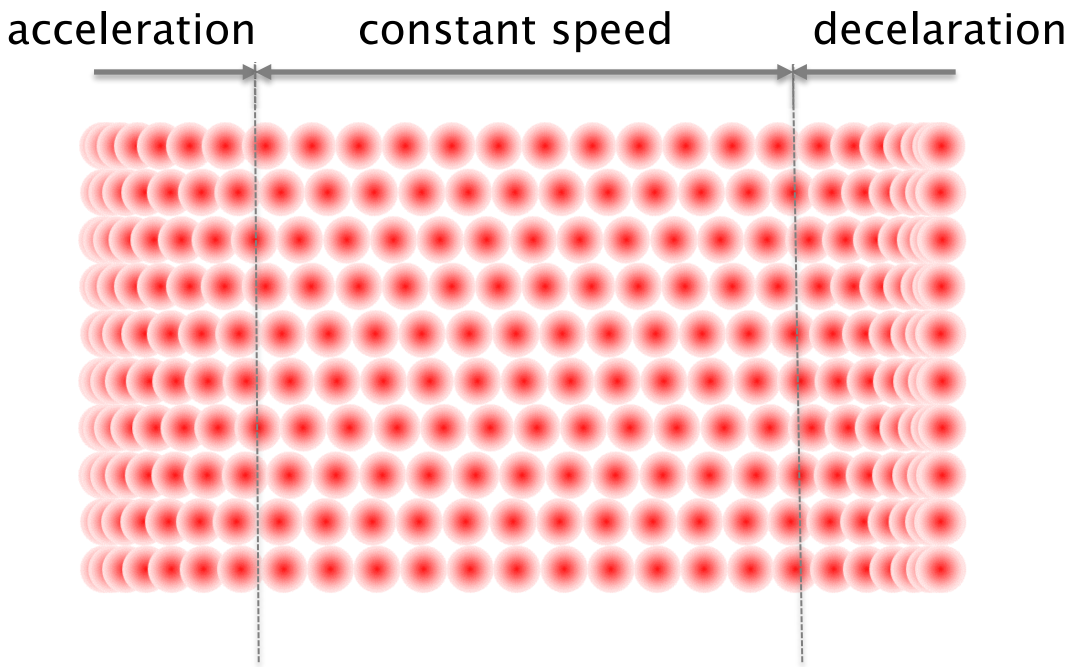
DOE combined with synchronized Galvo-Scanner

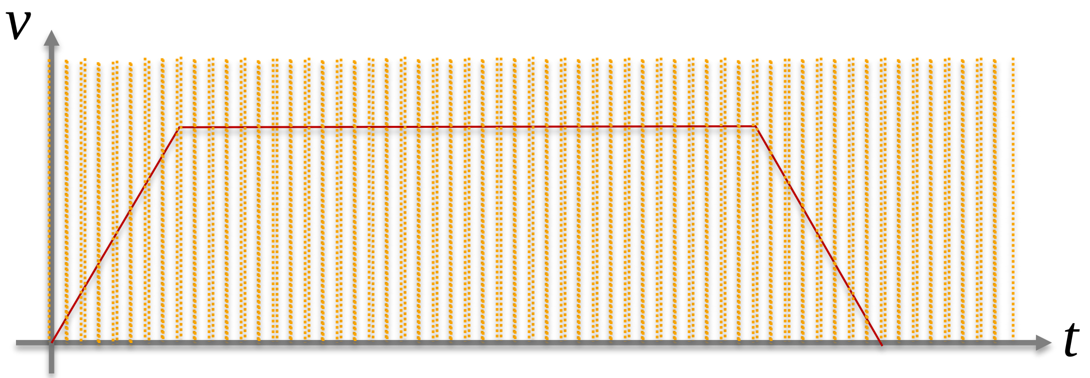
- Using only DOE and cage system to adjust correct DOE size
- Good beam quality is important (Gaussian beam) for correct structure
- Pitch has to be adjusted in both directions





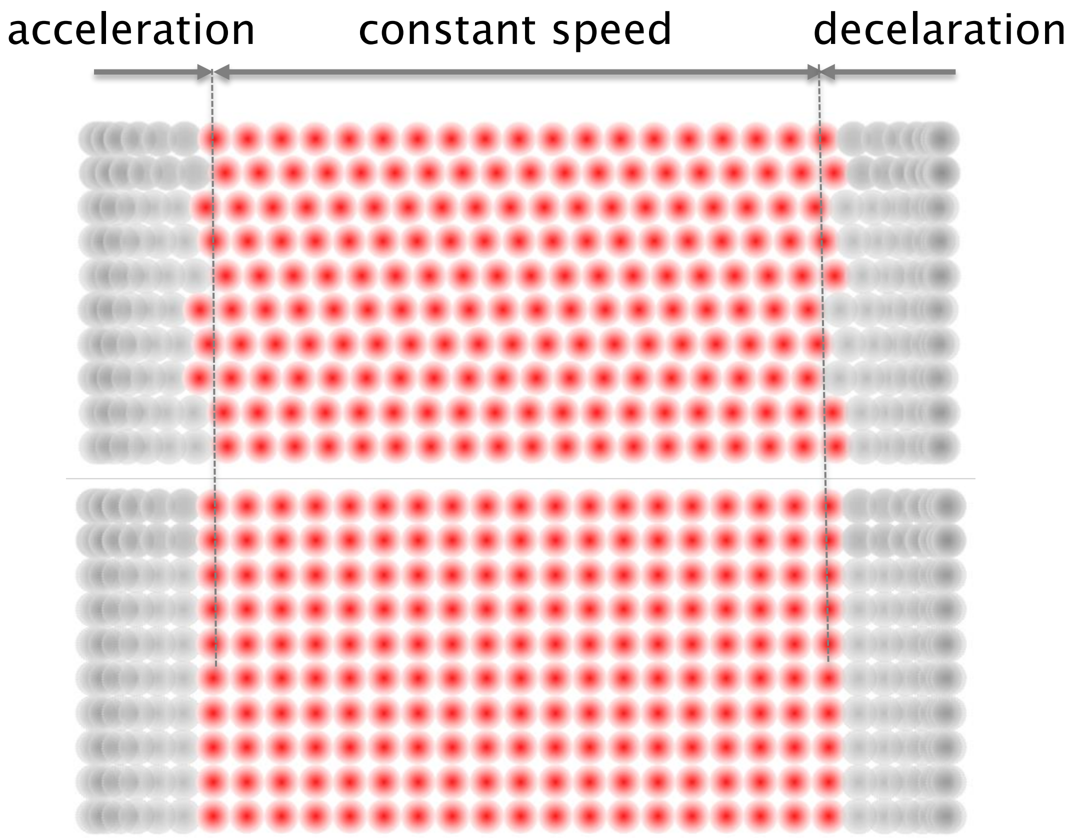
Full Synchronization: Marking of a straight line

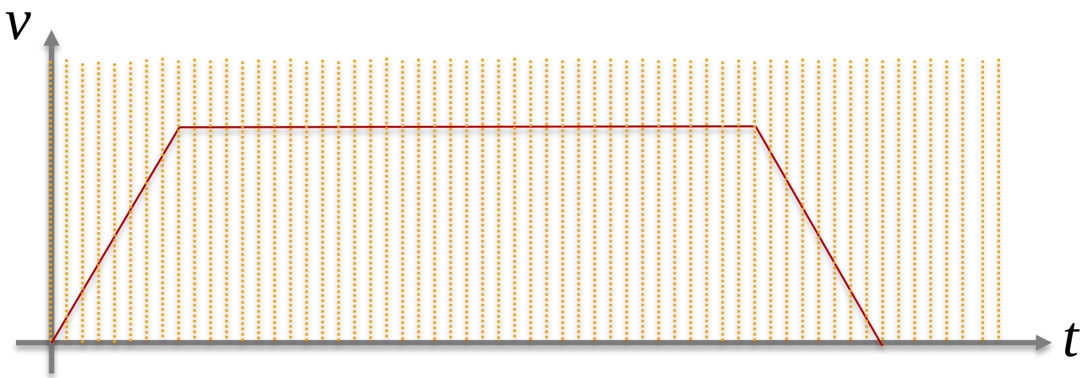




- The clock of the laser beam defines the position of the pulses in the line
- But the laser clock and the mirror motion are not linked together
- For the subsequent lines the laser clock is shifted relative to the start
- Leading to small differences in the position of the first pulse in the line

Full Synchronization: Marking of a straight line

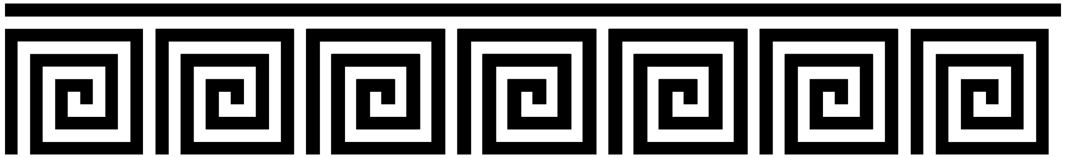


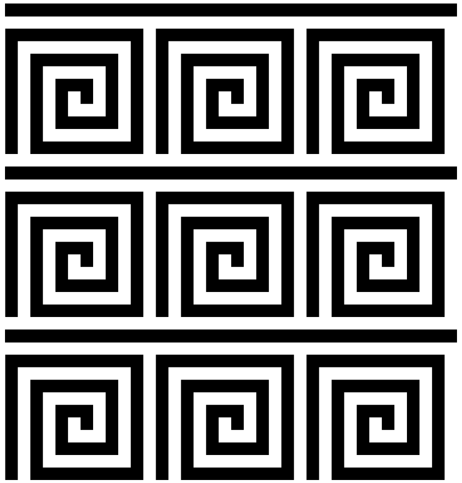


- The clock of the laser beam defines the position of the pulses in the line
- If the laser clock and the axis motion are synchronized highest precision is obtained
- Up to f_r = 16 MHz

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
- Pitch has to be adjusted in both directions
- Stitching with synchronized galvo scanner
- With correctly adjusted pitch and synchronized scanner also multiple elementary cells DOE’s can be used





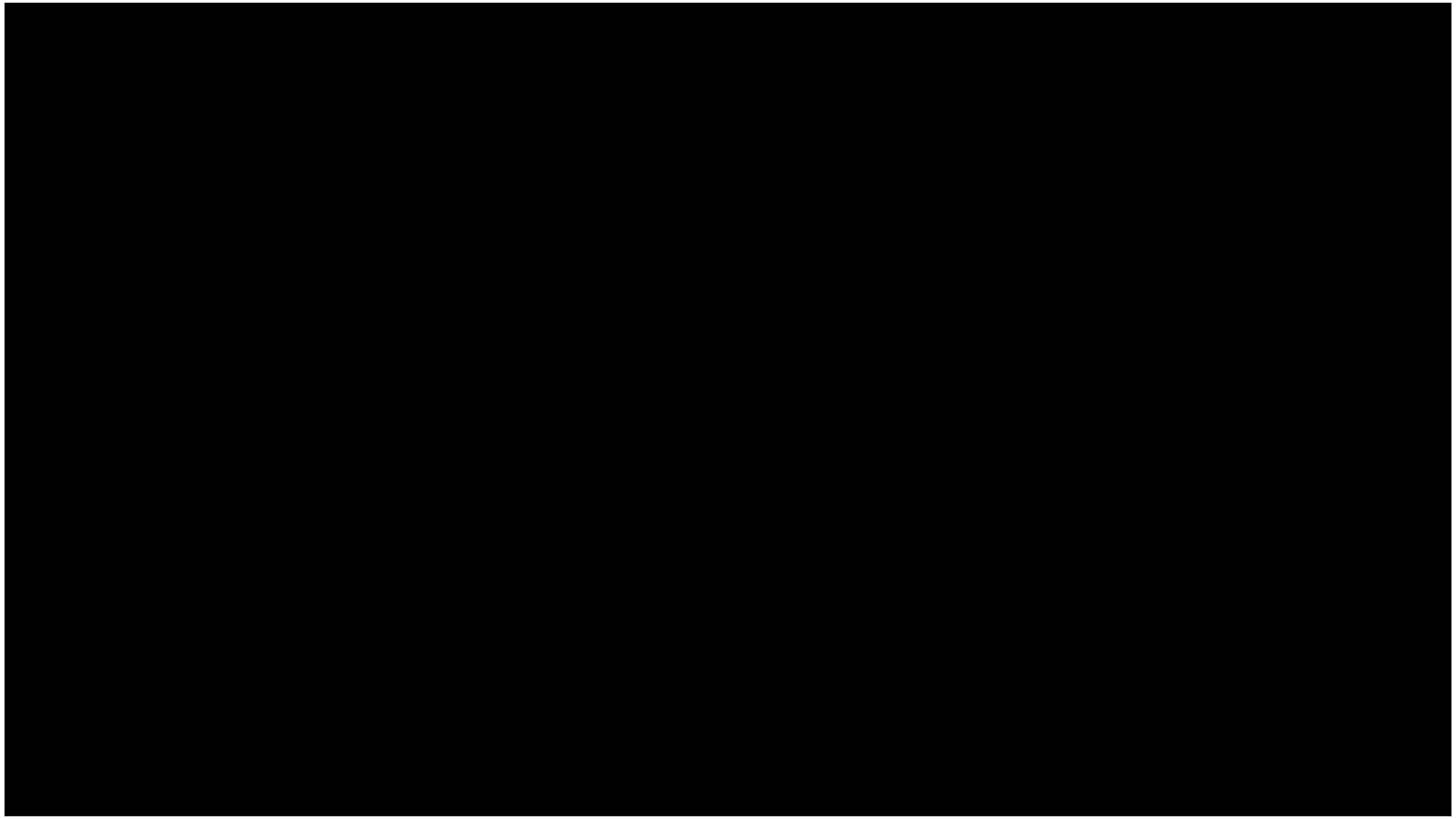
DOE combined with synchronized Galvo-Scanner

exelliSCAN synchronized

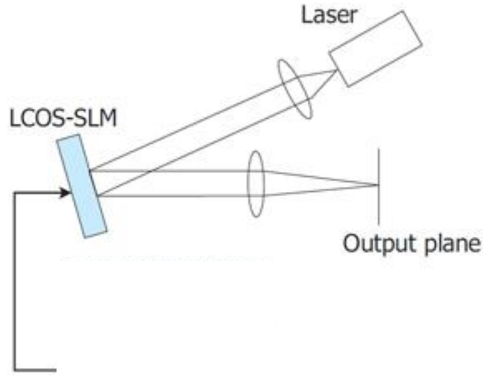
- f_{rep}=200kHz
- 250 layers
- 2.2µm depth
- 1 Elementary cell à 160 µm

	Time per layer	Process took	Machined area per time
5x5 mm	0.08 s	19.71 s	1.27 mm^2/s
10x10 mm	0.15 s	37.90 s	2.64 mm^2/s
20x20 mm	0.36 s	90.54 s	4.42 mm^2/s

20 x 20 mm



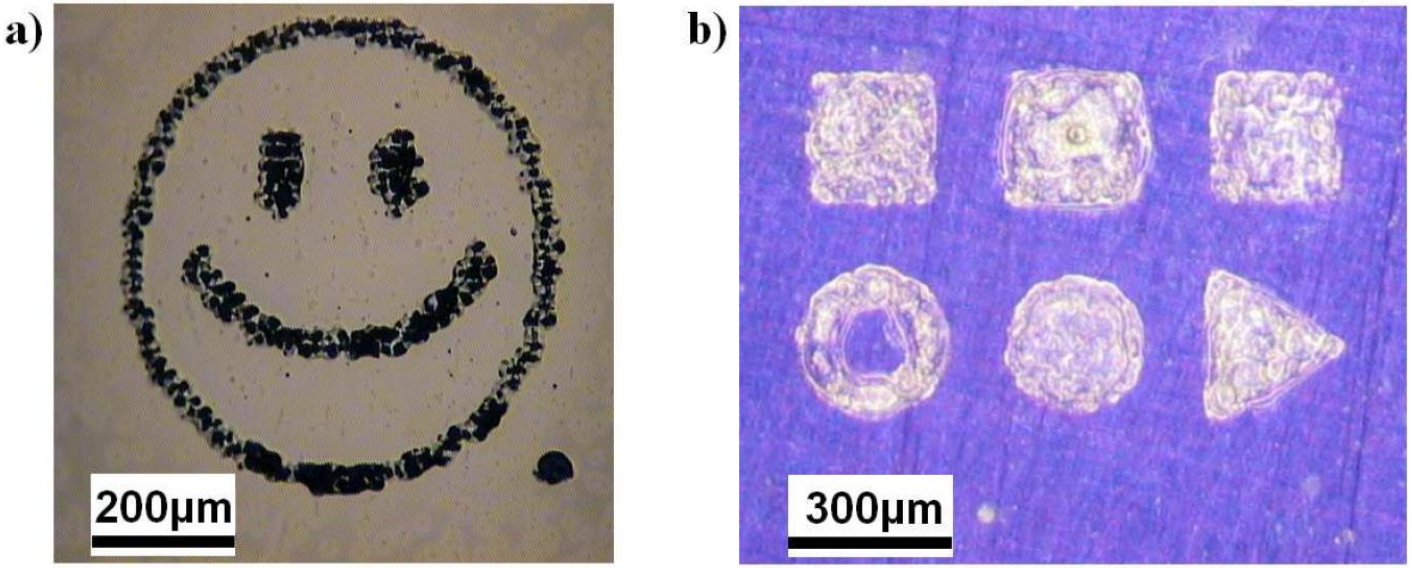
Typical SLM Set-Up



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

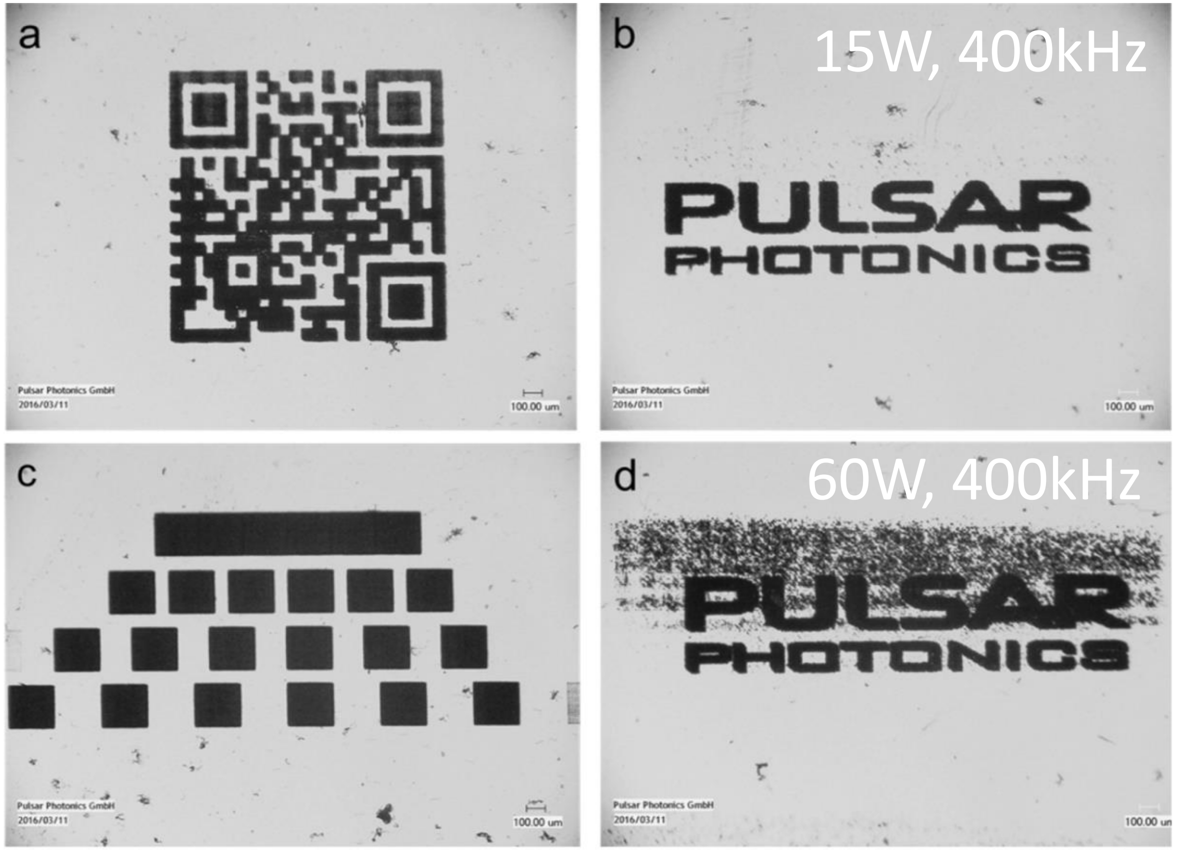
Beam Forming Example 2:



- Direct generation of a specific form by IFA
- Directly machined into stainless steel (65ns, 30kHz, 532nm, 14.7W, 3.2ms)
- Speckles observed in the patterns due to phase only modulation by the SLM

R. J. Beck, J. P. Parry, W. N. MacPherson, A. Waddie, N. J. Weston, J. D. Shephard, D. P. Hand, Opt. Expr., 18 (2010), 17059

Beam Forming Example 4: Industrial realisation



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

Conclusion

- To take full benefit of ultrashort pulses machining strategies have to be adapted
- Scanner
  - Optimize spot size
  - Marking on the fly, especially for short vectors
- Alternative approaches
  - Multi-spot strategies
  - DOE with Synchronized Scanner for repetitive Patterns
  - SLM for direct beam forming

- Introducing process know-how and optimized strategies into the control software and combine it with new sensors opens the door to real smart manufacturing

Thank you for your Attention