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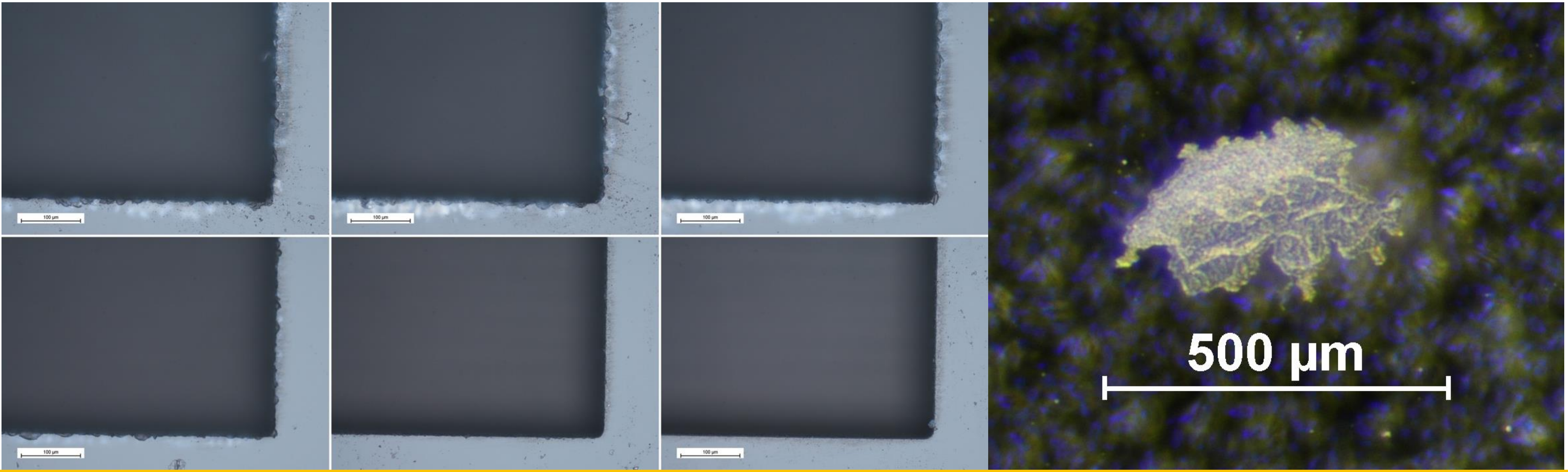

Super Short or Super Small: Exploring the Limits of Laser Microsprocessing with Industrial Grade Systems

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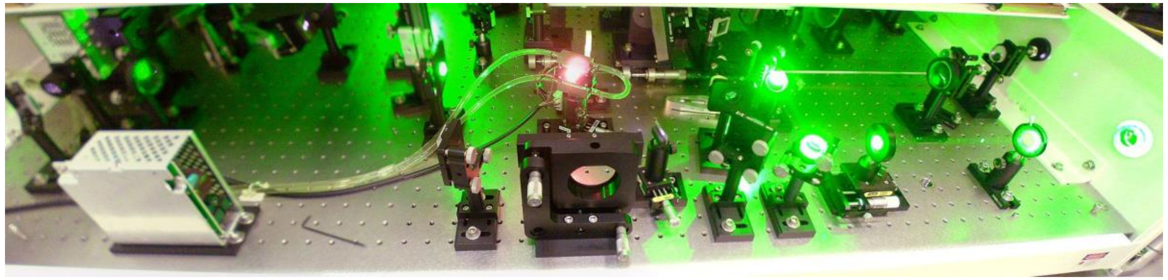
Super Short

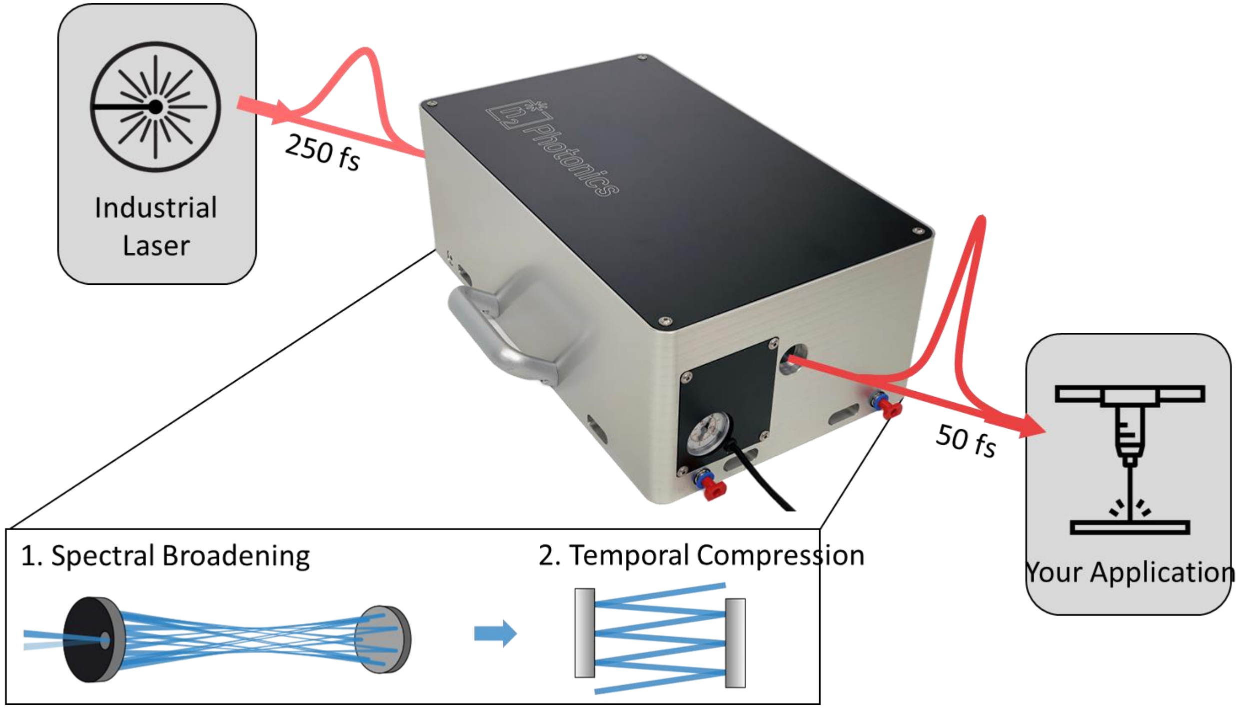
Motivation: Sub-100 fs Pulses



ODIN Ti-Sapphire laser in operation - Ti-sapphire laser - Wikipedia

- For long time the sub 100 fs regime was only accessible with Ti:Sapphire laser systems.
- They have the reputation to be complicate to operate and "demanding a physicist to drive them".

Motivation: Sub-100 fs Pulses

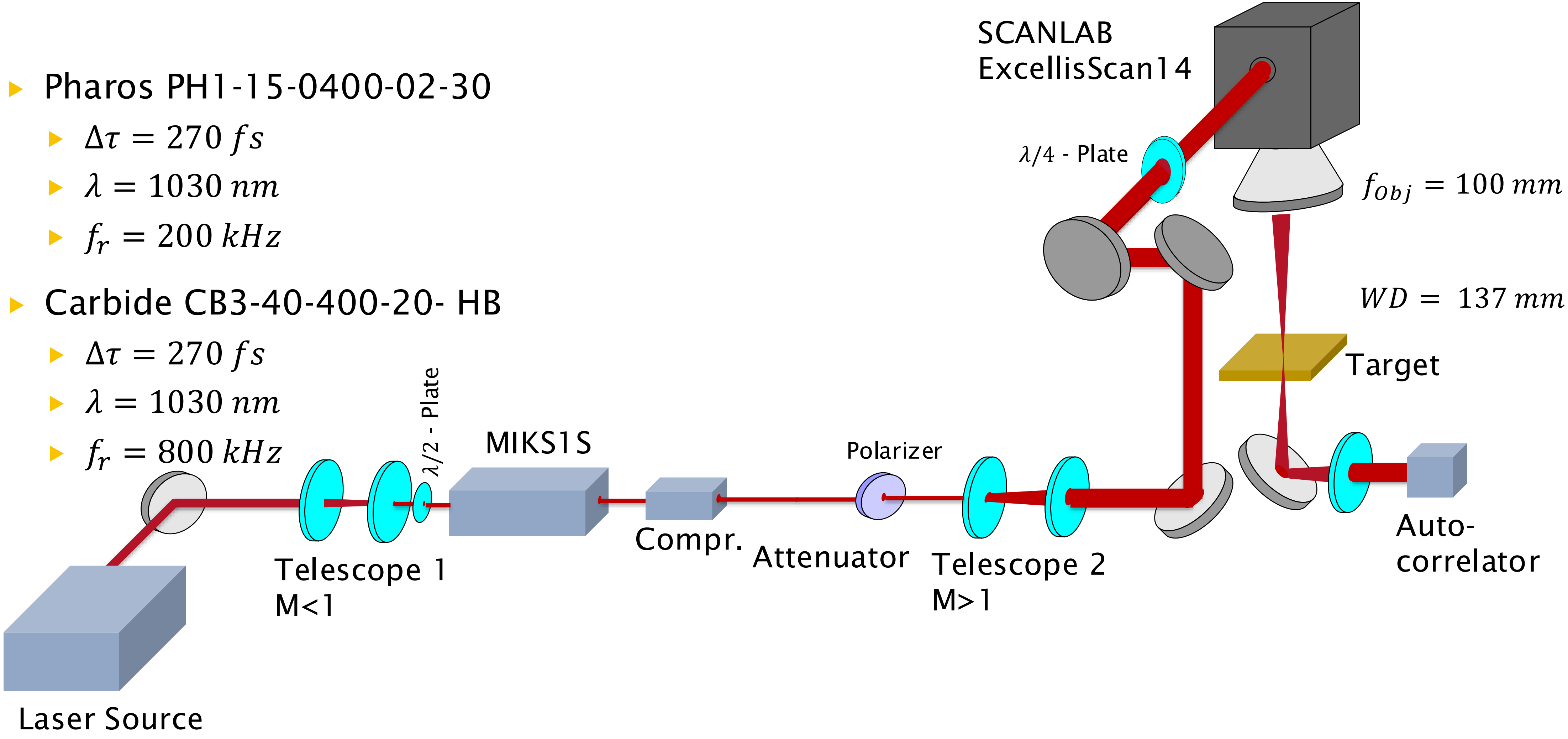


MIKS1_S | n2 Photonics (n2-photonics.de)

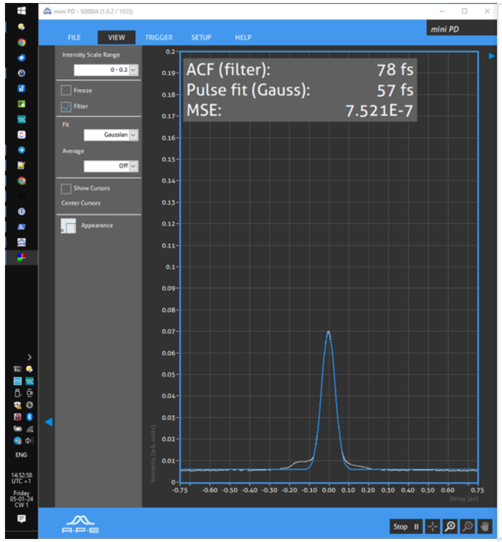
- For long time the sub 100 fs regime was only accessible with Ti:Sapphire laser systems.
- They have the reputation to be complicate to operate and "demanding a physicist to drive them".
- New devices allow to broaden the spectrum of industrial grade ultrashort pulsed laser systems to access the regime of sub 100 fs pulses for industrial micro-processing.
- Explore the sub 100 fs regime in an explorative study.

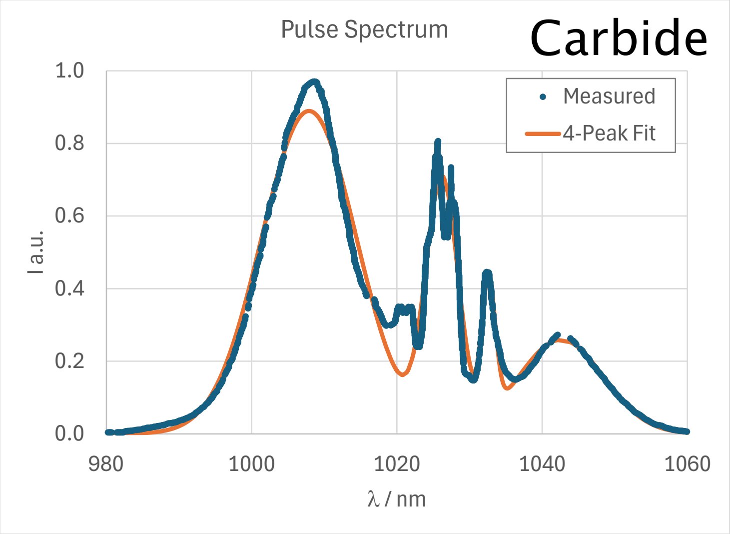
Experimental Set-Up IR Pulse Shortening

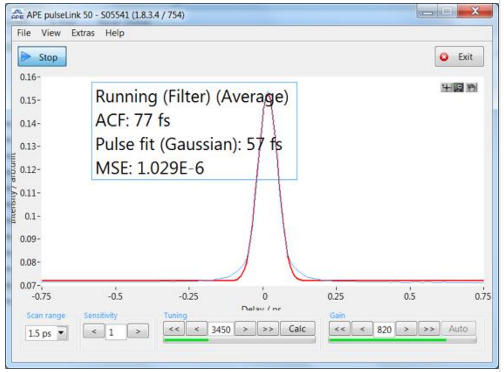
- Pharos PH1-15-0400-02-30
  - $\Delta\tau = 270\ fs$
  - $\lambda = 1030\ nm$
  - $f_r = 200\ kHz$
- Carbide CB3-40-400-20- HB
  - $\Delta\tau = 270\ fs$
  - $\lambda = 1030\ nm$
  - $f_r = 800\ kHz$

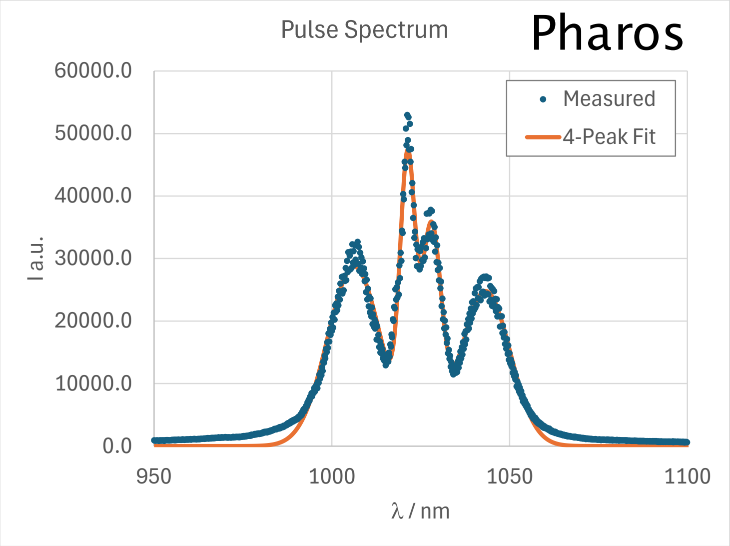


Autocorrelator Trace and Spectrum after Objective





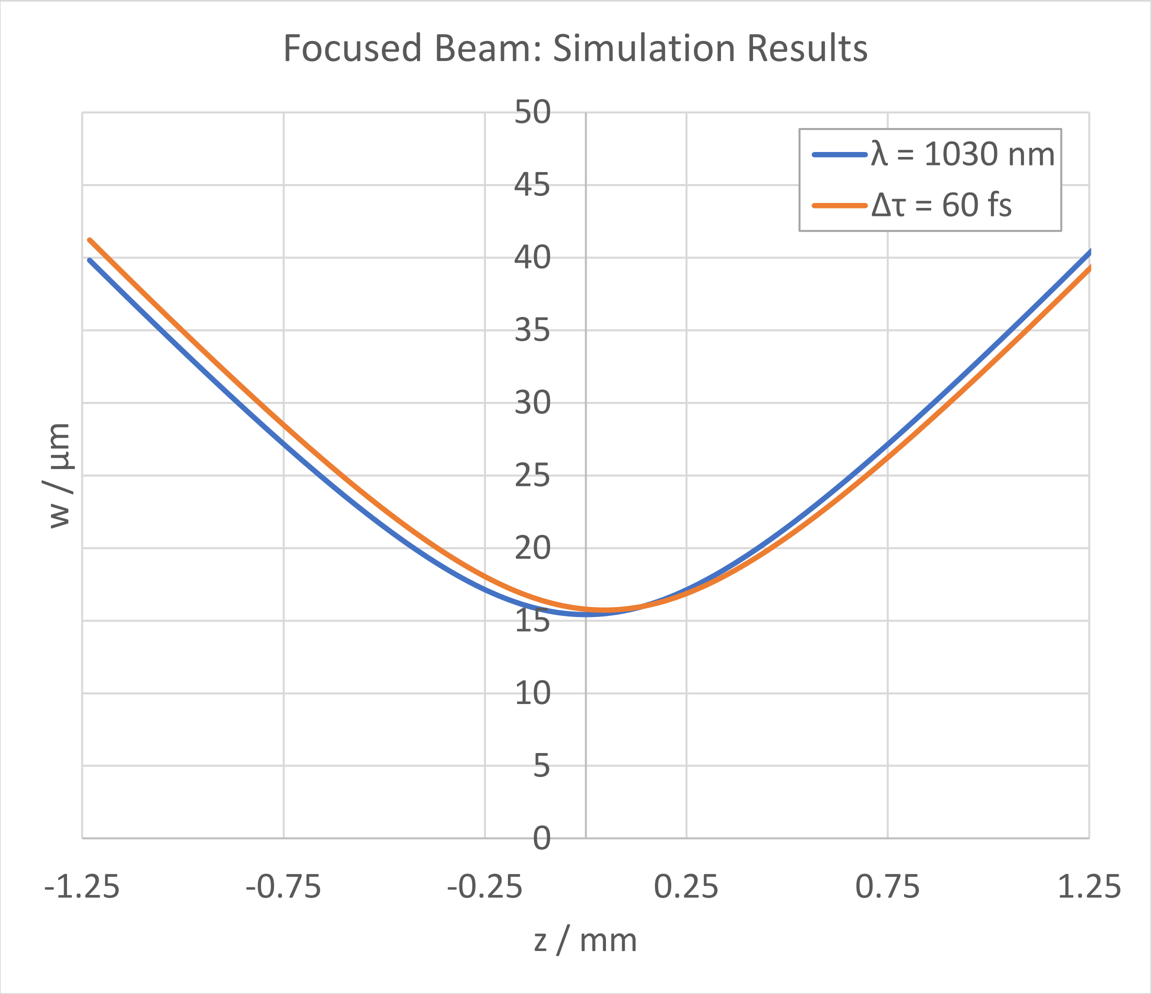




- $\Delta\tau_{min} \approx 57\ fs$
- $w_0 \approx 15\ \mu m$
- $M^2 \approx 1.5$
- Circular polarized
- Spot size and position independent on
  - Pulse duration
  - Pulse energy

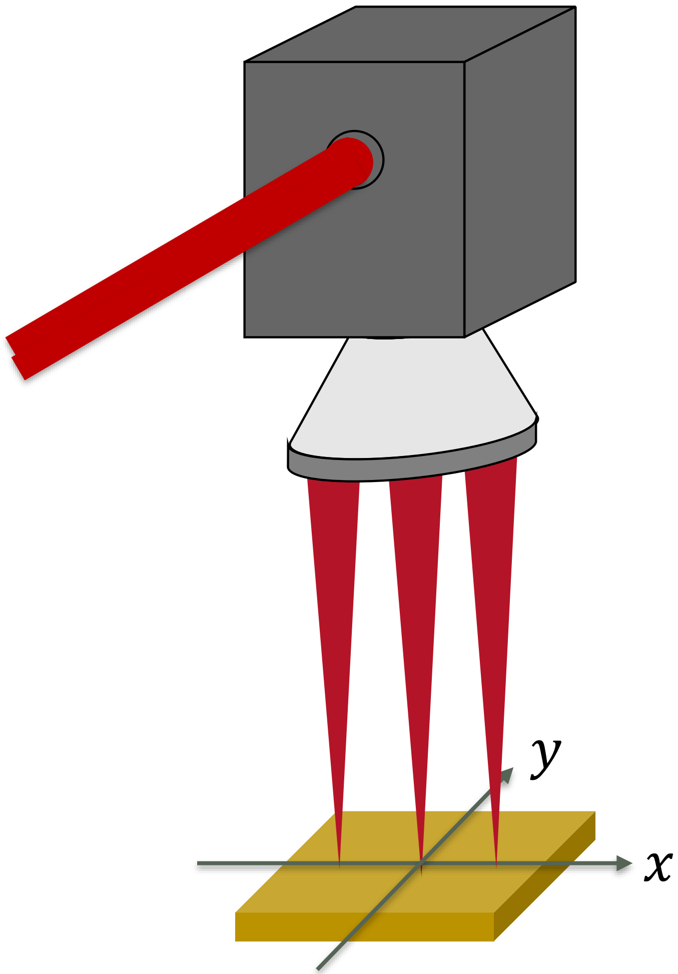
- Due to chromatic dispersion
  - Each wavelength is focused at different positions.
  - Waist radii $w_0(\lambda)$ will also slightly differ.
- Could this lead to an elongated focus?

Influence of Chromatic Dispersion on Focusing



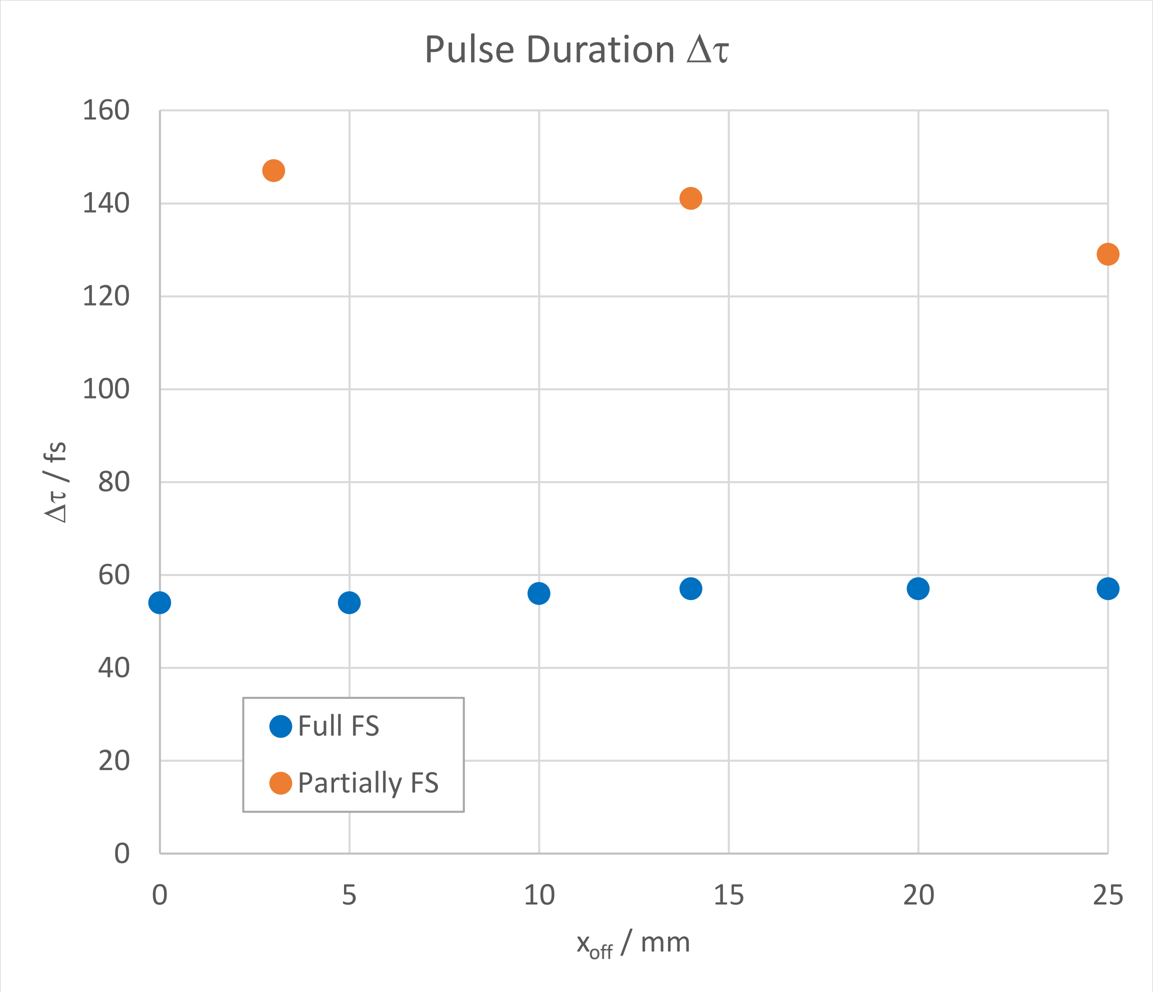
- Fitted parameters:
  - $\lambda = 1030\ nm$:
    $w_0 = 15.4\ \mu m, M^2 = 1.4$
  - $\Delta\tau = 60\ fs$, broad spectrum (Pharos):
    $w_0 = 15.7\ \mu m, M^2 = 1.43, d_{off} = 45\ \mu m$
- Focal position of $60\ fs$ beam is shifted by $45\ \mu m$ from objective away
- Spot size gets a little bigger $\approx 2\ \%$
- Slightly higher M^2
- No elongated focus

Chromatic Dispersion and Beam Deflection



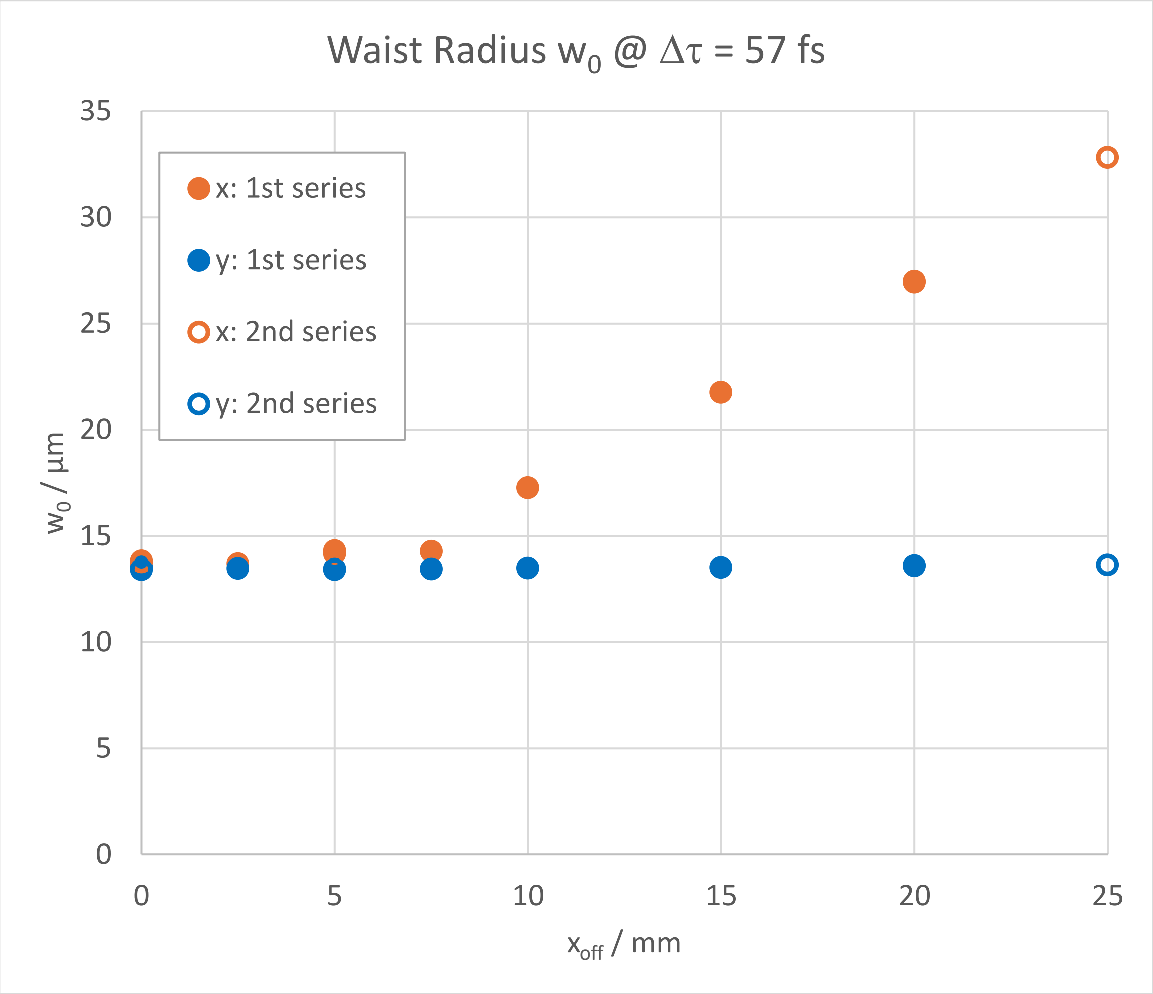
- Will beam deflection lead to beam distortion due to chromatic dispersion?
- Deflect the beam in x-direction and measure beam caustic and pulse duration.

Pharos: Influence on the Beam Deflection



- The pulse duration for the full-FS objective rests unaffected.
- Dispersion not compensated for partially FS objective.

Pharos: Influence on the Beam Deflection



- The pulse duration for the full-FS objective rests unaffected.
- Dispersion not compensated for partially FS objective.
- Waist in x-direction (offset direction) significantly increase for $x_{off} > 7.5\,mm$.
- For the y-direction (perpendicular to the offset) the waist radius is unaffected.
- Identical behavior for beam quality M^2.

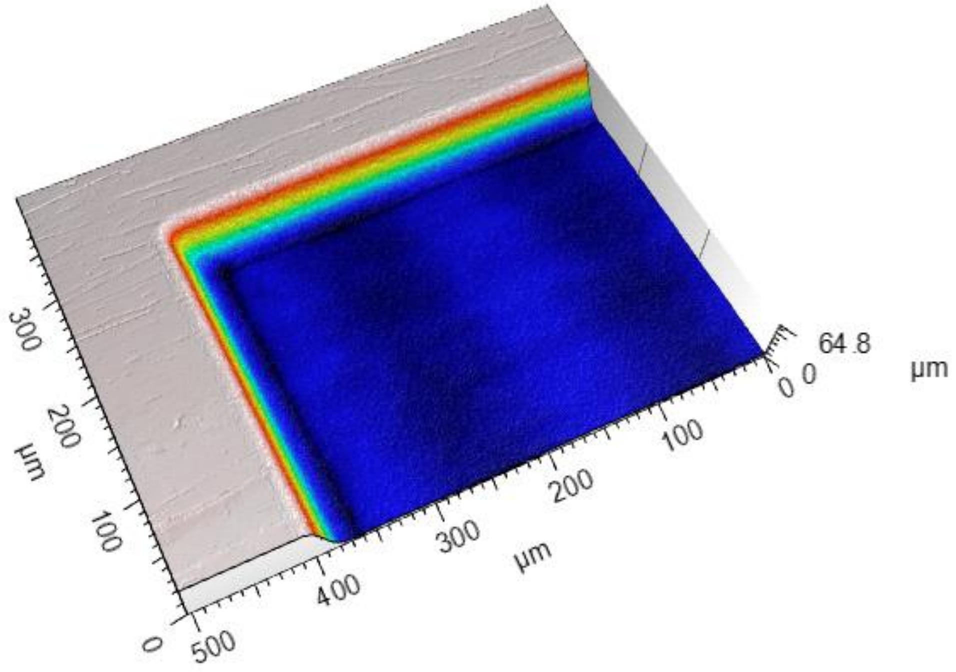
- For short pulses ($\Delta\tau < 500fs$) the scan-field should be limited from $\pm\,24\,mm$ to $\pm 5\,mm$ for the $f\ = 100\,mm$ Objective.

Experimental Procedure

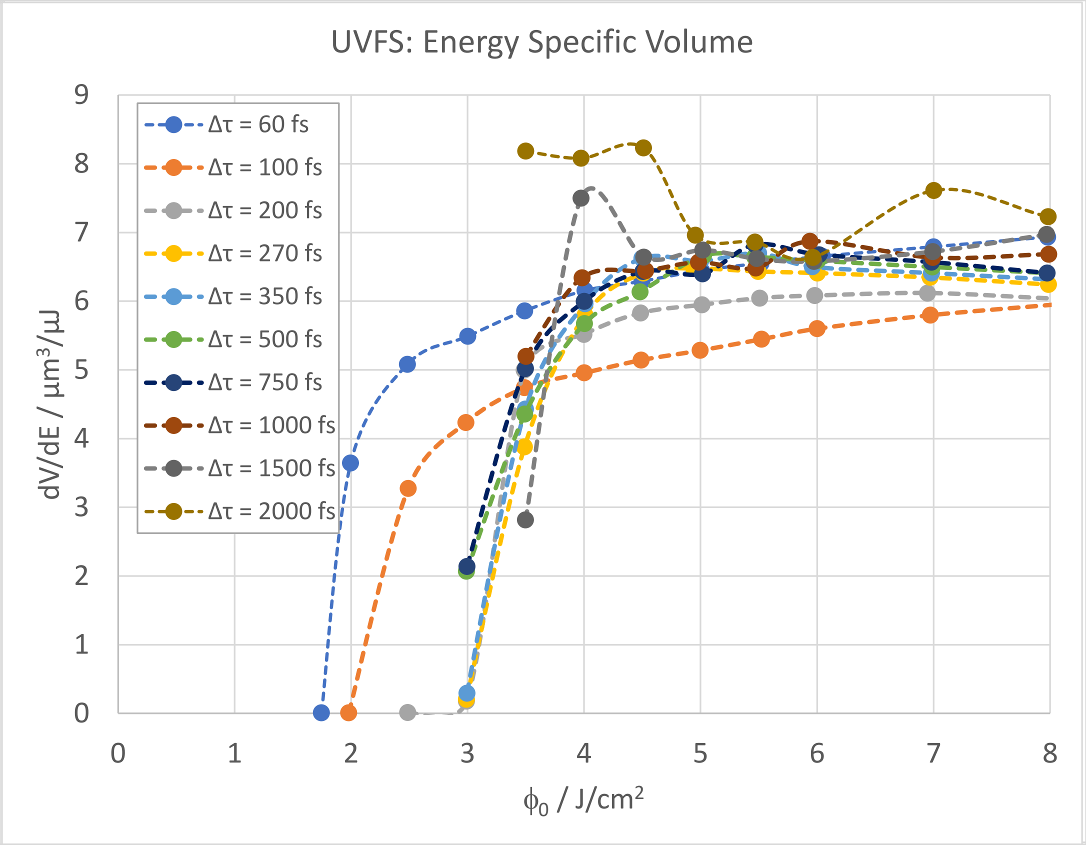
- f_r fixed to $800\,kHz$ respectively $200\,kHz$ and peak fluence increased from the threshold to several J/cm^2.
- Squares of side length $s = 1\,mm$ machined with spot and line distance $p_x = p_y = 5\,\mu m$ and a fixed number of pulses per area.
- Depth d measured with either a white lite interferometric microscope (WLI) or a confocal laser scanning microscope (LSM).
- Energy specific volume γ given by:

$$\gamma = \left(\frac{dV}{dt}\right)/P_{av} = \frac{dV}{dE} = \frac{s^2 \cdot d}{dt \cdot P_{av}} = \frac{d \cdot p_x \cdot p_y \cdot f_r}{N_{Sl} \cdot P_{av}}$$

- Surface roughness deduced following ISO 25178.



Carbide: UV Grade Fused Silica



- With decreasing pulse duration energy specific volume first drops ($\Delta\tau = 100\ fs$) and then increases again for $\Delta\tau = 57\ fs$.
- Significantly reduced threshold for $\Delta\tau = 57\ fs$ and $\Delta\tau = 100\ fs$.

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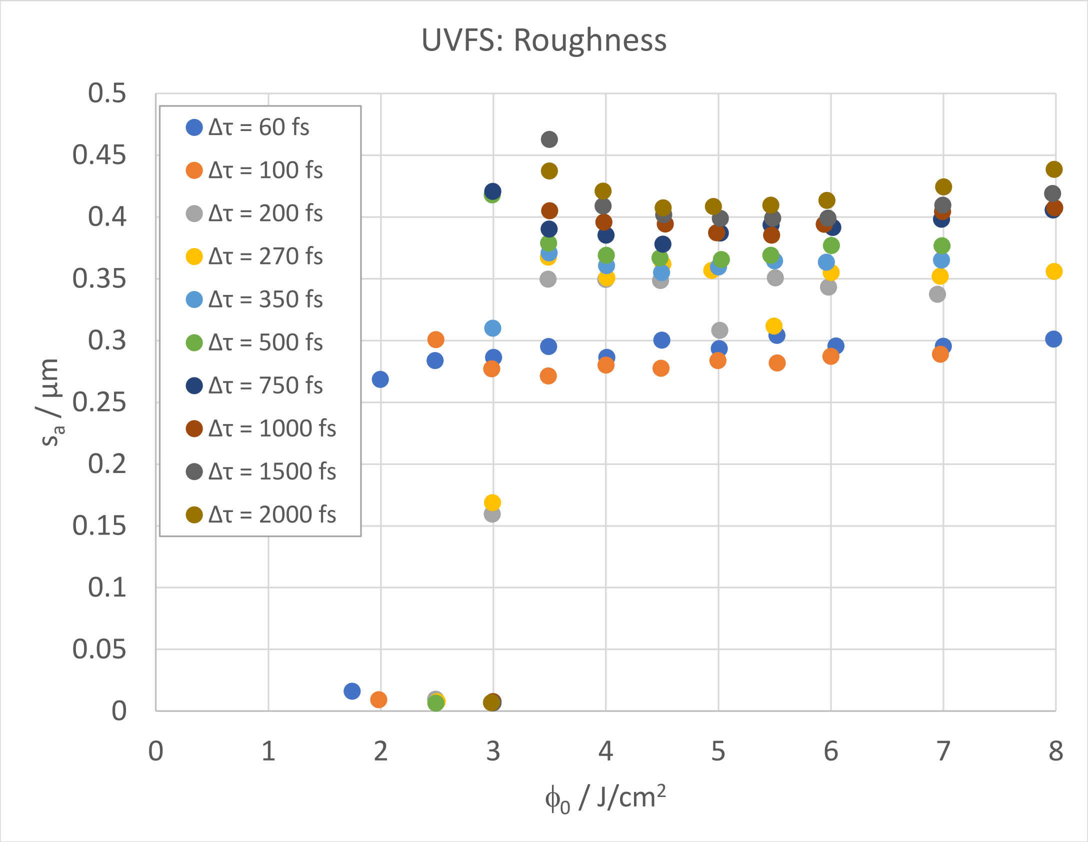

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- Smaller for $\Delta\tau = 57\ fs$ and $\Delta\tau = 100\ fs$.

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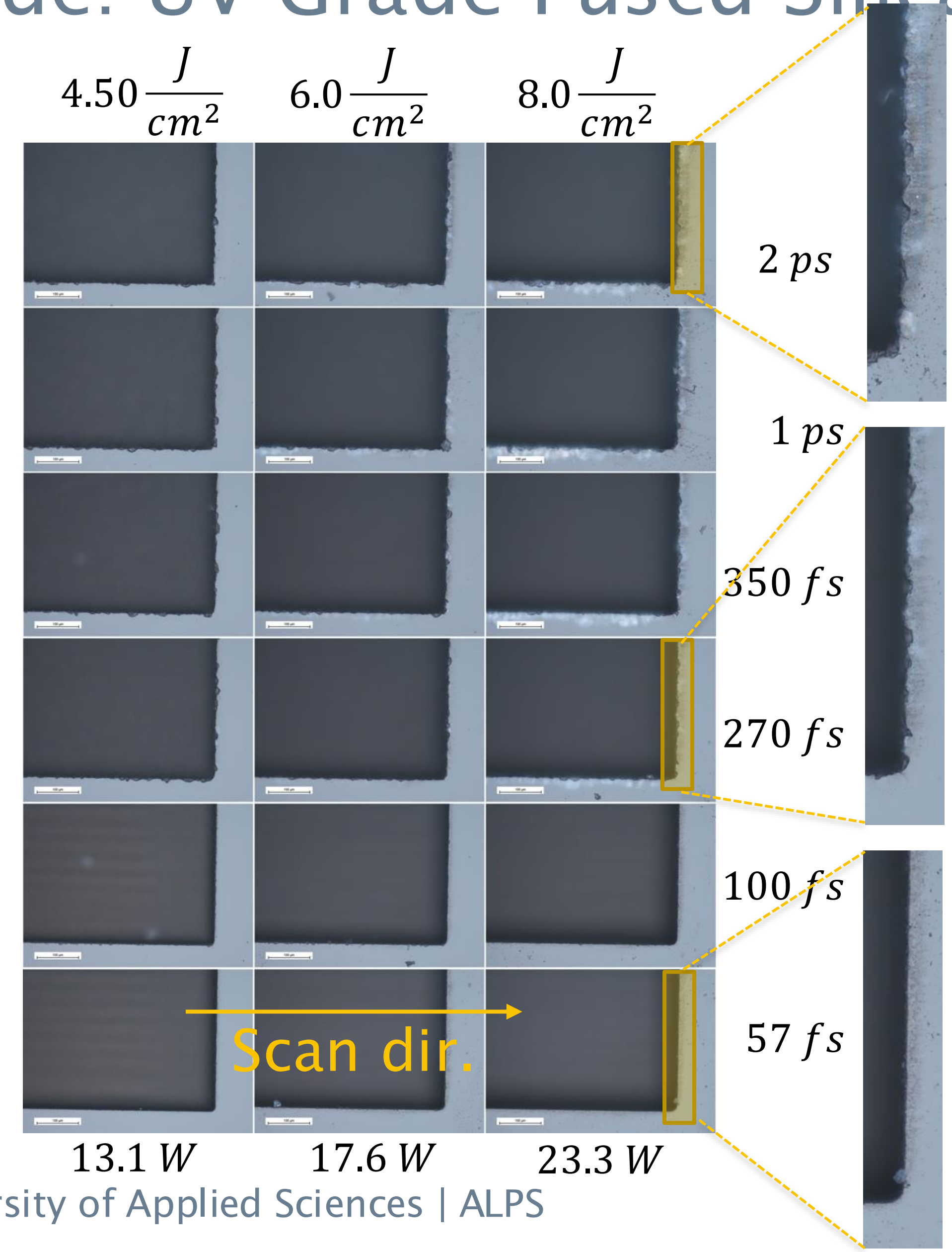

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- Edge quality massively improved for shorter pulse durations $\Delta\tau = 57\ fs$ and $\Delta\tau = 100\ fs$.
- No visible chipping for $\Delta\tau = 57\ fs$ and $P_{av} = 23.3\ W$.

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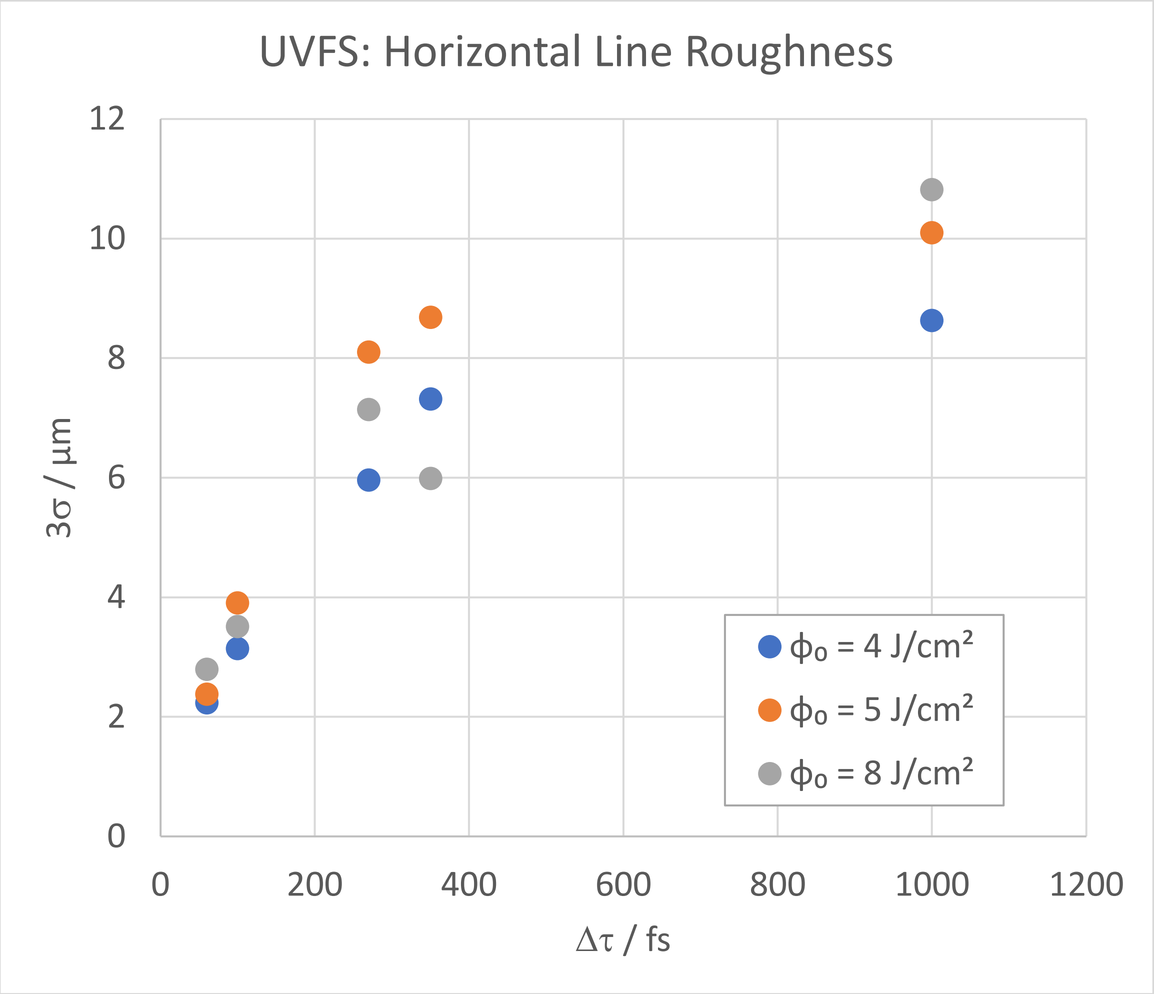

- With decreasing pulse duration energy specific volume first drops ($\Delta\tau = 100\ fs$) and then increases again for $\Delta\tau = 57\ fs$.
- Significantly reduced threshold for $\Delta\tau = 57\ fs$ and $\Delta\tau = 100\ fs$.
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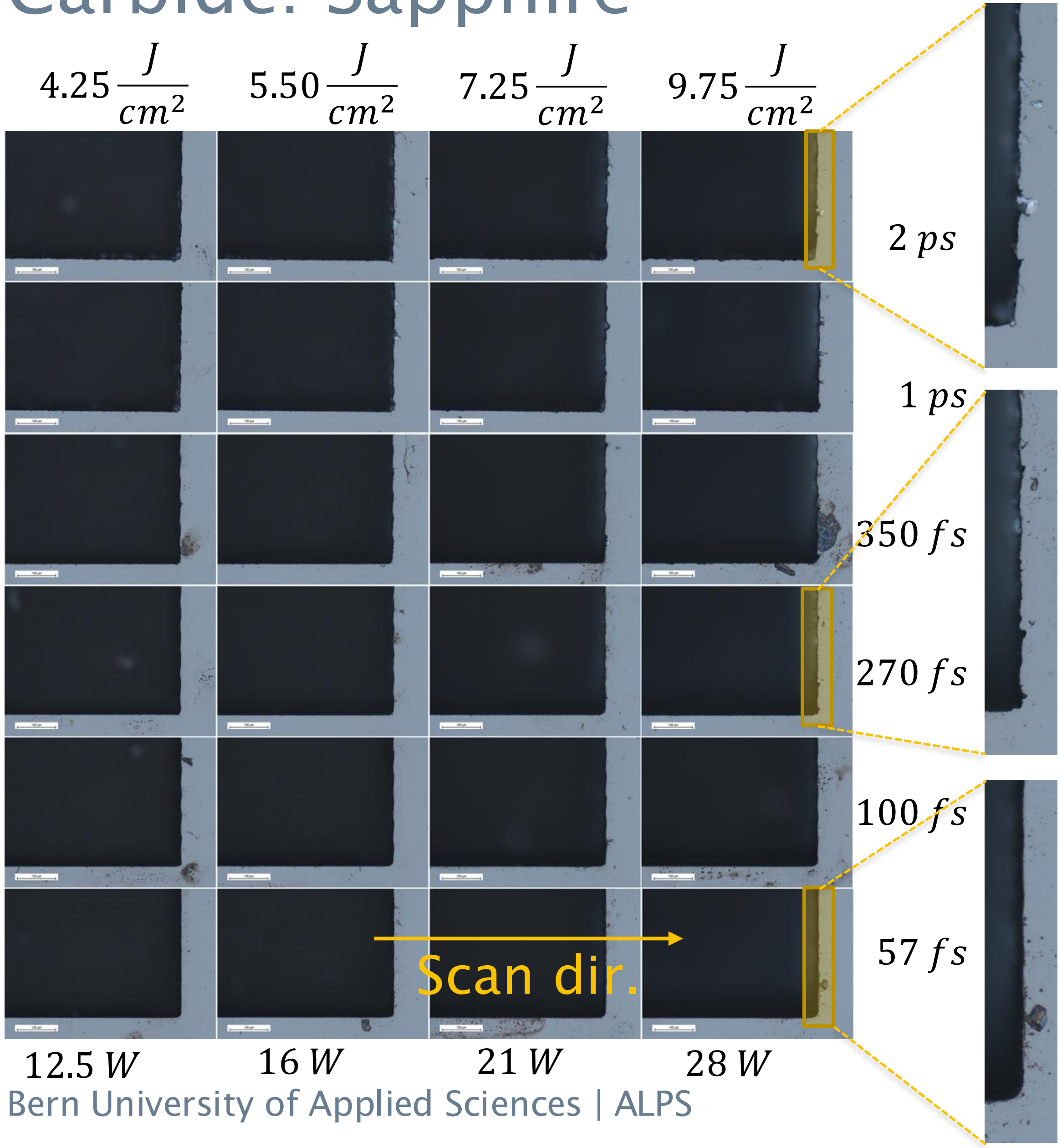
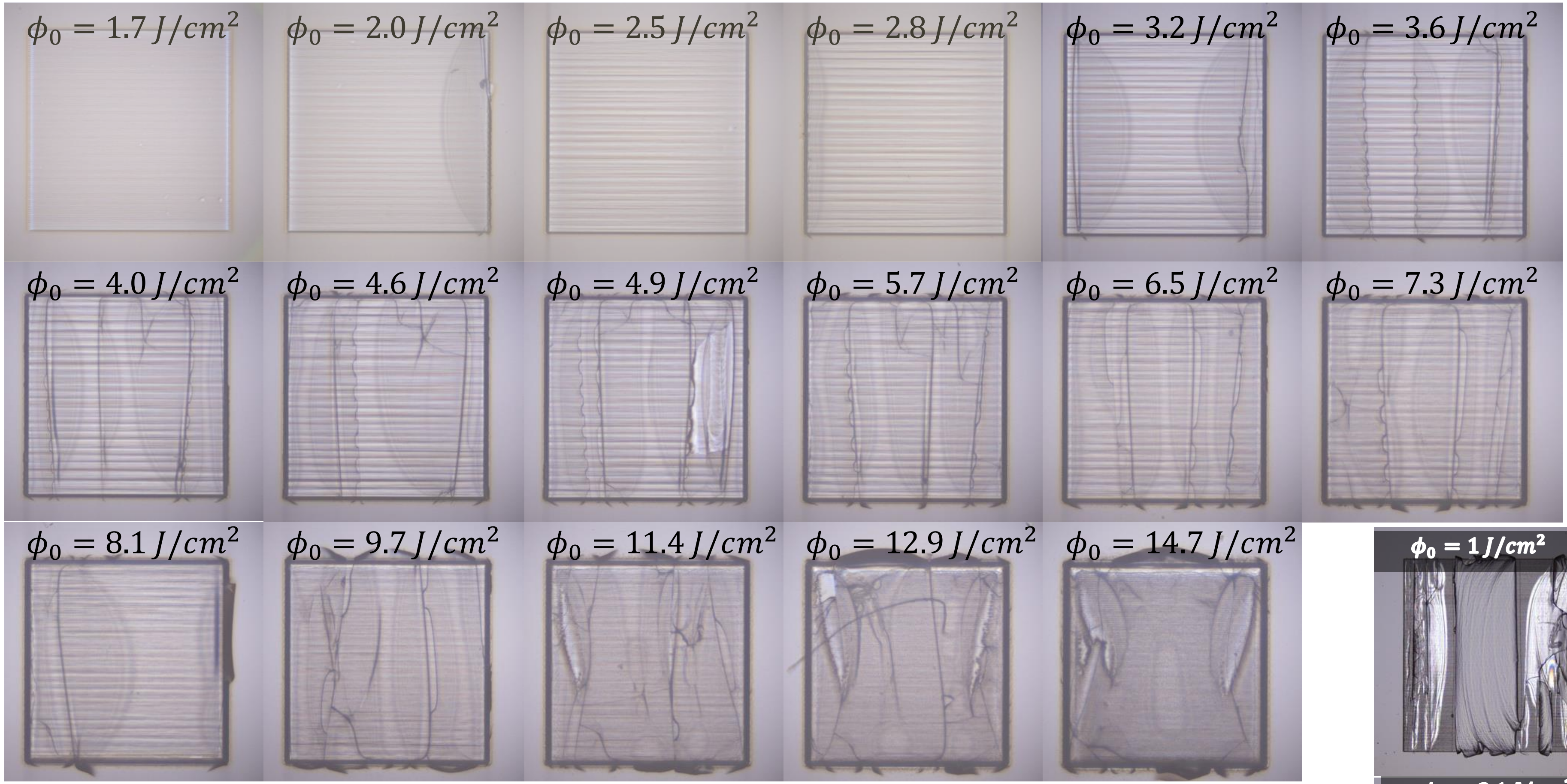
- Smaller for $\Delta\tau = 57\ fs$ and $\Delta\tau = 100\ fs$.
- Edge quality massively improved for shorter pulse durations $\Delta\tau = 57\ fs$ and $\Delta\tau = 100\ fs$.
- No visible chipping for $\Delta\tau = 57\ fs$ and $P_{av} = 23.3\ W$.
- Line Roughness strongly decreases for short pulses
- Sub 100 fs pulses lead to high edge quality also at high average powers.

Carbide: Sapphire

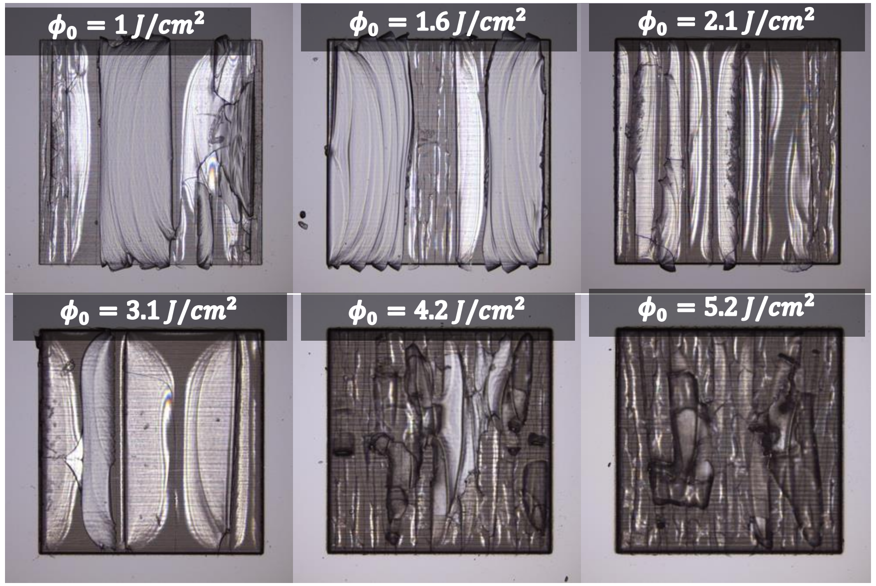


- Edge quality increases for shorter pulse durations.
- Almost no chipping for $\Delta\tau = 57\ fs$ and $P_{av} = 28\ W$.
- Sub 100 fs pulses lead to high edge quality also at high average powers.

Pharos: NSF2, $\Delta\tau_{Gauss} = 57\ fs$



cf. Satsuma 515 nm, 350 fs



- Cracking strongly reduced for $57\ fs$ pulses at $1030\ nm$.
- Even some squares without or with almost no cracks.

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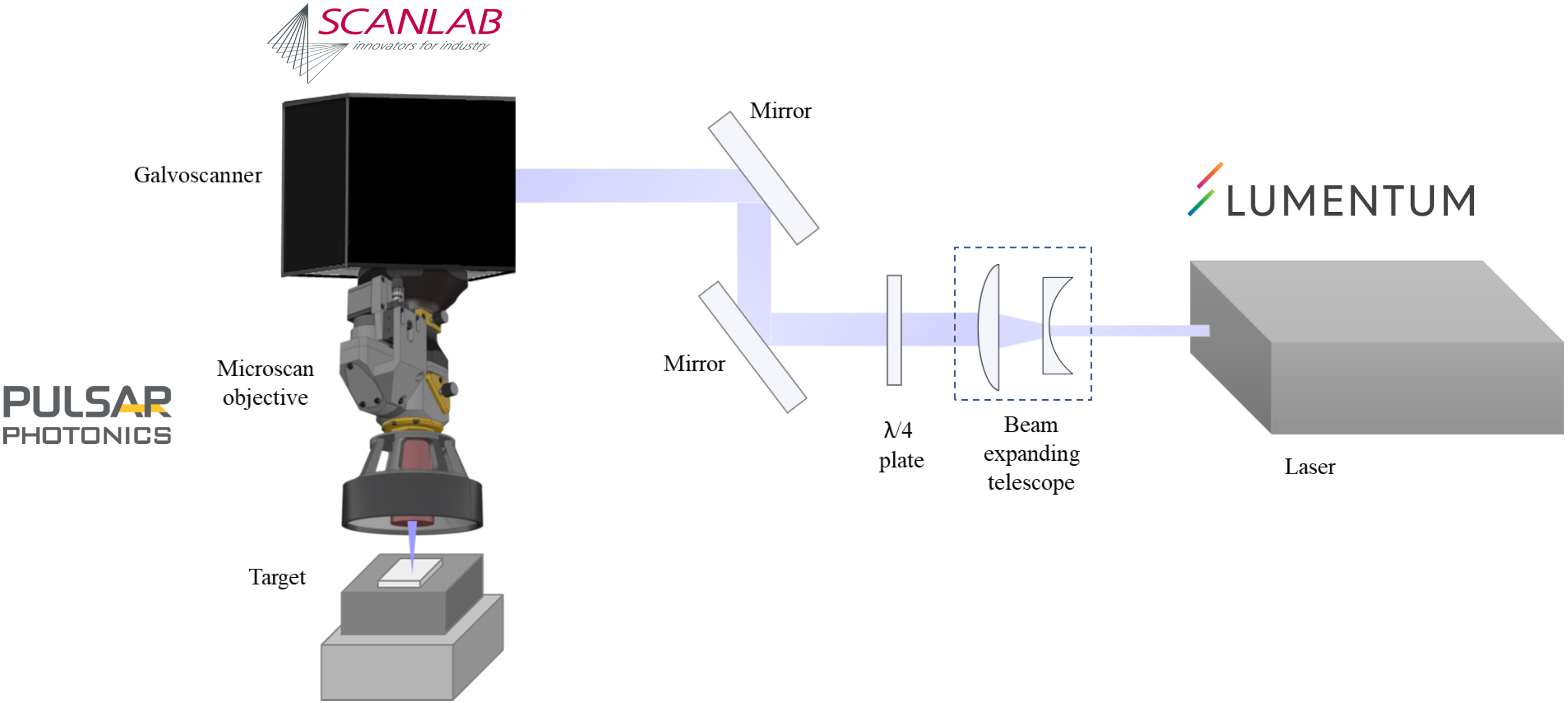
Super Small

Experimental Setup



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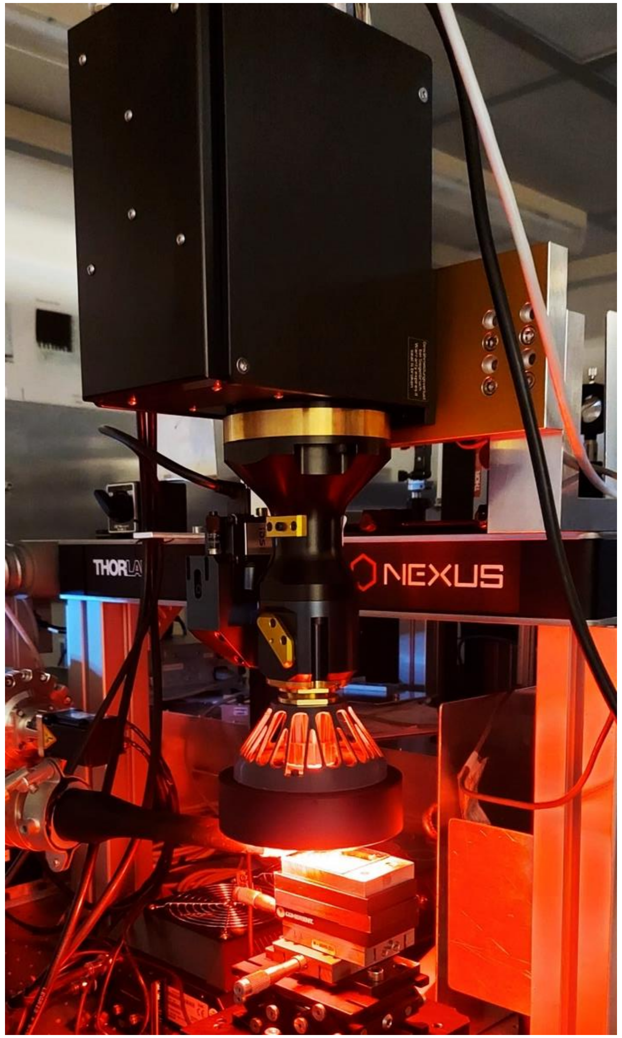
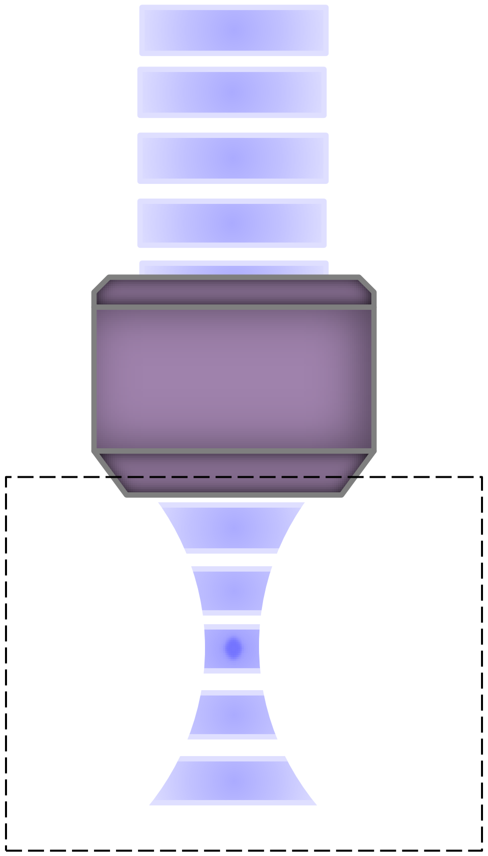
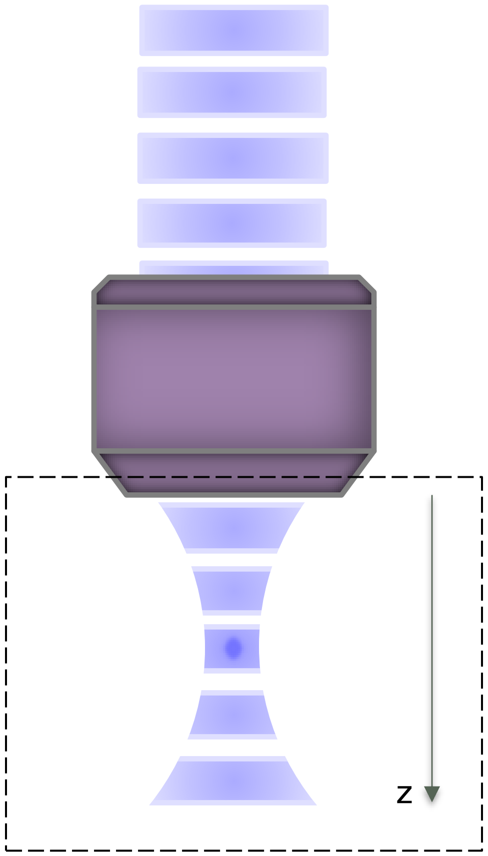


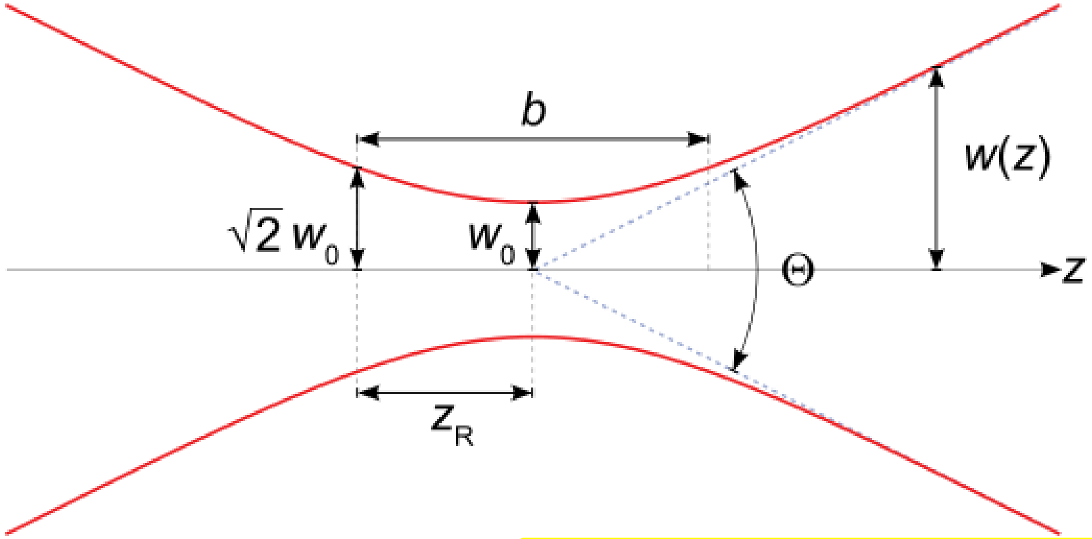
- Laser: Fuego UV
  - $\lambda = 355\ nm$
  - $\Delta\tau = 10\ ps$
  - $f_{rep} = 0.2\ - 2\ MHz$
- Galvo scanner: SCANLAB IntelliSCANde14
  - Synchronized on the laser pulse train
- Objective: Microscan Obj. UV (Pulsar Photonics)
  - $f_{obj} = 10\ mm$
  - $2 \cdot w_0 < 1.5\ \mu m$
- Smallest Structures:
  ~of the order of the beam spot diameter

Rayleigh Range



Rayleigh Range





Gaussian beam width

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$$

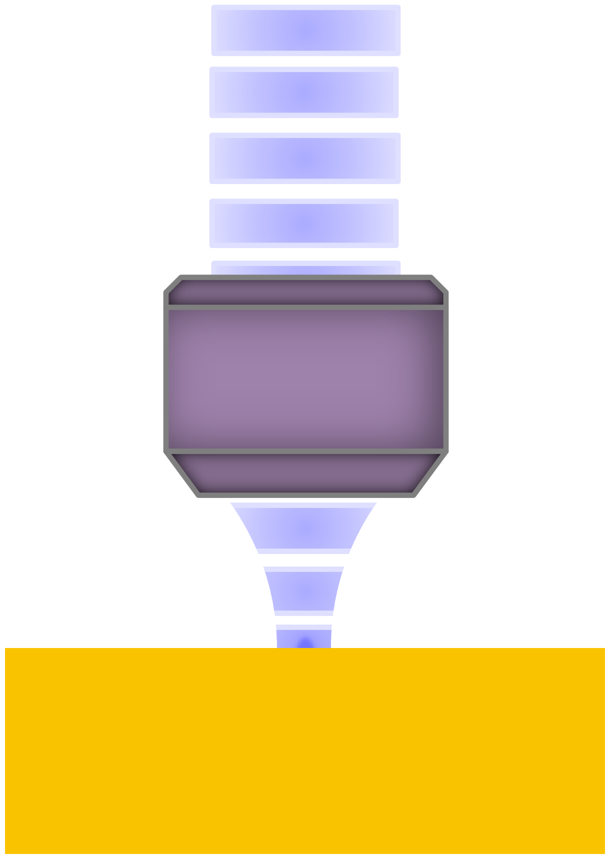
Rayleigh length

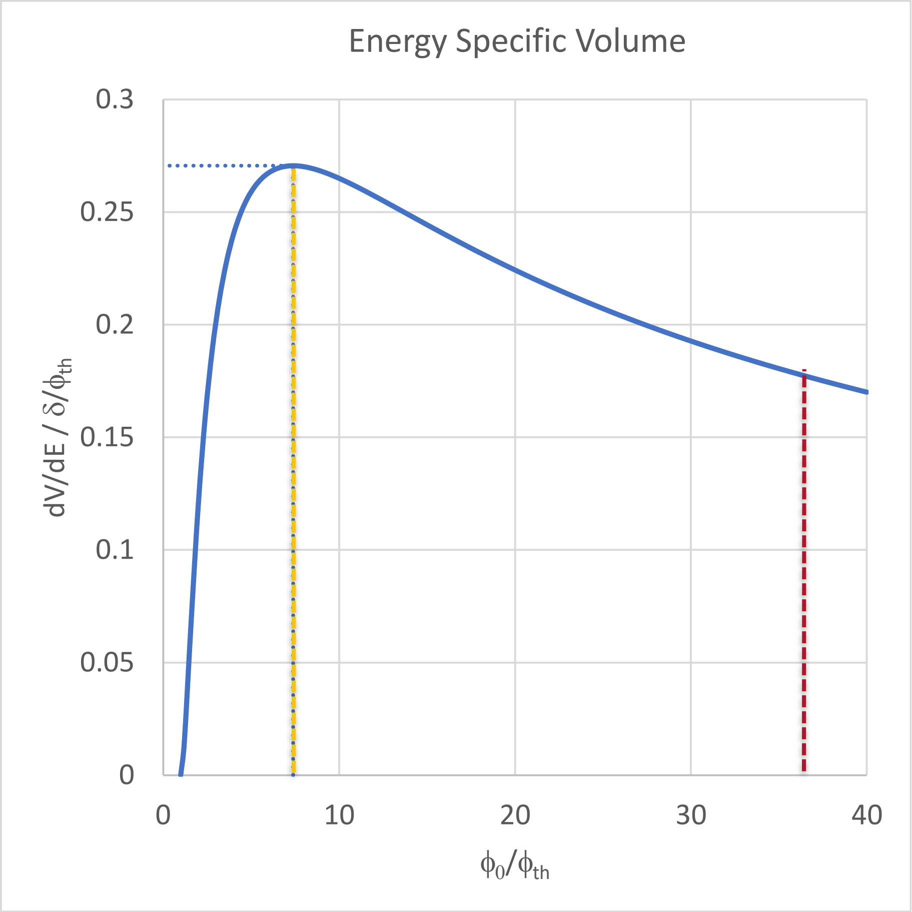
$$z_R = \frac{\pi w_0^2}{\lambda}$$

Microscan Objective, $z_R \sim 5\ \mu m$

https://commons.wikimedia.org/w/index.php?curid=6002103

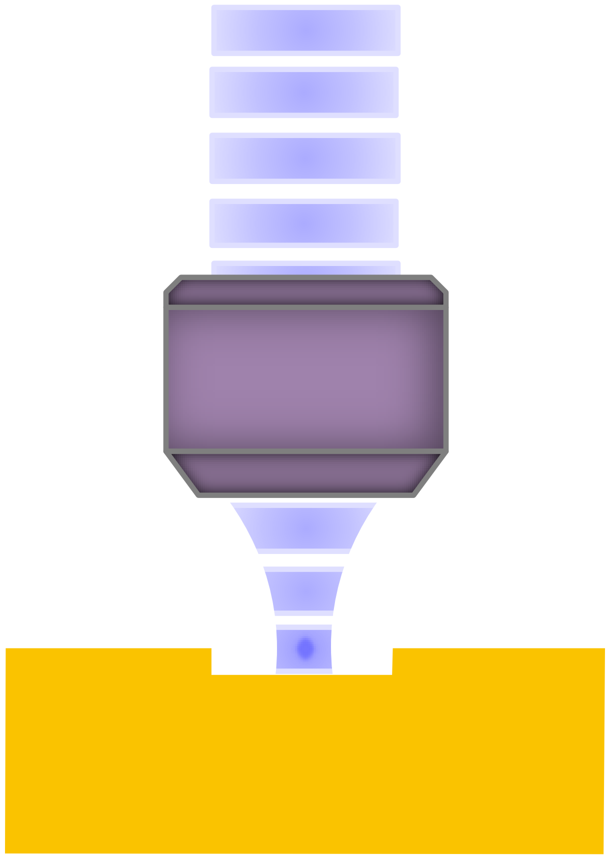
Rayleigh Range

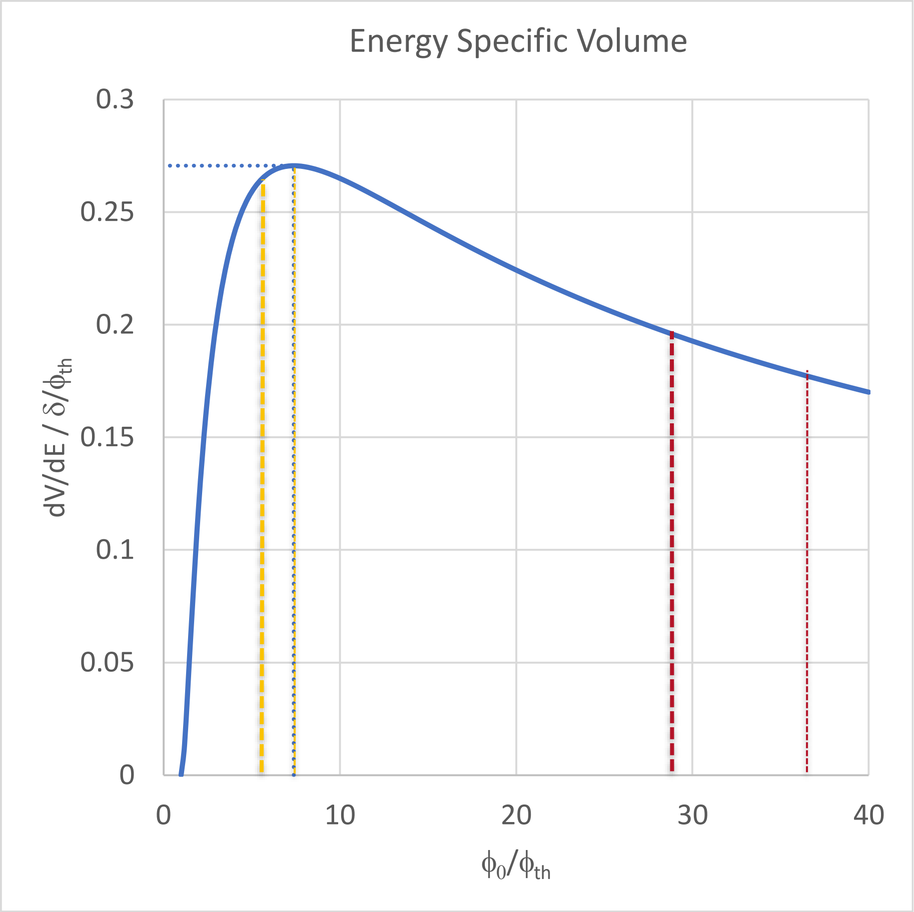




- Depending on the ablation depth the beam radius changes
- In case of a short Rayleigh length this can become significant.

Rayleigh Range





- Depending on the ablation depth the beam radius changes
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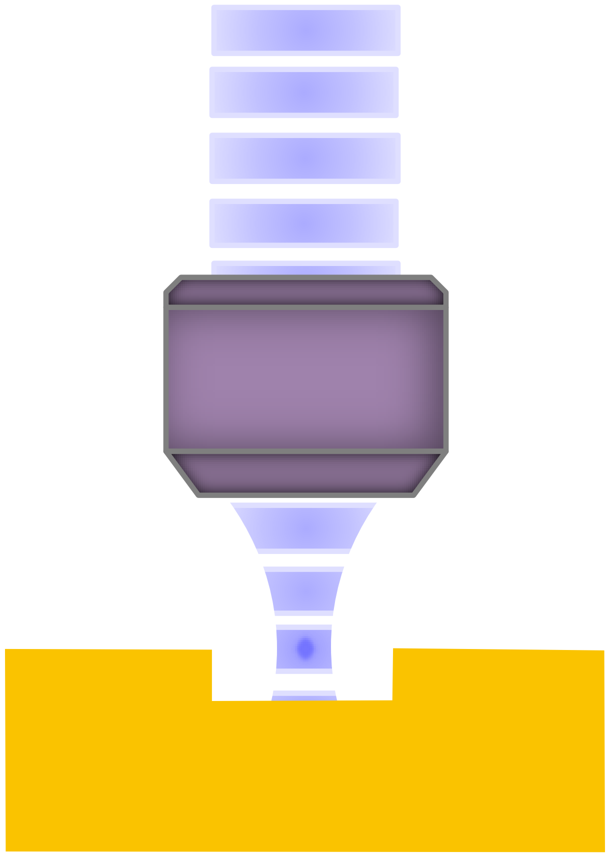
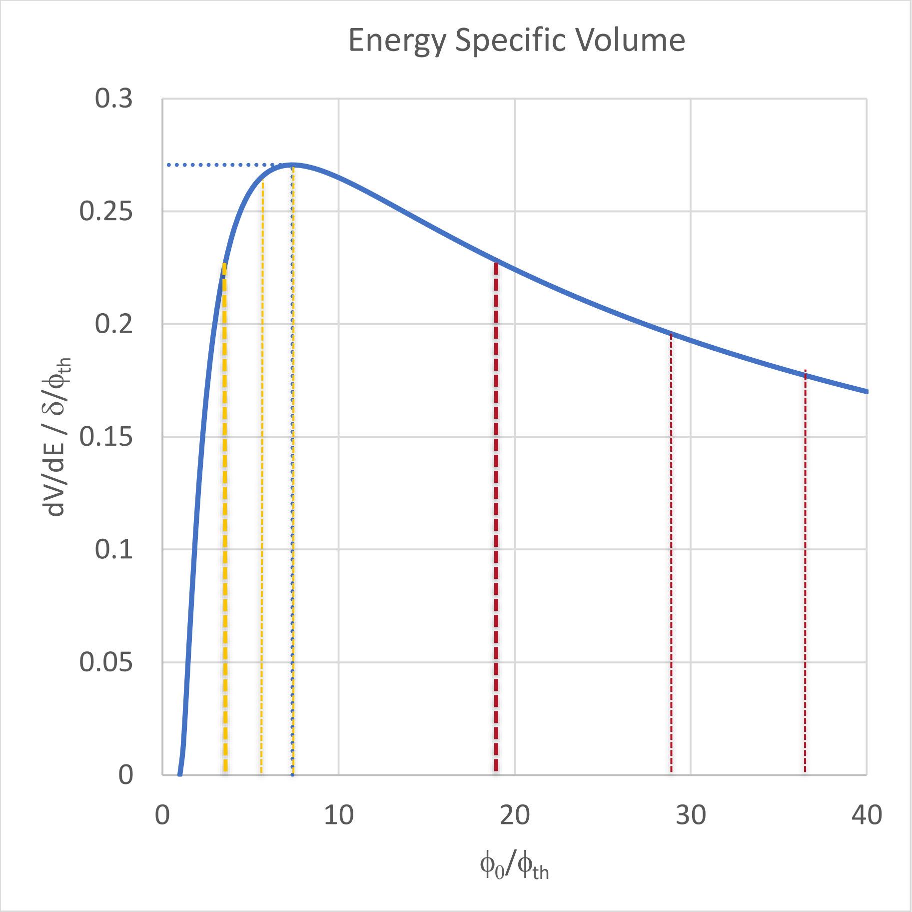
- And leads to an increase (red) or decrease (yellow) of the energy specific volume

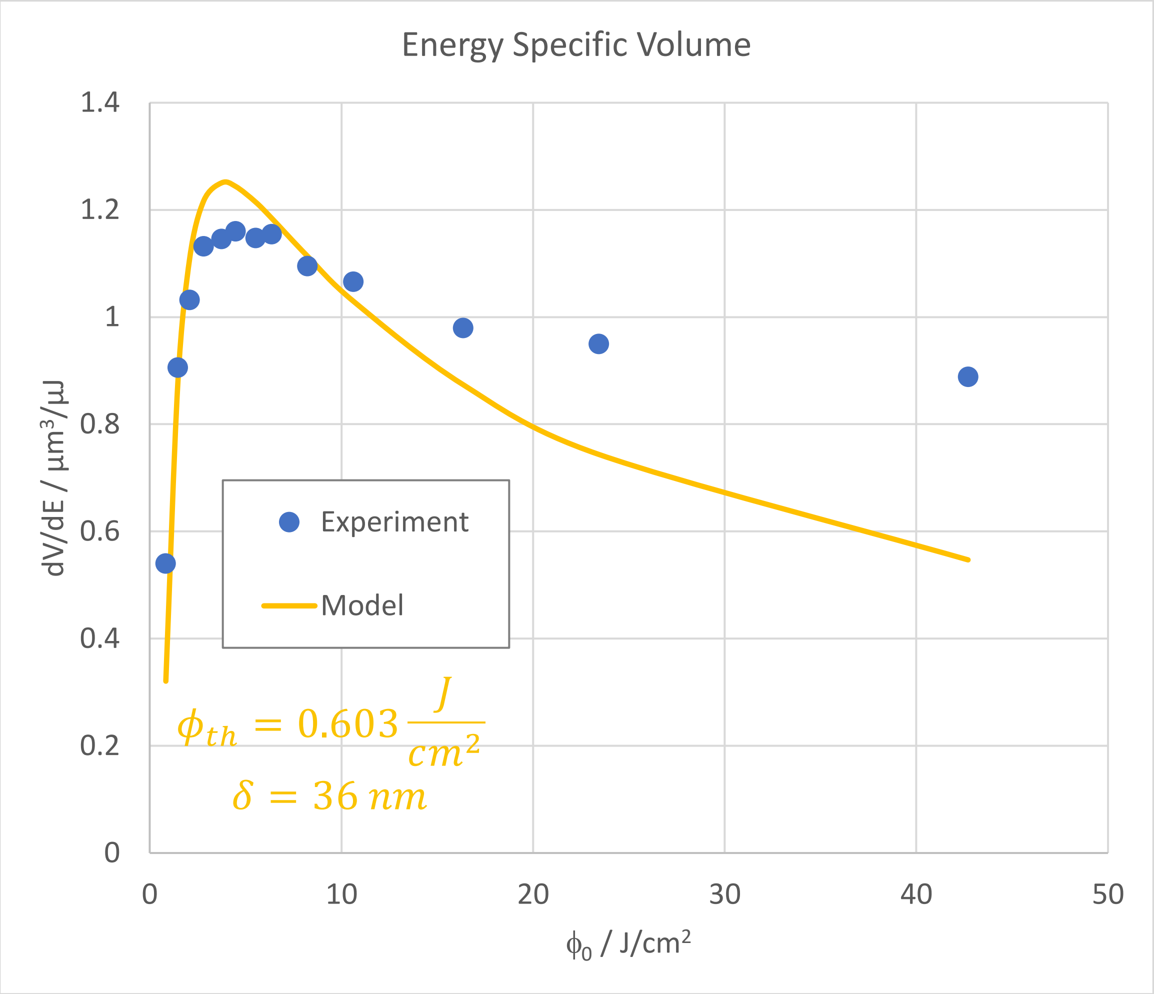
Rayleigh Range





- Depending on the ablation depth the beam radius changes
- In case of a short Rayleigh length this can become significant.
- And leads to an increase (red) or decrease (yellow) of the energy specific volume.
- The structures become deeper or less deep than expected (or the work piece has to be shifted)
- Adaption of the model might by needed

Model for short Rayleigh Length

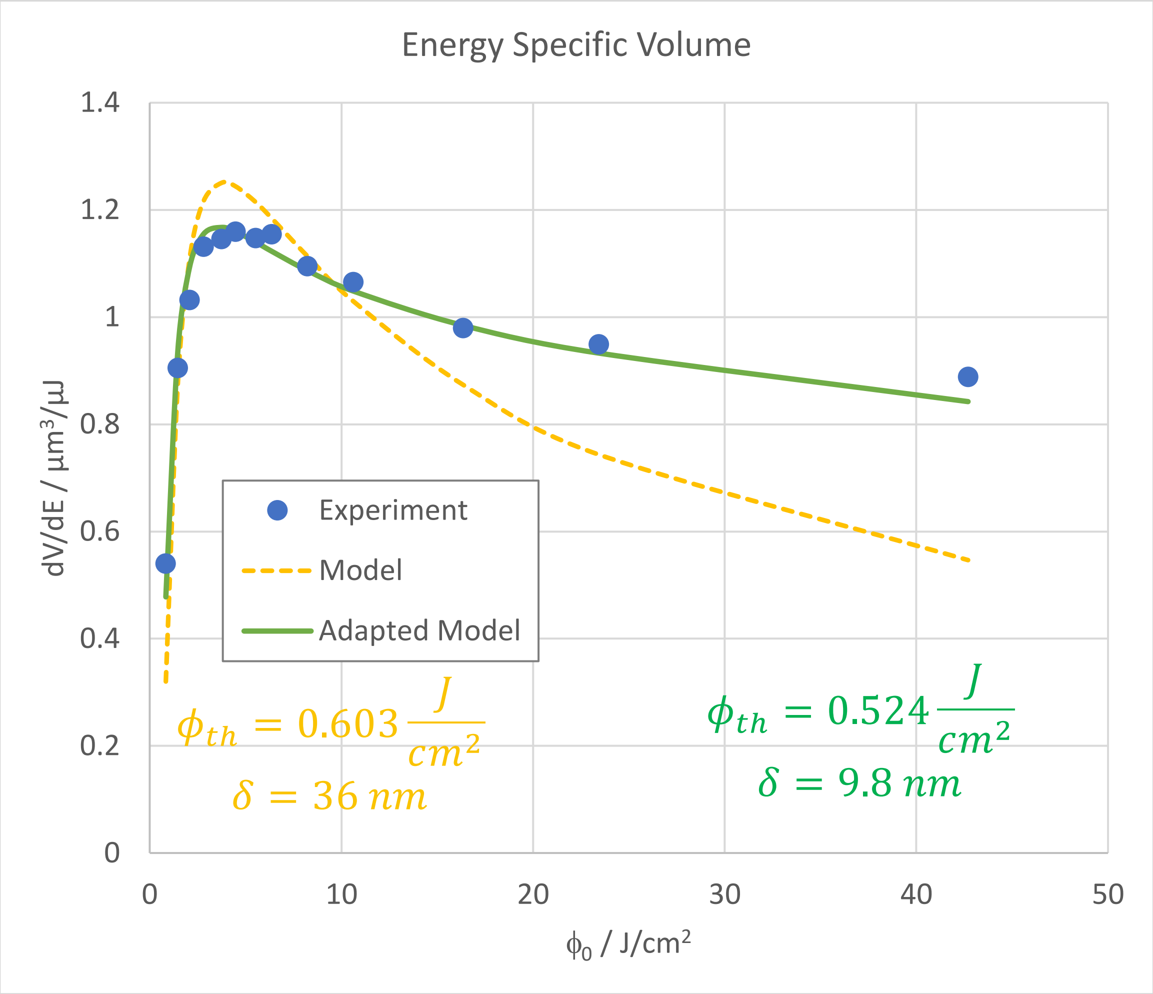


- Model:

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

- As expected, deeper squares at high fluences and therefore higher energy specific volume compared to the model.
- Adapted Model:
  - Calculate ablation depth for first layer
  - Adapt spot size resp. ϕ_0 accordingly
  - Repeat for each layer and calculate the full depth
  - Then calculate the energy specific volume
- Least square fit for ϕ_{th} an δ

Model for short Rayleigh Length



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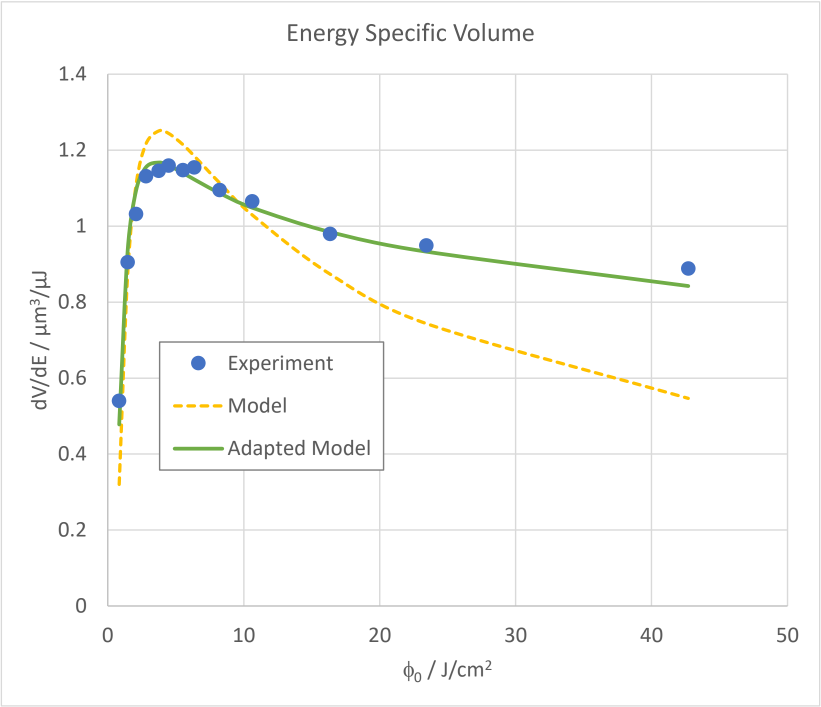
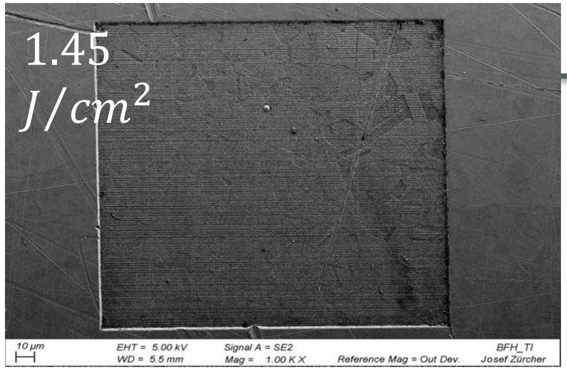
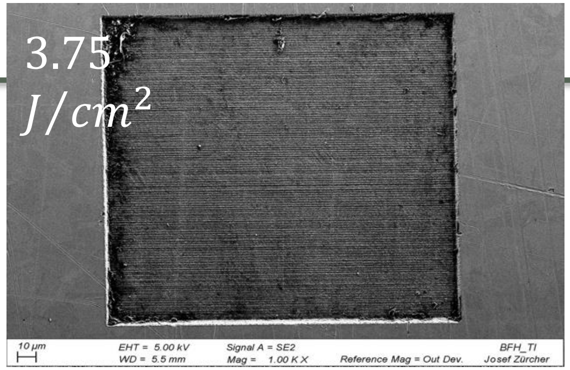
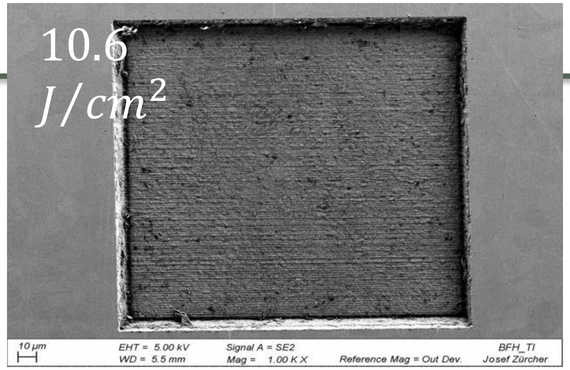
Steel AISI 304, $\Delta\tau = 10\ ps,\ \lambda = 355\ nm,\ w_0 = 0.77\ \mu m, N_{SL} = 10$

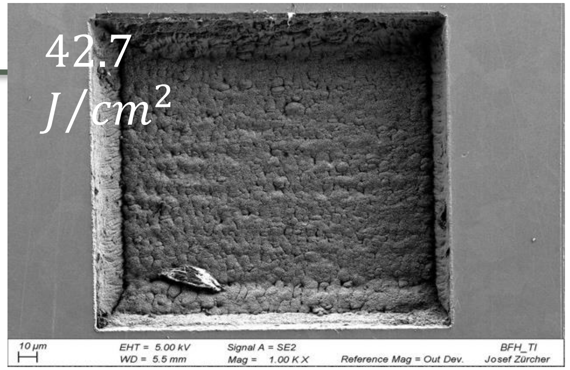


- No formation of CLP observed, also not for very high peak fluences



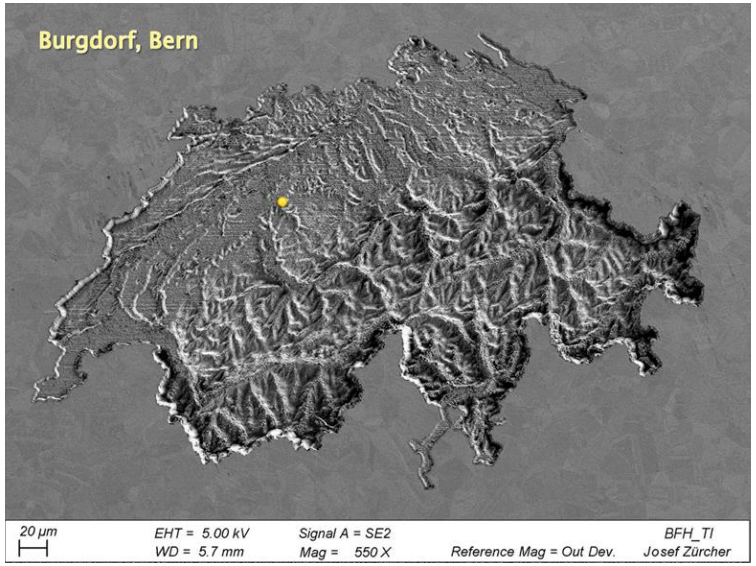




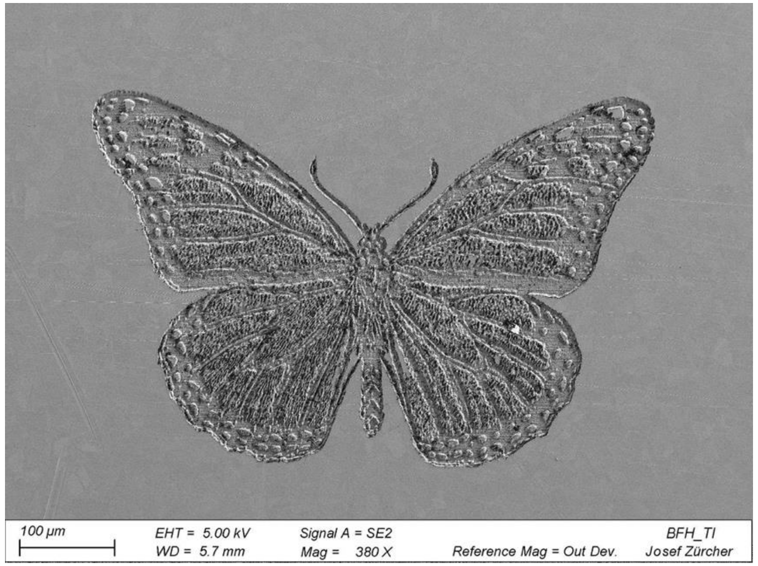


Some Examples

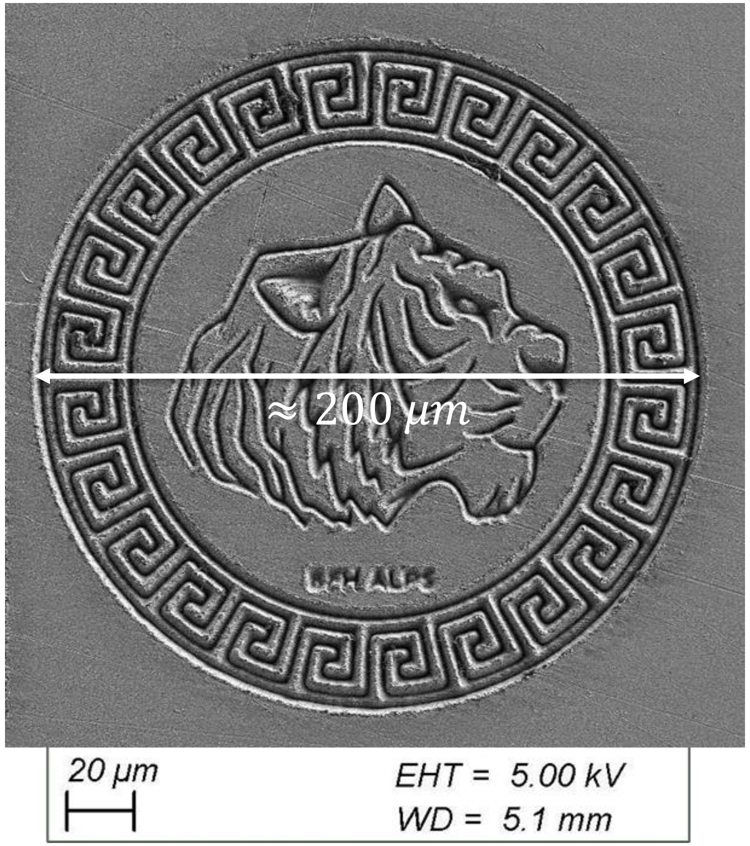
Micro-Swiss in Steel



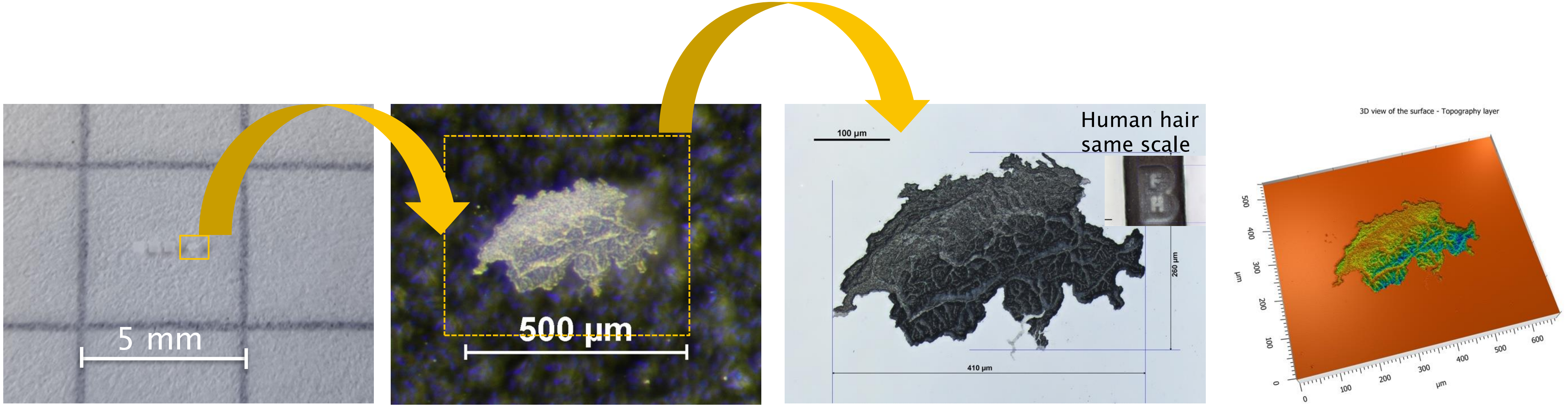
Butterfly in Steel



Structure in Copper

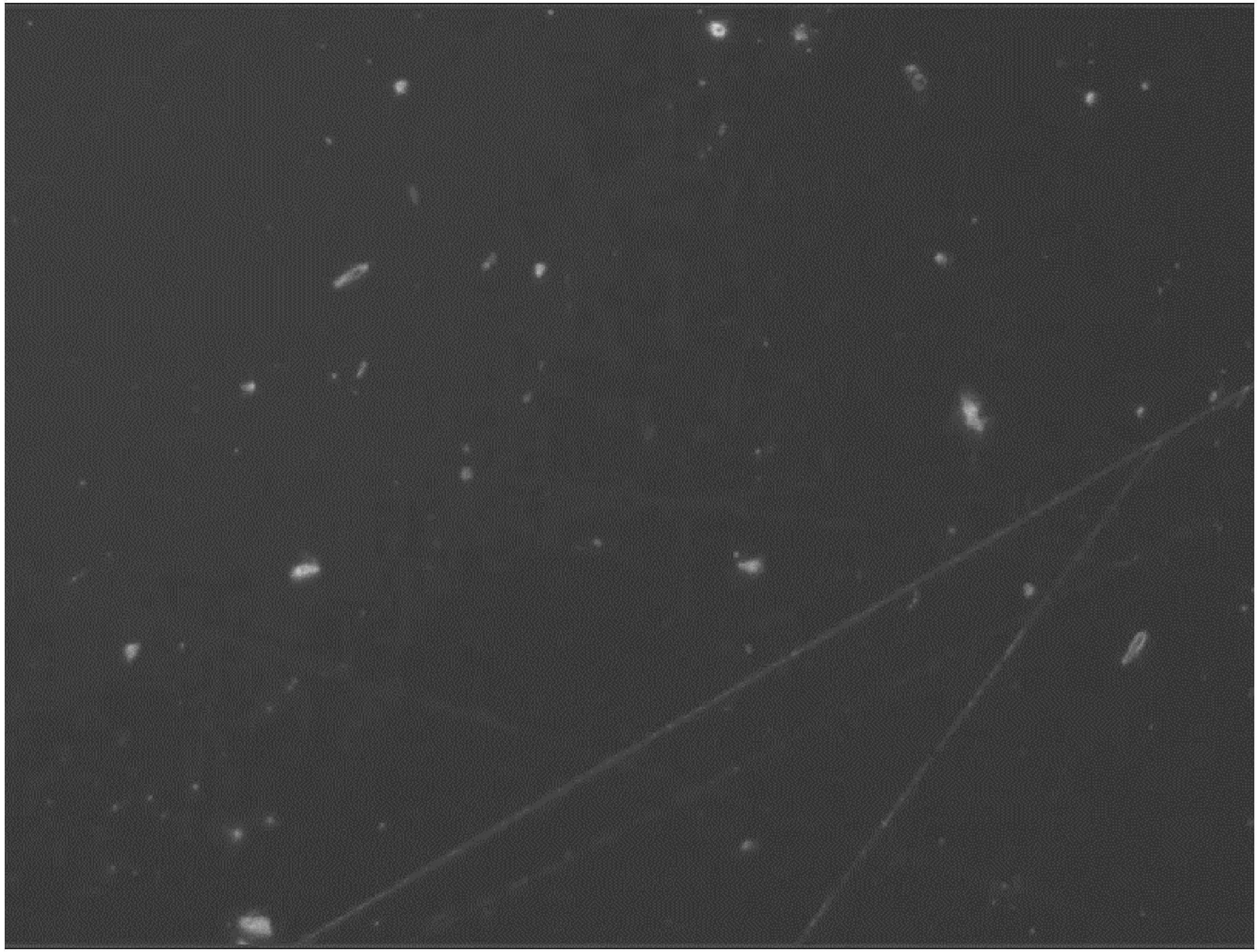


Extreme Precision: Small Spots



- Topographic map of Switzerland machined in sapphire with a scale of 1:850'000'000.
- Dimension: 410 µm x 220 µm with maximum depth of 20 µm.
- A disruptive technology in laser micromachining for highest precision and resolution.
- Applications: Almost invisible security features, watches and jewelry, functional surfaces.

Video (8x) of Machinig Switzerlands Topography



Summary

- Super Short:
  - The regime of sub 100 fs pulses with an industrial grade set up was investigated in an explorative study concerning ablation efficiency, surface roughness and edge quality.
  - Metals, tungsten carbide, PCD, Zirconia and other ceramics (all not shown here): No significant improvement
  - Glasses: Massively improved edge quality and reduced roughness at similar energy specific volumes.
  - Investigations ongoing

- Super small:
  - Microspot scanning system tested and very precise structures machined
  - No cavity formation in steel in UV with microscan
  - Limiting factor - Rayleigh range

Thank you very much for your kind attention