High-Quality Laser Processing of CFRP

Rudolf Weber

Christian Freitag, Margit Wiedenmann, Thomas Graf

15.6.2016

IFSW
UNIVERSITÄT STUTTGART
INSTITUT FÜR STRAHLWERKZEUGE
STUTTGART LASER TECHNOLOGIES

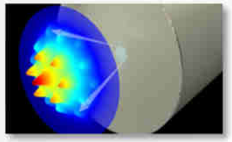
Institut für Strahlwerkzeuge, Stuttgart Laser Technology

- Founded 1986
- Turnover ~4,2 M€
- 42 Employees (+ ~45 Students)
- 80% Third party financing

Director: *Prof. Dr. Thomas Graf*
Deputy: *Akad. Oberrat Peter Berger*

Laser und Laser Optics
Marwan Abdou Ahmed

Disk Lasers and Laser Optics
S. Piehler

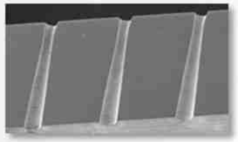


Fibre Optics und Fibre Lasers
M. Abdou Ahmed

Semiconductor Disk Lasers
Dr. U. Brauch

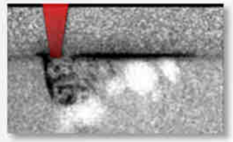
14 Scientists

Laser Materials Processing
Rudolf Weber



Precision Processing
C. Freitag

Application Development
D. Weller



Macro Processing
A. Heider

15 Scientists

Systemtechnik
Volkher Onuseit

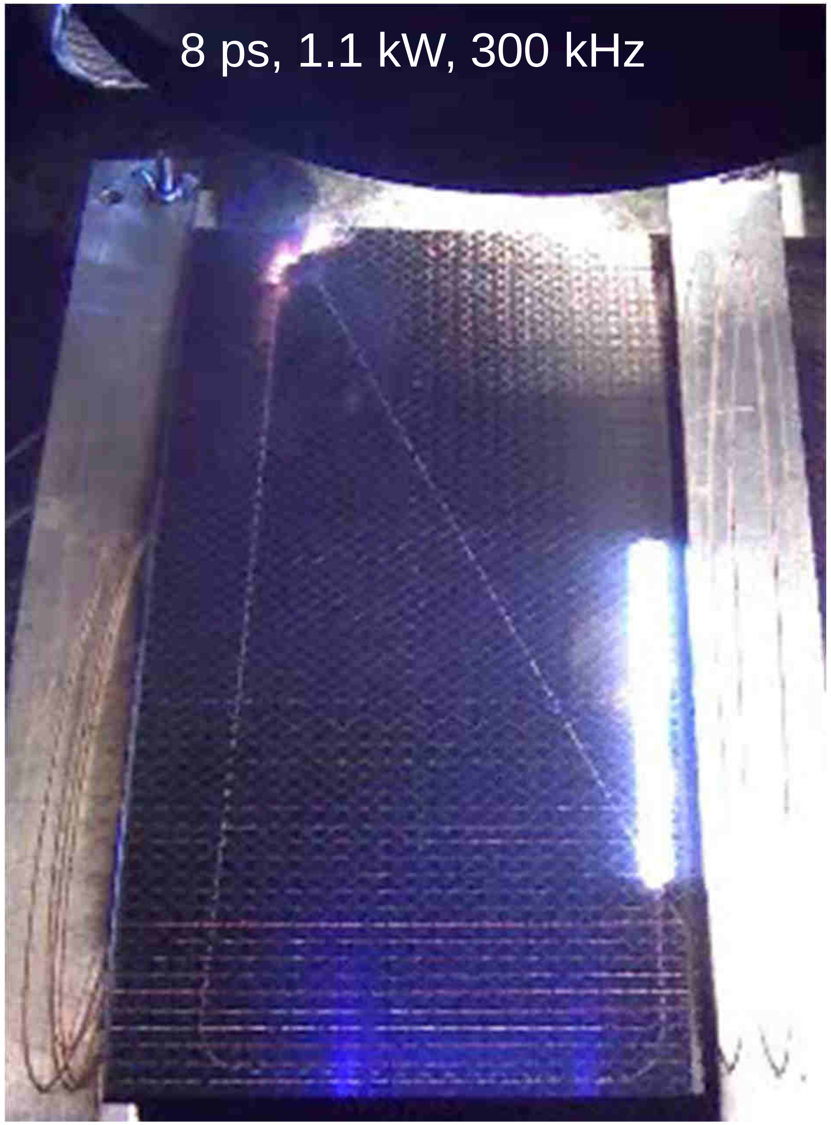
Hochdynamische Strahlführung
V. Onuseit

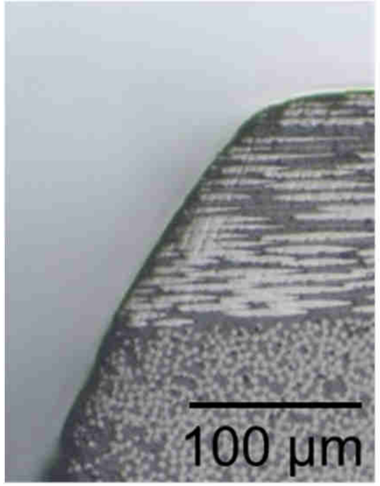
Anlagen Integration
S. Boley

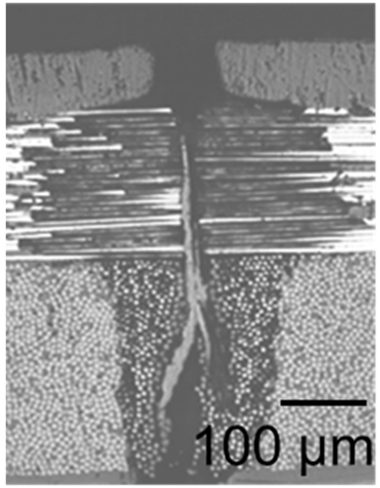
Mess- und Regelungstechnik
A. Peter

3 Scientits

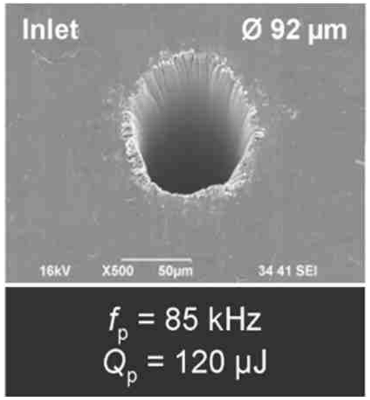
Technics und Safety, Metallografy, Administration, PR
A. Esser, Ch. Zeitvogel, R. Fischer, H. Götz

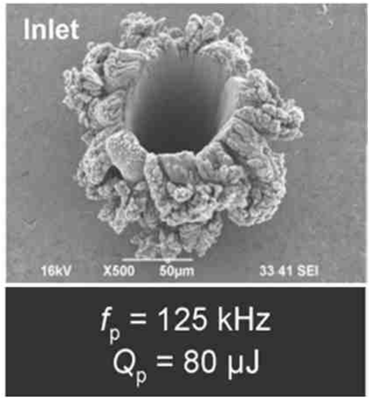






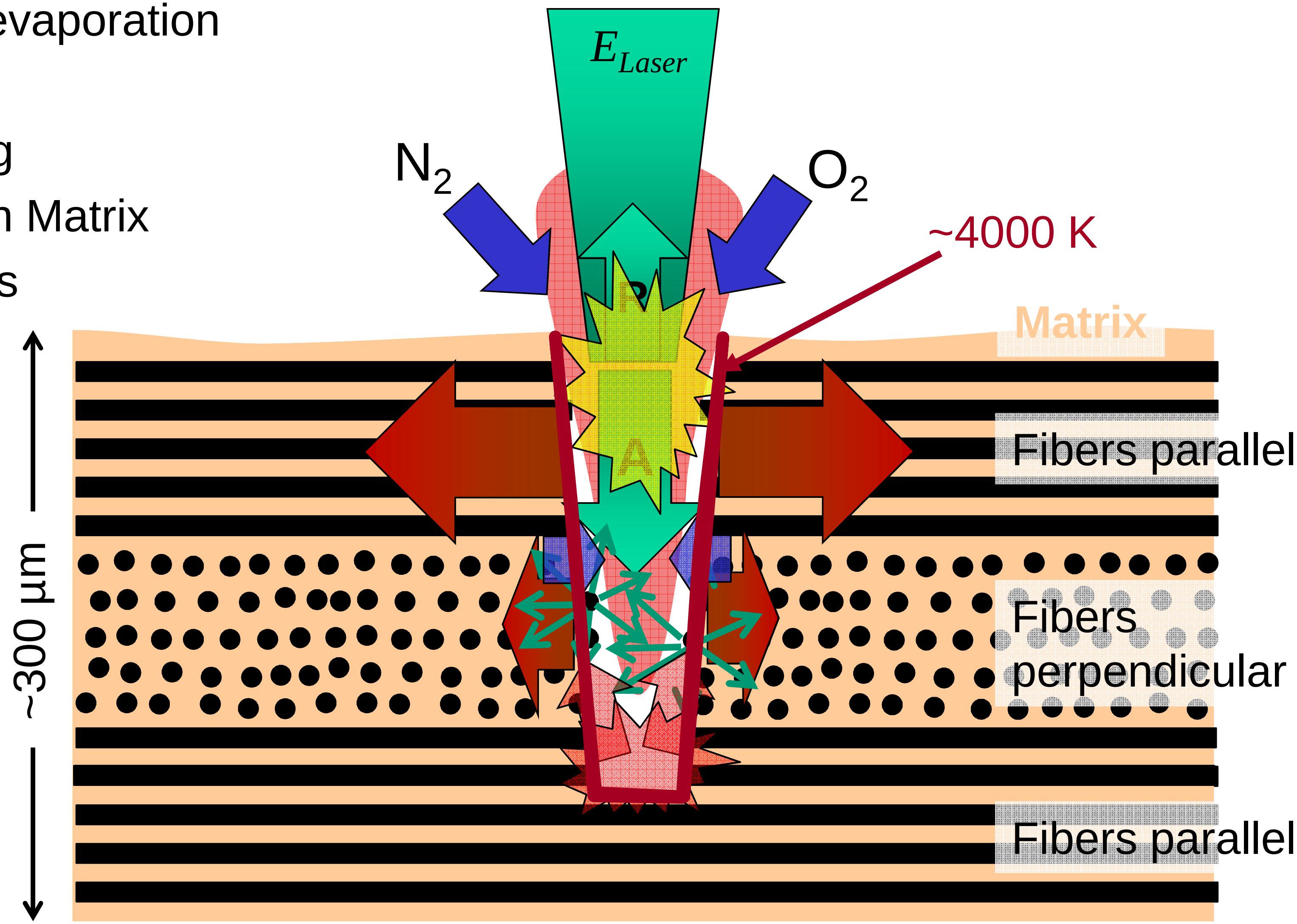
- Correct process strategies are the key
- Applies also to processing of metals





Energy Transfer Mechanisms During Ablation

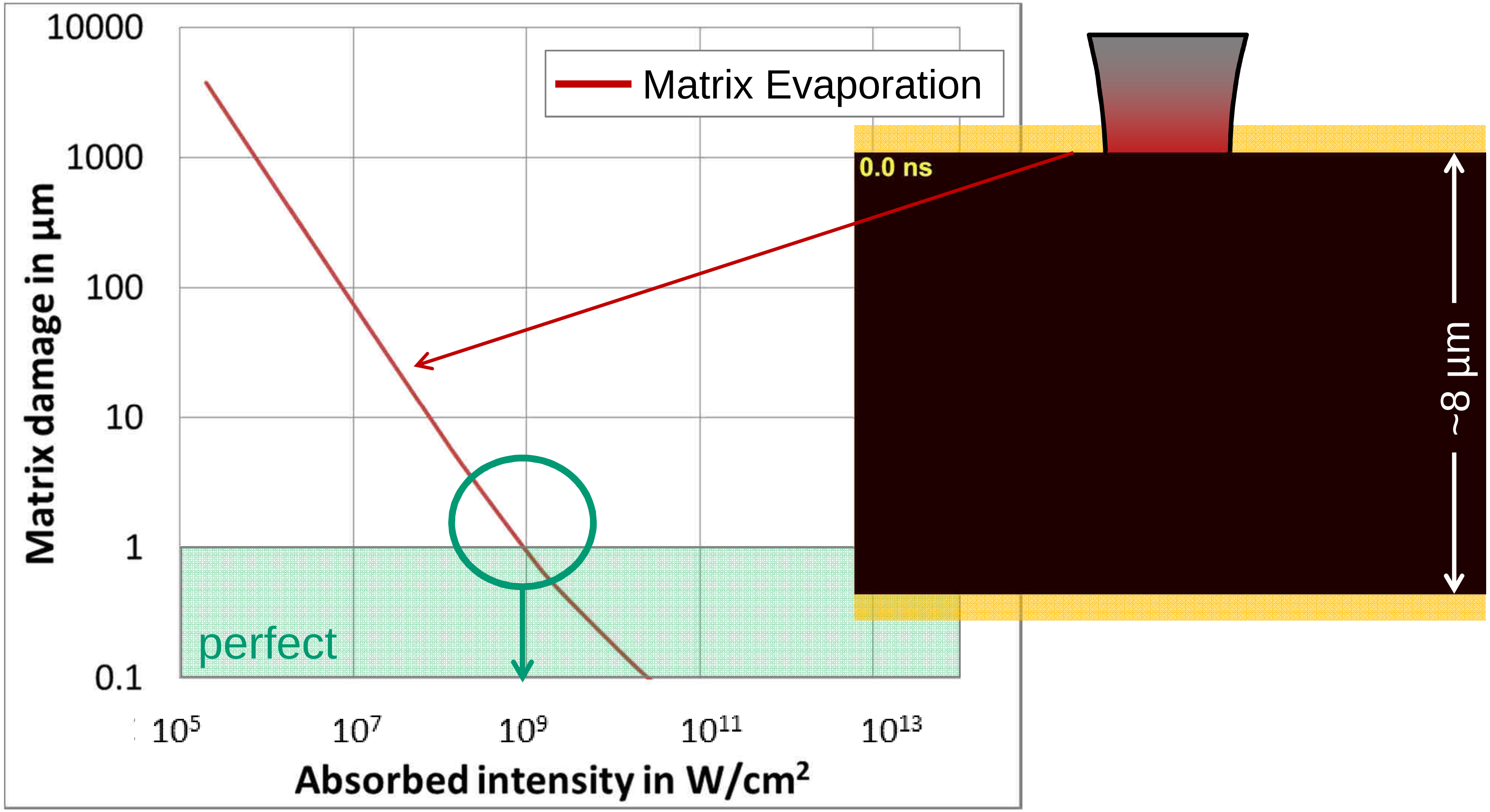
- Material evaporation
- Plasma
- Scattering
- Oxygen in Matrix
- Active gas



- Fraction η_{Heat} of absorbed energy is converted to heat
- Heat flow into the material source for matrix damage

Minimum Possible Damage Due to Basic Heat Flow

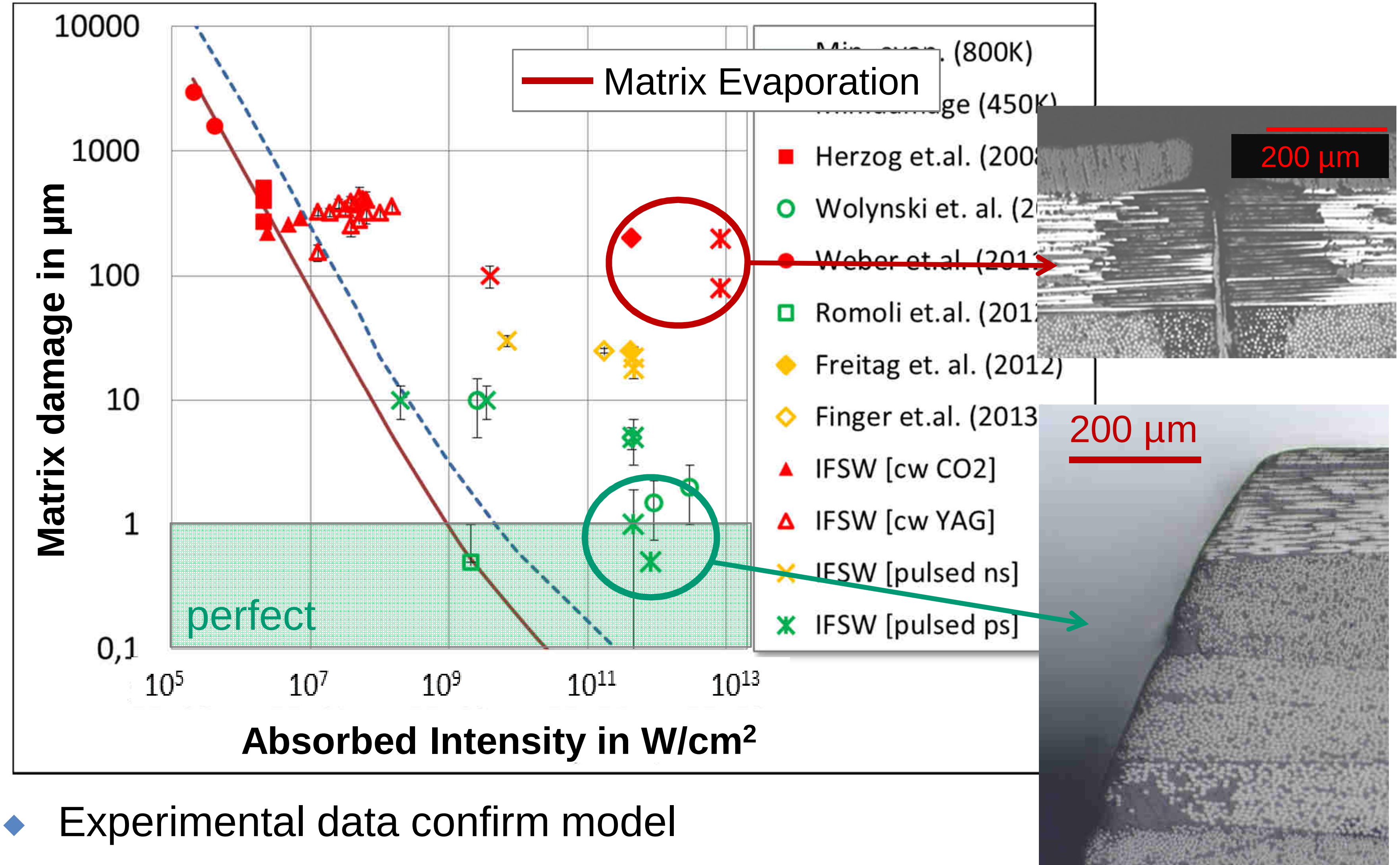
- Calculated maximum extension of 500 K isotherm on the fibre surface



> ➢ Perfect quality possible for intensity >10^9 W/cm^2

R. Weber, M. Hafner, A. Michalowksi, T. Graf, Physics Procedia 12 (2), 302-310 (2011)

Minimum Possible Damage Due to Heat Conduction



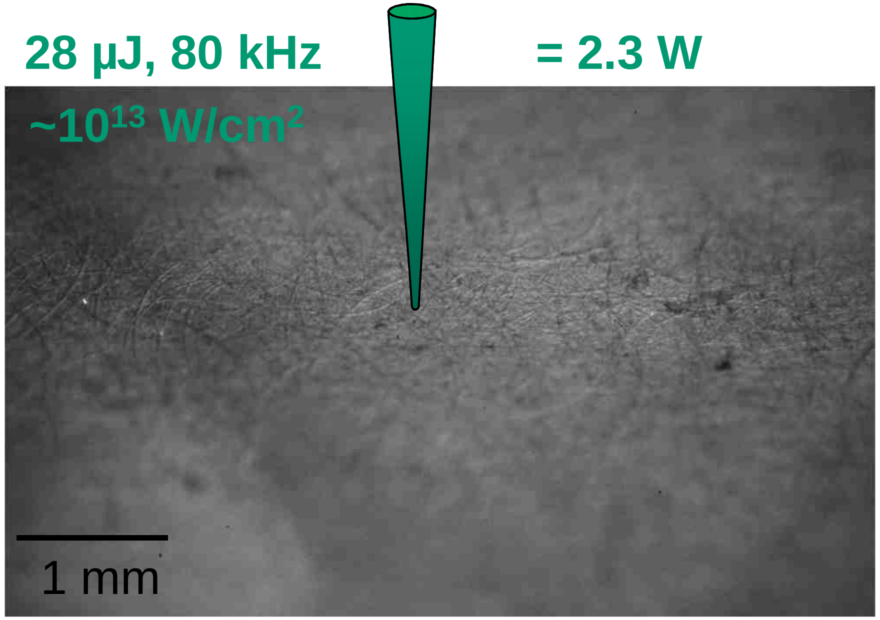
- Experimental data confirm model

> Perfect quality possible for intensity >10^9 W/cm²

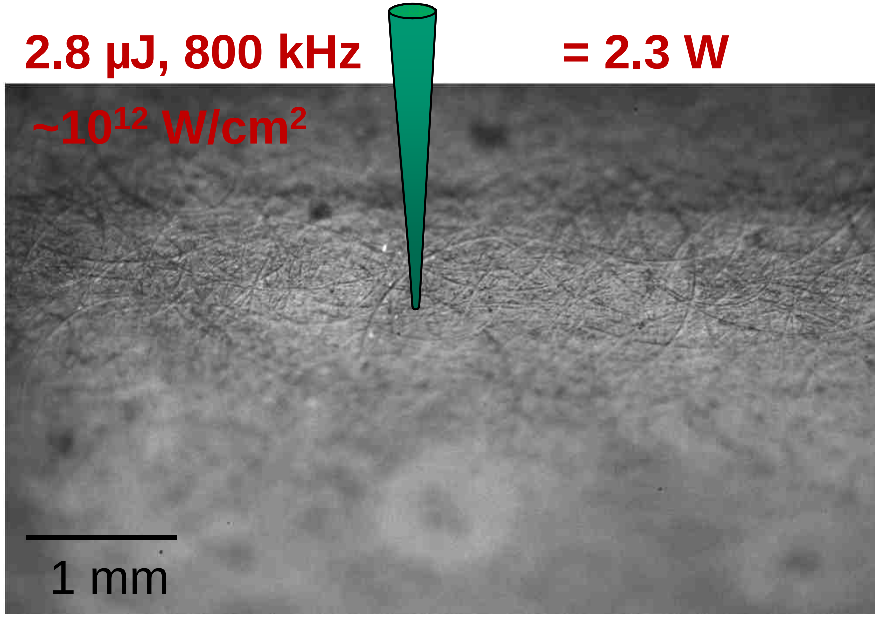
Pulse-to-Pulse Heat Accumulation

- Percussion drilling, 10 ps, 515 nm
- **Identical average power of 2.3 W**

28 µJ, 80 kHz = 2.3 W



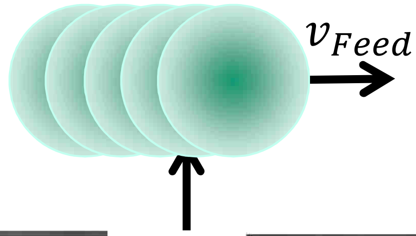
2.8 µJ, 800 kHz = 2.3 W



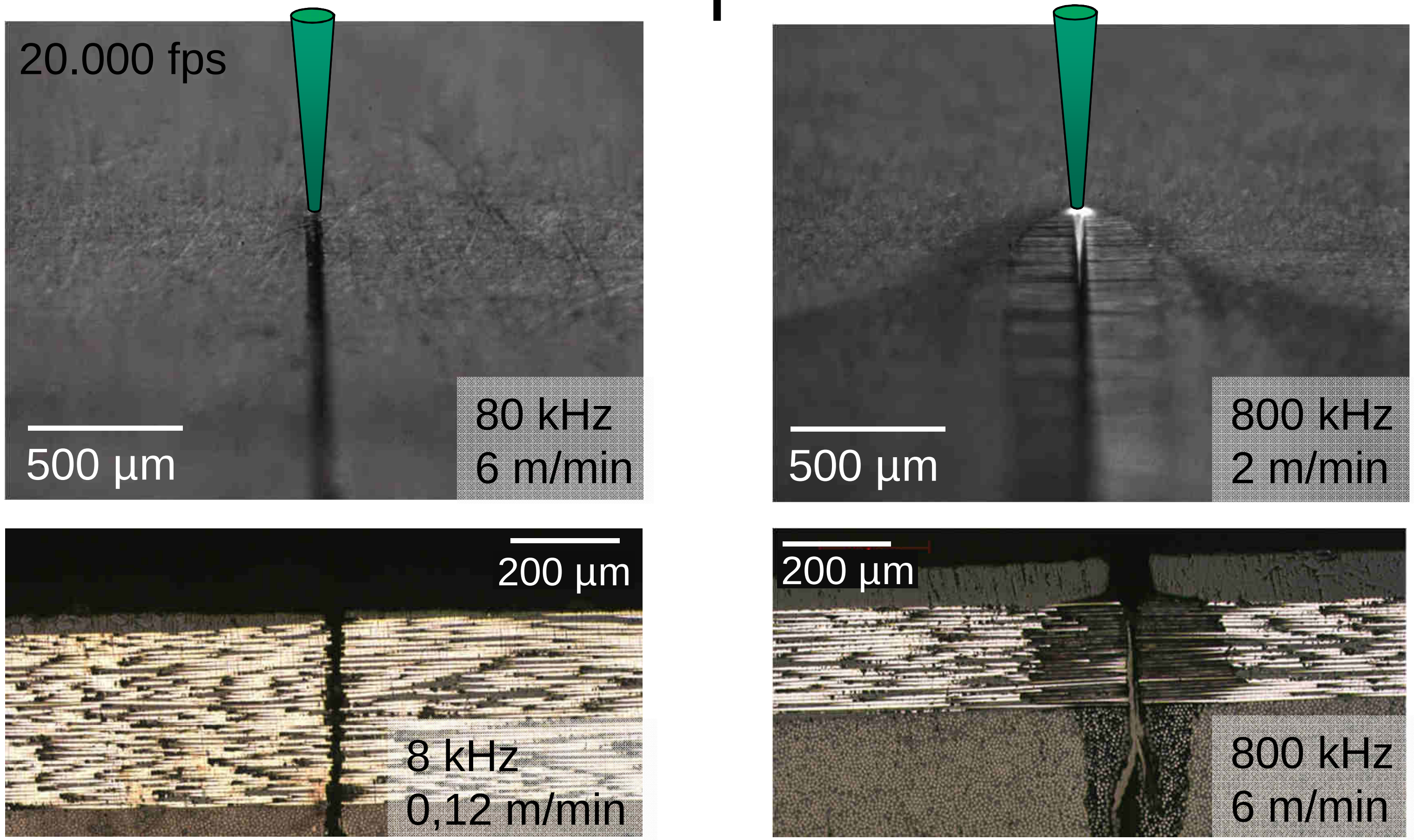
➢ **Strong pulse-to-pulse "heat accumulation" at higher frequency**

Moving Beams

- Number of pulses per spot proportional to frequency, spot size and feed

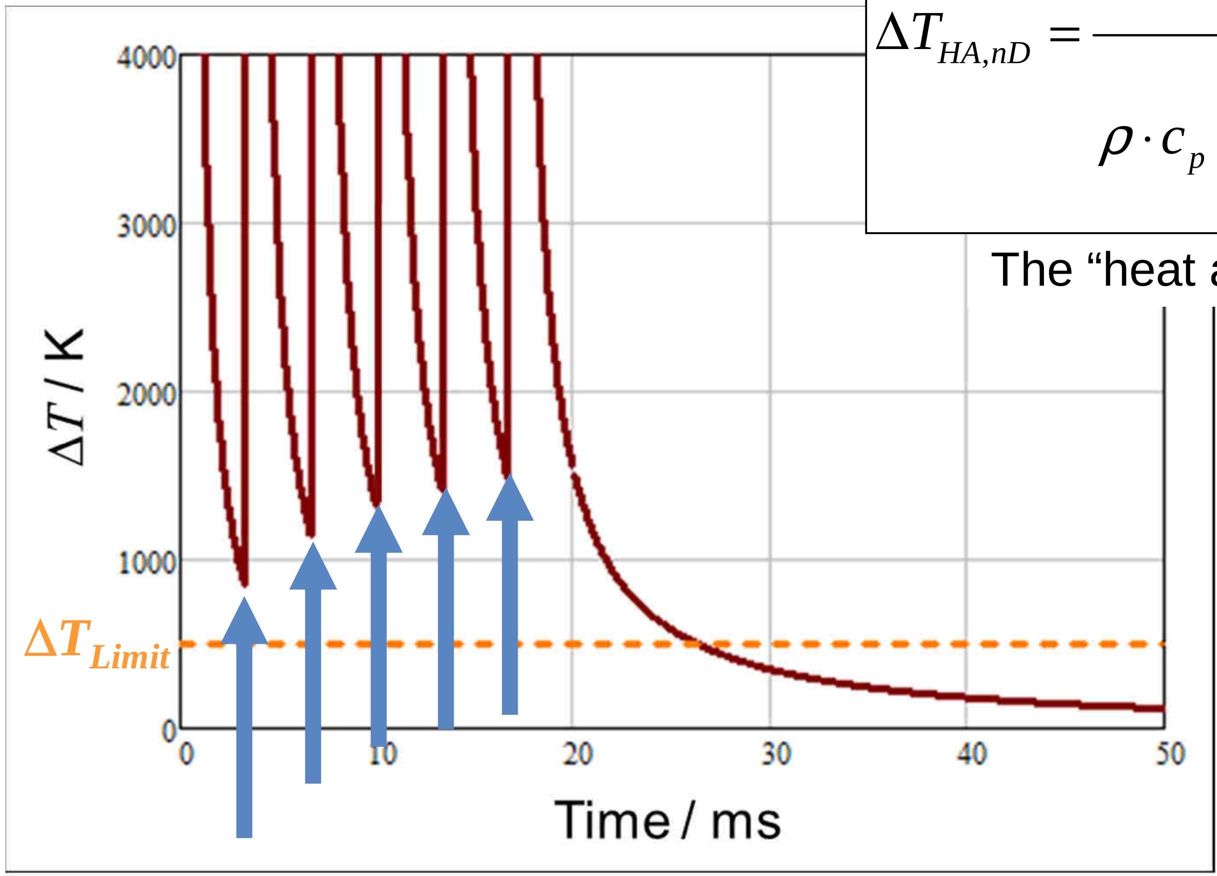


$$N_{Pulses} = \frac{d_{Focus} \cdot f_{Laser}}{v_{Feed}}$$



10 ps,
515 nm
28 µJ

➢ **Strong pulse-to-pulse "heat accumulation" at large N_{pluses} and high frequencies**



$$\Delta T_{HA,nD} = \frac{Q_{Heat,nD}}{\rho \cdot c_p \cdot \sqrt{\left(\frac{4 \cdot \pi \cdot \kappa}{f_L}\right)^{nD}}} \sum_{N=1}^{N_P} \frac{1}{\sqrt{N^{nD}}}$$

The “heat accumulation equation”

Solution to avoid HAP for moving beams:

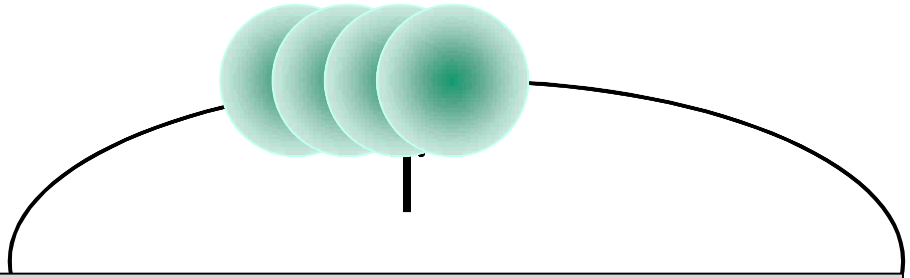
- **Fast beam movement, i.e.** $v_{Feed} \cong d_{Focus} \cdot f_{Laser}$

100 µm, 300 kHz
⇨ **30 m/s**

25 µm, 20 MHz
⇨ **500 m/s(!)**

R. Weber, et al., Optics Express 22 (9), 11312–11324 (2014)

Short Pulses Require Multi-Pass Processing



- **Required total number of scans given by material thickness!**

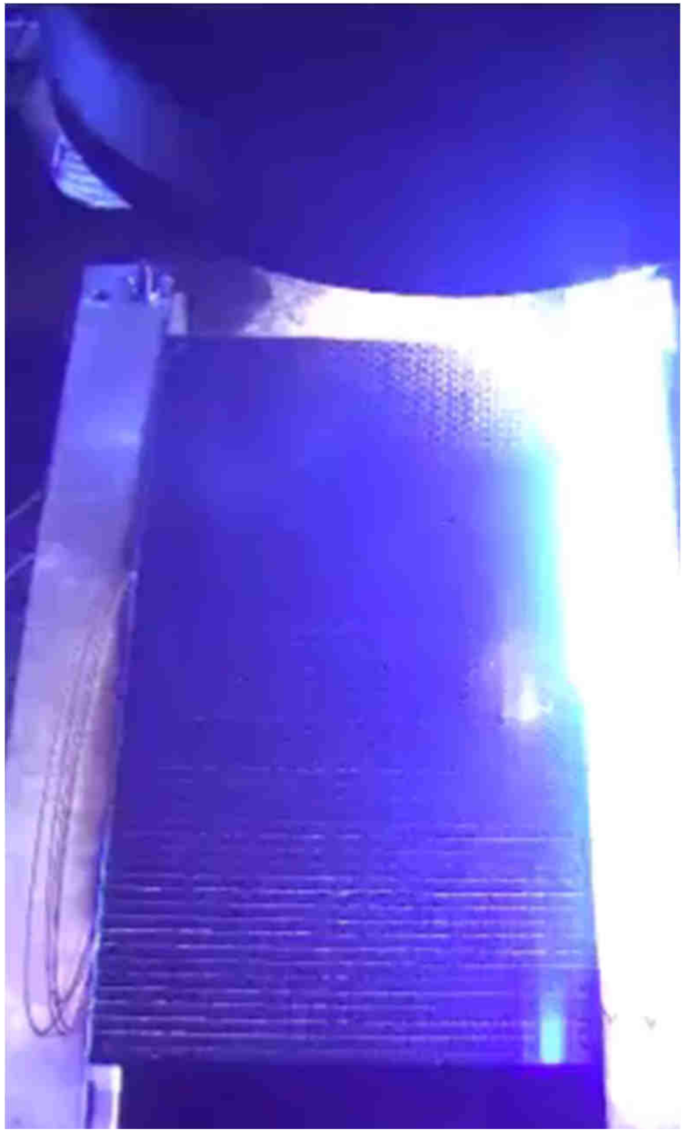
- Bi-axial CFRP, 2 mm
- 6 cm diameter circles
  Contour length ~180 mm

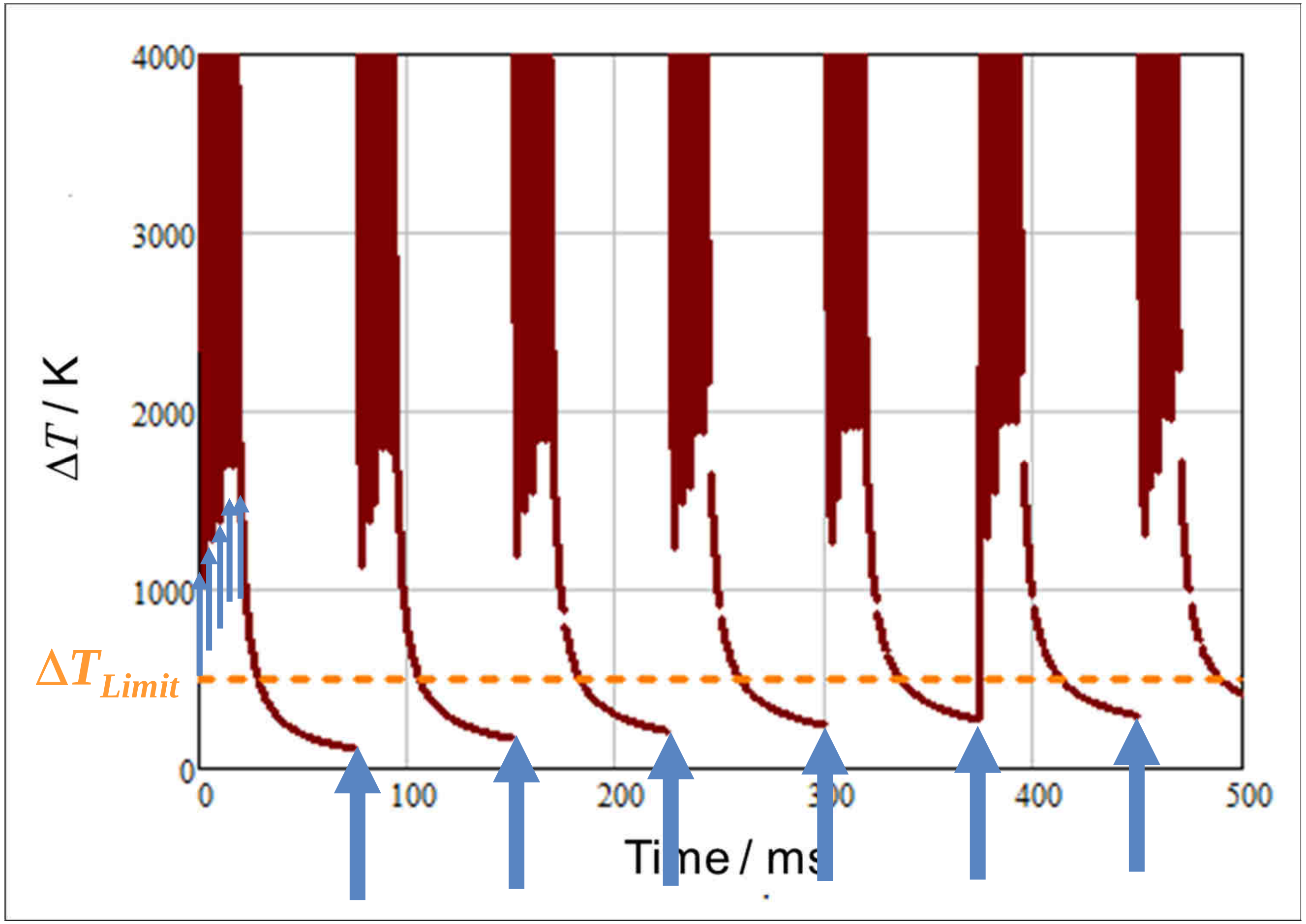
0.4 kW, 300 kHz, 1.3 mJ

$1 \cdot 10^{12}$ W/cm^2

30 m/s ⇨ $N_{Pulses} \simeq 1$

- **Strong heat accumulation for increasing number of scans**
- **Burning if > 200 scans**



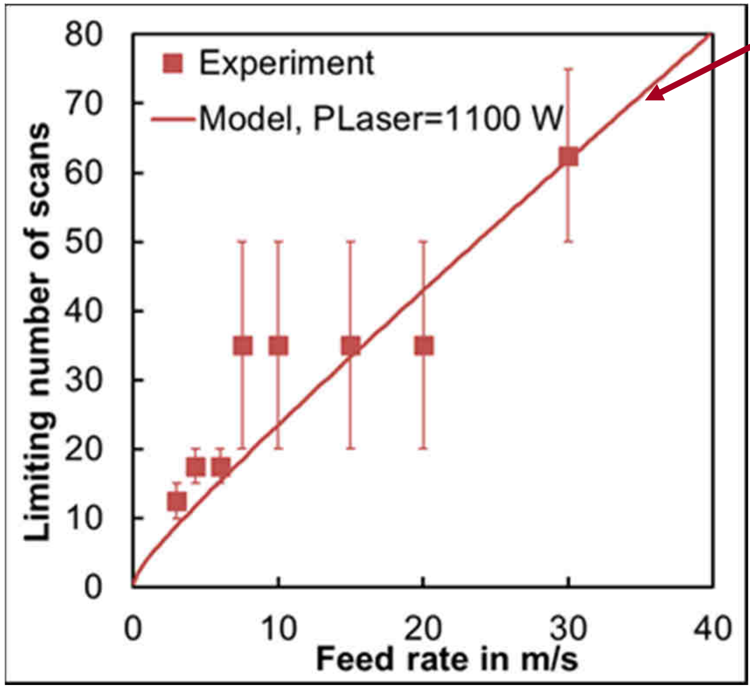


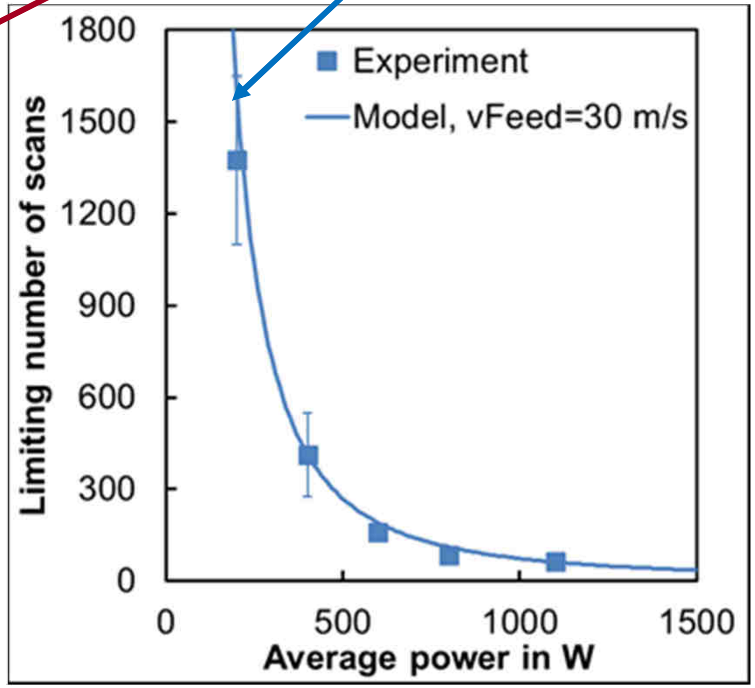
- N_{Scans} > 2000 for 2 mm thick CFRP
- **Process limits due to heat accumulation?**

Analytical Model for HAS and Experimental Verification

$$N_{Limit,approx} \cong \frac{C_{Mat,1D}^2 \cdot \Delta T_{Limit}}{4} \cdot d_{Mat}^2 \cdot \ell_{Contour} \cdot \frac{v_{Feed}}{P_{Laser,av}^2}$$

($C_{Mat,1D} \cong 9000\ \mathrm{J/s^{0.5}/m^2}$)





Solution to avoid HAS for moving beams:

- Increase feed, **reduce power per contour, make breaks**

Model: R. Weber, C. Freitag, T. Graf, Submitted to Optics Express 6/2016

Experimental data: C. Freitag, T. Kononenko et al, Applied Physics A , 119(4), (2015)

Mandatory Rules to Achieve Perfect Thermal Quality

1. Enough intensity (no SPD)

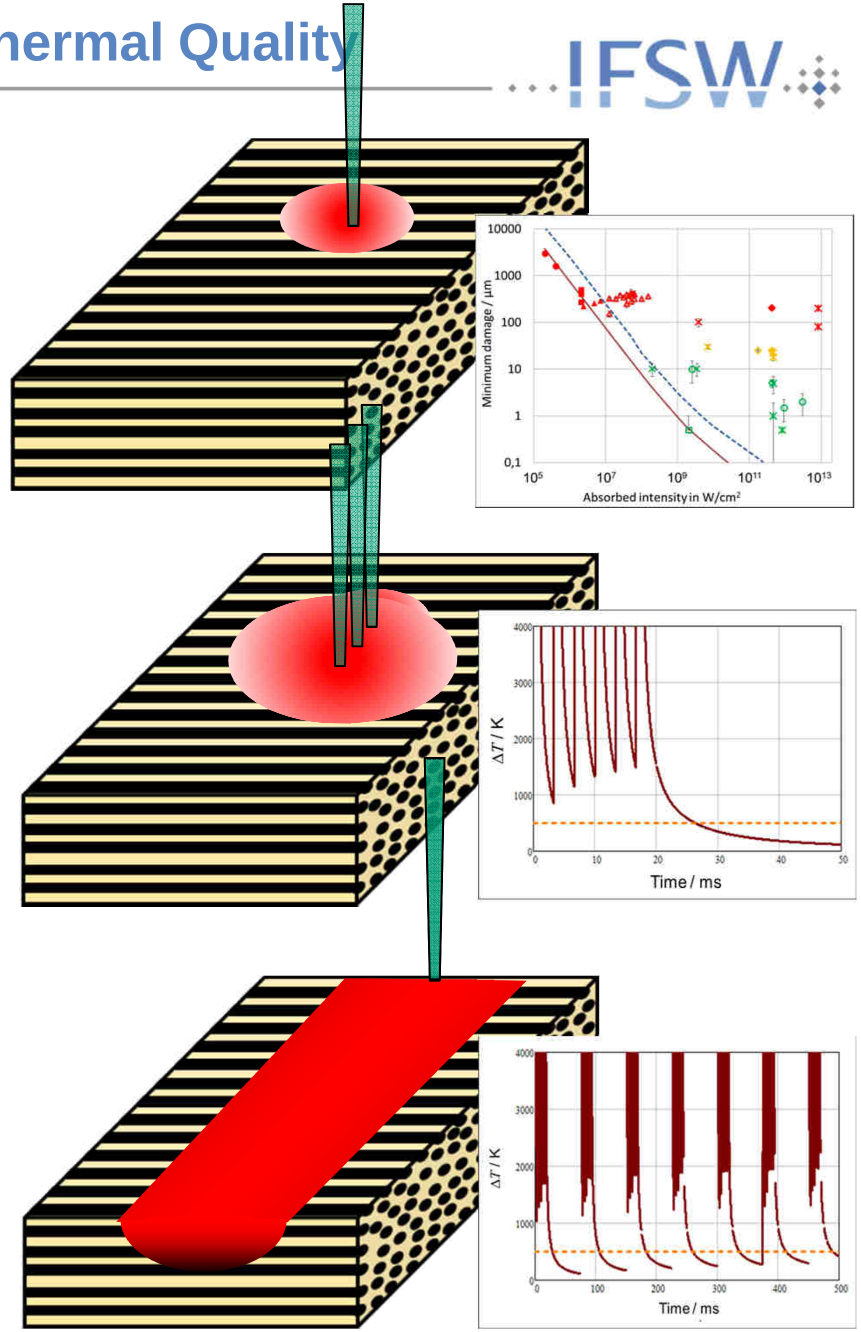
$$>10^9 W / cm^2$$

2. Fast beam movement (no HAP)

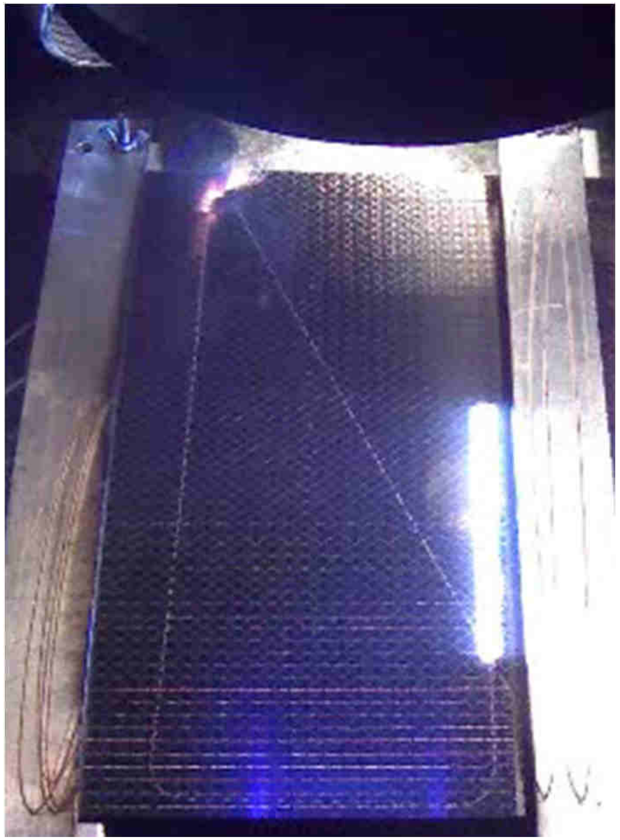
$$v_{Feed} \cong d_{Focus} \cdot f_{Laser}$$

3. Reduced power per contour and enough breaks (no HAS)

$$N_{Limit} \cong \frac{C_{Mat1D}^2 \cdot \Delta T_{Limit}}{4} \cdot d_{Mat}^2 \cdot \ell_{Cont} \cdot \frac{v_{Feed}}{P_{Laser}^2}$$



IFSW Disk-kW-ps Laser (Passive Multipass Amplifier)



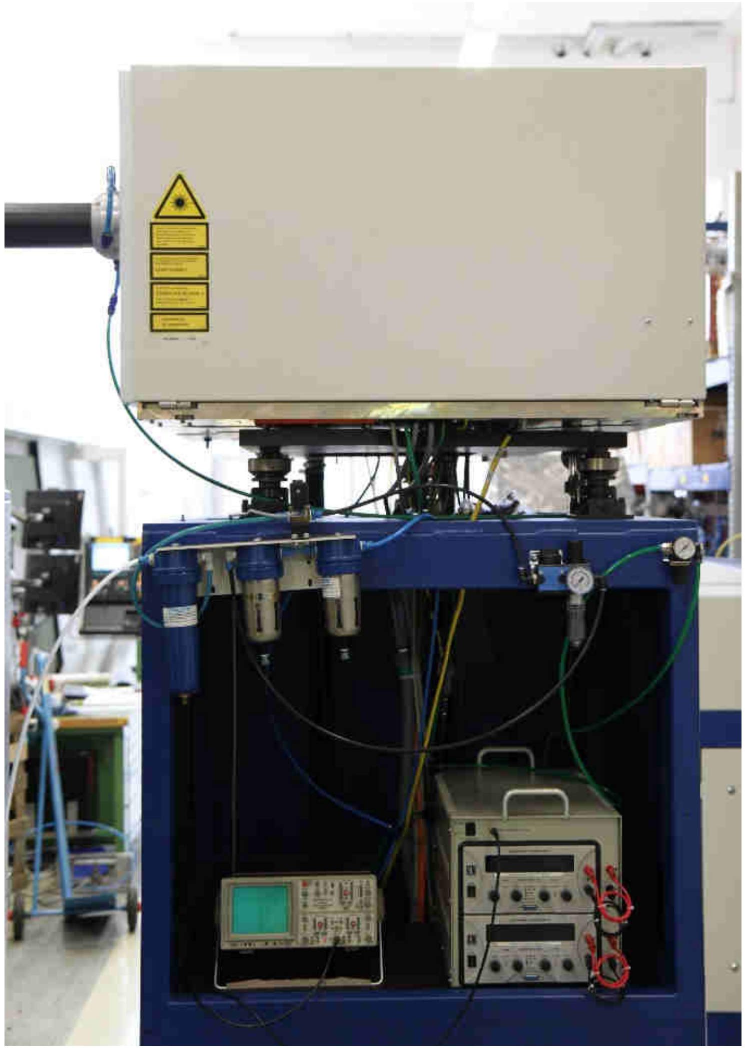
Laser 1.1 kW
1.03 µm, 8 ps
300 kHz, 3 mJ

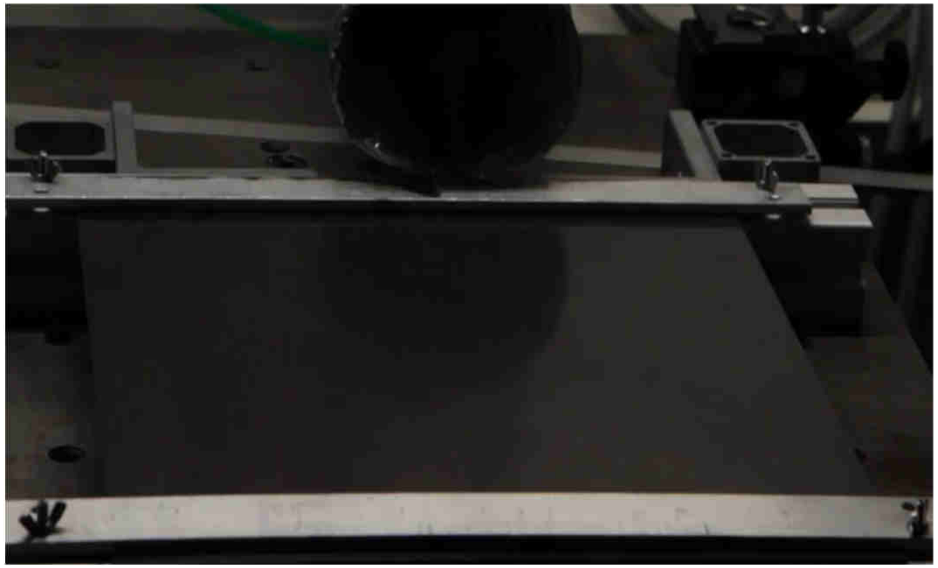
Scanner
f = 340 mm
d_f = 120 µm

Process
~0% absorptance in the matrix
~80% absorptance in CFRP

C. Freitag et al., Applied Physics A,119(4) (2015)

Trumpf CO_2-kW-ns Prototype Laser





Laser 1.1 kW
10.6 µm, 170 ns
20 kHz, 60 mJ

Scanner
f = 450 mm
d_f = 360 µm

Process
~100% in the matrix
~40% absorptance in carbon fibers

1 µm Disk-kW-ps Laser

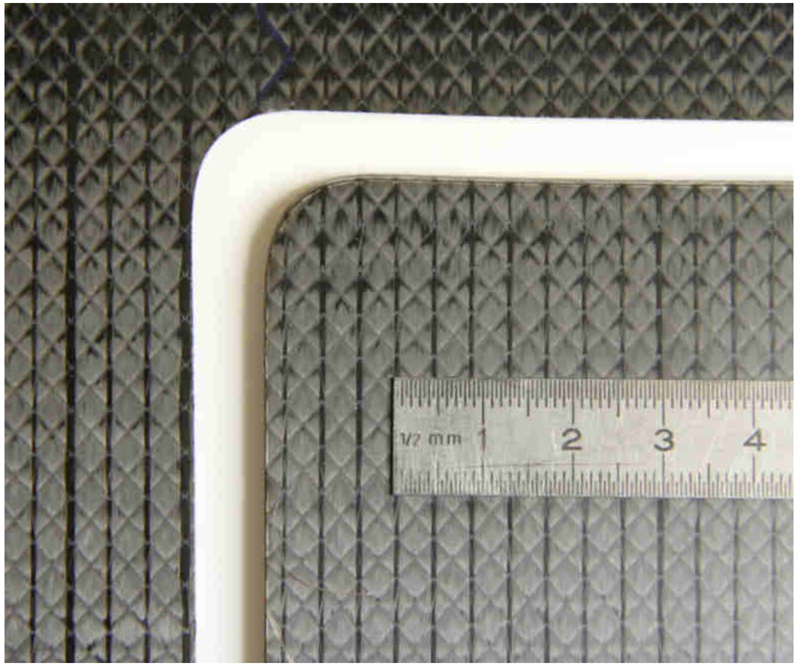
Contour size	20 x 10 cm^2
Intensity	$7 \cdot 10^{12}$ W/cm^2
Feed rate	30 m/s
N_{Pulses} / spot	1.25
Total Scans	2100

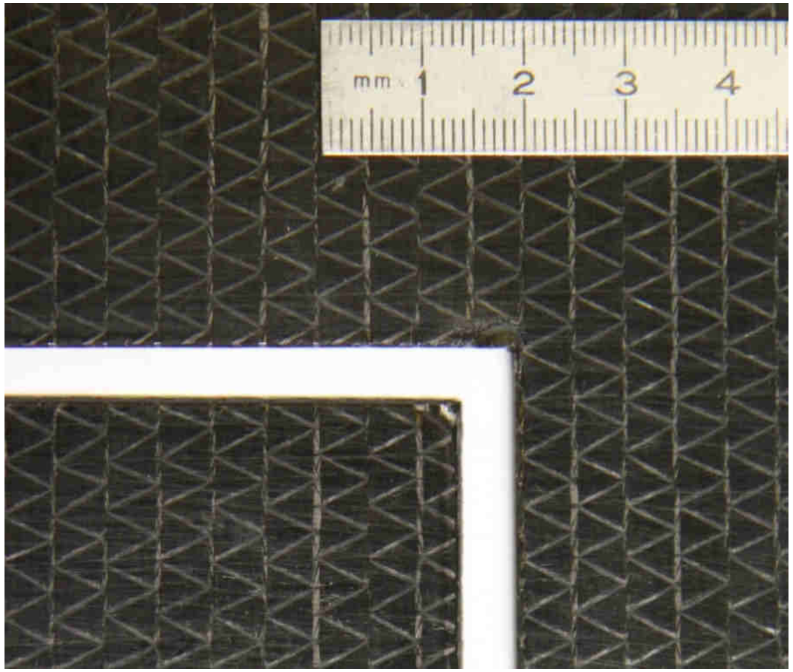
Break after 200 consecutive scans

10 µm CO_2-kW-ns Laser

Contour size	18 x 18 cm^2
Intensity	$6 \cdot 10^{8}$ W/cm^2
Feed rate	15 m/s
N_{Pulses} / spot	7.5
Total Scans	2300

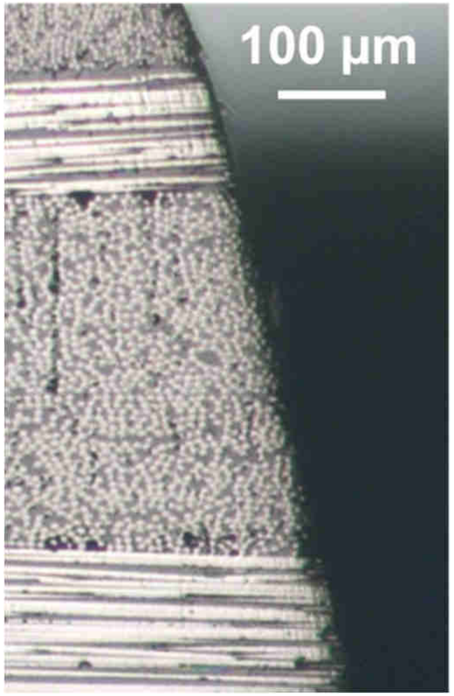
Break after 50 consecutive scans



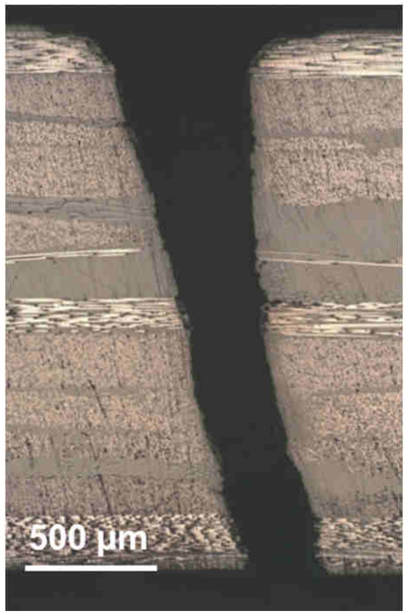


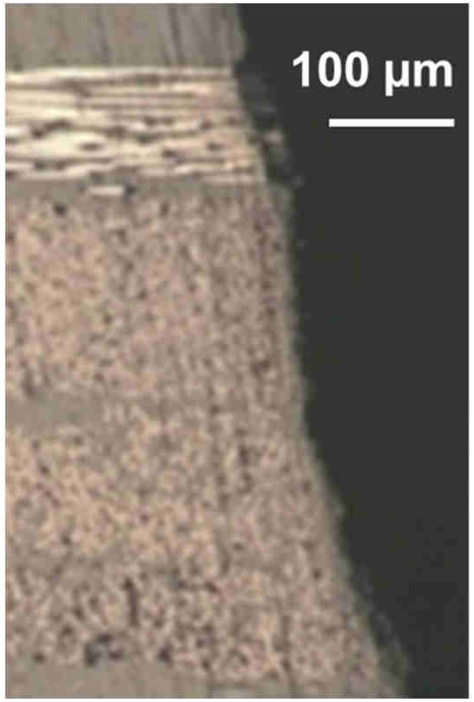
High Quality Cuts - Cross Sections

Disk-kW-ps Laser:



CO_2-kW-ns Laser:

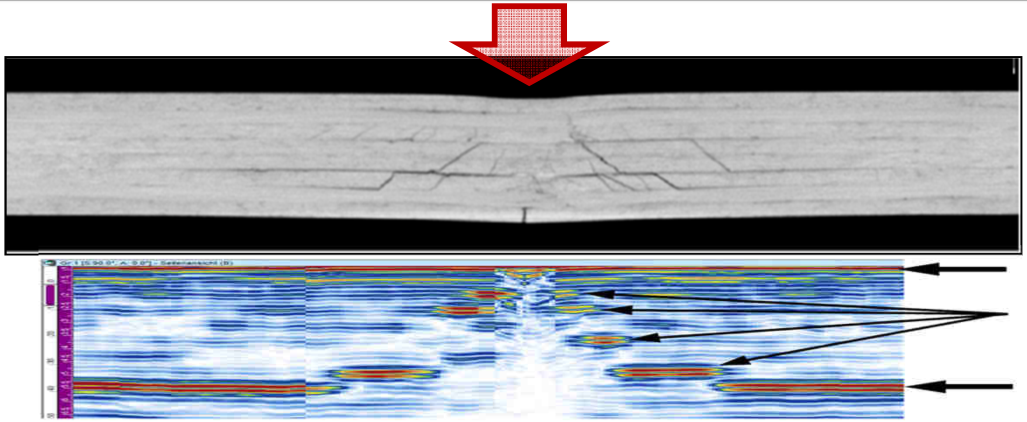




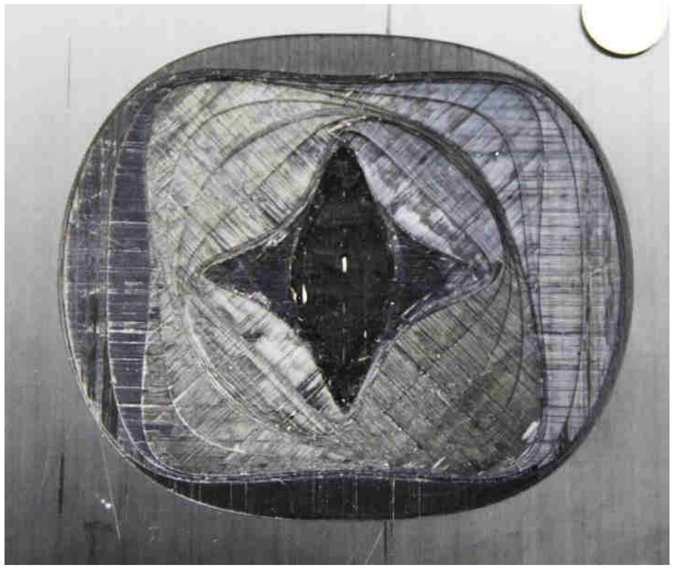
- **Magnification shows "perfect" thermal quality**
- Largest measured extent of the thermal damage was < 20 µm (Disk) and < 30 µm (CO_2)

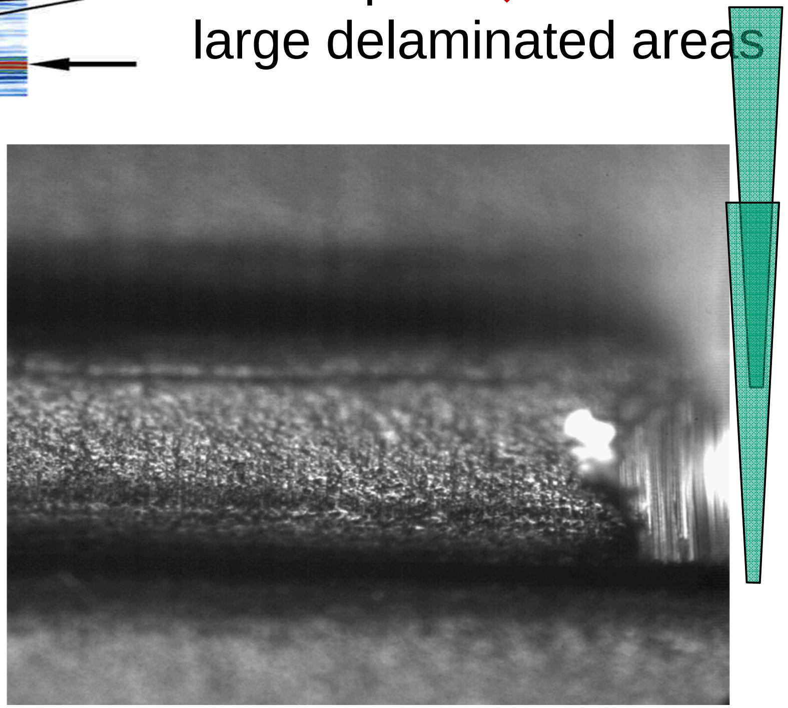
- Relative position of the two halves and the kerf width is arbitrary
- Additional effects slightly reduce quality to about $< \pm 50$ µm
- **System design challenges**

"Clever" Surface Ablation of CFRP for Repair Preparation



20 J impact creates large delaminated areas



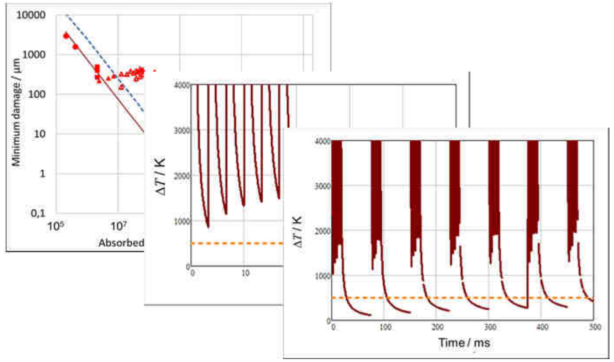


- Damage-repair pattern yields for 95% strength
- **Large volume to remove**

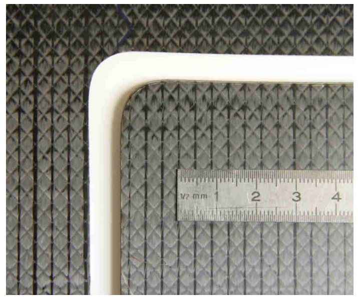
- **Take benefit of heat accumulation**
- Very efficient "grooving-removing"
> 5x increase of process efficiency

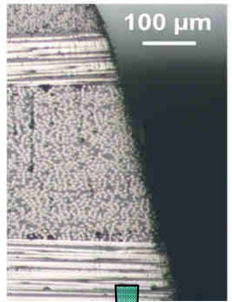
Conclusion

- Correct processing parameters and strategies to avoid single pulse thermal damage and heat accumulation effects

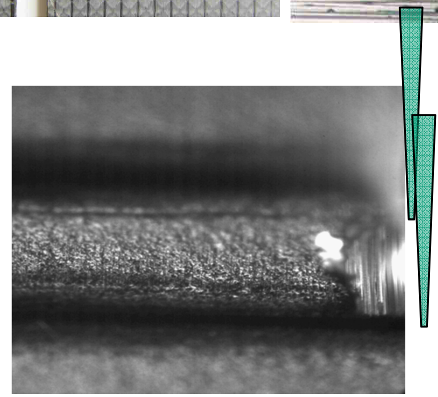


- Applying these strategies yields perfect "thermal quality"





- New process strategies allow significant increase of the efficiency

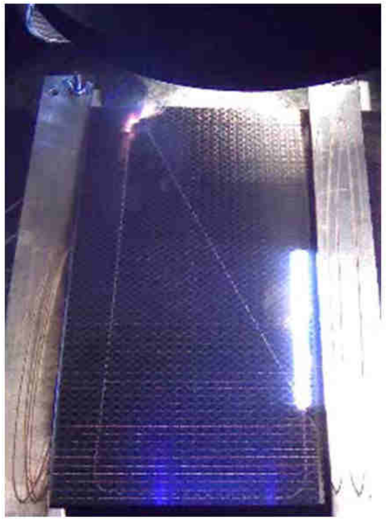


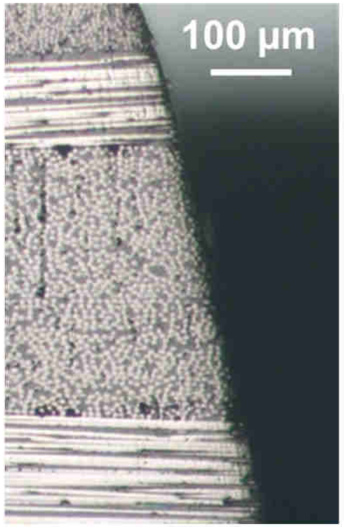
High-Quality Laser Processing of CFRP

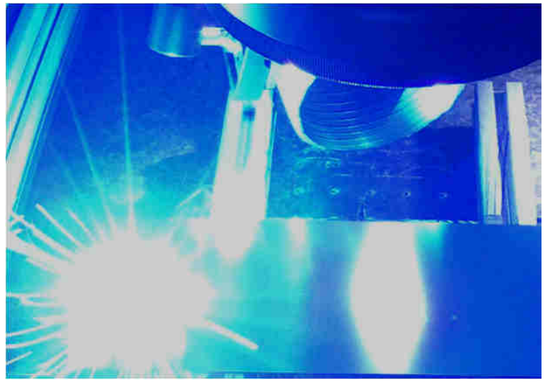
Rudolf Weber

Christian Freitag, Margit Wiedenmann, Thomas Graf

15.6.2016







SALON INTERNATIONAL
LEADER DE LA HAUTE PRECISION
HORLOGERIE-JOAILLERIE · MICROTECHNOLOGIES · MEDTECH

SWISS PHOTONICS

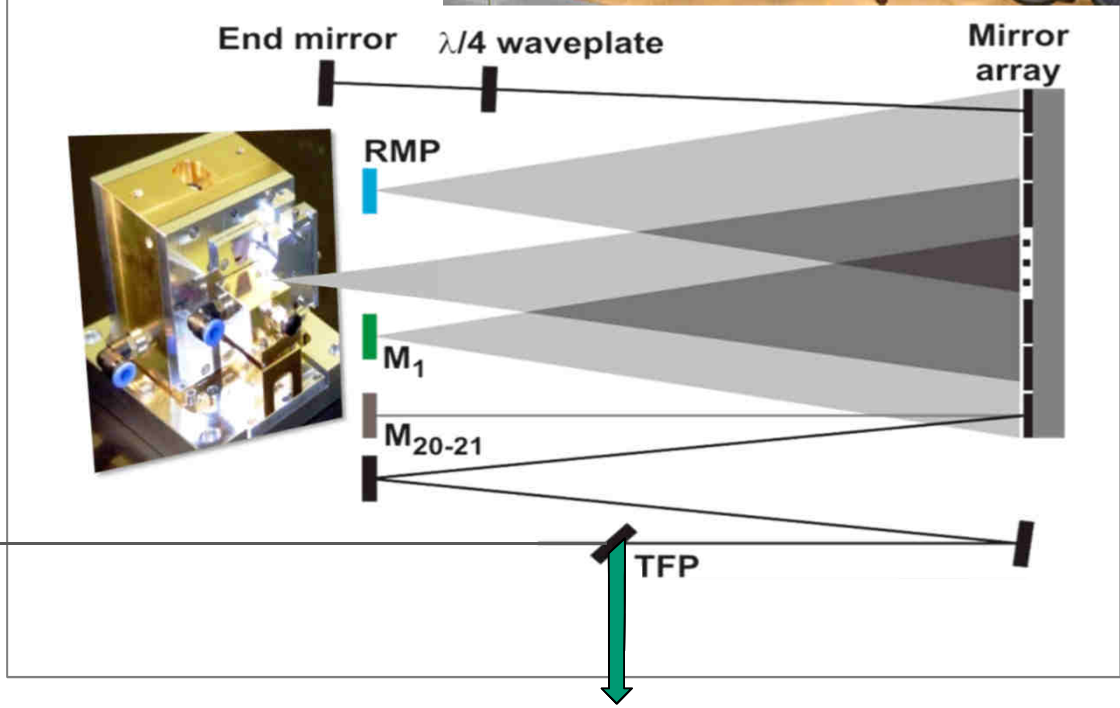
IFSW
UNIVERSITÄT STUTTGART
INSTITUT FÜR STRAHLWERKZEUGE
STUTTGART LASER TECHNOLOGIES

Scaling to Kilowatt Picosecond Lasers

Array of 40 mirrors
for 40 reflections on the disk

Seed Laser
(TruMicro 5050-LE)

115 W, 300 kHz,
1030 nm, $M^2 < 1.4$

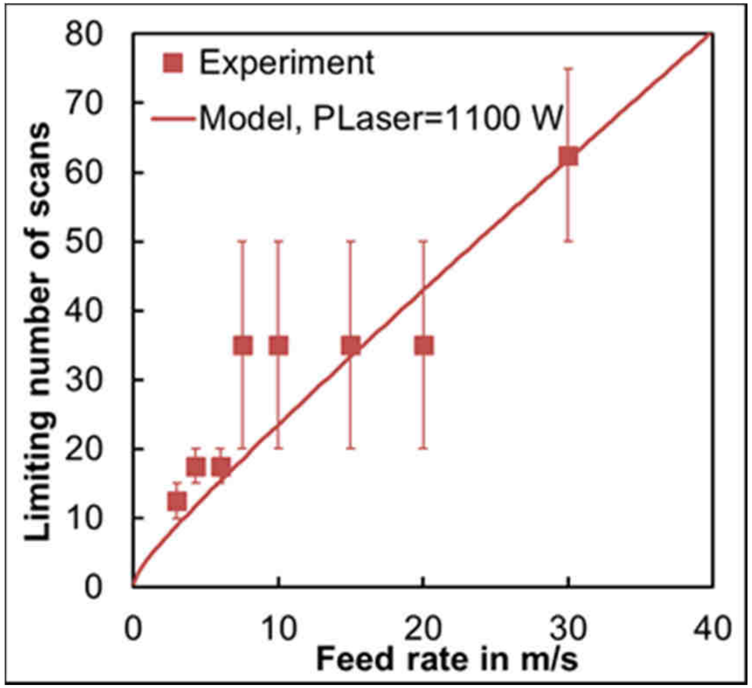


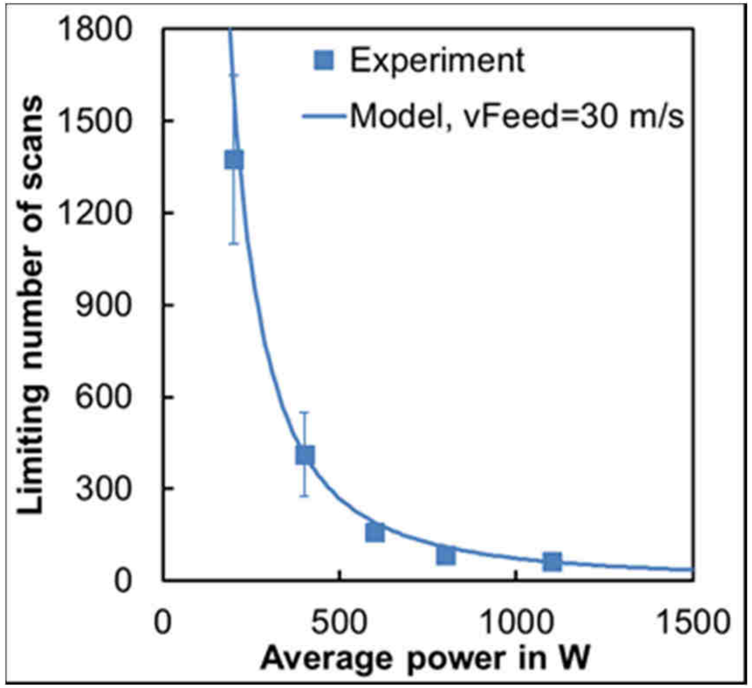
1.4 kW @ 300 kHz
⇨ 4.7 mJ

J. Negel et al., Opt. Lett. 38, 5442-5445 (2013)

Analytical Model for HAS and Experimental Verification

$$N_{Limit,1D} = \left(\frac{C_{Mat,1D} \cdot \Delta T_{Limit}}{2} \frac{d_{Mat} \cdot \sqrt{v_{Feed} \left(\ell_{Contour} + v_{Feed} \cdot t_{Pos} \right)}}{P_{Laser,av}} - \frac{C_{1D}}{2} \right)^2$$





Solution to avoid HAS for moving beams:

- **Reduce power per contour, make breaks**

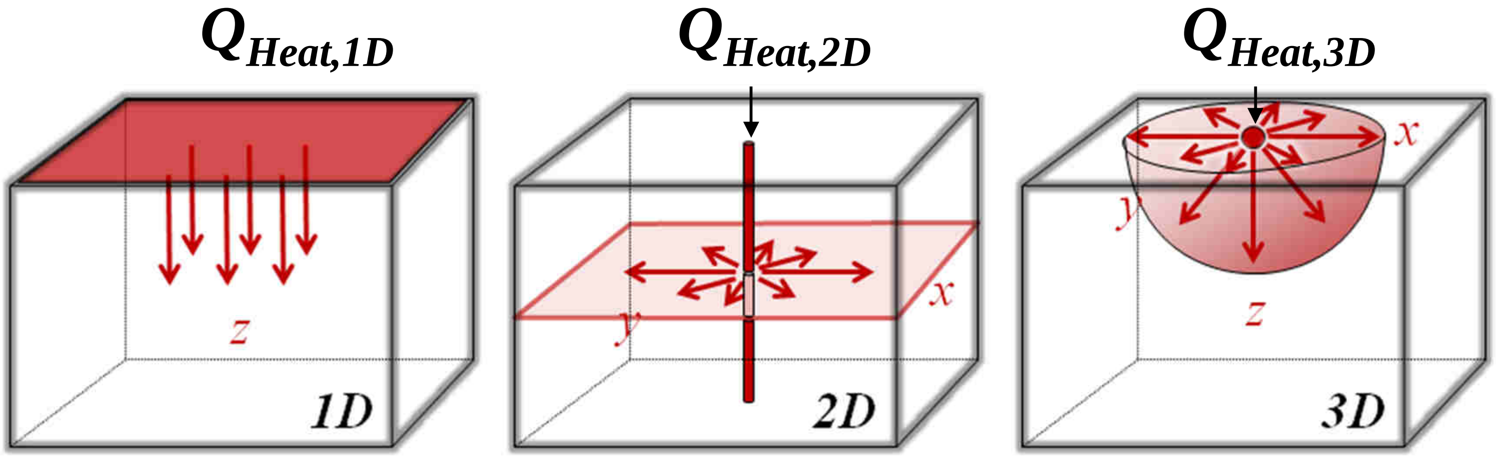
Model: R. Weber, C. Freitag, T. Graf, Submitted to Optics Express 6/2016

Experimental data: C. Freitag, T. Kononenko et al, Applied Physics A , 119(4), (2015)

($C_{Mat,1D} \cong 9000$ J/s$^{0.5}$/m^2

$C_{1D} \cong -1.46$)

- *nD*-dimensional geometry depending on setup

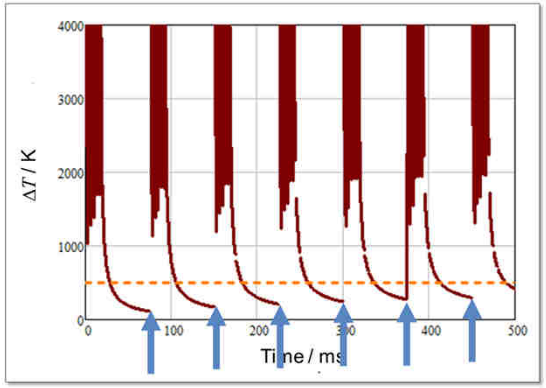


- Pulsed heat input, each creating a temperature field
- Summing up the temperature fields created by each heat input $Q_{Heat,nD}$
- Temperature increase after N_P pulses

$$\Delta T_{HA,nD} = \frac{Q_{Heat,nD}}{\rho \cdot c_p \cdot \sqrt{\left(\frac{4 \cdot \pi \cdot \kappa}{f_L}\right)^{nD}}} \sum_{N=1}^{N_P} \frac{1}{\sqrt{N^{nD}}}$$

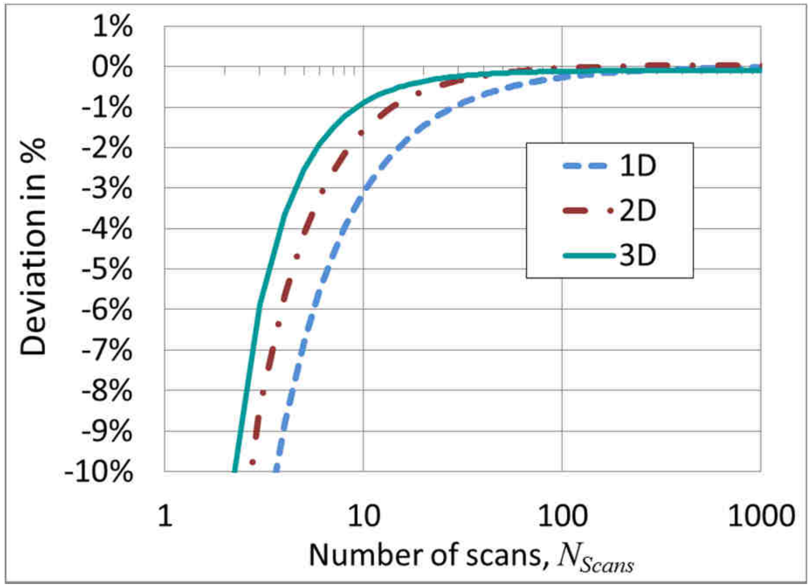
R. Weber, T. Graf, P. Berger, V. Onuseit, M. Wiedenmann, C. Freitag, A. Feuer, "Heat accumulation during pulsed laser materials processing", Optics Express 22 (9), 11312–11324 (2014)

- 1-D heat accumulation by scans (HAS)



$$\Delta T_{HA,1D} = \frac{Q_{Heat} \cdot \sqrt{f_{Scans}}}{\rho \cdot c_p \cdot \sqrt{4 \cdot \pi \cdot \kappa}} \sum_{N=1}^{N_{Scans}} \frac{1}{\sqrt{N}}$$

- Approximation for the sum

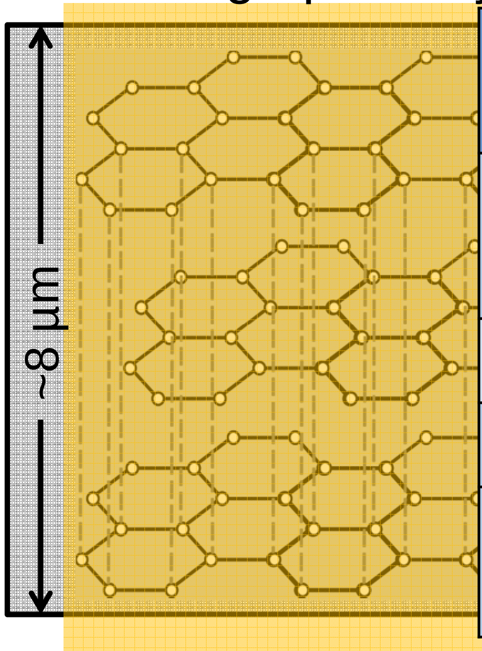


$$\sum_{N=1}^{N_{Scans}} \frac{1}{\sqrt{N}} \cong \int_{1}^{N_{Scans}} \frac{1}{\sqrt{N}} dN + C_{1D}$$

$$\cong 2\sqrt{N_{Scans}} + C_{1D}$$

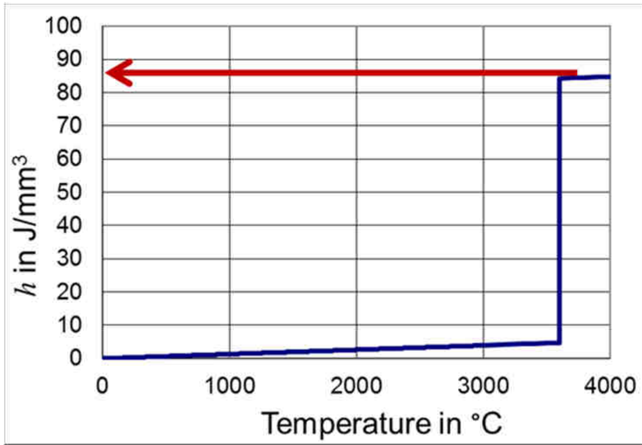
Thermo-Physical Data of CFRP

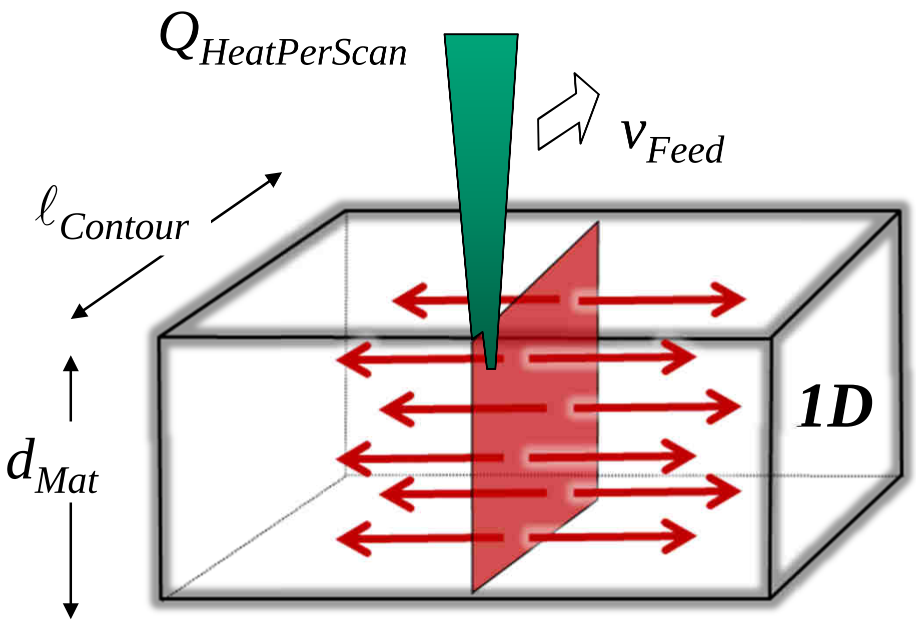
50-80% graphite layers



Thermo-physical data	Carbon Fibers	Matrix
Heat conductivity k in W/m·K	50 / 5 (∥ / ⊥)	0.2
Evaporation temperature T_V in °K	~3,900	800
Enthalpy for evaporation h_V in J/mm³	85	2
Threshold fluence (10 ps) in J/cm²	0.3	1.2 (1µm) 0.2 (0.3 µm)

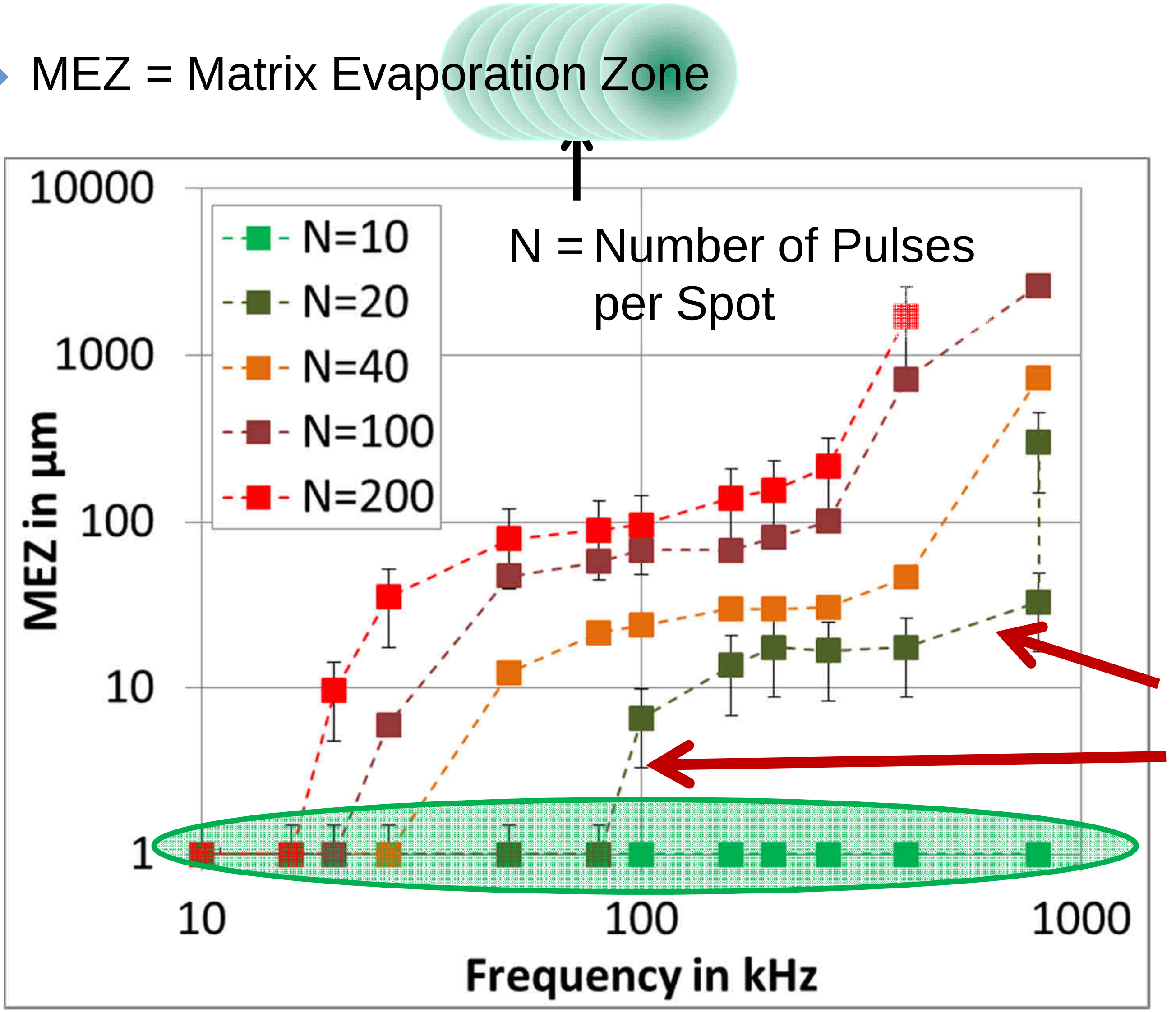
- About 60% carbon, 40% matrix
- Heat conduction mainly **along** the carbon fibers
- Very high evaporation temperature of carbon
- Low matrix damage temperature
- 85 J/mm³ enthalpy for carbon evaporation
- Picosecond ablation threshold ~0.3 J/cm²





- 1-D applies if $t_{Process} > d_{Mat}^2/(4 \cdot \kappa)$ $\kappa = \lambda_{th}/(\rho\, c_p)$
- Reached in <0.5 s in the case of 2 mm thick CFRP

- MEZ = Matrix Evaporation Zone



Average power increases ⇨

E = const! = 31 µJ

Φ = 28.8 J/cm²

I = 3.6·10¹² W/cm²

N set with feed

2. Increase

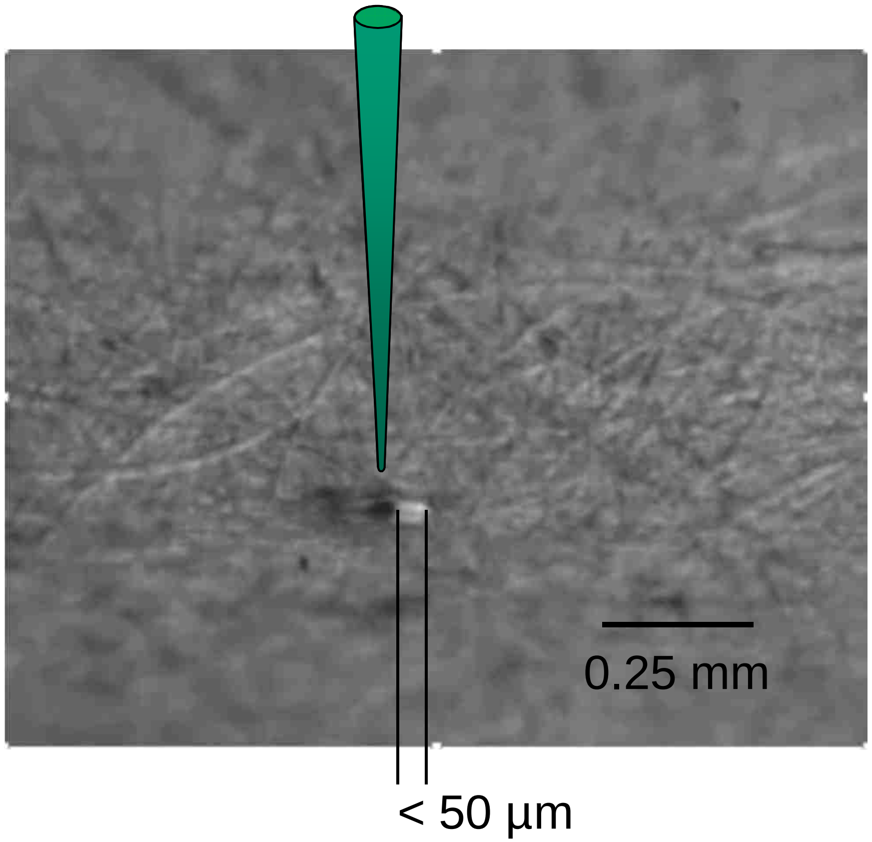
1. Increase

Perfect

T.V. Kononenko, C. Freitag, M.S. Komlenok, V. Onuseit, R. Weber, T. Graf, and V.I. Konov,

Single-Pulse Damage

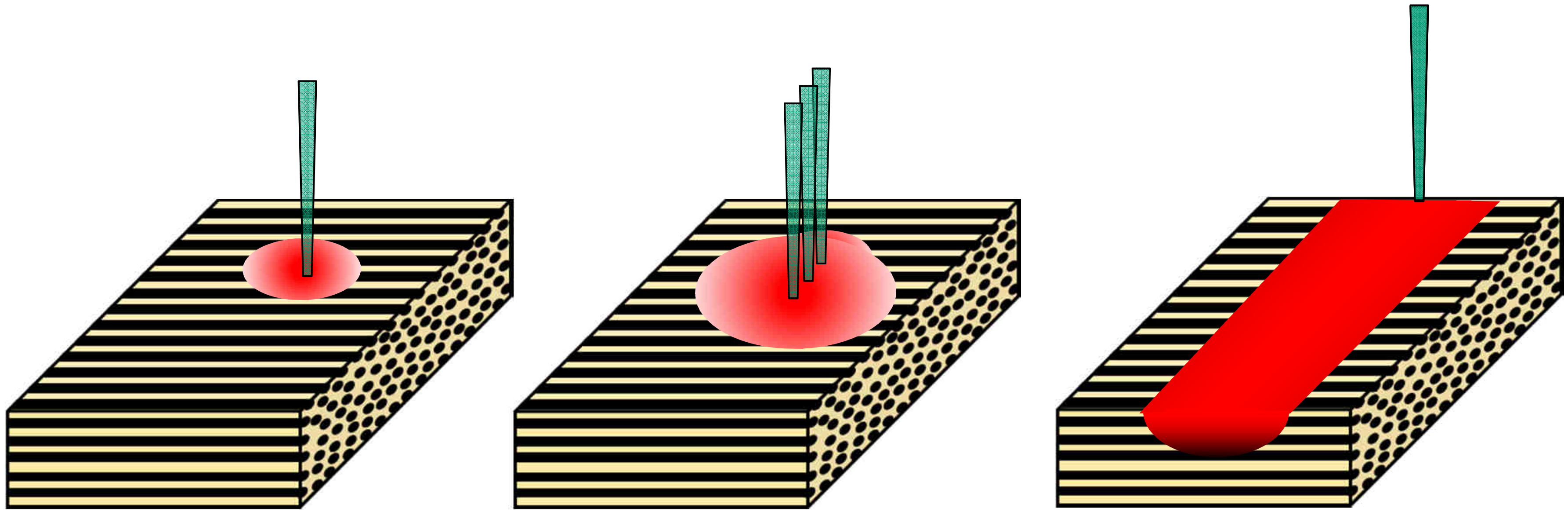
- Percussion drilling
- First ~30 pulses



- 10 ps, 515 nm
- 28 µJ, 80 kHz = 2.3 W
- ~10^{13} W/cm^2

> **Very small single-pulse thermal damage possible**

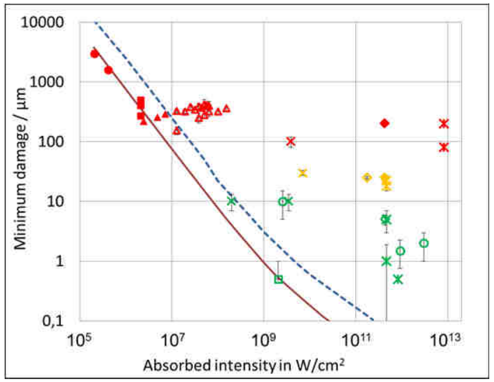
- Heat flow from a **single laser pulse (SPD)**
- Heat accumulation between consecutive **laser pulses (HAP)**
- Heat accumulation between consecutive **scans (HAS)**



Mandatory Rules to Achieve Perfect Thermal Quality

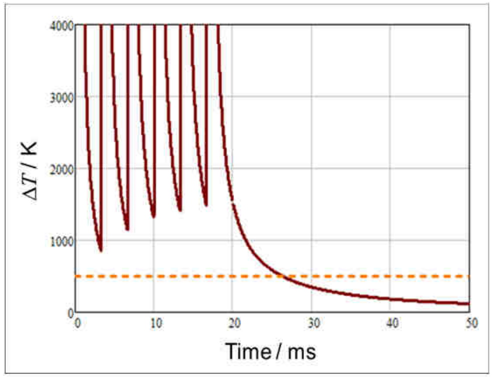
1. Enough intensity (no SPD)

$$>10^9 W / cm^2$$



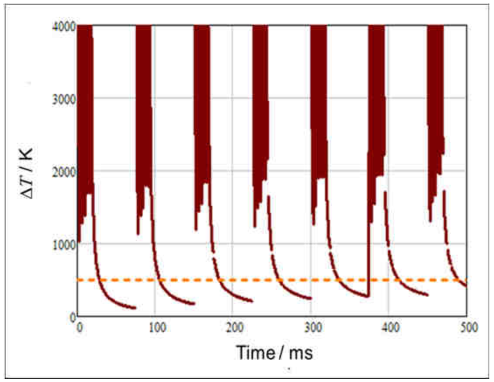
2. Fast beam movement (no HAP)

$$v_{Feed} \cong d_{Focus} \cdot f_{Laser}$$



3. Reduced power per contour and enough breaks (no HAS)

$$N_{Limit} \cong C^2_{Mat1D} \cdot \Delta T \cdot \frac{d^2_{Mat} \cdot v_{Feed} \cdot \ell_{Contour}}{4 \cdot P^2_{Laser}}$$



Four Rules of Thumb to Achieve Perfect Thermal Quality

1. Correct effective fluence (minimize heat)

   $\Phi_{Abs} \cong 5 - 10x \text{ threshold}$

2. Enough intensity (no SPD)

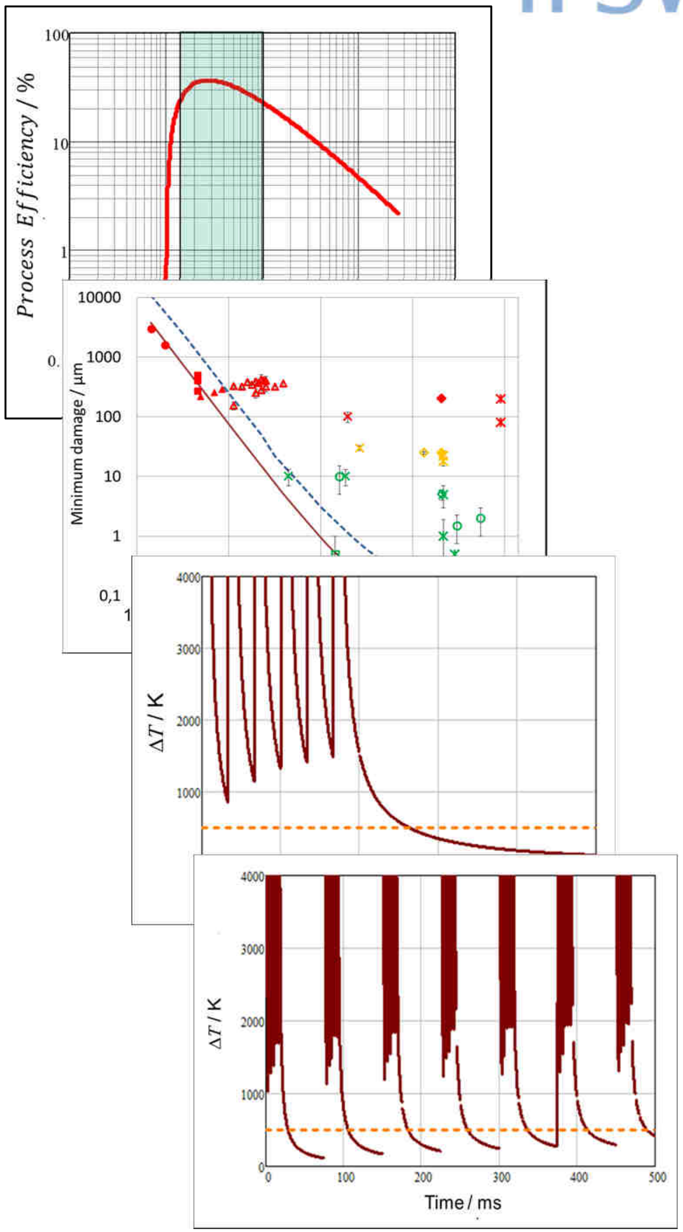
   $> 10^9 W / cm^2$

3. Fast beam movement (no HAP)

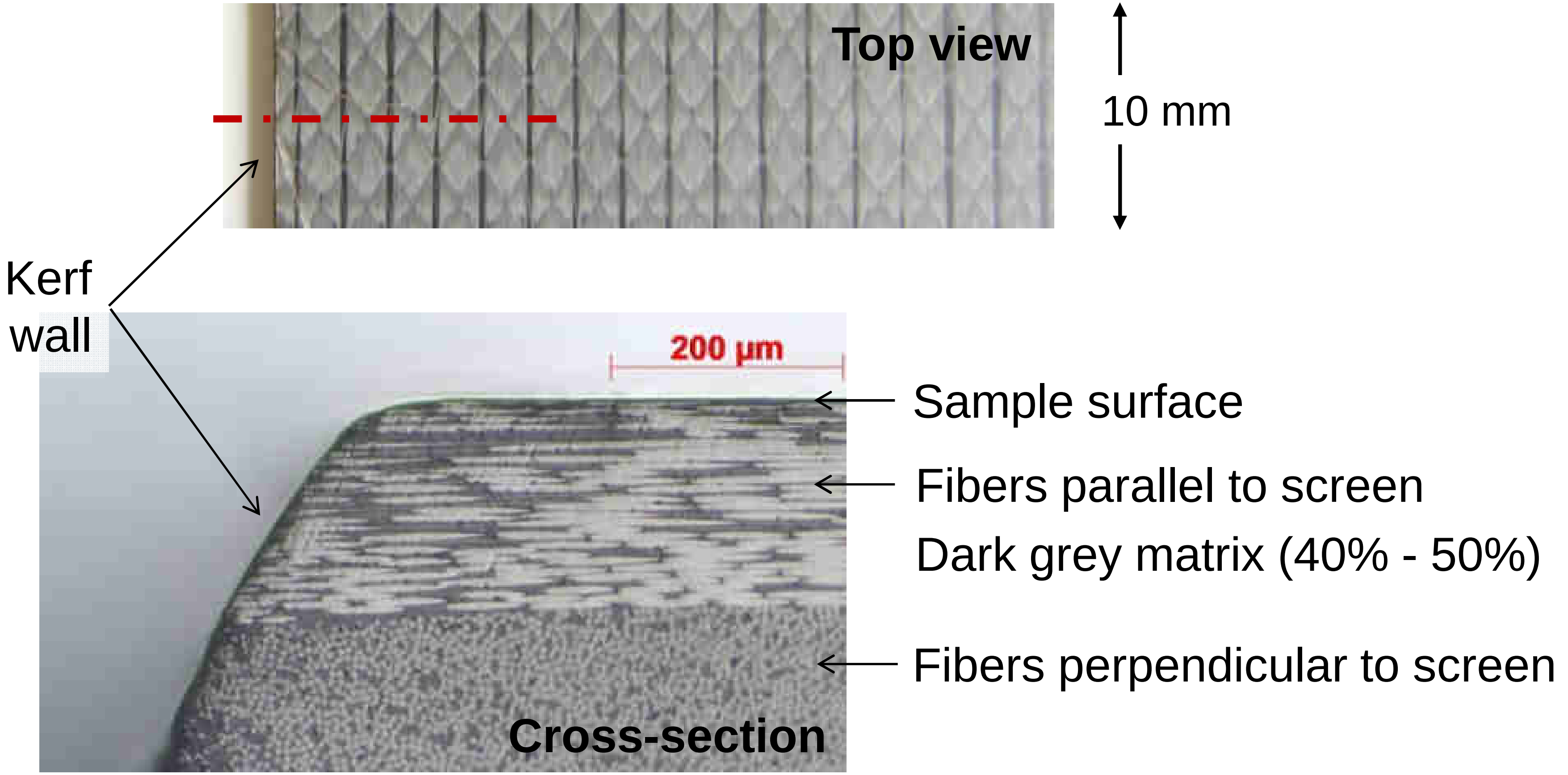
   $v_{Feed} \cong d_{Focus} \cdot f_{Laser}$

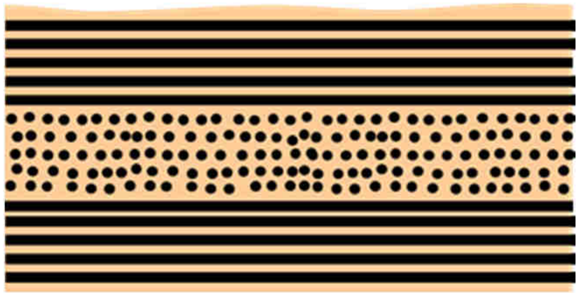
4. Enough breaks (no HAS)

   $$N_{Limit} \cong C^2_{Mat1D} \cdot \Delta T \cdot \frac{d^2_{Mat} \cdot v_{Feed} \cdot \ell_{Contour}}{4 \cdot P^2_{Laser}}$$

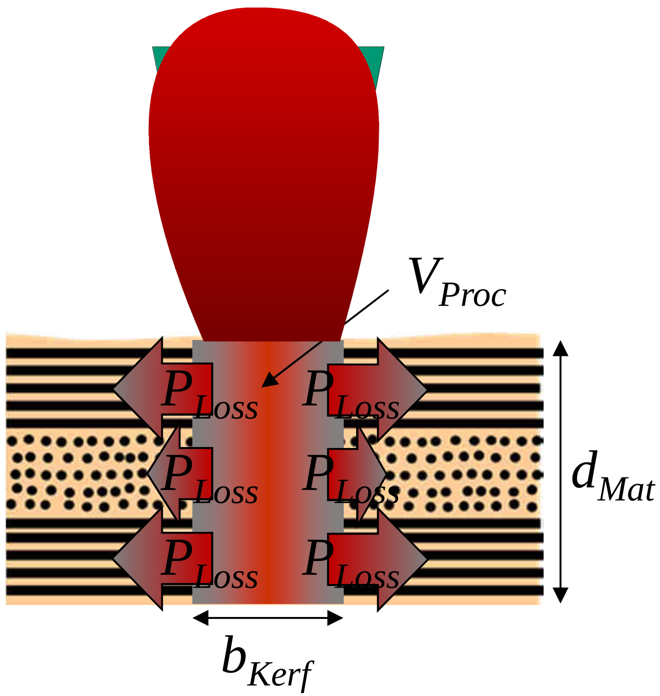


"Typical" High-Quality Cutting Result





Sketch of cross-section
used in the following



- "Typical" industrial requirement for CFRP cutting
  - d_{Mat} = 2 mm
  - b_{Kerf} = 0.1 mm
  - v_{Feed} = 20 mm/s (1 m/min)

⇨ The required ablation rate
$\dot{V} = dV_{Proc}/dt \cong$ 4 mm³/s
$(= v_{Feed} \cdot d_{Mat} \cdot b_{Kerf})$

$$P_{Av,Laser} = \frac{C_{Carbon}}{\eta_{Abs}} \left(h_{V,Proc,eff} \cdot \dot{V}_{Proc} + P_{Loss} \right)$$

- $h_{VProc,eff}$ $\cong$ 85 J/mm³
- C_{Carbon} $\cong$ 60%
- η_{Abs} $\cong$ 70%
- P_{Loss} $\cong$ 75%

➢ **$P_{Av,Laser}$ > 1000 W for productive cutting of CFRP**

➢ **Severe challenge to avoid thermal damage!**

- Absorbed volume-specific enthalpy h_V as a function of space for $\alpha = 5.3 \cdot 10^5$ cm^{-1} (ultra-short pulse situation)

$$h_V(z) = \alpha \cdot \Phi_{Absorbed} \cdot e^{-\alpha \cdot z}$$

- Absorbed laser fluence

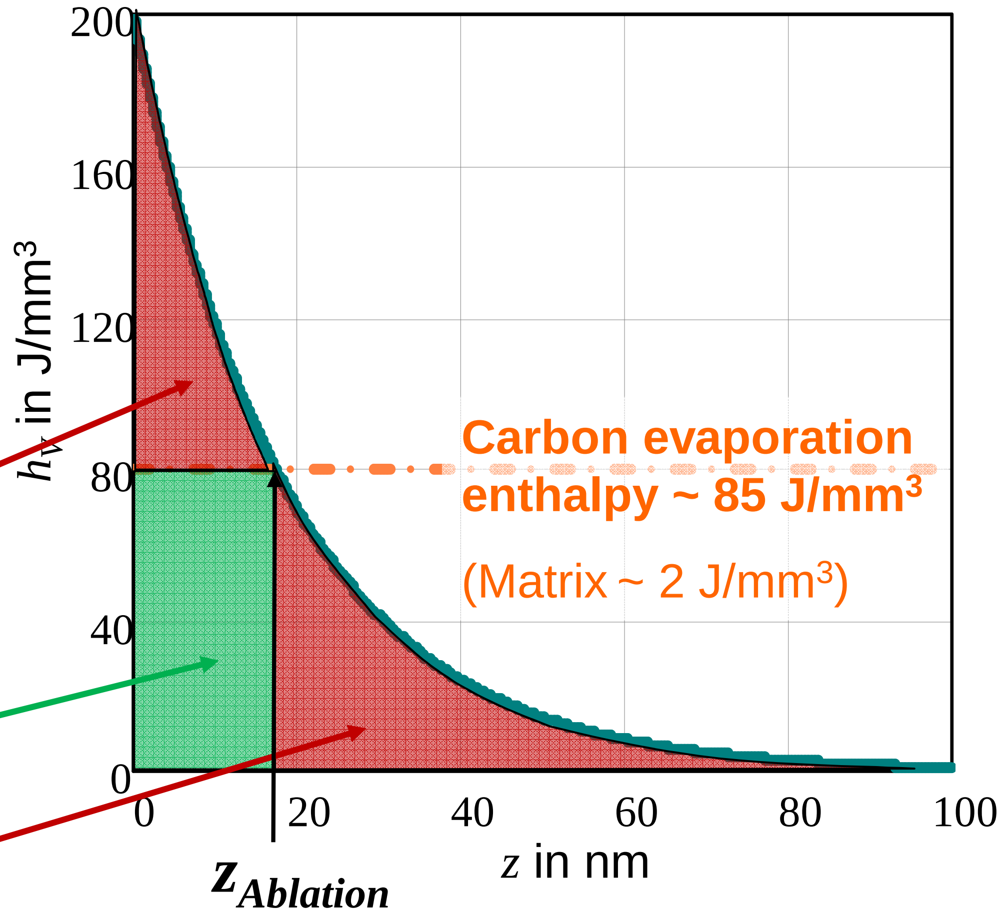
$$\Phi_{Absorbed} \cong \frac{\eta_{Abs} \cdot E_{Pulse}}{\pi \cdot r_{Focus}^2}$$

Overheating of vapor

- Kinetic energy for leaving kerf/hole
- Heating of material

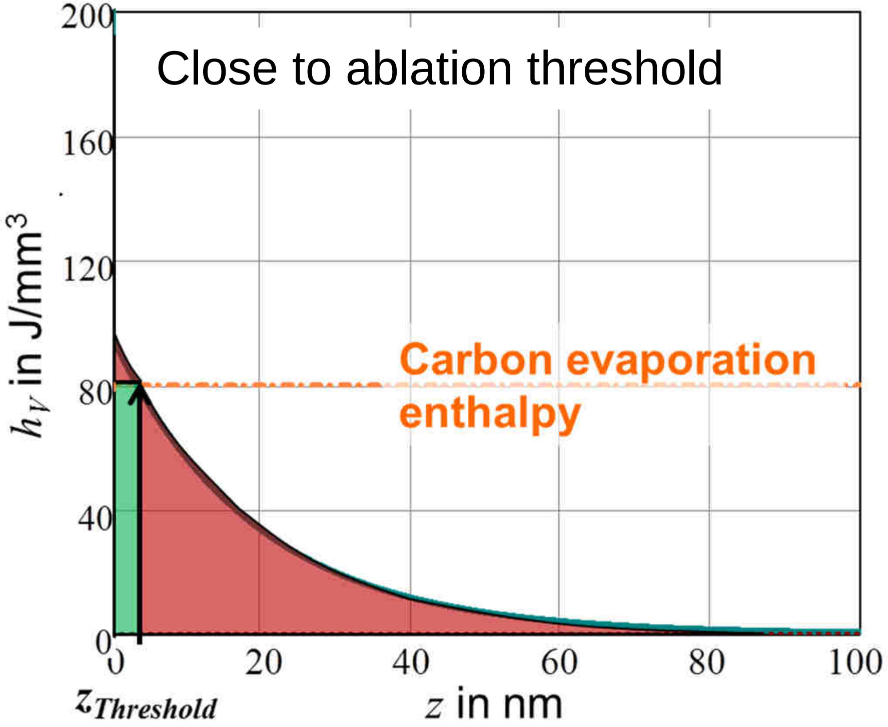
Absorbed energy used for evaporation

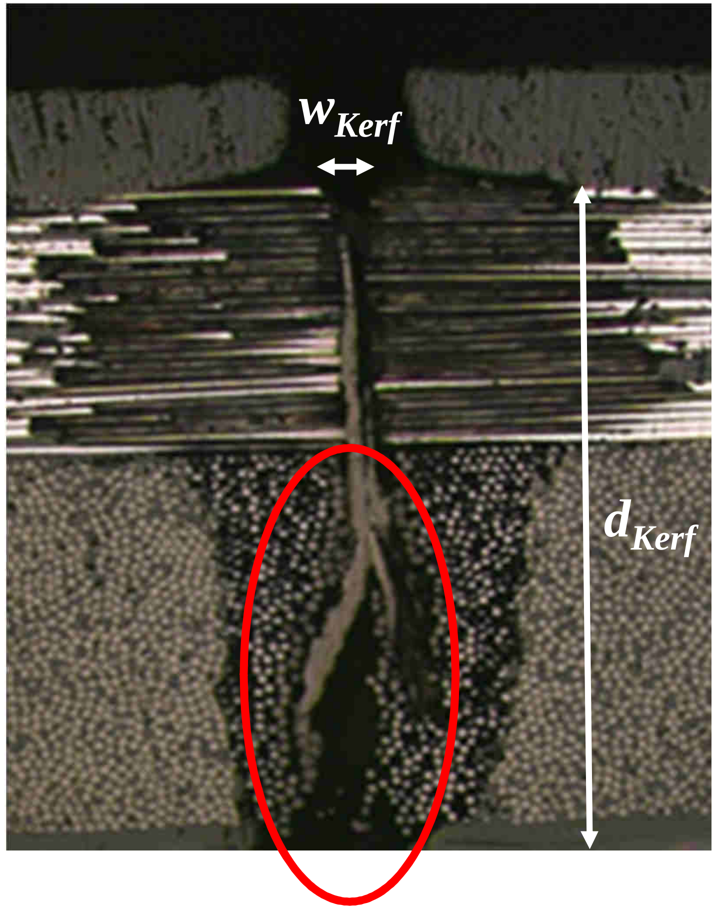
Heating of material



- Effective fluence decreases with ~2x aspect ratio $A = d_{Kerf} / w_{Kerf}$

$$\Phi_{Abs,Effective} \cong \frac{\eta_{Abs} \cdot E_{Pulse}}{2A \cdot \pi \cdot r_{Focus}^2}$$

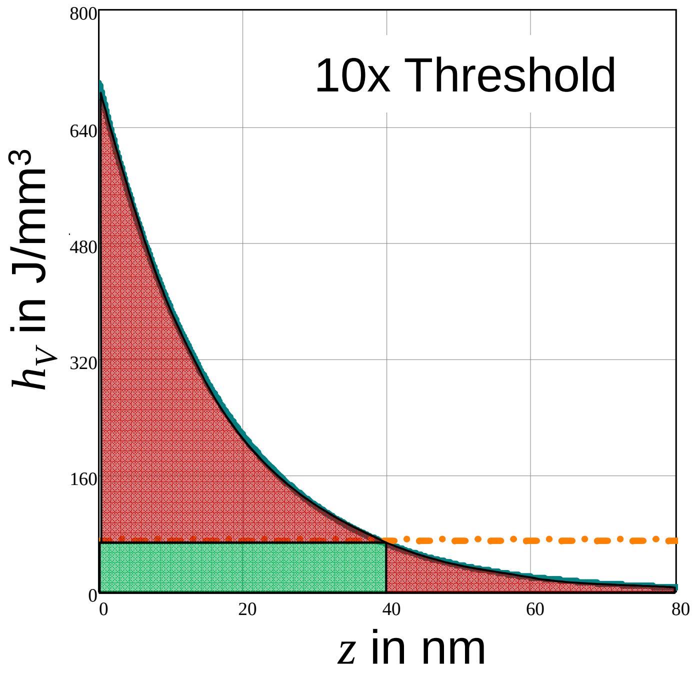


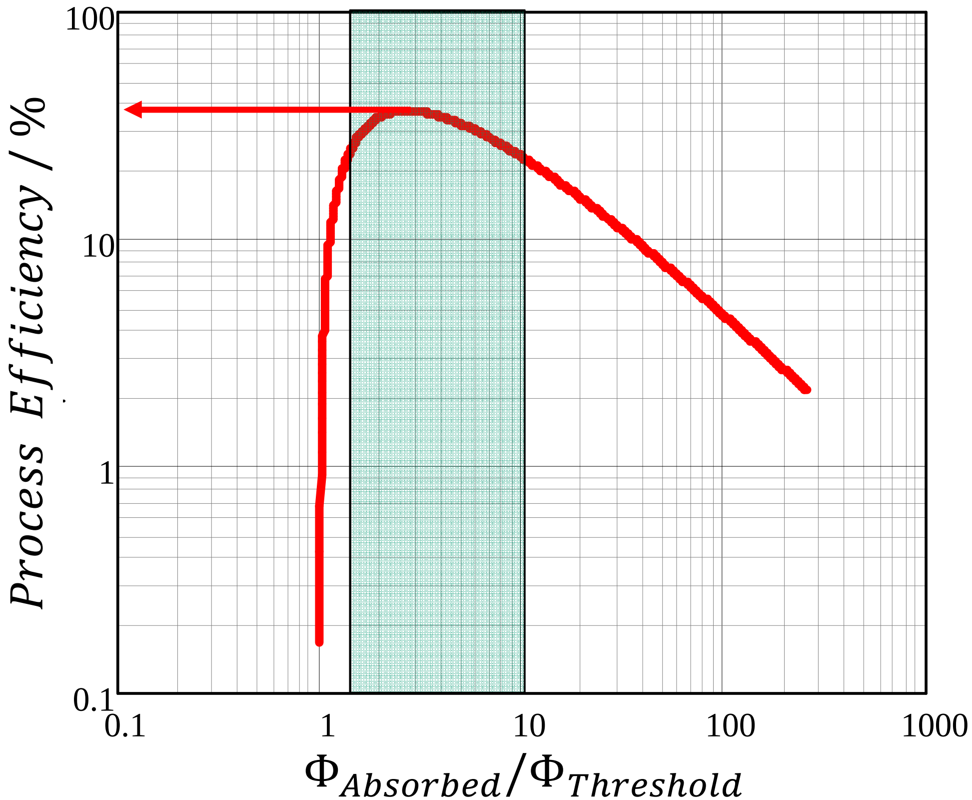


- E_{kin} not large enough to leave kerf
- 100% of laser energy is deposited in the material
- Re-condensation of evaporated material

Efficiency Defines Optimum Fluence Regime

- Process efficiency = [green area] / absorbed energy





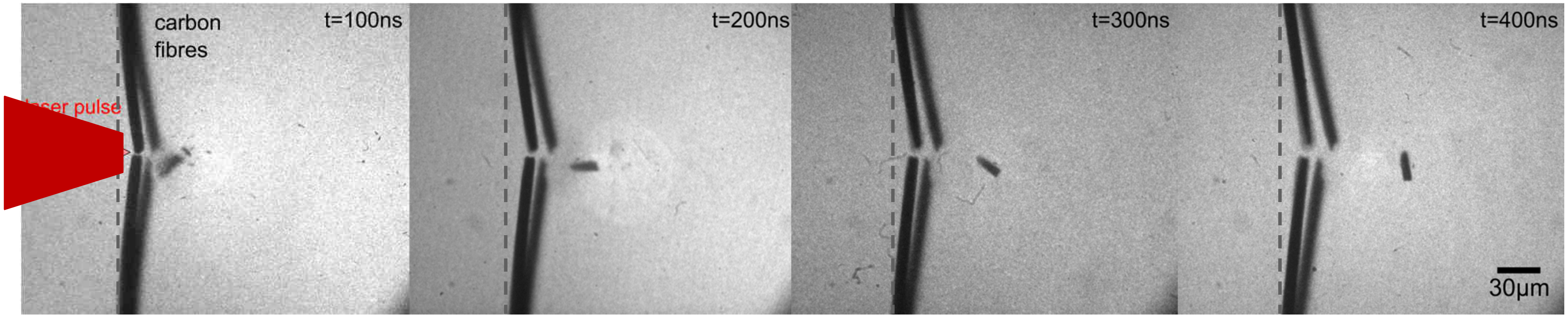
- Maximum ~35% of laser energy used for evaporation ⇨ P_{Loss} > 65%

- To minimize vapor damage keep effective absorbed fluence
  $$2 \cdot \Phi_{Threshold} > \Phi_{Absorbed} < 10 \cdot \Phi_{Threshold}$$

B. Neuenschwander et al, Physics Procedia 56, p. 1047 – 1058 (2014)

Generation of Fiber Fragments

- Fibre diameter ~8 µm
- Single pulse, 800 nm, 6 ps, 0.6 mJ, focus diameter 30 µm
- Four frames, one frame every 100 ns



- Cracking of Fibers, ejection of Fragments
- Fragment velocity ~200 m/sec

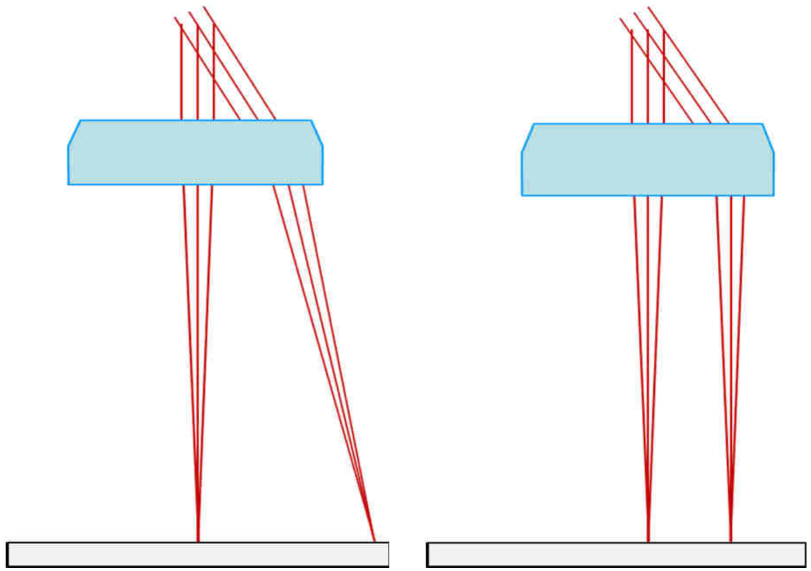
> ➢ Creation of fragments might be used to reduce required enthalpy

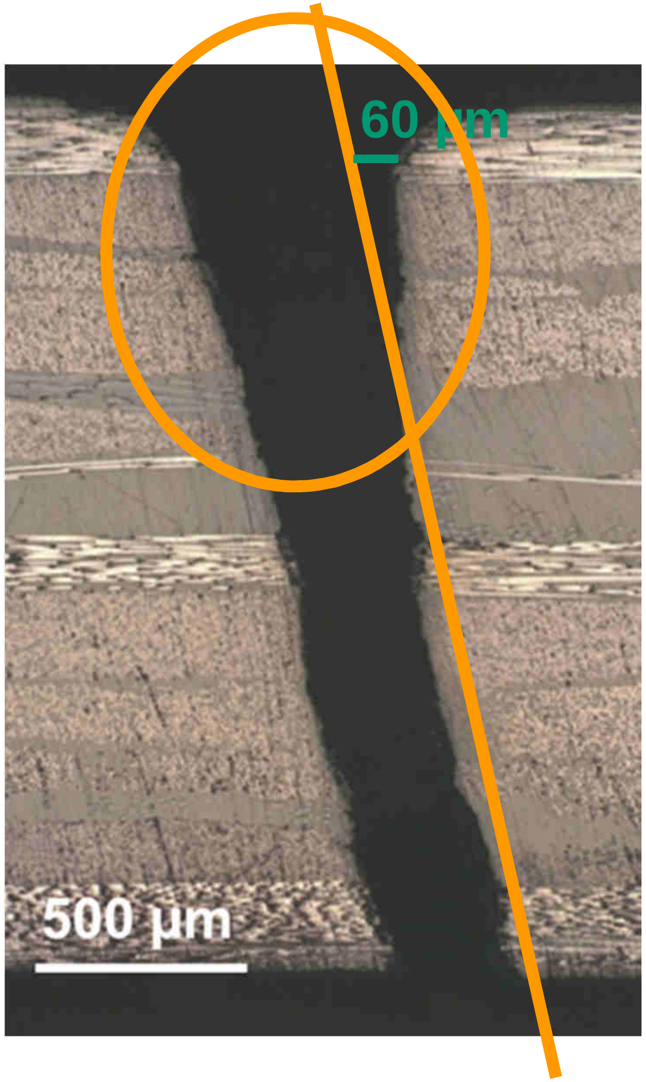
System Challenges: Inclined Kerf

- Extent about ±220 µm @ 2 mm thickness

- F-Theta scanner optics
- Angle depends on part size
- Accuracy depends on thickness

- Telecentric optics
  ⇨ Contour size additionally limited





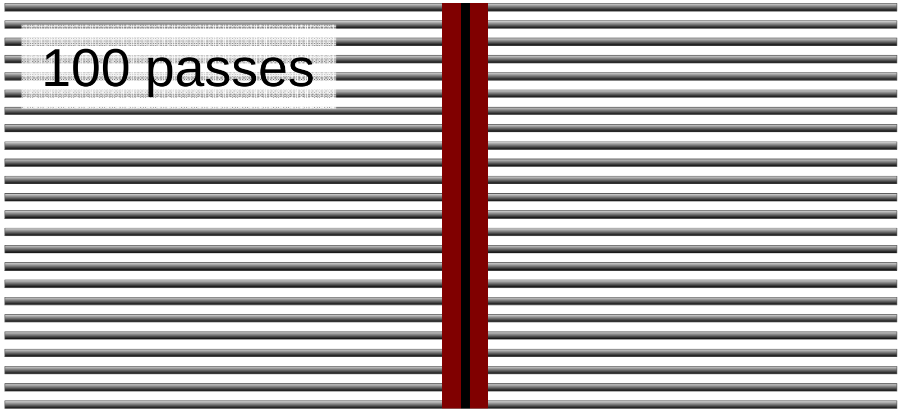
- Extent about 60 µm

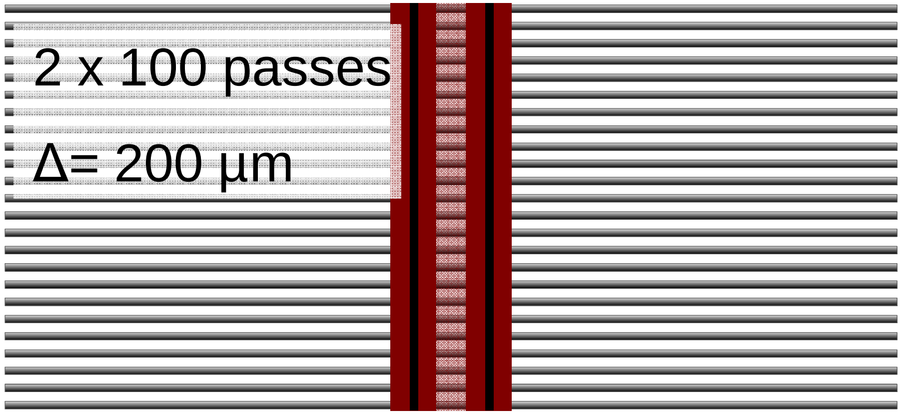
- Rayleigh-Length (was 10 mm)
- Focus position
- Thermal focus shift

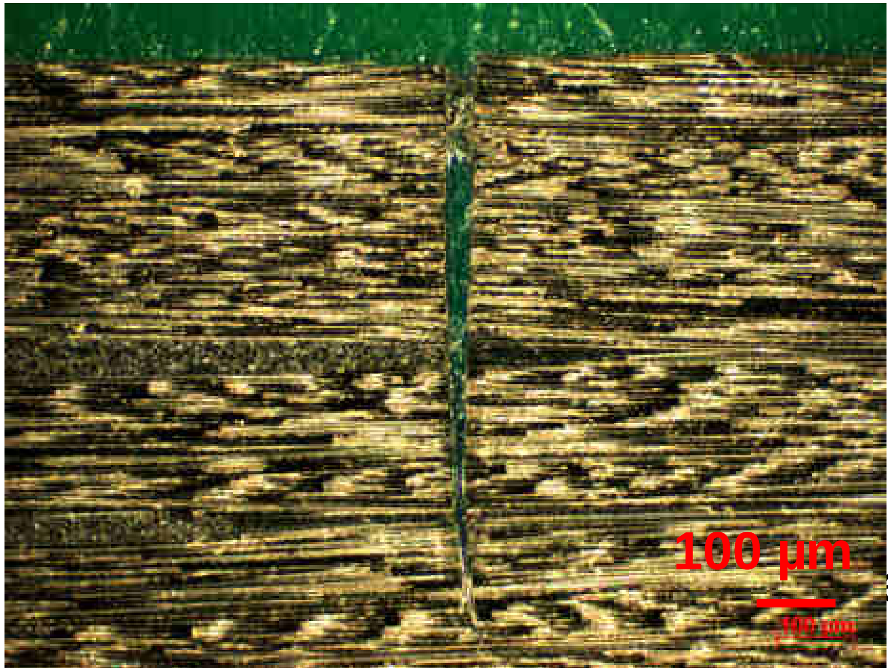
$$z_R = \frac{\pi \cdot w_0^2}{M^2 \cdot \lambda_{Laser}}$$

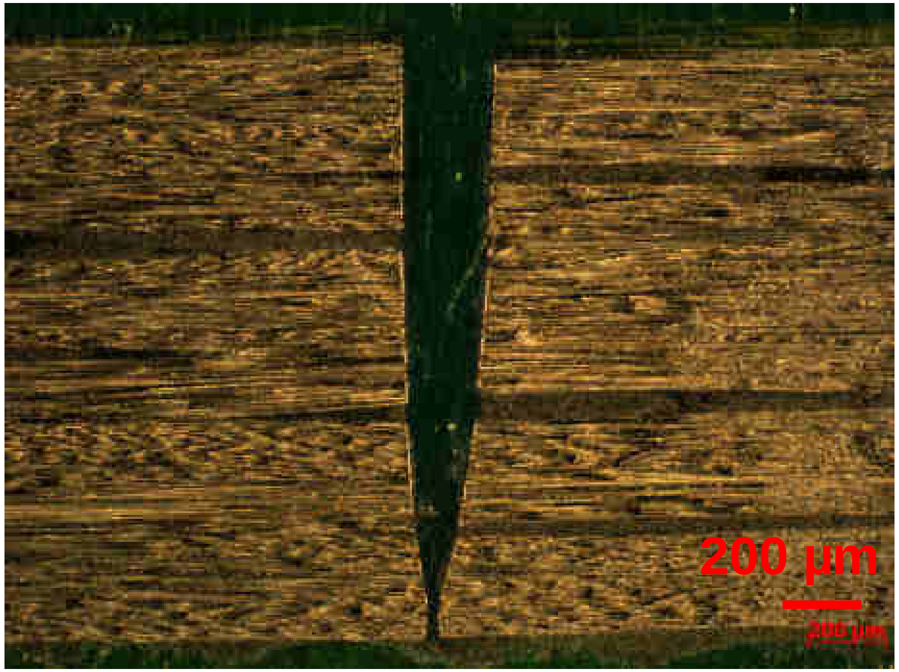
> Larger spots, better M^2, **shorter wavelength**

> Very fast active control of focus position ⇨ To be solved





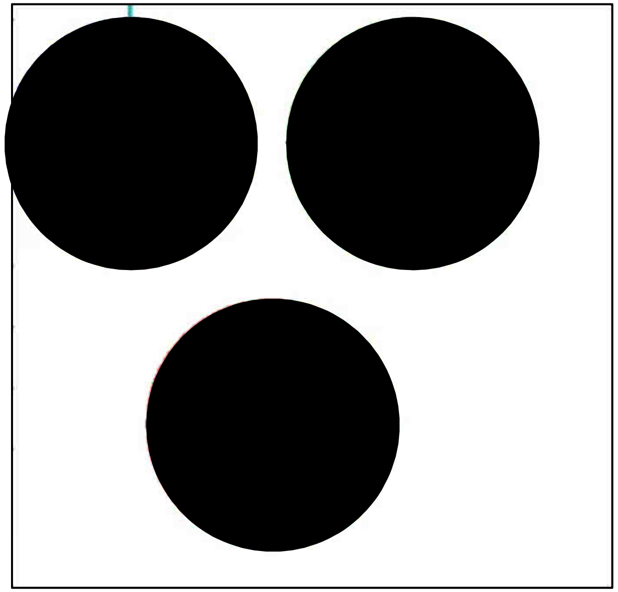


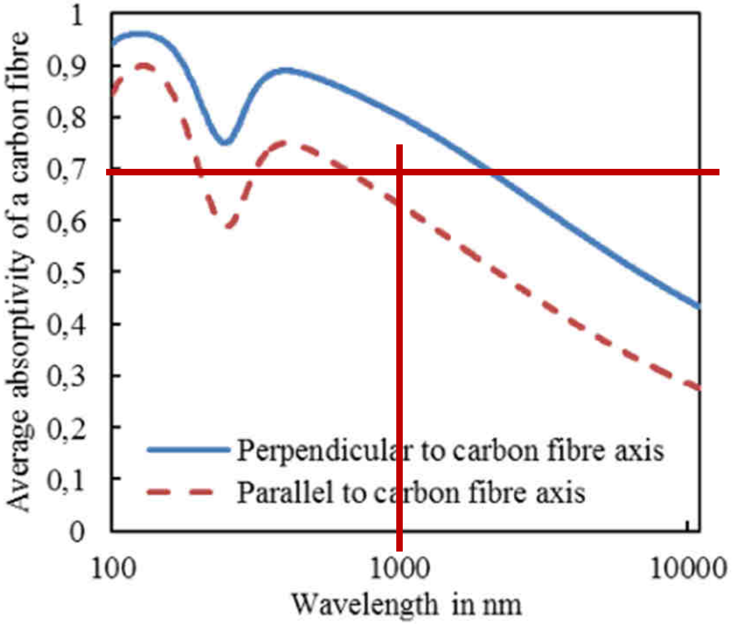


- **> 5x increase of process efficiency**

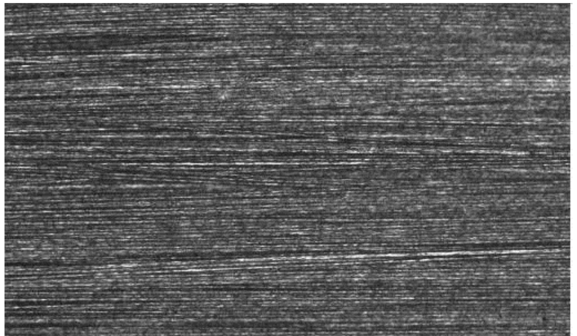
R. Weber, V. Onuseit, S. Tscheulin, T. Graf; Proc. ICALEO 2013

- Raytracing calculation
- Fresnel equation including birefringence

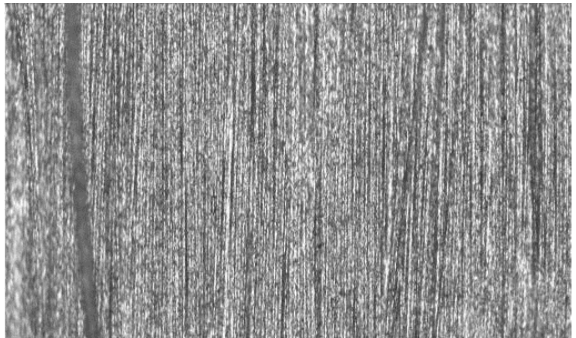




~ 70%
for lasers



a) Polarization perpendicular to carbon fibre axis

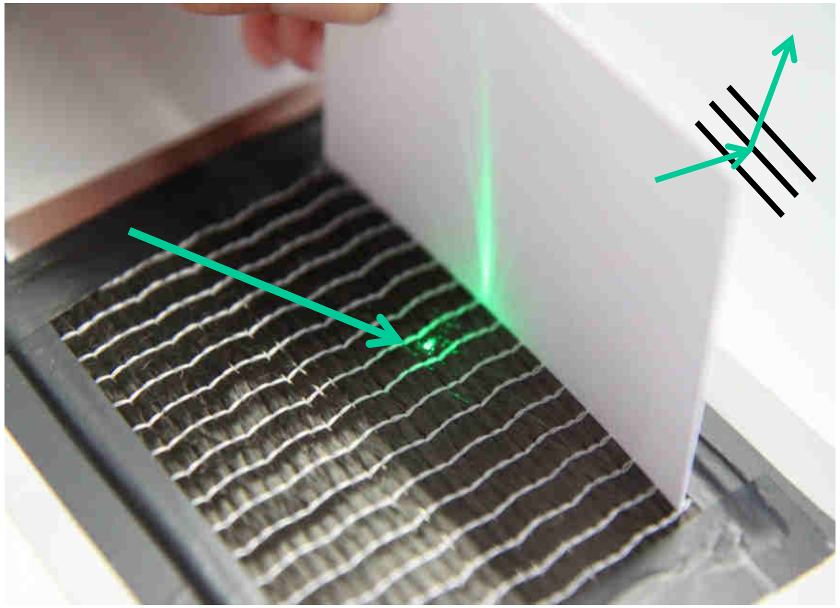


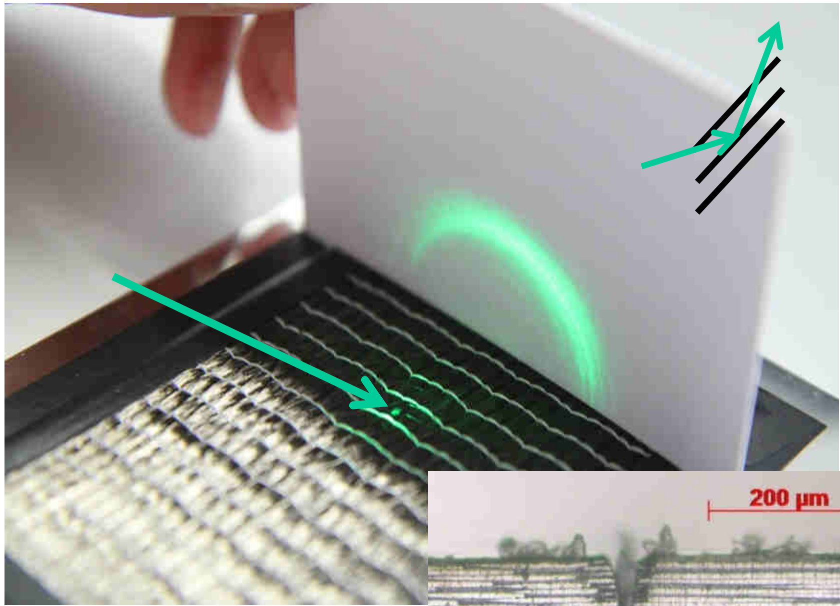
b) Polarization parallel to carbon fibre axis

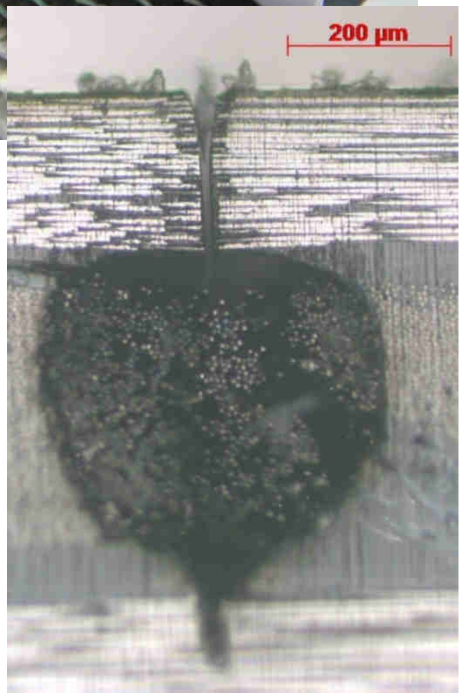
Image Brightness
p-pol / s-pol

- Calculated ~ 77%
- Measured ~ 62%

C. Freitag, R. Weber, and T. Graf, Optics Express, 22 (2), 1474-1478 (2014)
A.B. Djurisic, E.H. Li, "Optical properties of graphite", Journal of Applied Physics 85 (10), 1999

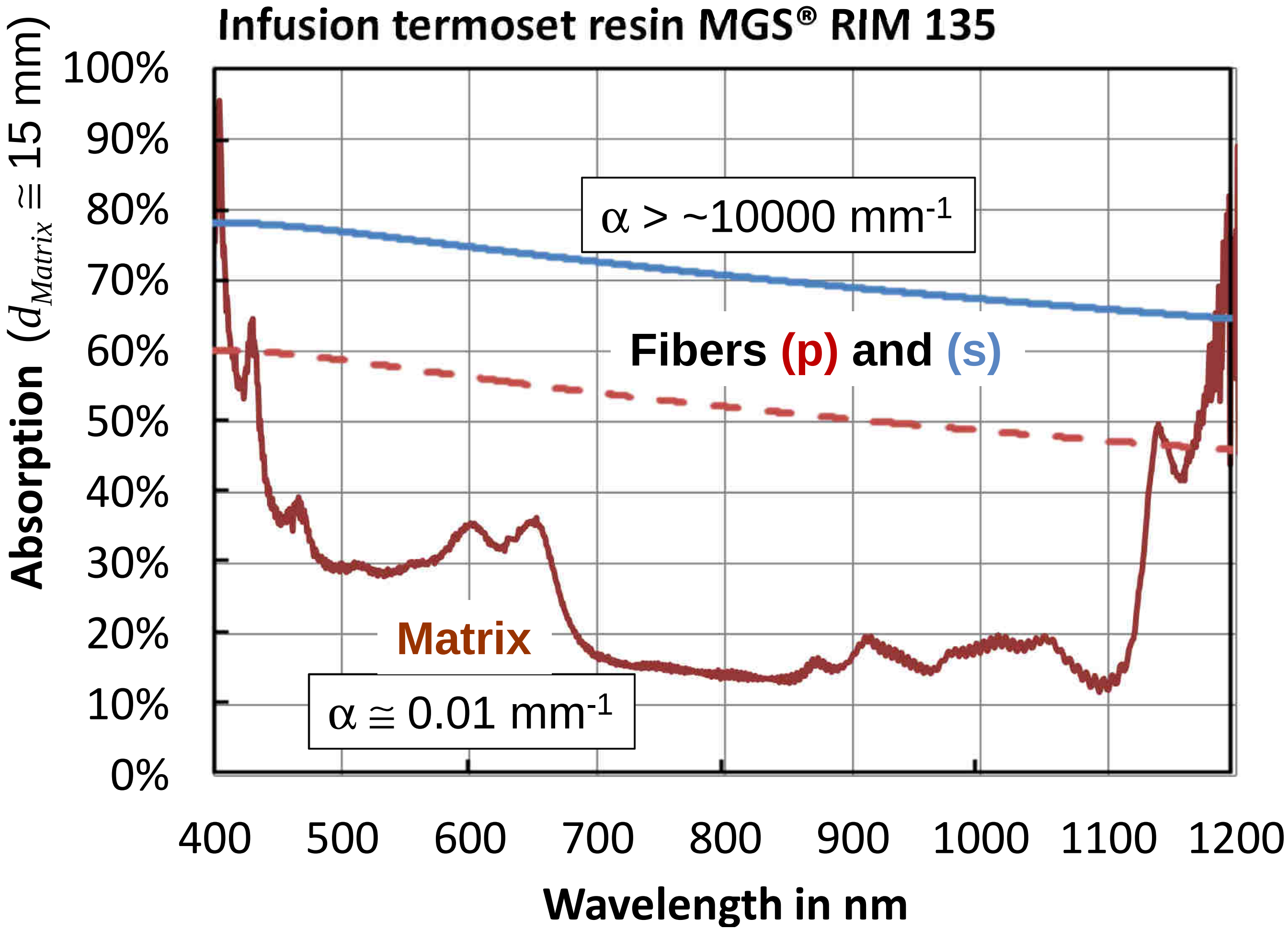






- Cylindrical structures show scattering mainly perpendicular to cylinder axis
- Strong dependence on fiber orientation
- Strong anisotropic scattering

- Fibers laid open by hot vapor(?)
- Possible reason for strange damage patterns



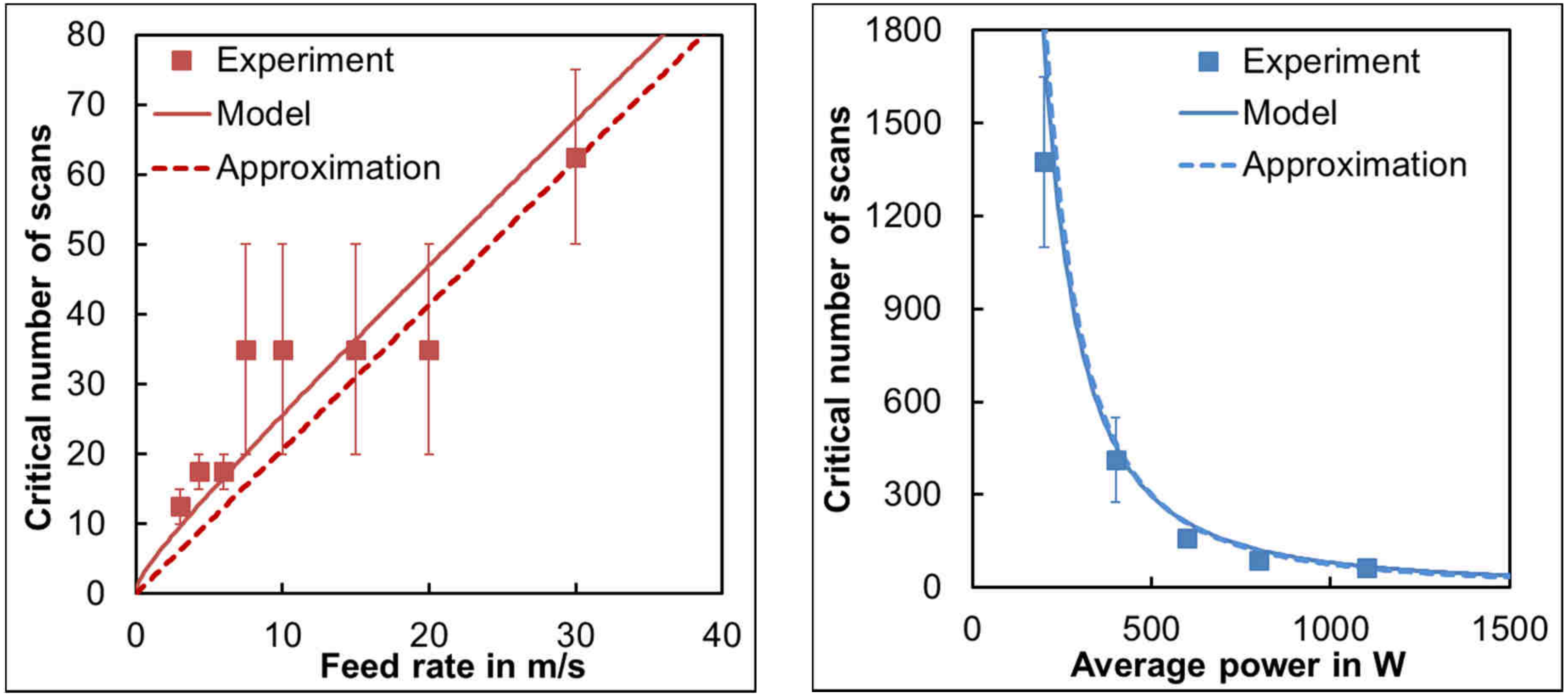
- Matrix almost transparent
- Scattering even with matrix present

C. Freitag, R. Weber, and T. Graf, Optics Express, 22 (2), 1474-1478 (2014)

Analytical Model for HAS and Experimental Verification

$$N_{Limit} \cong C_{Mat,1D}^2 \cdot \Delta T_{Limit} \cdot \frac{d_{Mat}^2 \cdot v_{Feed} \cdot \ell_{Contour}}{4 \cdot P_{Laser,av}^2}$$

($C_{Mat,1D} \cong 7440$ J/s$^{0.5}$/m^2)



Solution to avoid HAS for moving beams:

- **Reduce power per contour, make breaks**

Model: R. Weber, C. Freitag, T. Graf, Submitted to Optics Express 6/2016

Experimental data: C. Freitag, T. Kononenko et al, Applied Physics A , 119(4), (2015)