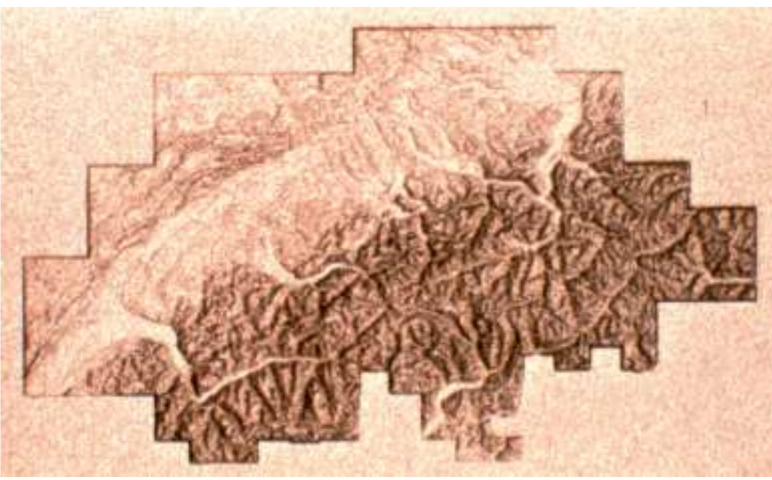
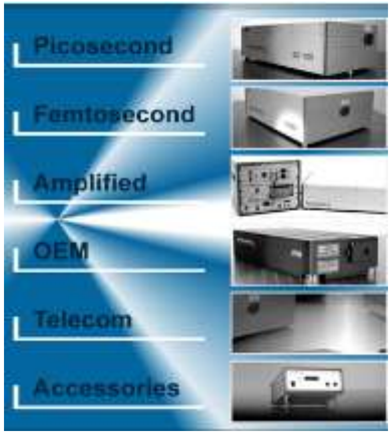
Industrial turn-key laser solutions for ultrafast micromachining

Dr. Kurt Weingarten
kw@time-bandwidth.com



Background of Time-Bandwidth Products

- Spin-off of ETH Zurich - "SESAM®" know-how, technology leader
- First product sales 1996
- Headquartered at Technopark Zurich
- International sales network representatives/distributors in all key markets
- Products established as reliable in "24/7" operation for industrial applications
- Industrial customers in semiconductor, biotech, material processing, and more



Ultrafast Laser Product Range

Based on **SESAM**® Technology for modelocking (**SE**miconductor **S**aturable **A**bsorber **M**irror) and diode-pumped laser materials

Pulse durations	<50 fs to >500 ps
Wavelengths	260 nm – 1550 nm
Output power	<1 W to >50 W
Pulse energies	up to 1 mJ
Repetition rates	single shot to >10 GHz

Modular design

Customizable for scientific or industrial applications

Broad set of performance parameters

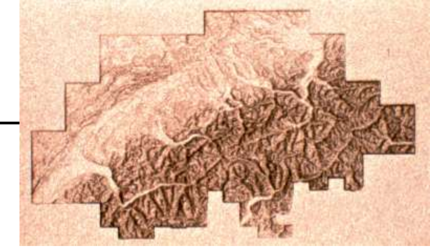
Cold ablation – advantages of picosecond lasers

- Substantial advantages compared to nanosecond lasers:

- mostly non-thermal process
  - significantly reduced Heat-Affected-Zone (HAZ)
  - significantly reduced recast
  - less micro-cracks
- mostly wavelength independent (multi-photon-absorption)
- suitable for almost all materials

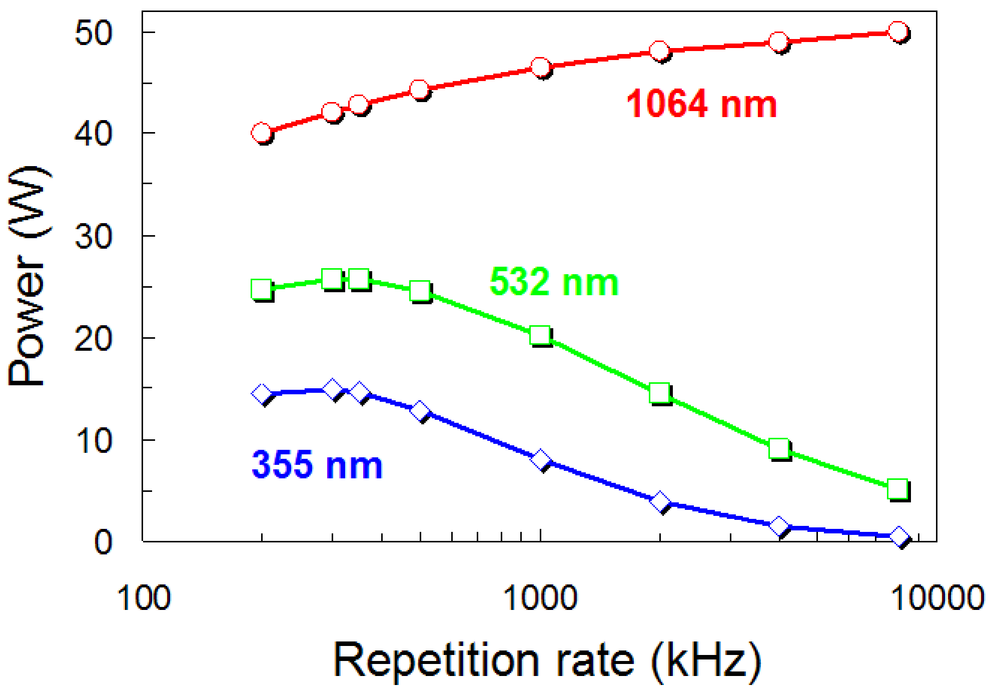
- **better precision**
- **higher surface quality**

Consider picosecond micromachining when:

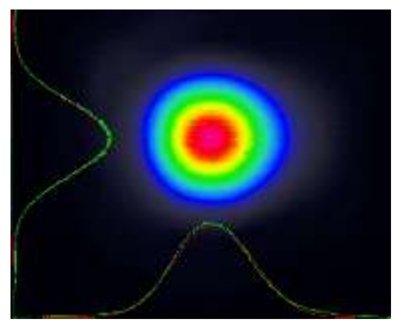


- Nanosecond lasers don't deliver the quality required (heat affected zone, recast, etc.)
- Very small, precise features required
- Highly brittle materials (ceramics, glass, …)
- Very strong materials (carbides, diamond, …)
- Mixed materials (polymers on hard substrates, …)
- Selective processing of multi-layer thin films (CIGS, …)
- and more …

DUETTO product family - key performance parameters



output power	up to 50 W
repetition rate	50 kHz – 8 MHz
pulse energy	up to 200 µJ
pulse width	10 ps
peak power	up to 20 MW
wavelength	1064 nm
M^2 (TEM_{00})	< 1.3



DUETTO – integrated industrial MOPA

Master Oscillator Power Amplifier diode-pumped picosecond laser system

Seed oscillator

- 1 W average power
- 1064 nm wavelength
- High repetition rate (quasi-CW)
- based on proven LYNX design

Seeds amplifier stage with user selectable pulse repetition rate

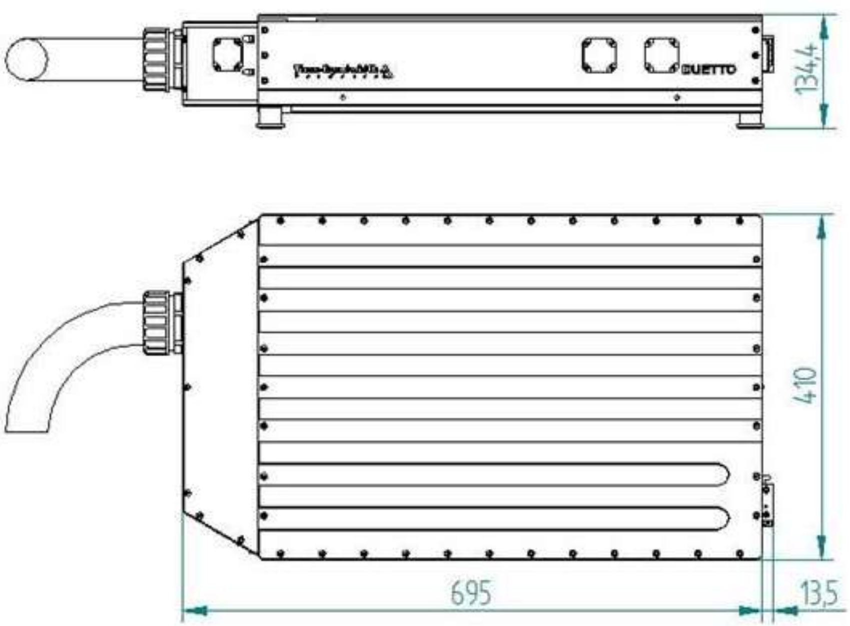
Pulse Picker

Amplifier stage(s)

- >10 W to 50W average power
- >200 µJ pulse energy
- 10 ps pulse width
- >20 MW peak power
- 50 kHz to 8 MHz repetition rate
- M^2 <1.3 spatial mode quality

- **Wide range of repetition rates**
- **Fast change of repetition rates**
- **Bursts with 12 ns pulse spacing**
- **Full control of intensity distribution inside the bursts**
- **High reliability and robustness**

Duetto Base Model



- 10 - 15W average power
- Footprint: 41 x 71 cm (laser head)
- Compact, rack mountable controller & chiller
- Front panel control or via computer (RS-232)

controller unit

chiller unit

DUETTO - modular, customizable options

- **Power scalable with booster amplifier**
  - **FUEGO optional power booster to 10W to <u>50W</u> average power**

- **Frequency Conversion**
  - **to 532 nm (green): >60% conversion efficiency**
  - **to 355 nm (UV): >30% conversion efficiency**

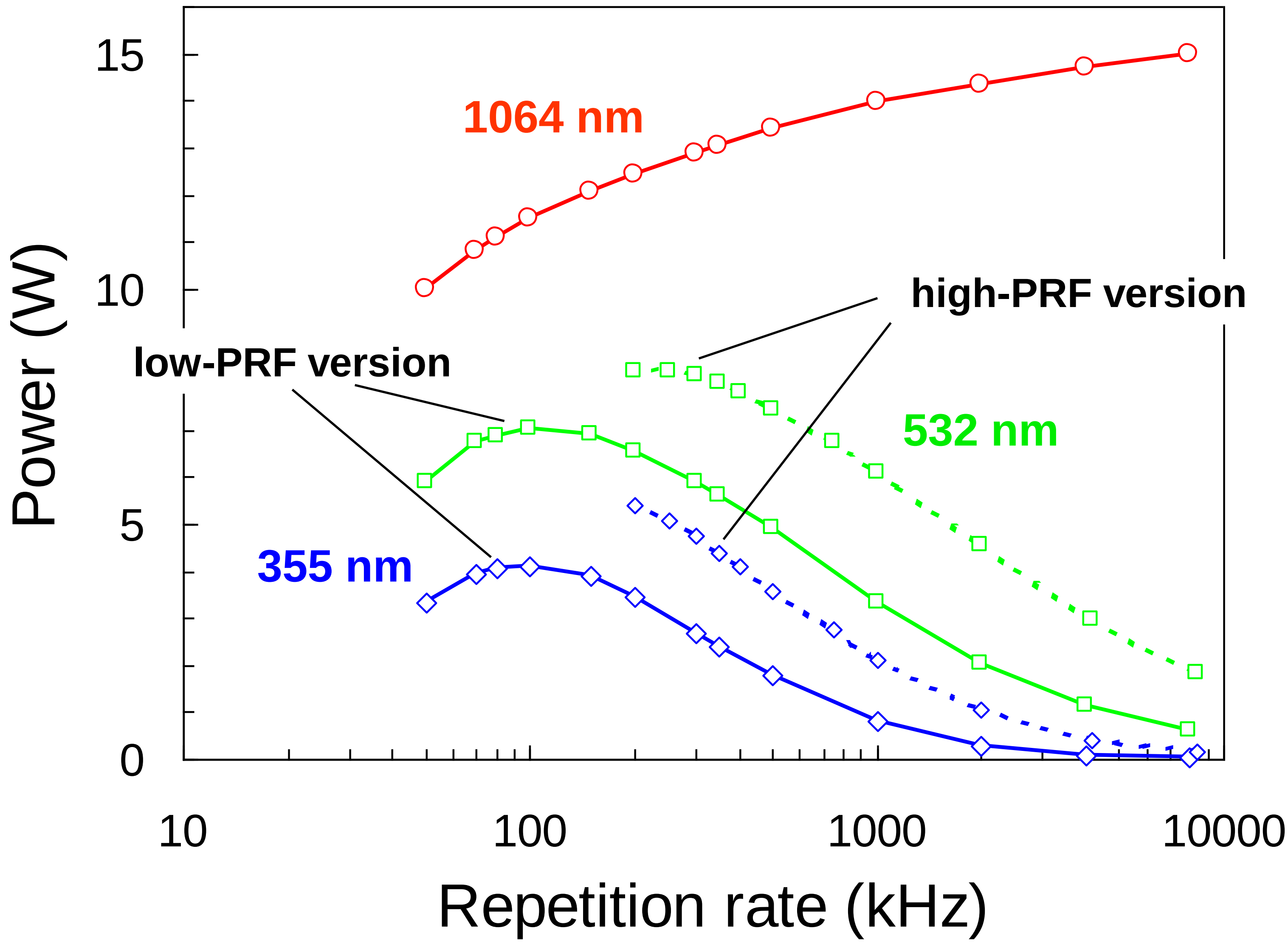
1-color

3-color

- **Pulse on demand - POD**
  - **required for sophisticated scanning / patterning**
  - **avoids typical <u>pre-pulse or first-pulse overshoot</u> often seen in other systems**
  - **Individually triggerable pulses single-shot to MHz regime**
  - **or arbitrary groups of pulses**
  - ***FlexBurst*™ technology**

- **Other options**
  - **timing synchronization to external clock with sub-picosecond accuracy**
  - **variable (switchable) pulsewidths**
  - **repetition rate at oscillator output (80 MHz typical)**

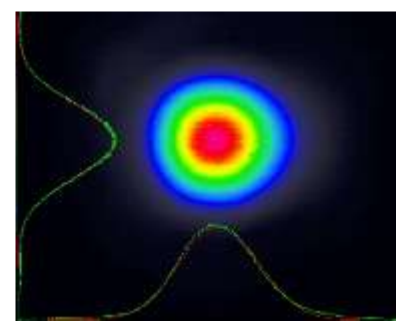
Flexibility: Wavelengths



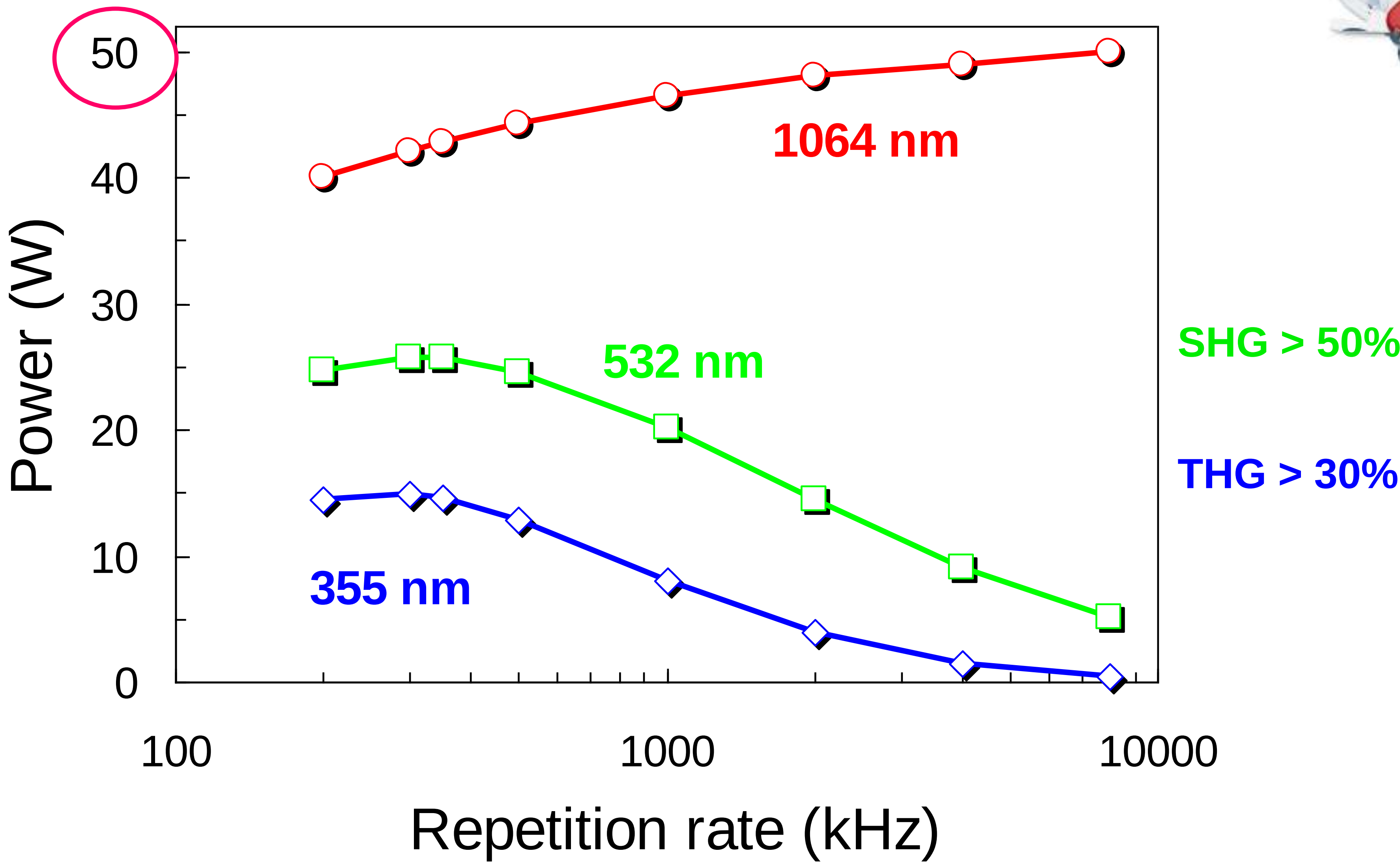
SHG > 60%

THG > 35%

M2 <1.3



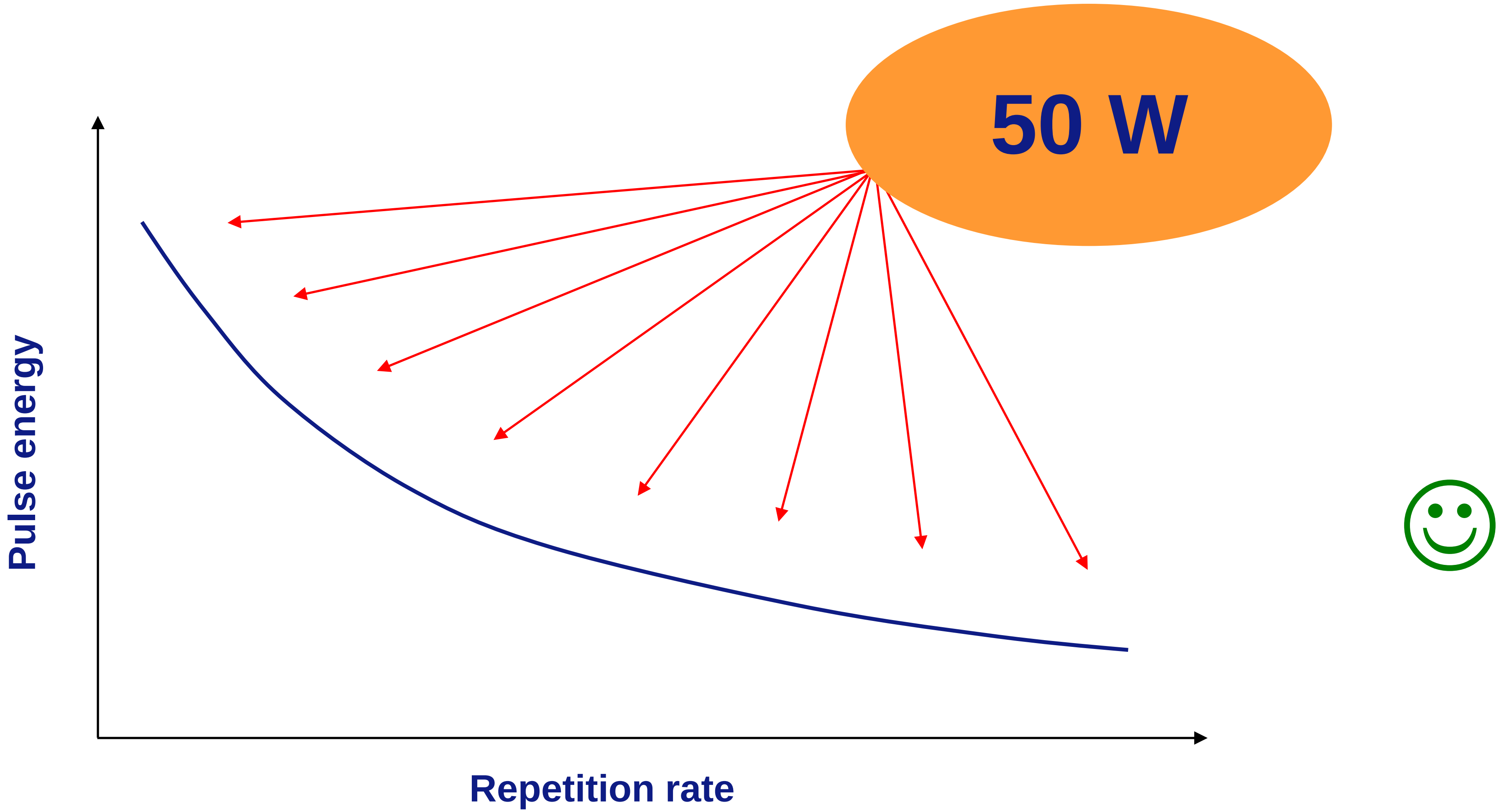
Flexibility: More Power



Fixed versus variable repetition rate (1/2)

Variable repetition rate:

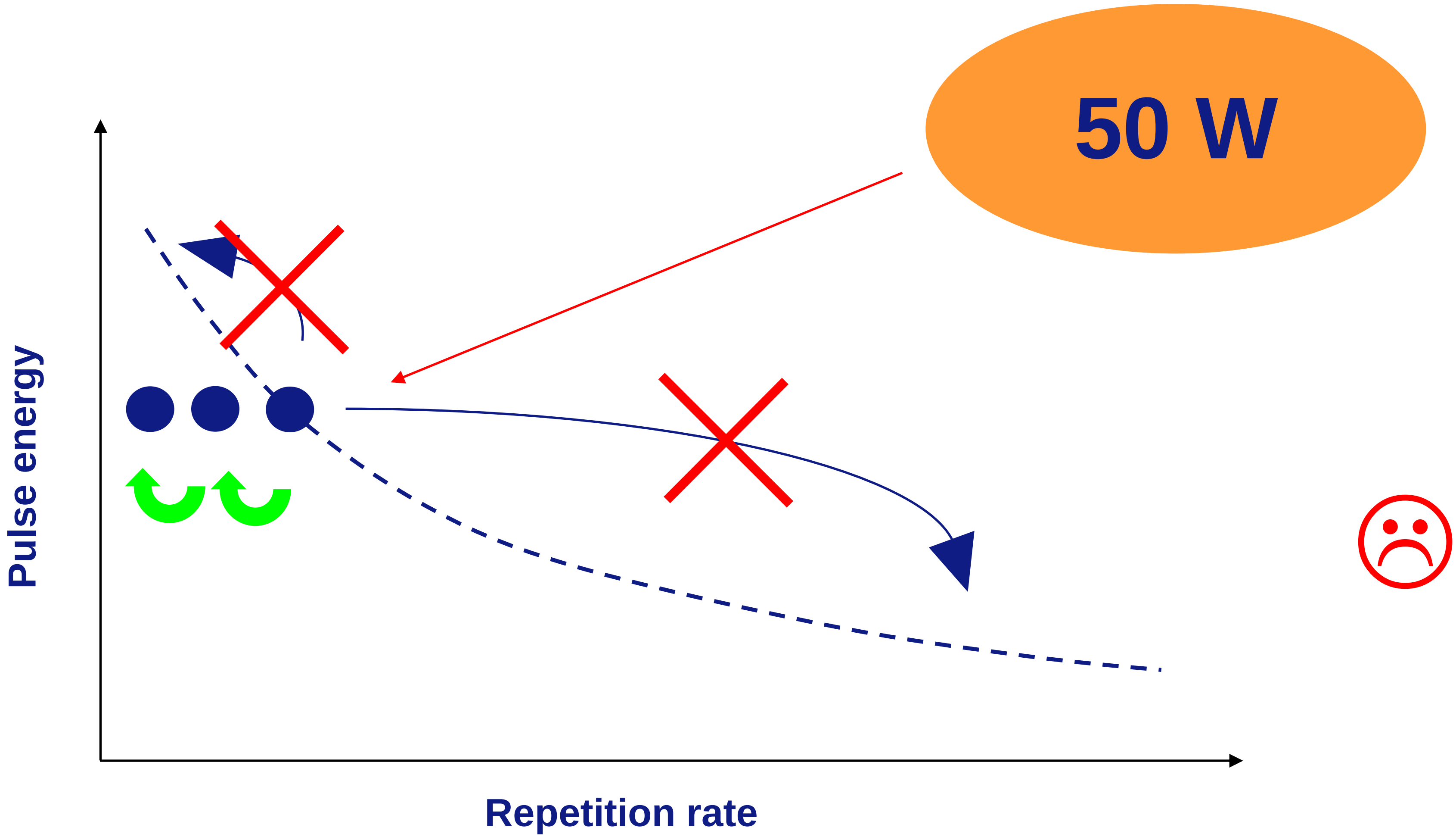
The maximum power is always available at every repetition rate.



Fixed versus variable repetition rate (2/2)

Fixed repetition rate:

The maximum power is available only at one repetition rate (max.)



Variable pulse rate gives more speed

Typical ablation rate (for most materials):

r_A = 0.1 mm^3/min per Watt

⇨ slow ⇨ speed is an important (productivity) factor

process speed = laser power * r_A

laser power = E * PRF = F * A * PRF

- F, A → determined by material & process
- PRF → *Pulse Repetition Frequency*
- A → *beam area* ← *process feature size*
- F → *pulse fluence* ← *just above ablation threshold*

pulse energy E determined by material and process requirements

process speed = F * A * r_A * PRF

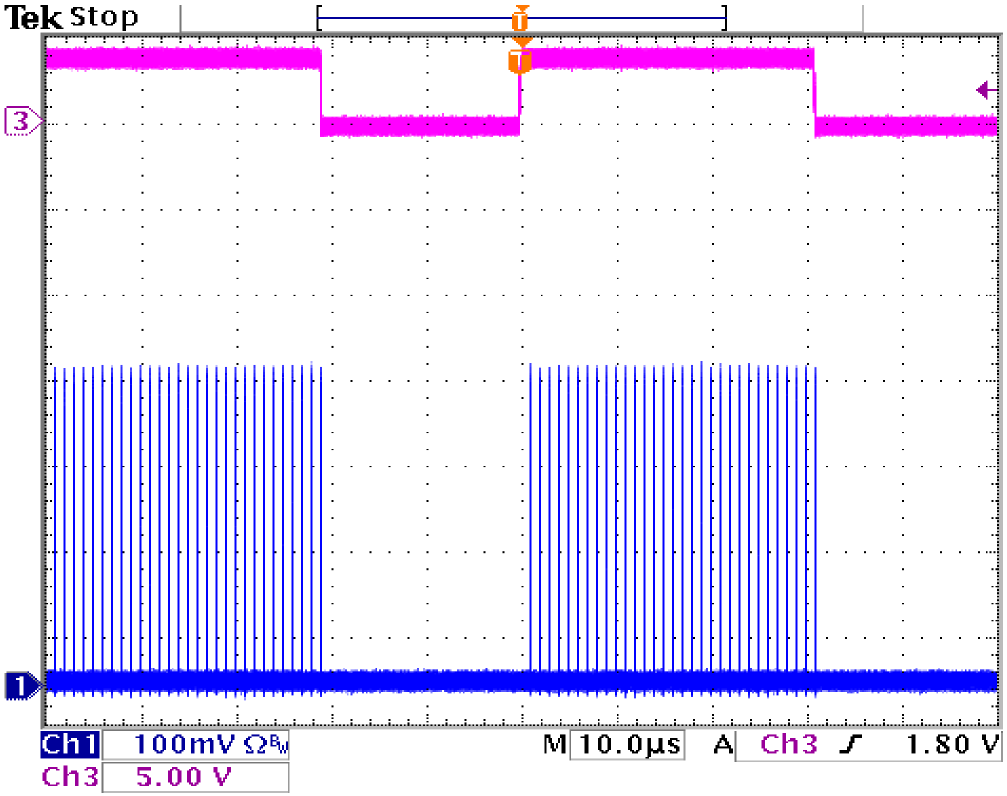
F * A * r_A: set by material and process

PRF →

Time-Bandwidth® Products

Flexibility – PoD – digital switching

PoD = Pulse on Demand

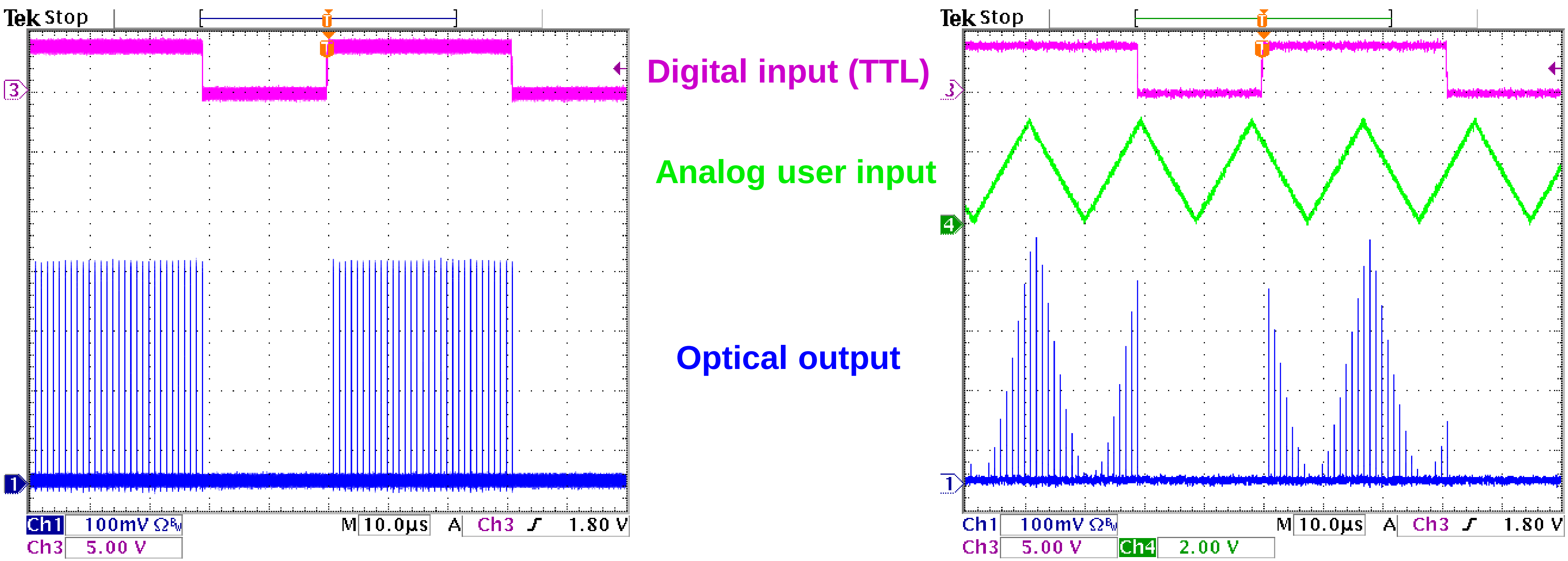


Digital user input (TTL)

Optical output

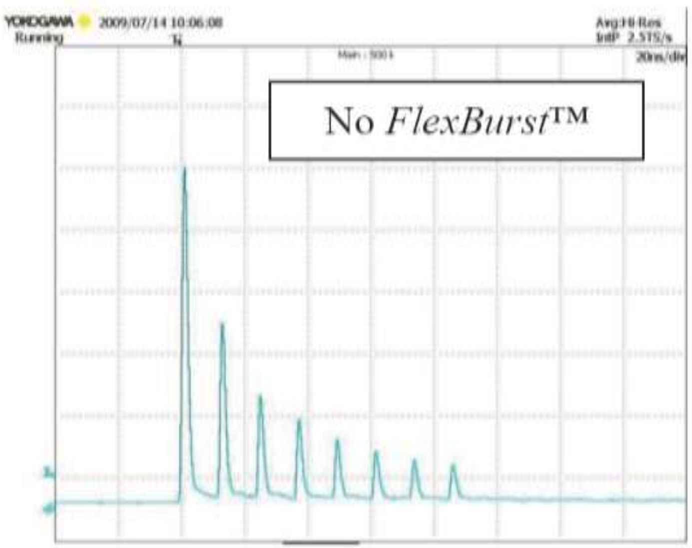
- ▶ **No overshoot (no first-pulse problem)**
- ▶ **Single-pulse precision up to > 4 MHz (fastest on market)**

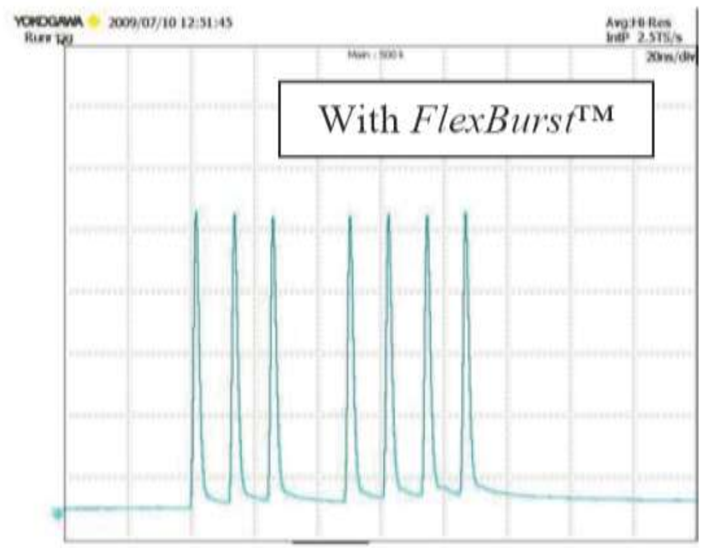
Flexibility – PoD – fast analog modulation



► **Fast and simple analog modulation (e.g. attenuation of laser output)**

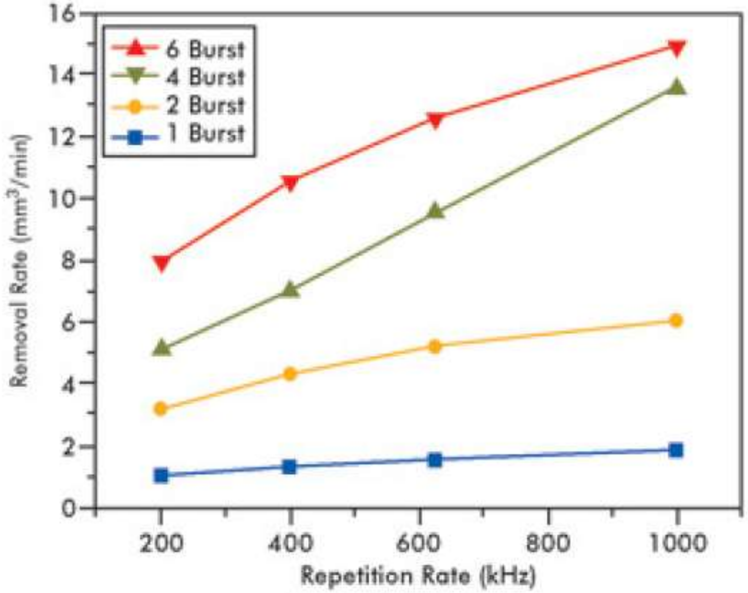
Flexibility – FlexBurst™ technology (1/2)





- ► **Generation of <u>arbitrary</u> bursts of pulses**
- ► **Frequency of bursts adjustable**
- ► **Time between pulses within burst 12 ns**
- ► **Number of pulses adjustable**
- ► **Amplitude of each <u>individual</u> pulse adjustable**
- ► **NO first pulse problem !**

Flexibility: Why burst mode?

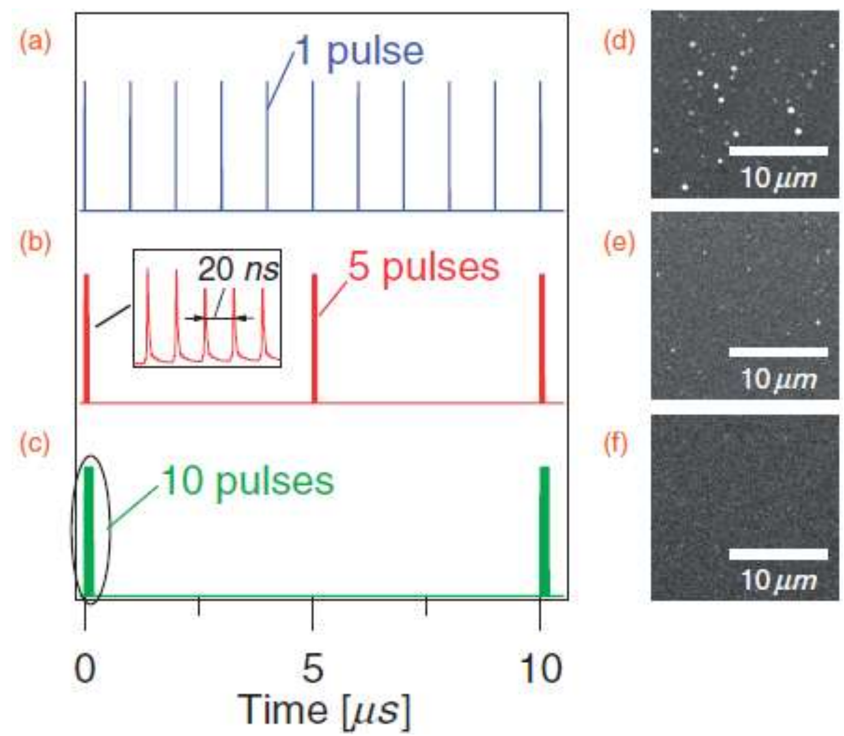


Burst mode increases ablation rate

Phot. Spectra, issue 11, 2009.
(Ablation of Si)

Burst mode improves deposition rate and surface smoothness

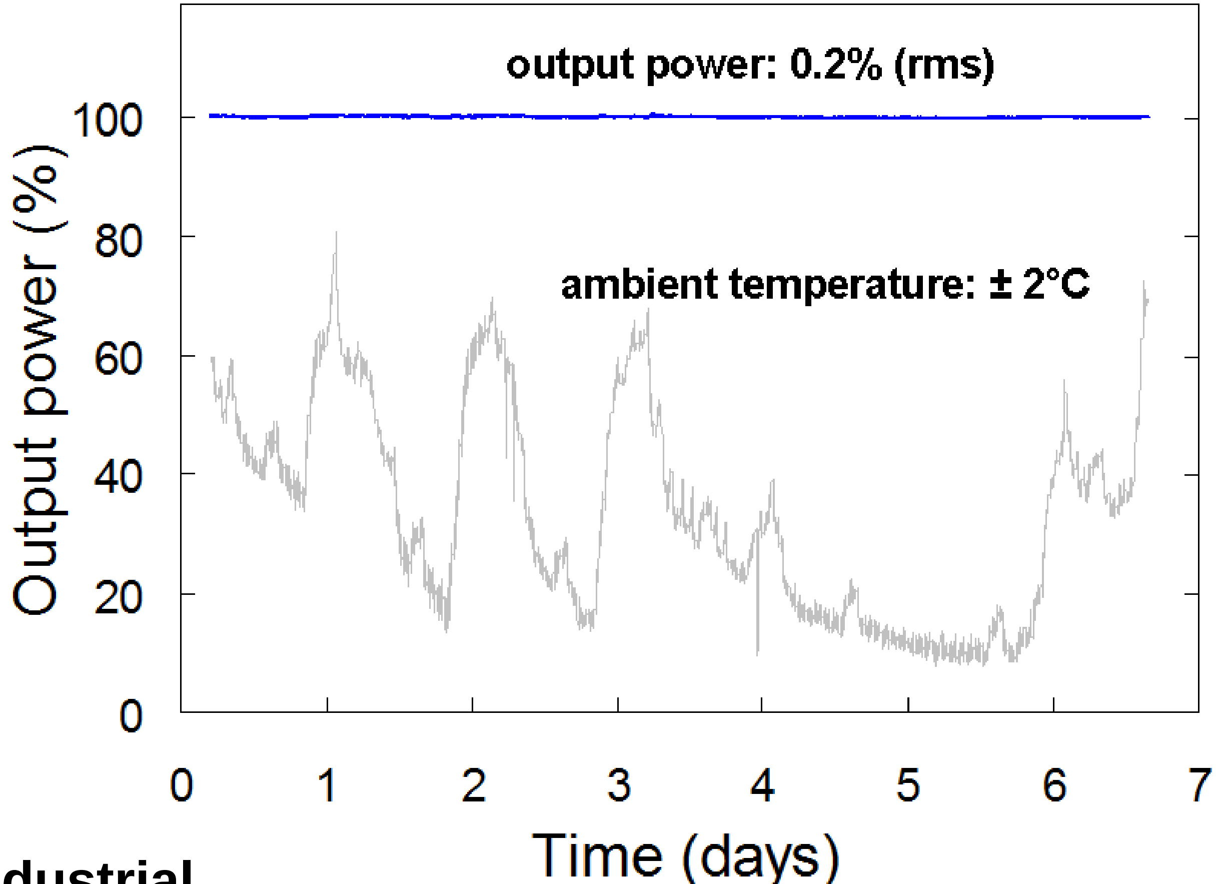
Applied Physics Express 2 (2009) 042501
(Deposition of TiO_2 thin film)

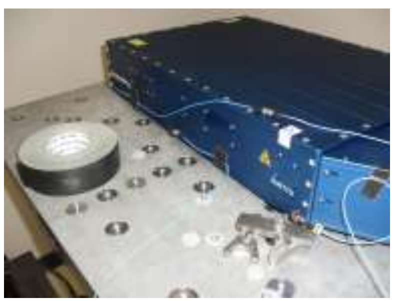


DUETTO – excellent field reliability

- **Engineering driven performance**
  - attentive, responsive, highly trained team
  - emphasis on accurate (conservative) specifications and promises
  - focus on cost transparency and effectiveness
- **Field service resolved remotely (phone and/or email) in most cases**
- **Excellent design minimizes problems**
  - SESAM IP and know-how results in excellent oscillator reliability
  - Key choices in "sensitive" components for lower cost, better performance, stability, and reliability
- **Result: Duetto systems work in the field, factory returns not required …**
  - first units in the field since 2005

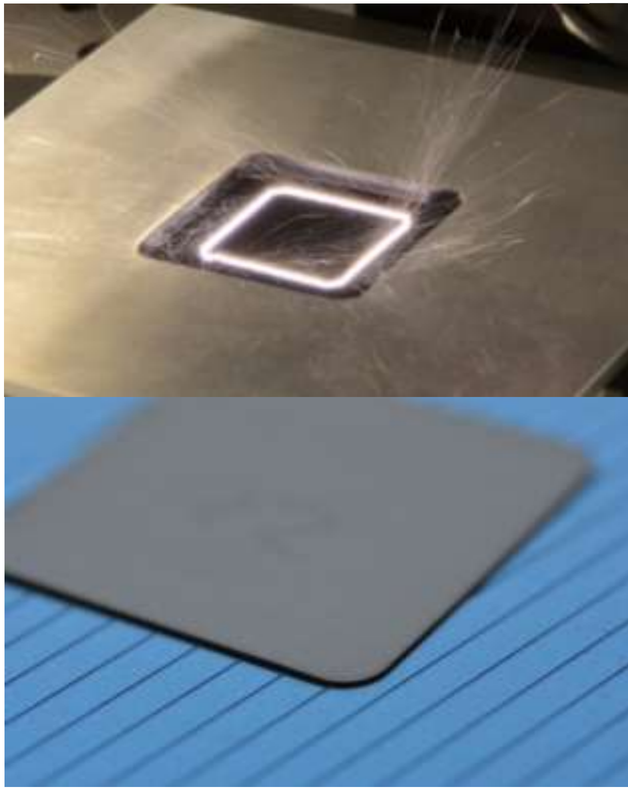
DUETTO – excellent long-term stability characteristics



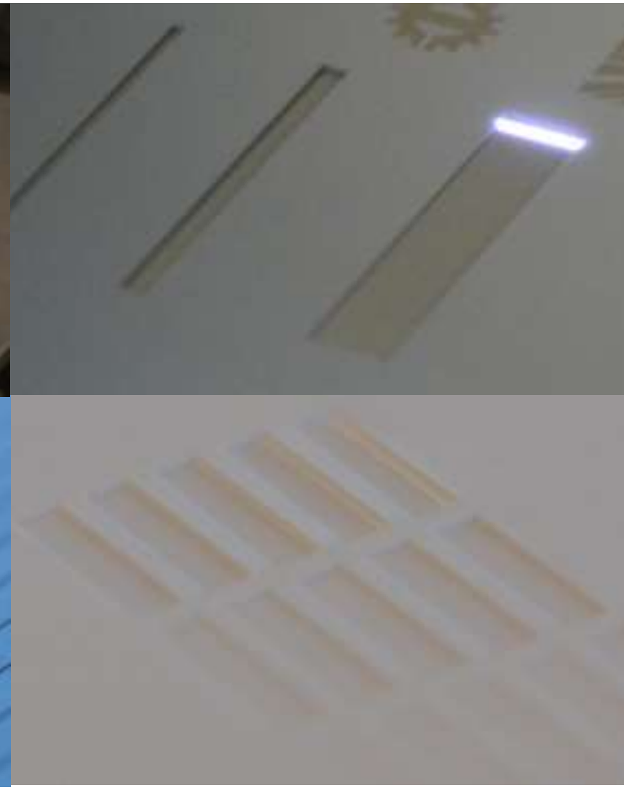


passes standardized industrial shock and vibration testing

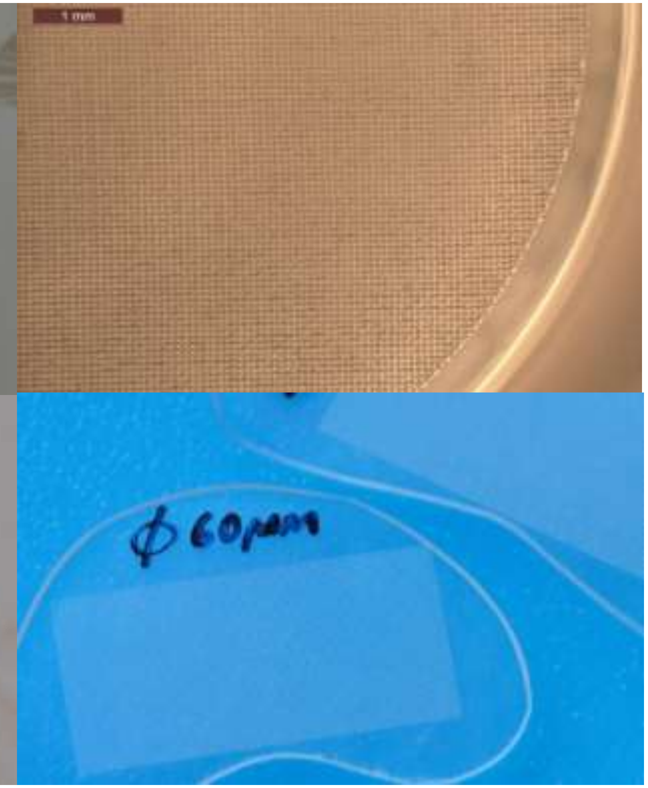
Many (many!) possible applicatons ...



Cutting of battery-foils (mixed metal-ceramic compound materials)



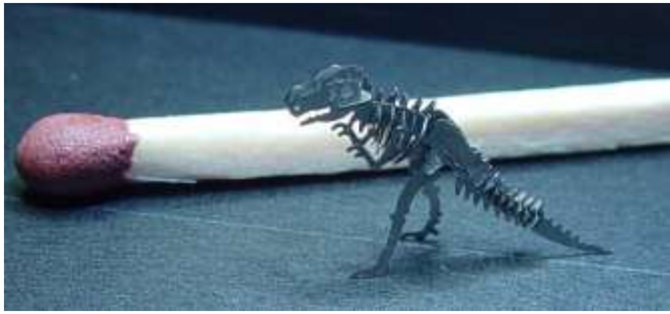
Cutting and structuring of LTCC and Al_2O_3 ceramic



Structuring of glass and polymers for enhanced cell-growth & implants

DUETTO product family offers

- Modular options
- Flexibility
- Industrial Reliability
- Optimized process
- Cost-efficiency, competitive TCO



Time-Bandwidth® Products

Thank you very much

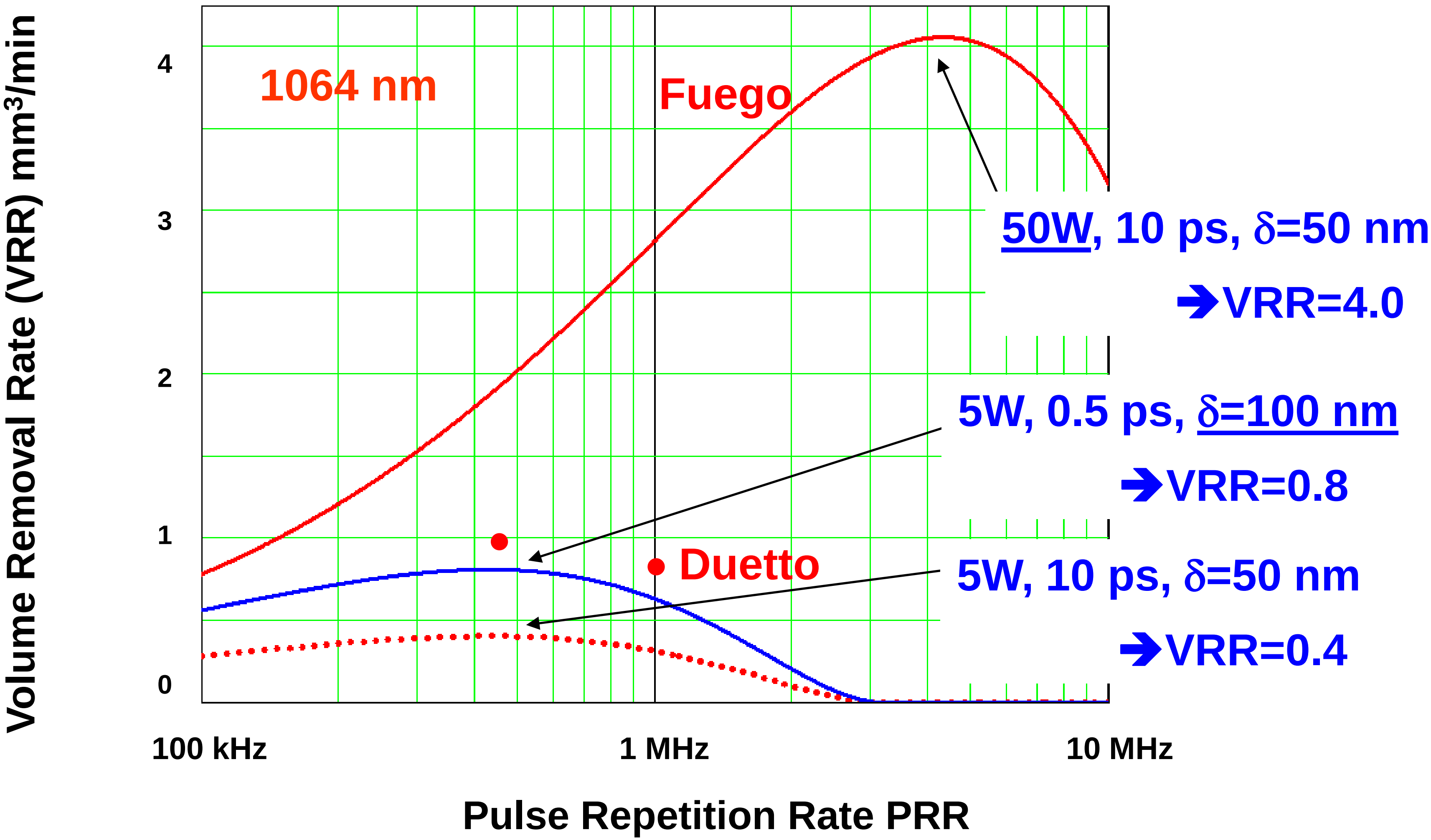
- **for your attention !**
- **and special thanks for their support to**
- **Department of Photonic Technologies at Friedrich-Alexander-University- Erlangen-Nürnberg**
- **Bern University of Applied Sciences**
- **Bavarian Laser Centre**
- **Kugler GmbH**
- **3D-Micromac**
- **ETH Zürich**

Examples

Picosecond versus Femtosecond

- **Complicated: depends on many process and material parameters**
  - Two key criteria
    - Quality
    - Productivity or Process Speed: volume removal rate (VRR, mm^3/minute/Watt)
- **Recent measurements have shown**
  - VRR can be better with femtoseconds – for some materials, some wavelengths
  - due to some increase in penetration depth (circa 2X)
  - at a given average power
- **However:**
  - 10X more available picosecond power results in 5X greater VRR
  - difference is smaller or negligible for many materials and other wavelengths (e.g. green)
  - VRR "always" better for higher power systems
- **Picosecond quality excellent, good enough in most (>90%) manufacturing applications**
  - UV picosecond can be better than IR femtosecond depending on the application
    smaller spot size
    different absorption and photo-chemical reaction – can give very high quality
- **Picosecond systems are turn-key and proven for approaching 10 years in industrial environments**

Picosecond versus Femtosecond



Femtosecond MOPA-system – LIFT EU project

Why move to femtoseconds?

- Processing of materials transparent for cw and ns-pulses at same wavelength
  - stronger multi-photon absorption than picoseconds
  - HAZ can go from sub-micron with picoseconds to sub-sub-micron with femtoseconds
- LIFT fiber-components
  - support sub-picosecond pulsewidths (glass fiber optical bandwidth)
  - can scale into multi-100W average power (large-mode fiber)
  - can demonstrate adequate pulse energy for cold ablation (10’s of microjoules)
- enables (requires) high-speed scanning
  - e.g. line scanning >10m/s
- Because its new ☺
- LIFT: Leadership in Fiber Technology www.lift-project.eu

Femtosecond MOPA-system development

Parameter	Current performance	Goal
Average power	> 50 W	> 200 W
Pulsewidth	~ 700 fs	< 500 fs
Pulse energy / rep. rate	100 µJ @ 400 kHz	> 100 µJ @ 2 MHz
Peak power	> 20 MW	200 MW
Center wavelength	1030 nm	1030-1040 nm
Output polarization	linear, 250:1	polarized, >100:1
Pulse-to-pulse stability (energy)	< 0.4% rms	< 1% rms (short term) < 1% rms (long term)
Beam quality (M^2)	< 1.3	< 1.2

Glass welding (1/2)

Process mechanism:

Plasma generation

↓

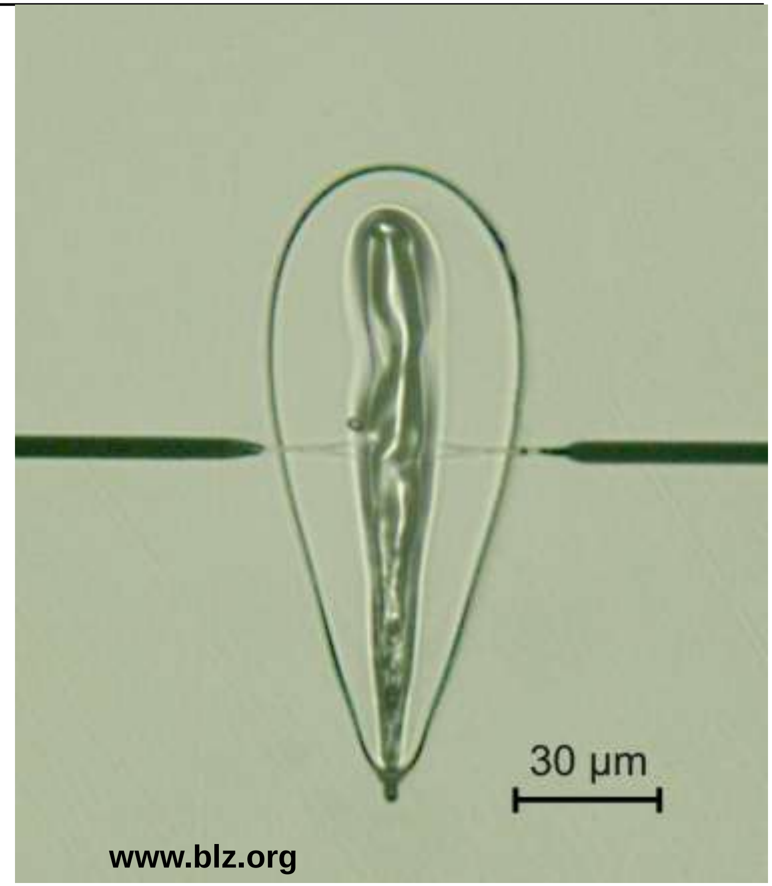
High laser repetition rate (≥ 1 MHz) leads to quasi-continuous energy coupling into glass

↓

Plasma heats glass material

↓

Result: Internal melting (= welding) of glass material



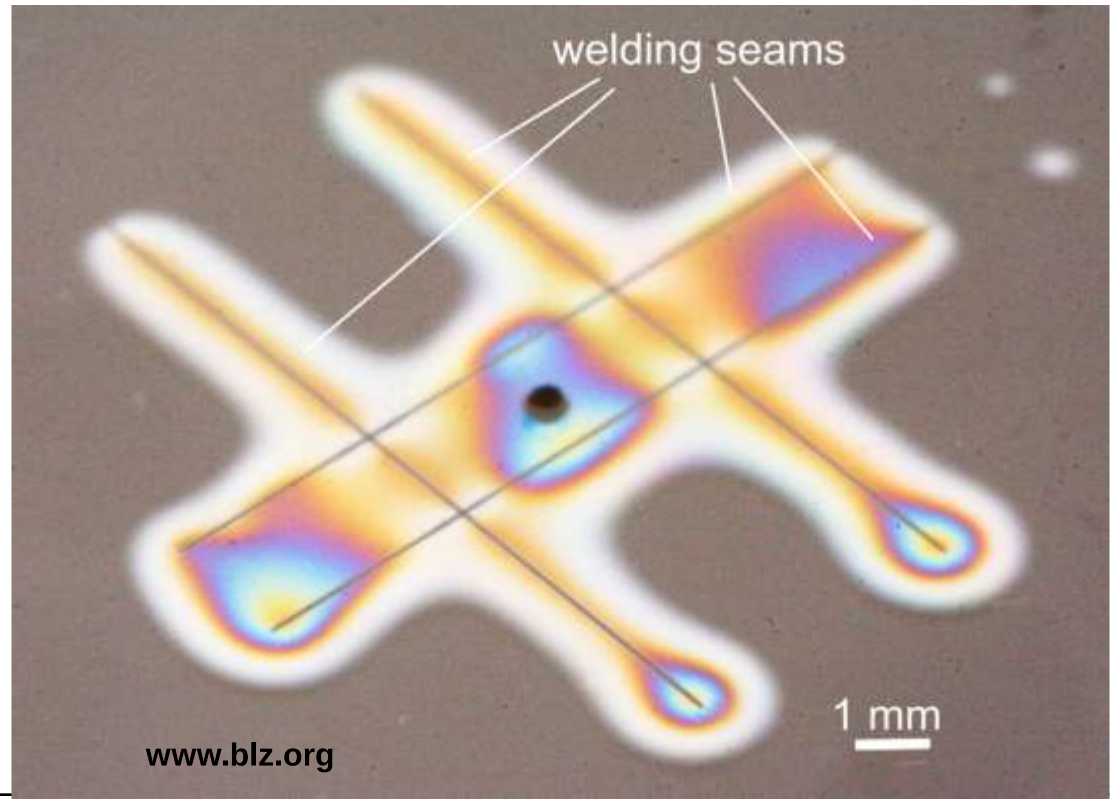
Typical laser process parameters:	
Wavelength:	1064 nm
Laser pulse duration:	~ 10 ps
Laser pulse energy:	1 µJ – 10 µJ
Repetition rate:	≥ 1 MHz
Speed:	10 mm/s – 200 mm/s

Glass welding (2/2)

Advantages over other joining techniques:
(mechanical bonding, optical contacting, gluing, soldering, diffusion bonding, laser welding (CO_2))

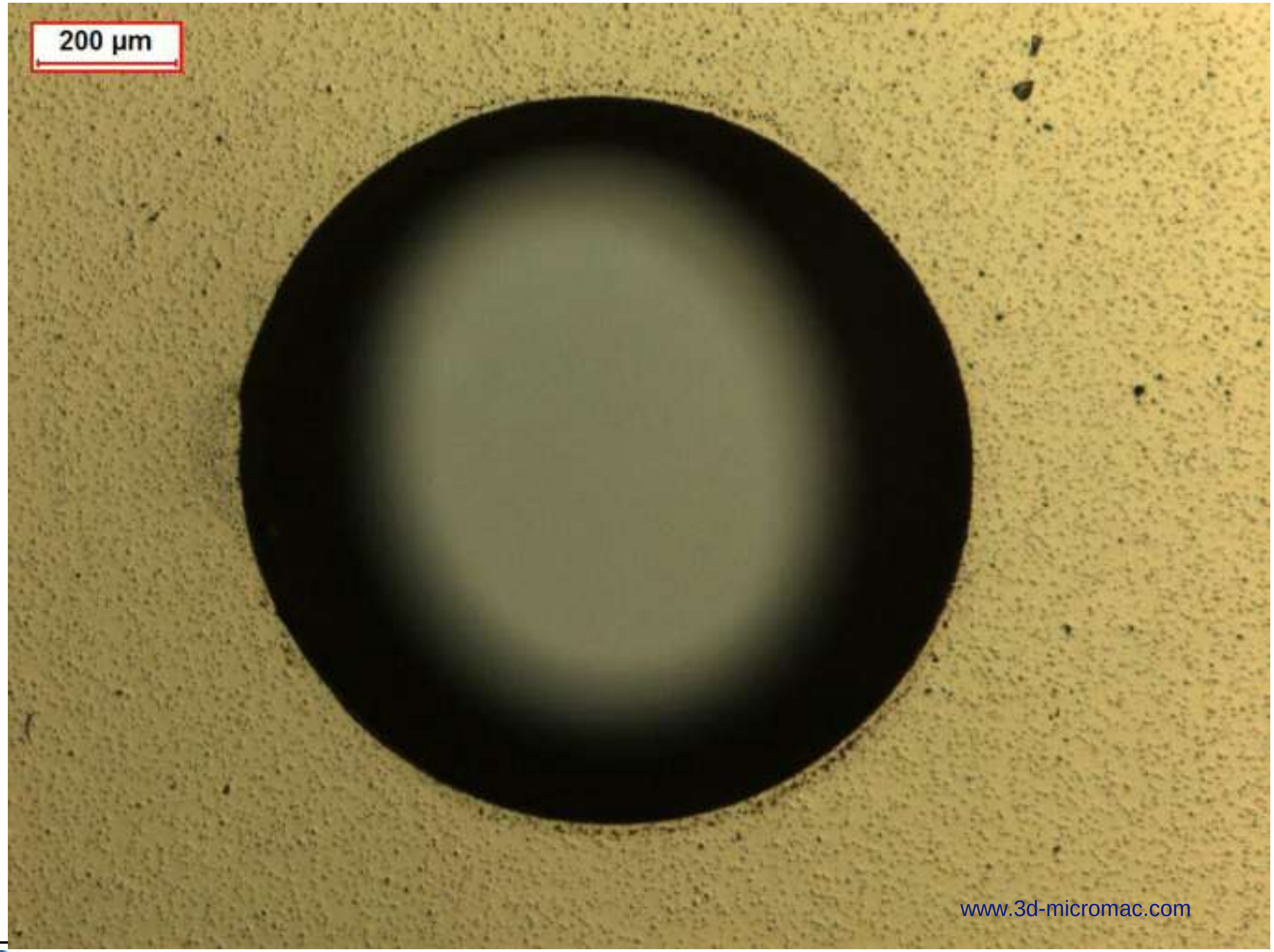
- no additional material required
- chemically stable
- no big thermal expansion
- no cracks
- small weld seams
- weld strength could be comparable to the strength of base material
- single-step process

Example: leak test of weld seams



Drilling of holes in metal (1/2)

- **Through holes in 600 µm thick Fe_2O_3**
- **1064 nm**
- **task in this case:**
  -quality of edge



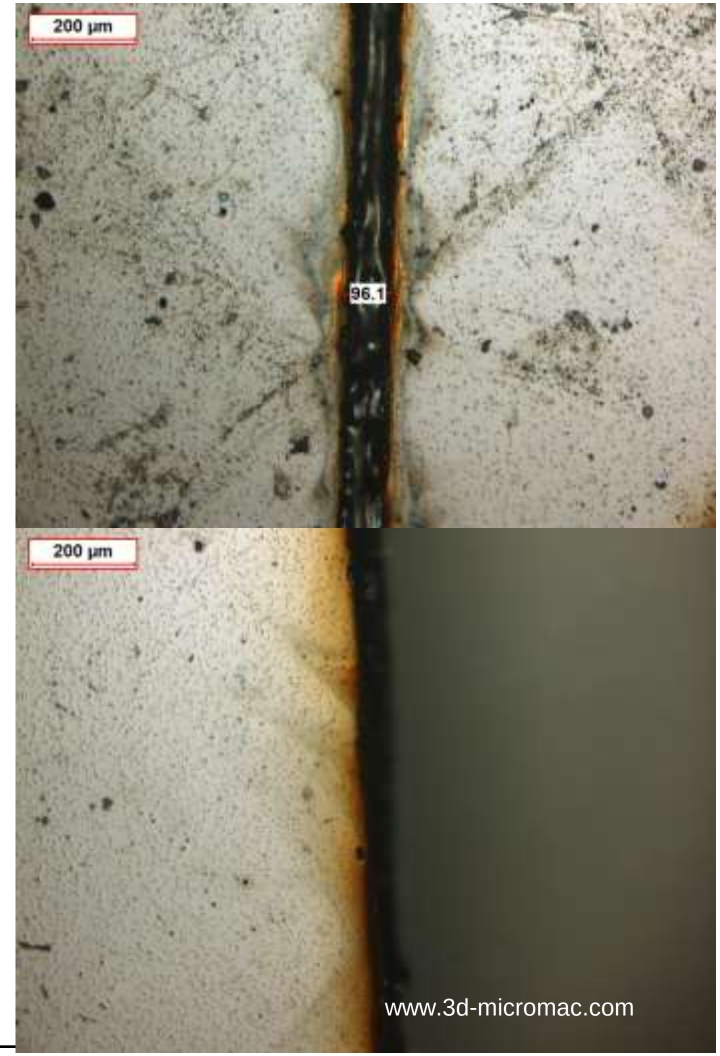
Time-Bandwidth® Products

Drilling of holes in metal (2/2)

- Through holes in 600 µm thick Fe_2O_3
- Advantage of picosecond laser:

► No burr
► No debris

**Comparison:
nanosecond fiber laser at 1070 nm**

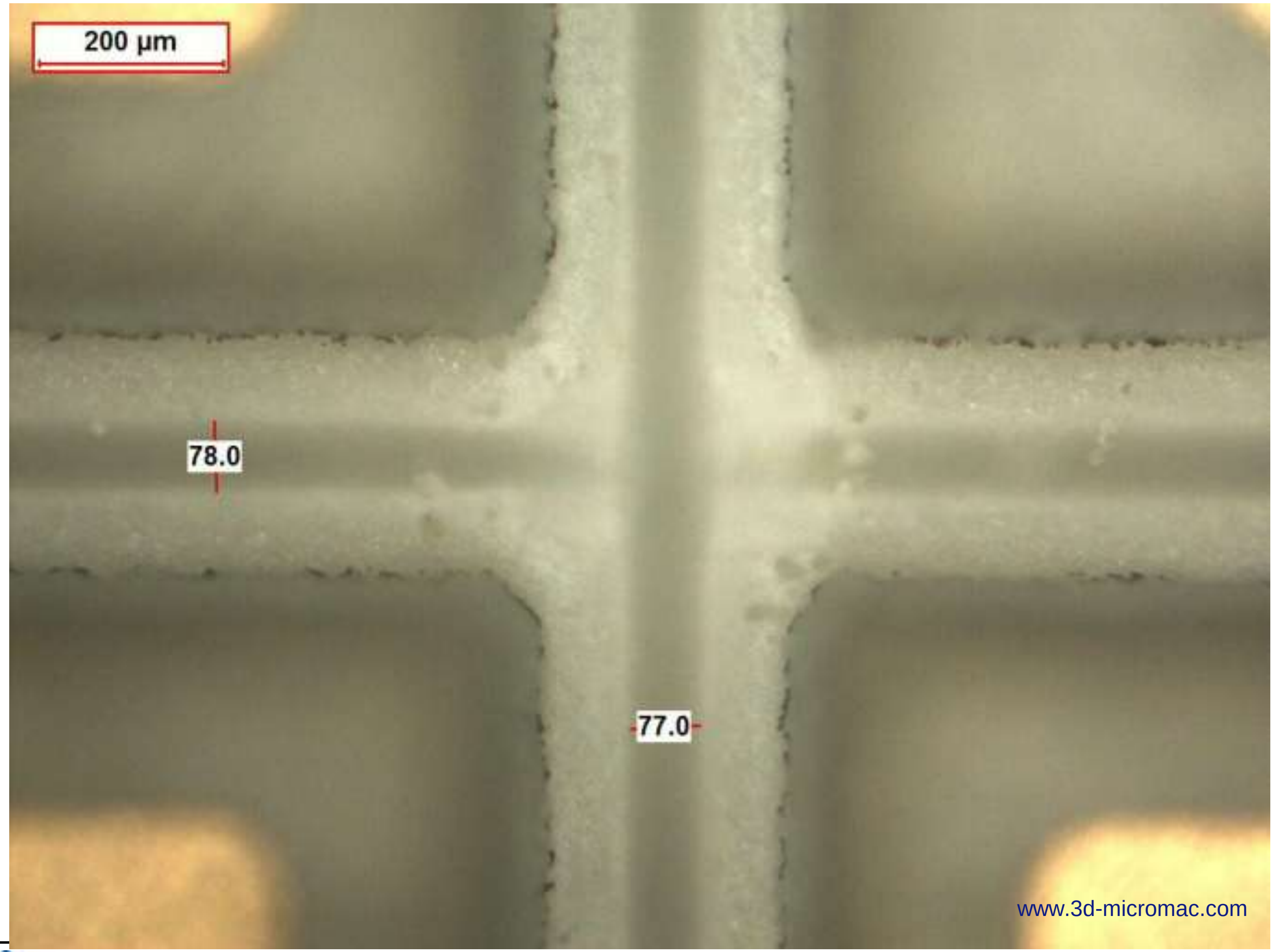


Time-Bandwidth® Products

Scribing of Al_2O_3 (1/2)

Scribing of aluminium oxide ceramic substrates.

Example for mechanical scribing



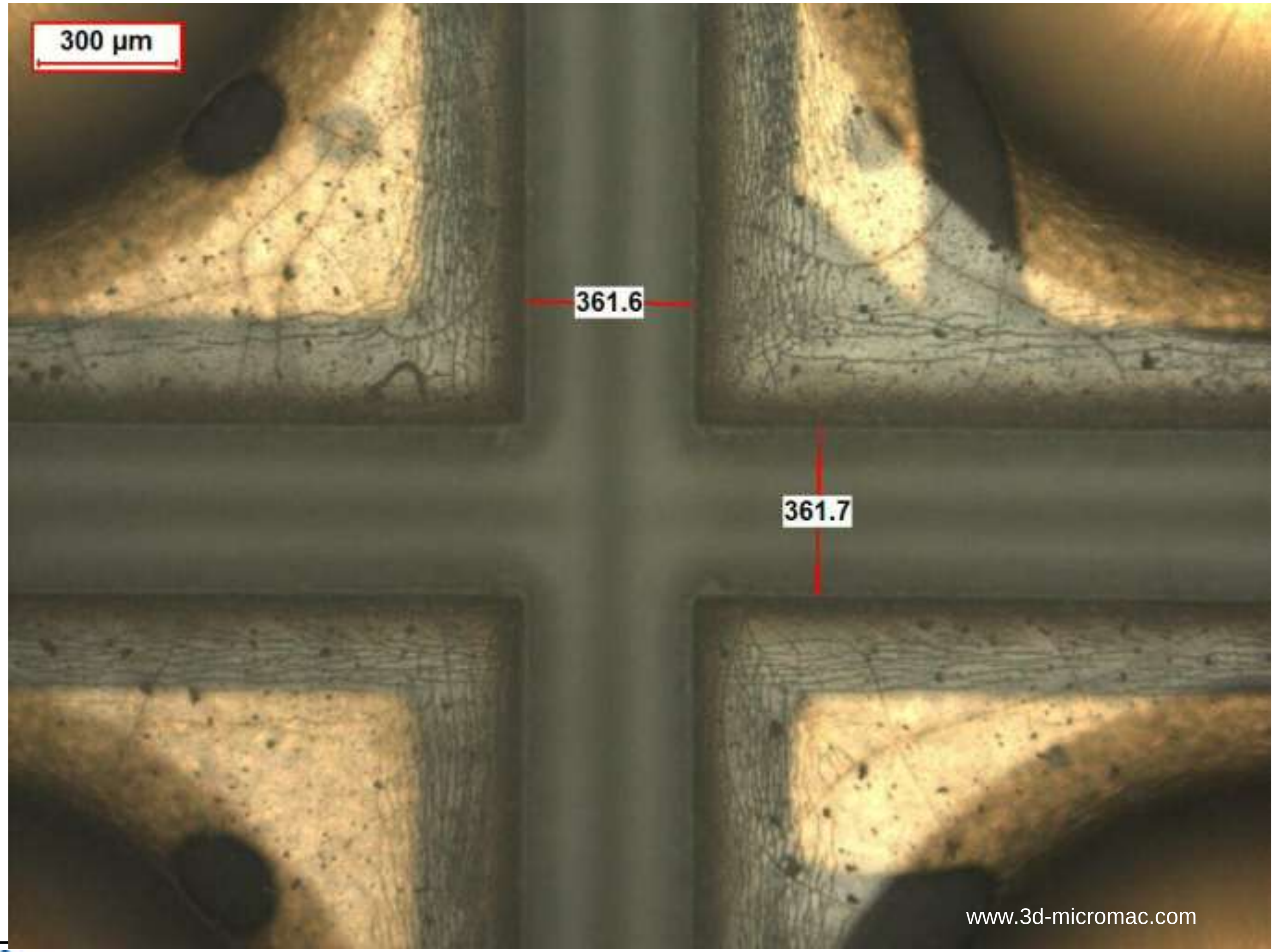
Scribing of Al_2O_3 (2/2)

Scribing of aluminum oxide ceramic substrates.

Scribing with picosecond laser (1064nm, low energies)

Advantages:
(vs. mech. method or nanosecond laser)

- ► less debris
- ► less melt effects
- ► less thermal load for el components
- ► less cracks



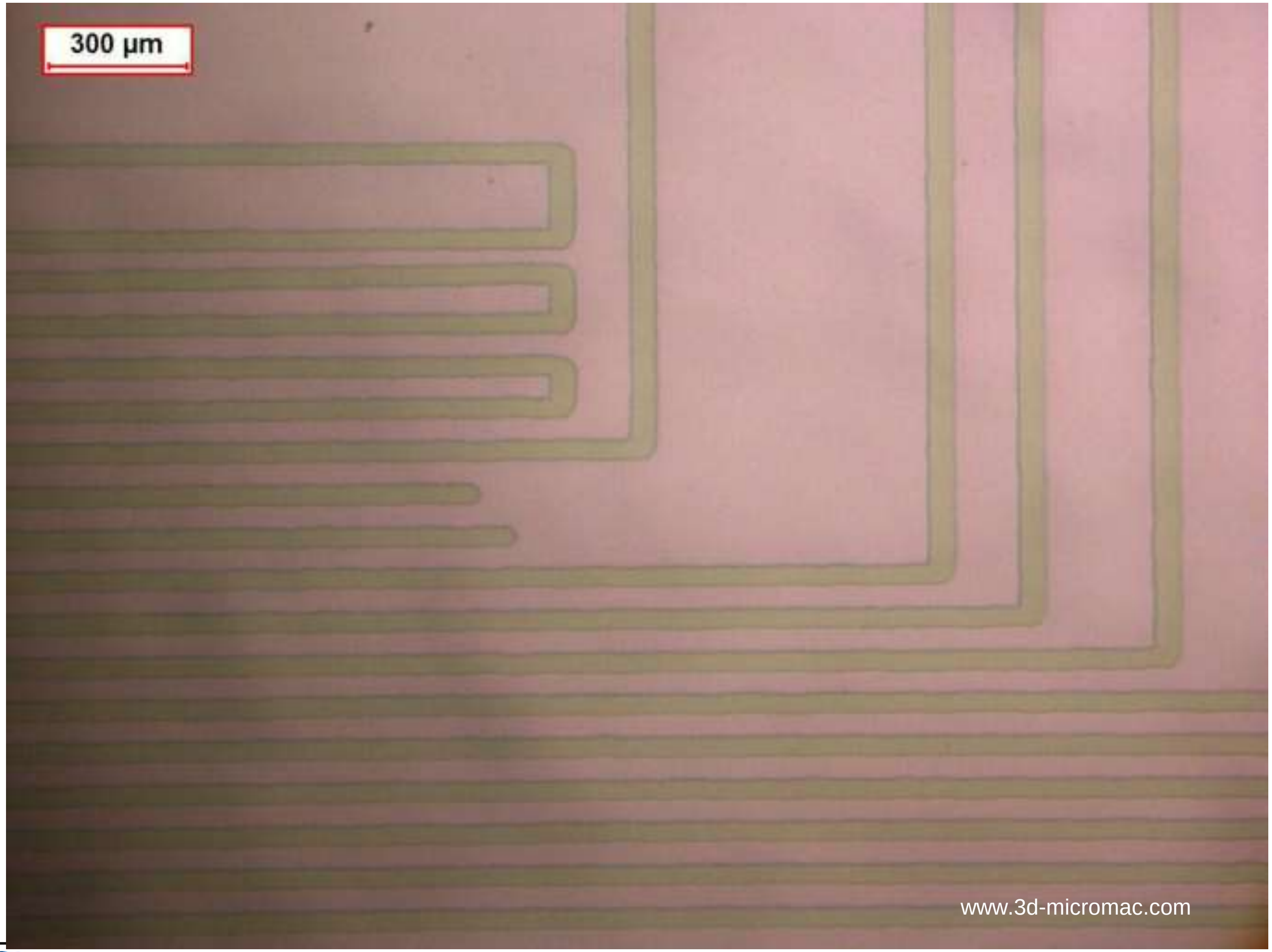
Time-Bandwidth® Products

Ablation of Indium Tin Oxide (ITO)

- 300 – 400nm thick ITO layer on glass

- 1064 nm
- very low pulse energy
- but high speeds
- of ≥ 2 m/sec

- different substrates possible, such as organic thin films

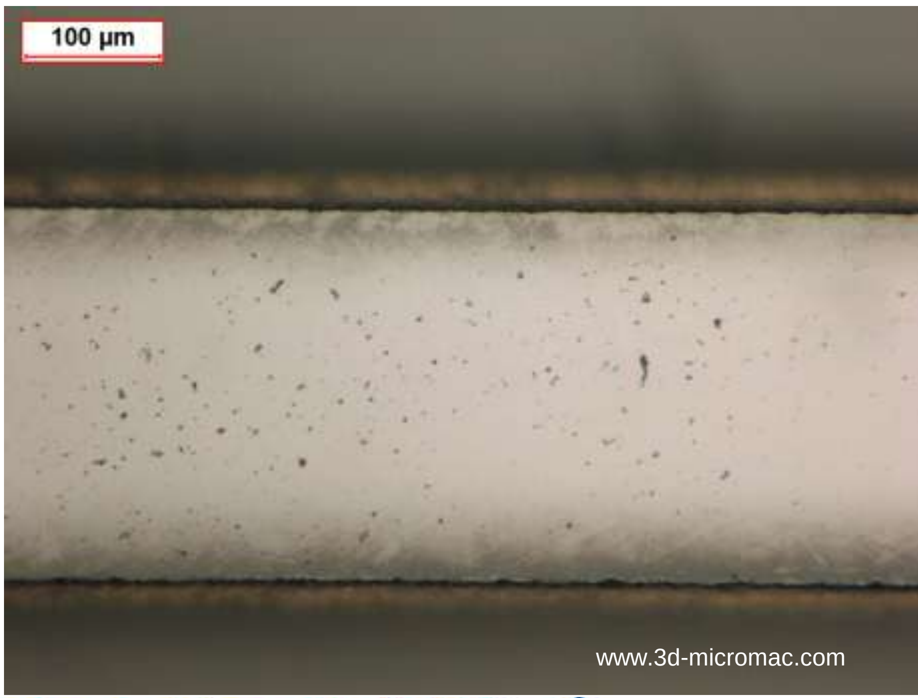


Time-Bandwidth® Products

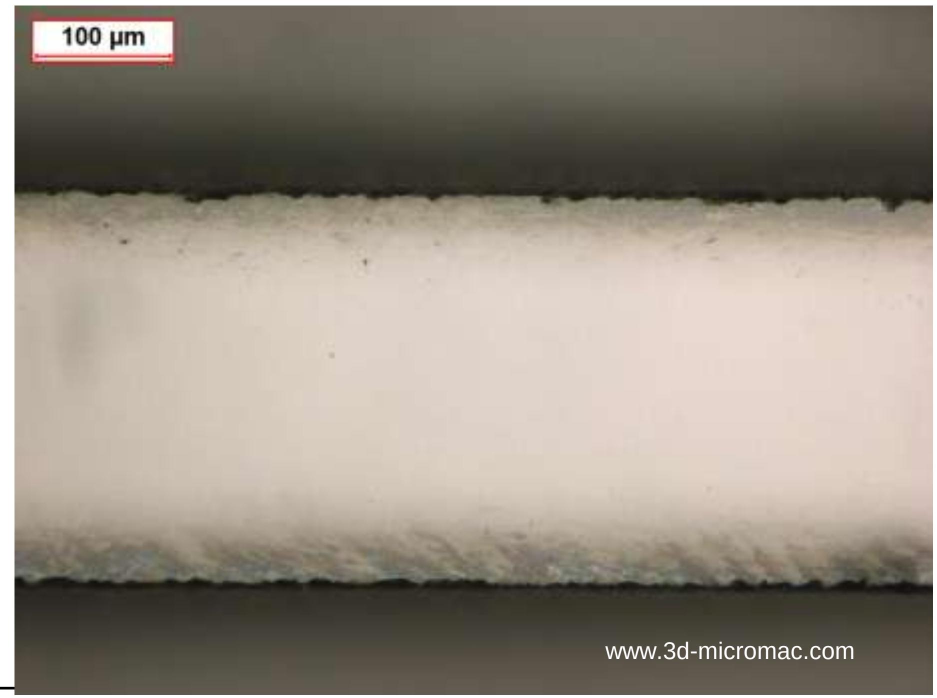
Cutting of quartz glass

- Cutting of quartz glass: comparison 532 nm vs. 355 nm
- Higher pulse energies required by quartz, and low repetition rates due to sensitivity to heat

- 355 nm
- slower, but sharper, nicer edges



- 532 nm
- faster, but slightly worse edges



Inner glass micro marking (1/3)

Photonische Technologien

Process mechanism:

Plasma creation inside glass

↓

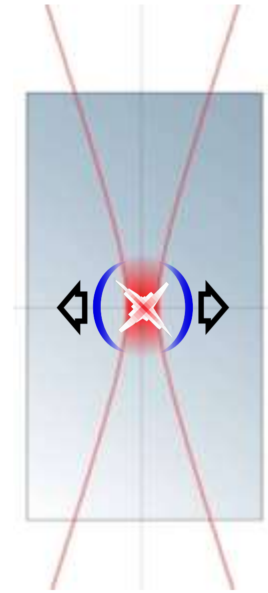
Formation of controllable shock wave

↓

Material deformation inside interaction zone

↓

Result: light scattering microcracks

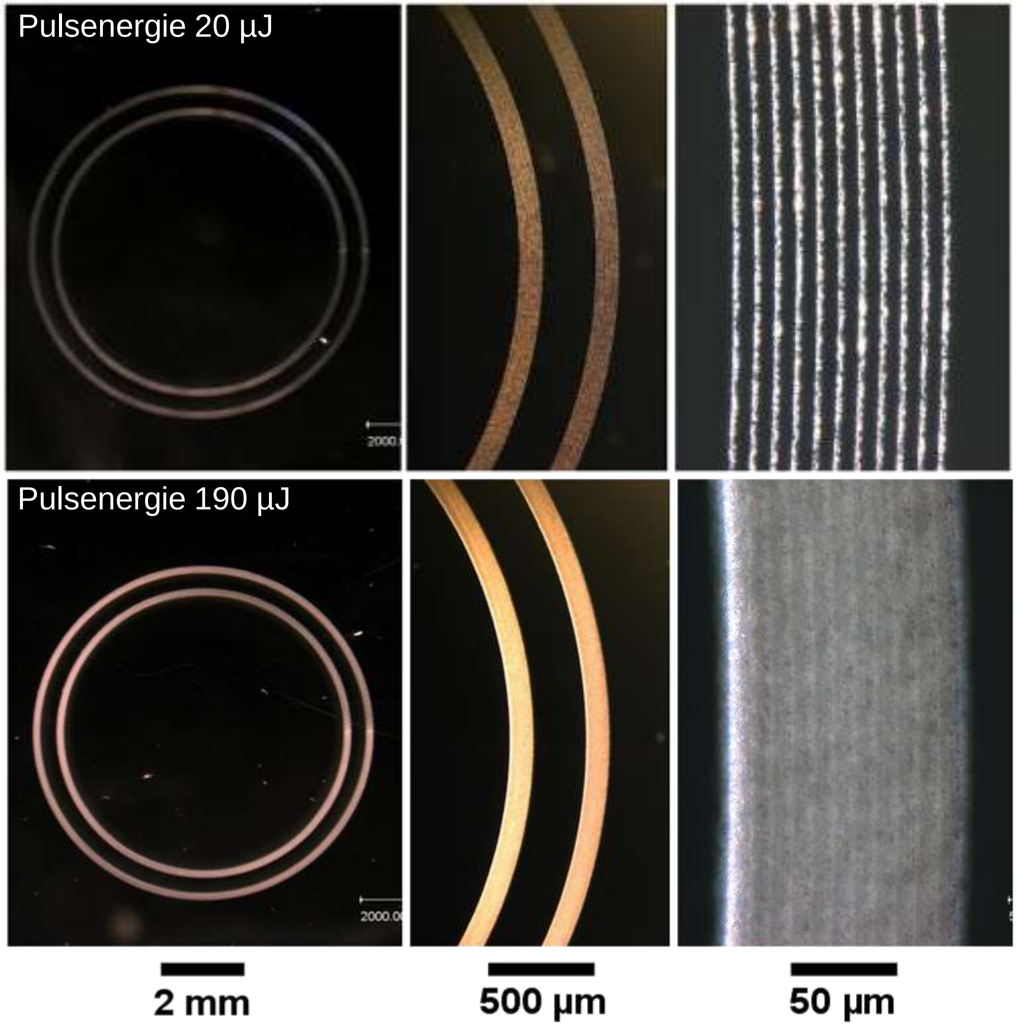


Typical laser process parameters:

Laser pulse duration:	10 ps
Laser pulse energy:	10 µJ – 100 µJ
Speed:	0.5 mm/s – 500 mm/s

www.lpt.uni-erlangen.de

Inner glass micro marking (2/3)



www.lpt.uni-erlangen.de

Example:
Marking of quartz glass

Duetto, 1064 nm, 10 ps
Repetition rate 50 kHz
Speed 20 mm/s

22 single circles in 2 bundles,
Ø ≈ 5 mm

100 µm below surface

Inner glass micro marking (3/3)

Photonische Technologien

Advantages of ps-laser vs. ns-laser

- microcracks scalable down to ~1 µm
  (~50 µm with ns-laser)
  ➔ sharper edges
- marking very close to surface possible
  without damaging the surface
- robust process window
- Marking of highly transparent materials possible like quartz
- possible marking speed: ≫ 100 mm/s
  10^6 spots/s vs 10^4 spots/s

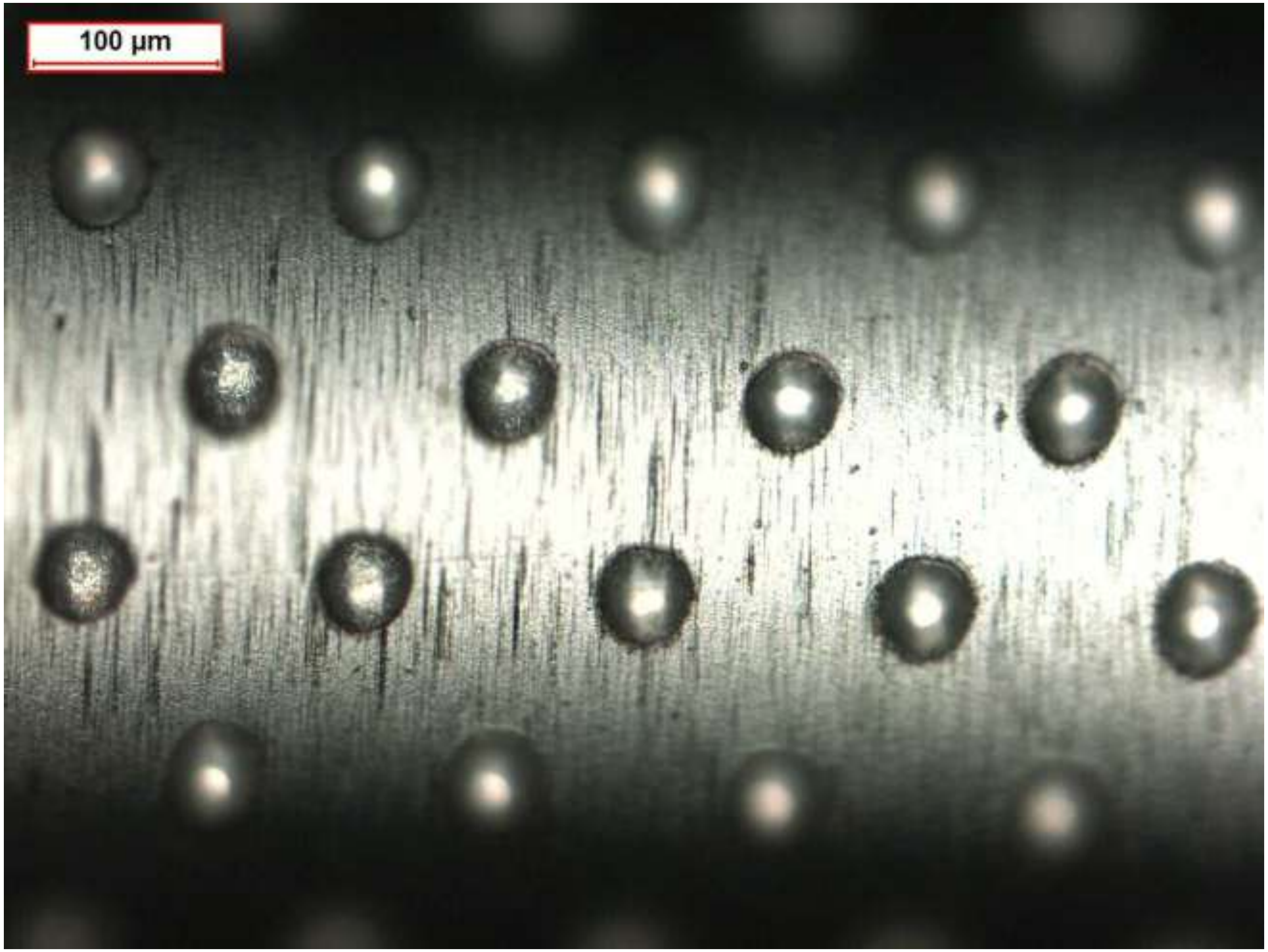
ns-laser, 532nm
(thermal process
causes microcracks)

Applications in biotechnology and medical engineering (ophthalmology)

Dimples in stainless steel

- Drilling of dimples on stainless steel cylinder, a few cm diameter
- 1064 nm
- low pulse energy to avoid melting

► low burr
► low debris
► smooth profile



- Comparison to ns Nd:YAG laser:
  - lots of debris
  - high burr

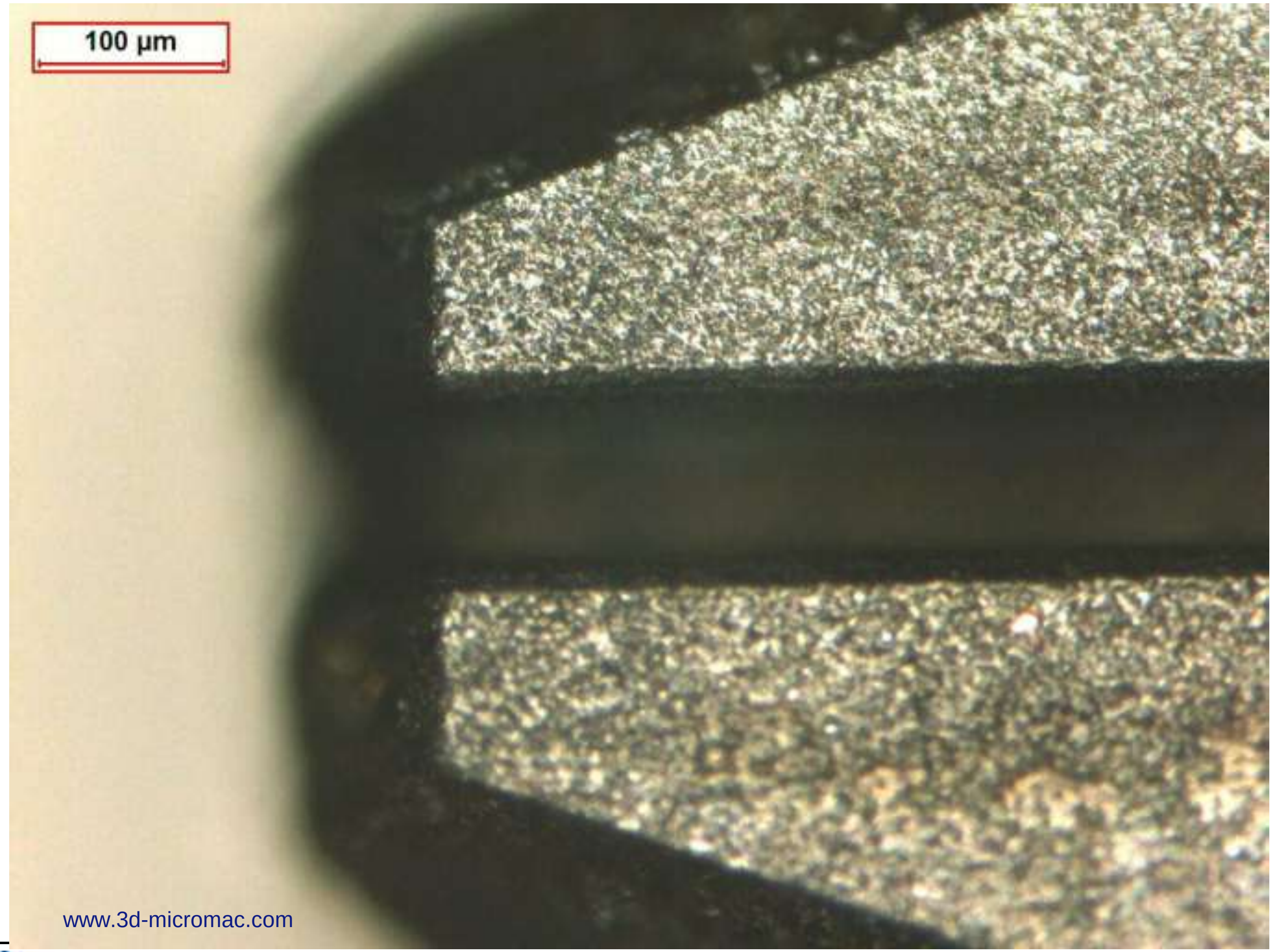
Machining of PKD nozzles

- Machining of nozzles in Poly Crystalline Diamond

- 1064 nm
- motivation to use picosecond laser:

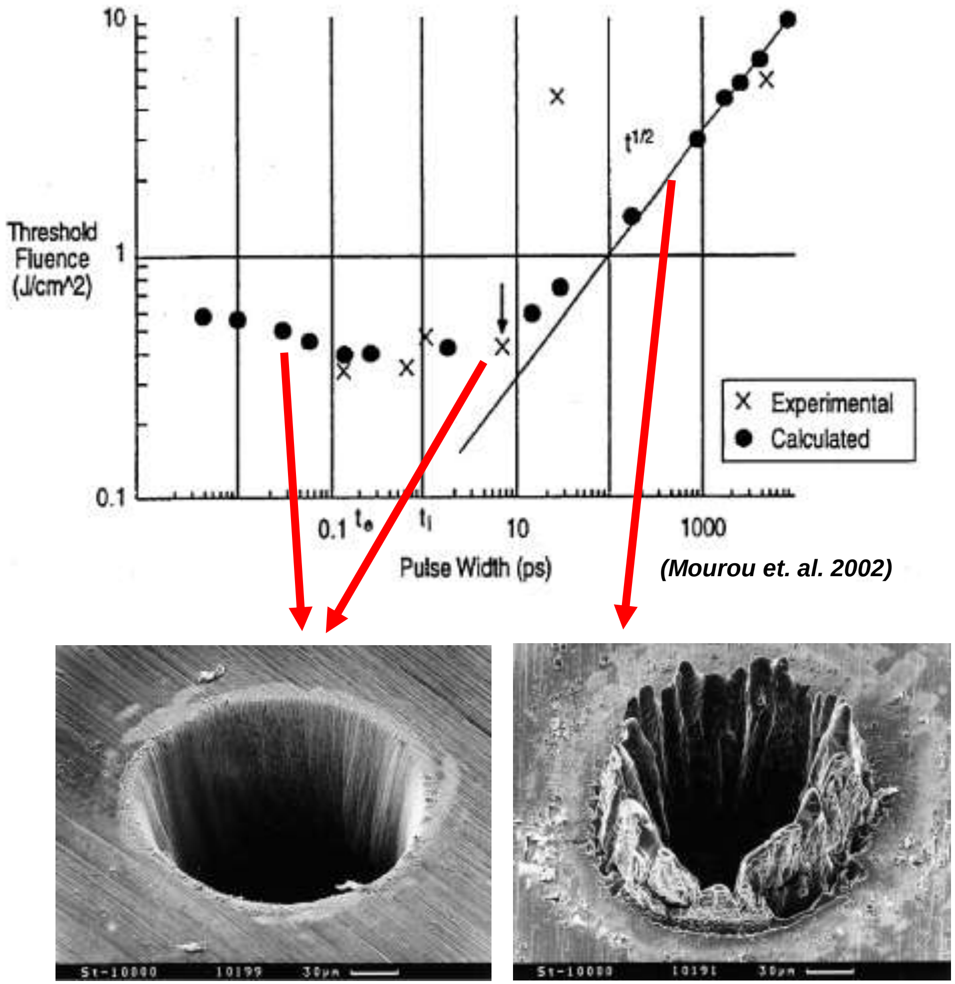
► precision

► high surface quality



Cold ablation – simple guidelines

Cold ablation ⇨ operate near threshold fluence ⇨ need moderate pulse energy



Chichkov, et al., *Appl. Phys. A* **63**, 109 (1996)

$$fluence = \frac{pulse\ energy}{beam\ area}$$

High quality ablation is a *gentle* process, it requires:

- ✓ short pulses
  typically < 10 ps
- ✓ high enough fluence
  typically > 1 J/cm^2

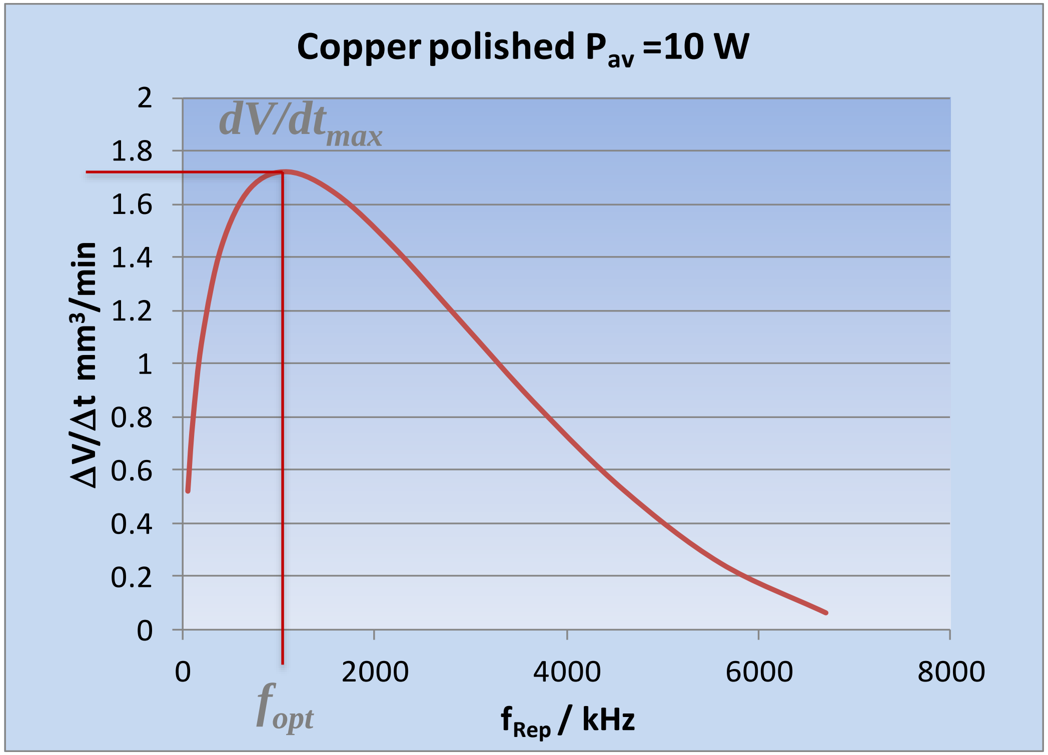
&

- ✓ not <u>too</u> high fluence
  typically < 3 x threshold

Time-Bandwidth® Products

Cold ablation – simple guidelines

Cold ablation ⇨ operate near threshold fluence ⇨ need moderate pulse energy



www.laserlab.ti.bfh.ch

$$fluence = \frac{pulse\ energy}{beam\ area}$$

High quality ablation is a *gentle* process, it requires:

- **short pulses**
  typically <10 ps
- **high enough fluence**

  &
- **not <u>too</u> high fluence**

⇨there exists an optimum repetition rate for maximum ablation rate

(Prof. Beat Neuenschwander, AKL ‘12 Aachen)

Cold ablation – typical numbers

Example :

$F_{threshold}$ = 1 J/cm^2

$F_{operation}$ = 1.5 J/cm^2

Area = 500 µm^2

(~25 µm spot diameter)

} E = 10 µJ at focus

high quality and efficient processing

⇕

moderate and adjustable pulse energy