# Laser Applications R&D at Fraunhofer Institute for Laser Technology

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# Outline



•The Fraunhofer Institute for Laser Technology

•Related Results & Planned Experiments at JLAB FEL

- Micro-ablation with tailored pulse trains
- Drilling with µs-laser radiation
- PLD

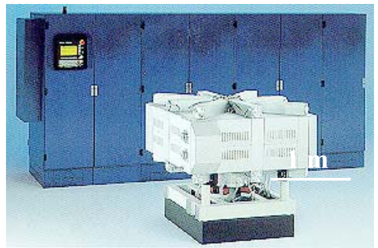
•Conclusion

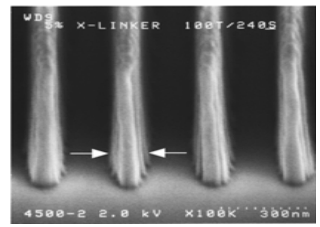
## Lasers

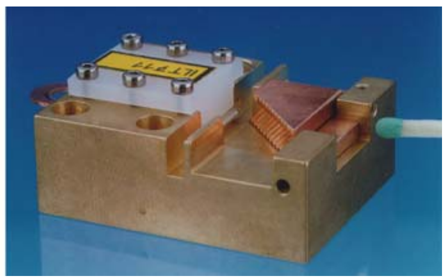
- Power/ Energy
- Quality
  - space (focusability)
  - time (pulse duration and formation)
  - spectral (wavelength, Laser types)

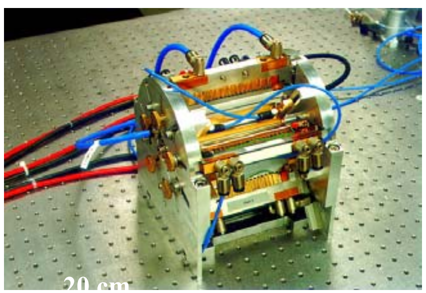
## Application

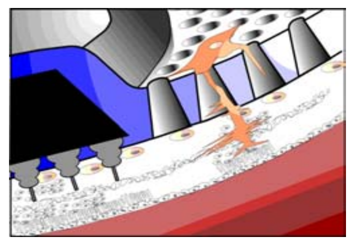
- Manufacturing
  - Processes
  - System technology
- Microelectronics (EUV)
- Life science
  - Biophotonics
  - Biocompatible Materials
- Atomic and molecular

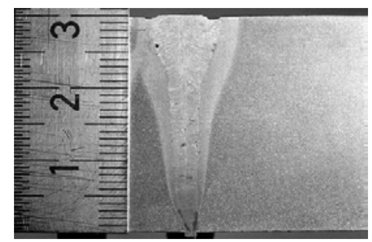




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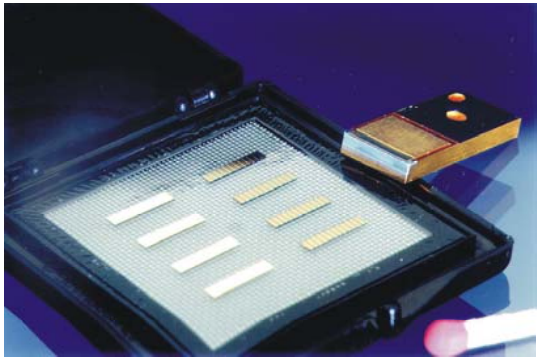
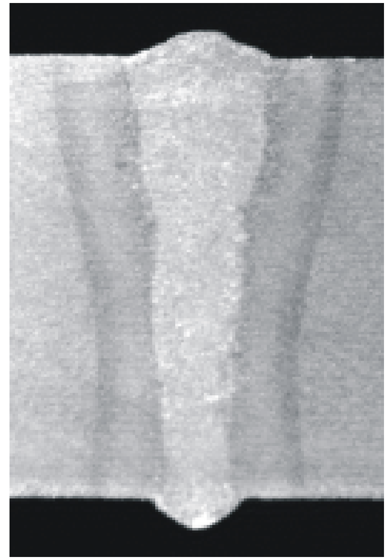
# Vertical Structure: Car body welding with a high power DPSSL





High-power
diode-laser chips and
packaging Lifetime



Welding
process and
materials
science

Systems design:
high efficiency and
beam quality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# Organisation of Fraunhofer-ILT and of LLT  RWTH Aachen University



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**Prof. Dr. R. Poprawe**
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Dr. B. Weikl

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A. Bauer

**Quality Management**
Dr. A. Drenker
M. Talkenberg

## Beam Sources

- **Integrated Optics**
- **Beam Sources**
- **Metrology and Surface Analysis**
- **Plasma and X-Ray**

- **Laser Components** – Dr. K. Boucke
- **Solid State/Diode Lasers** – D. Hoffmann
- **Metrology** – Dr. R. Noll
- **Plasma Technology** – Dr. W. Neff

- **CLT  Plymouth** – Dr. S. Heinemann
- **CLFA Paris** – Dr. W. Knapp

## Laser Applications

- **Joining and Cutting** – Dr. D. Petring
- **Surface Technology** – Dr. K. Wissenbach
- **Micro Technology** – Dr. A. Gillner
- **System Integration** – Dr. S. Kaierle

- **Surface Technology**
- **Micro Structuring Thin Film Technology**
- **System Integration**

**Modelling and Simulation** – Dr. W. Schulz

# Planned Experiments at JLAB FEL

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**Industry** needs e.g. drillings and microstructures

- more reproducible
- faster production
- higher quality (e.g. melt-free)

Development of an application-adapted laser system

⇑

**Solution** new laser system

- high-power
- high repetition rate
- ultra-short pulse duration

**Challenge**

- plasma formation
- interaction of laser radiation with plasma

**Use a FEL**

Variation of

✓ repetition rate

✓ wave length

✓ pulse duration

# Related Results & planned Experiments



- Micro-ablation with tailored pulse trains
- Drilling with μs-laser radiation
- PLD

# Micro-ablation with tailored pulse trains

Claudia Hartmann

Fraunhofer Institut Lasertechnik

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# Micro-ablation with laser radiation



**state of the art**

micro-ablation with femtosecond - microsecond pulses

- materials: metals and ceramics
- 2.5 dimensional structures
- 355 nm - 1064 nm (depending on material)

**Used Laser for Project at ILT/LLT**

- pulse duration 15 ns to 50 ns
- burst energy 2 mJ
- pulses per burst ≤ 4
- pulse distance 0,1 µs to 3 µs

**aim**

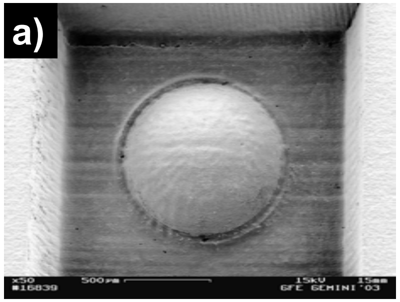
expansion of process limits during micro-ablation of metal (1064 nm)

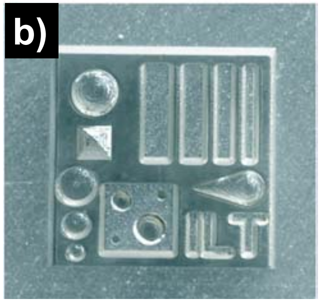
- less melt on the surface
- high ablation rates

⇒ use of tailored pulse trains

**interdepartmental cooperation of core competence teams of ILT/LLT**

- process know-how
- laser techniques
- system technology
- modelling and simulation





Ablated structures in:
a) $Al_2O_3$
b) sapphire
c) steel

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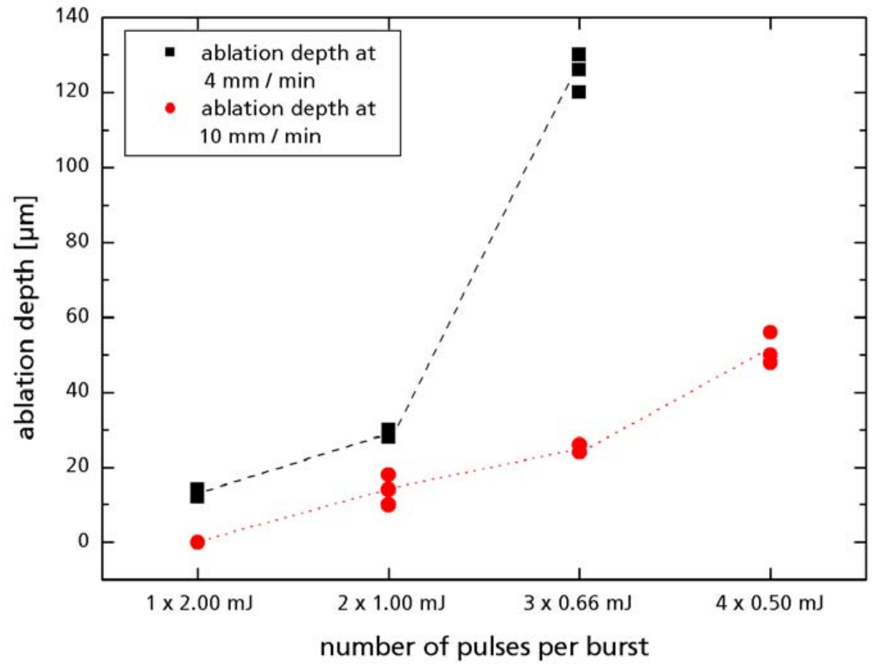
## variation of parameters

- burst and pulse energy
- number of pulses per burst
- pulse duration
- pulse distance
- repetition rate

## purpose

- high ablation rate
- high ablation quality (melt reduction, small $R_a$, ...)

→ ideal ablation parameters




**Parameter:**

$\nu_l$ = 10 Hz
$E_B$ = 2 mJ
$\tau_l$ = 14 ns to 50 ns
$\Delta t$ = 0,1 µs to 2µs

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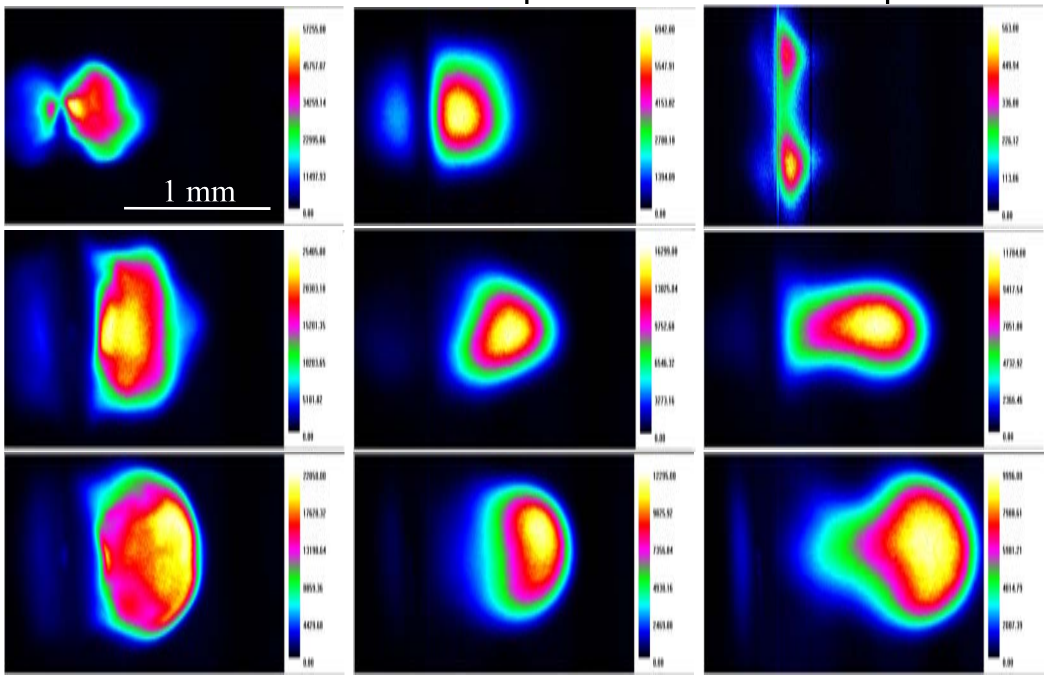
# Process analysis by high speed photography

$t_{del}$ =250ns | $t_{del}$ =5µs | $t_{del}$ =15µs

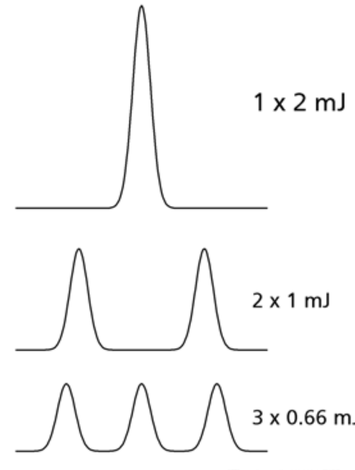
single pulse
$E$ = 2 mJ

double pulse
$E_B$ = 2 x 1 mJ
$\Delta t$ = 2 µs

triple pulse
$E_B$ = 3 x 0,66 mJ
$\Delta t_1 = \Delta t_2$ = 2 µs




Pulse bursts:

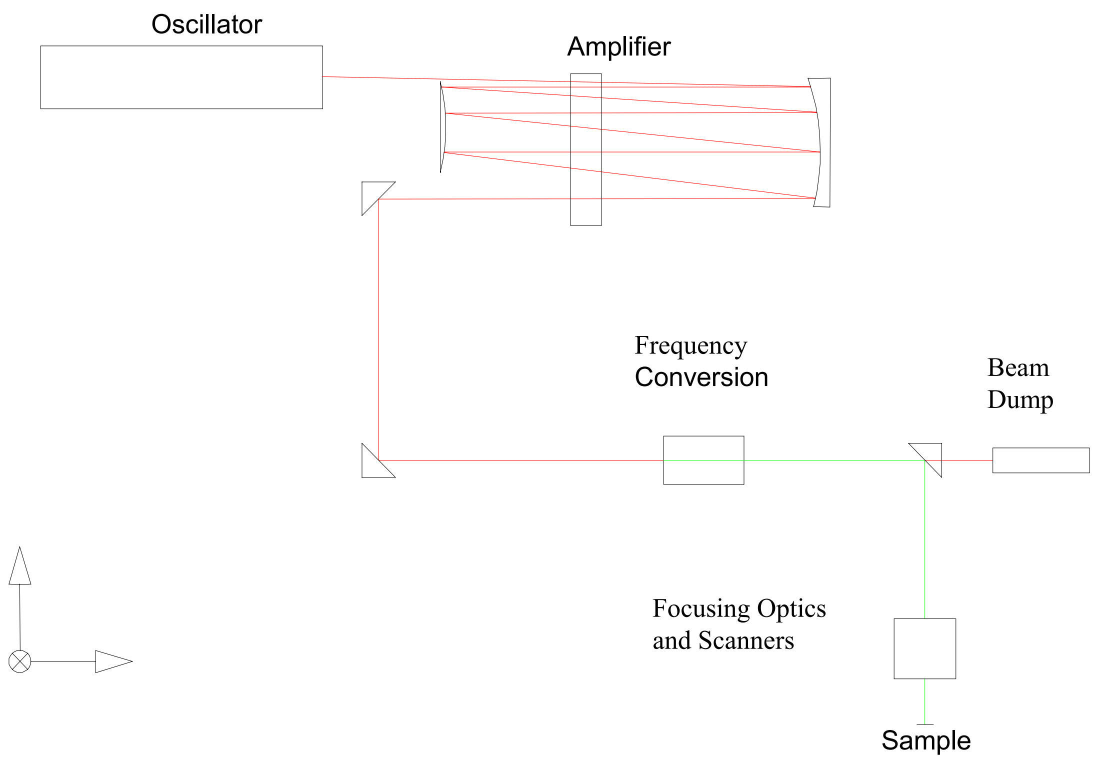



## Results

- Plasma of pulse bursts strips of the surface
- Magnification factor of the plasma volume: 10 for double pulse, 15 for triple pulse
- Plasma emission of pulse bursts have larger emission times

# High-speed Microstructuring of Copper, Aluminum and Steel

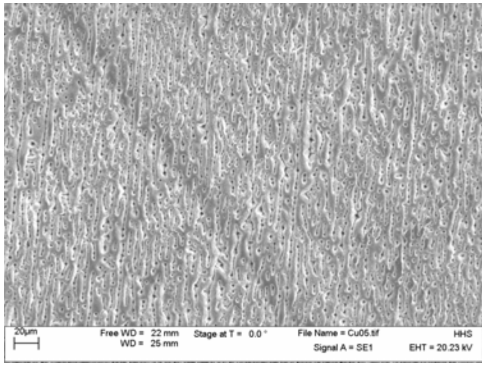
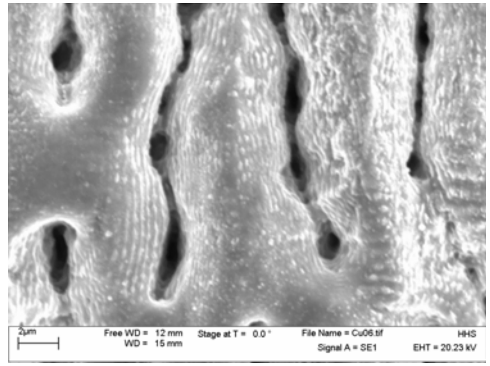
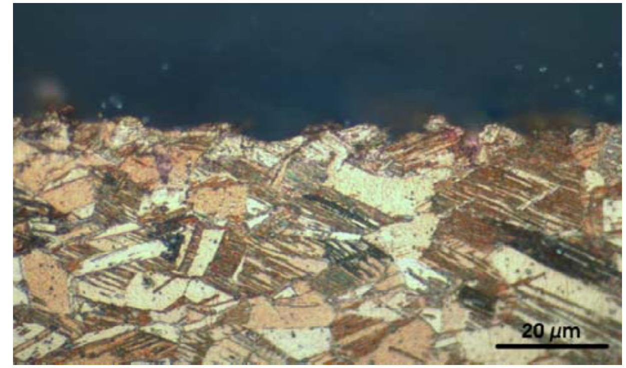
| | |
|---|---|
| Average Power at the Sample Surface, $P_t$ | 26 W |
| Maximum Average Pulse Peak Intensity, $I_P$ | 92 MW/cm$^2$ |
| $M^2$ - Value (focused beam) | 1.6 |
| Repetition Rate, $f$ | 4.1 MHz |
| Wavelength at Workpiece $\lambda$ | 532 nm |
| Pulse Duration, $\tau_p$ | 13 ps |



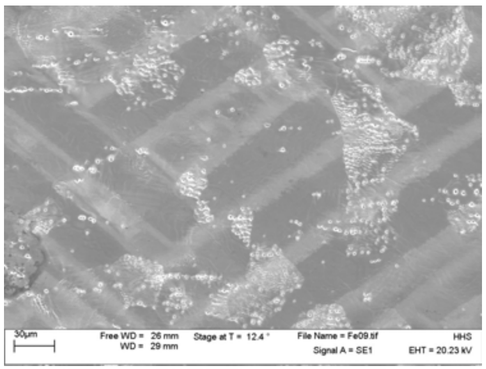
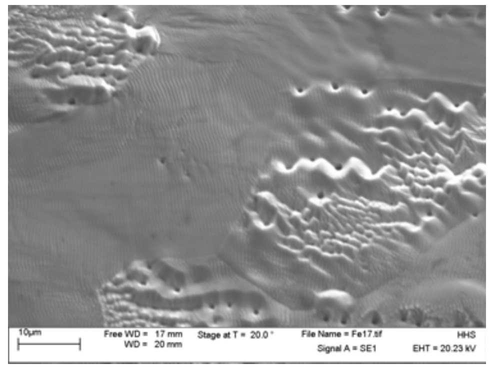
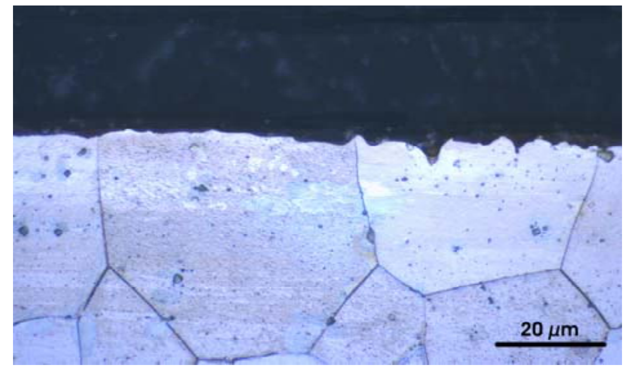
# Results

Top view | Top view | Cross-section view

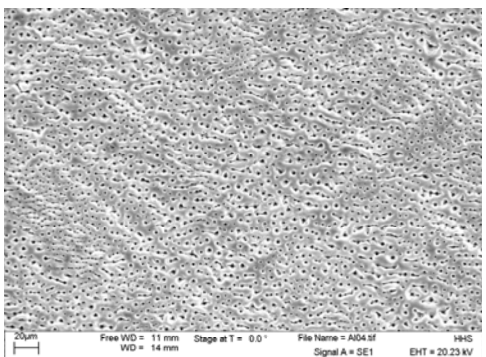
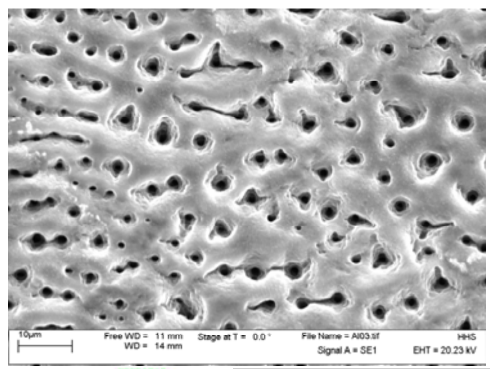
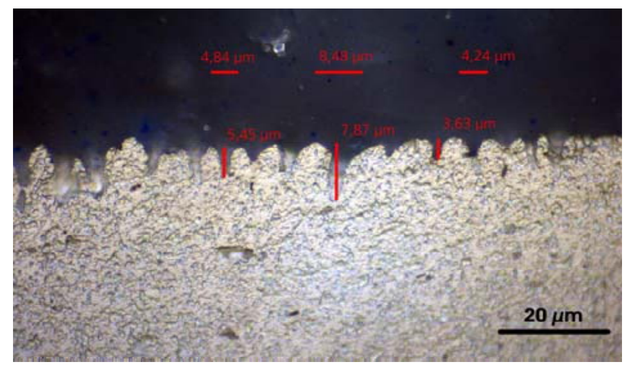
Copper


Steel


Aluminium

# Ablation Experiments at FEL

A: ablation experiments in steel 1.4301 (=304) and C70

A1: single pulse ablation

- different pulse delays (=rep. Rate.)
- variation of: - pulse energy
  - pulse overlap
  - wavelength

A2: ablation with pulse bursts

- different delays: • pulse delay during one burst
  • burst delay
- variation of: - number of pulses per burst (1,2,5, …)
  - burst energy
  - pulse overlap
  - wavelength

High-speed-photography of plasma dynamics
metallography, SEM and optical microscopy

# Drilling with µs-laser radiation

Lena Trippe

Fraunhofer Institut Lasertechnik

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# Drilling at LLT / ILT with laser radiation

**state of the art**: single pulse and trepan drilling with µs-laser-radiation

- stainless steel, nickel-based superalloy
- cylindrical hole geometry
- resolidified melt layers ≤ 15µm
- aspect ratio ≡ 20 : 1
- time / hole < 20s (trepan drilling)

Nd:YAG Slab Laser
pulse duration: 100-500µs
max. pulse power: 2kW
focal diameter: 40µm
$M^2 < 2$

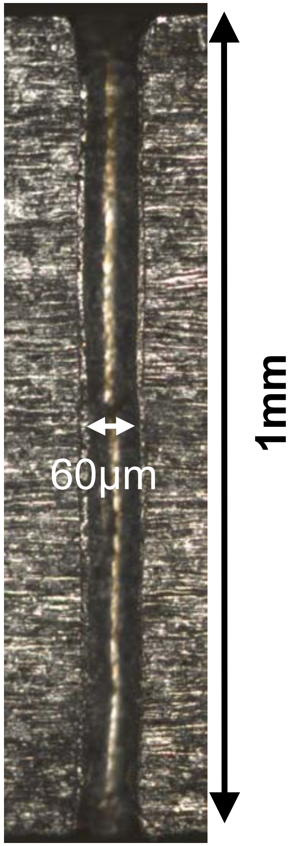
**aim**: expansion of process limits during percussion drilling (high speed drilling)

- metals and ceramics
- material thickness 5mm
- aspect ratio > 100 : 1
- time / hole ⑥ 1s

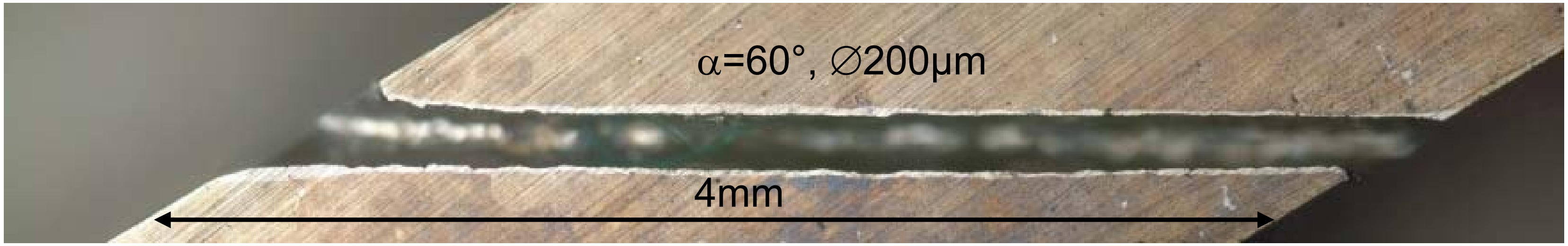
interdepartmental cooperation of core competence teams:

- process know-how
- laser techniques
- system technology
- modelling and simulation

**process limits**
process monitoring
process control
**understanding of processes**
modelling, analysis
simulation, numerical approximation
**process diagnostic**




**single pulse drilling (X5CrNi18-10)**

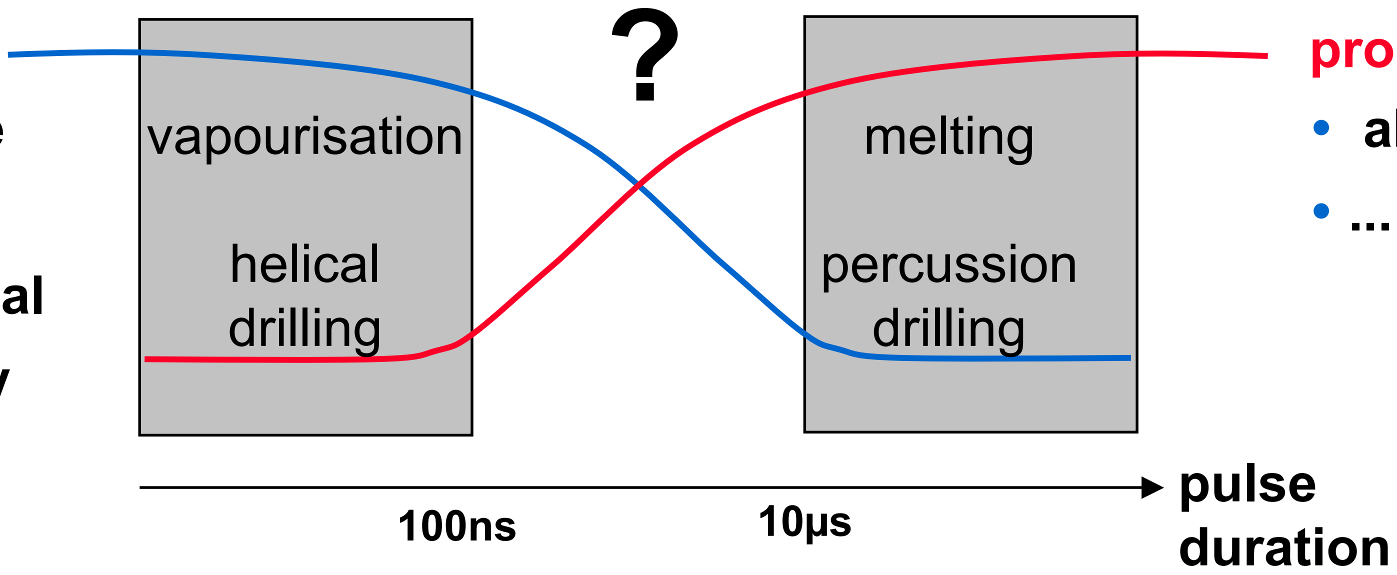



**trepan drilling (CMSX-4)**

| | | |
|---|---|---|
| < 500nm | ablation depth/pulse | < 1-5mm |
| < 3mJ | pulse energy | < 0.1-50J |
| < 1.5mm | material thickness | < 10mm |

**quality**

- **complete removal of material**
- **geometry**
- **...**




**productivity**

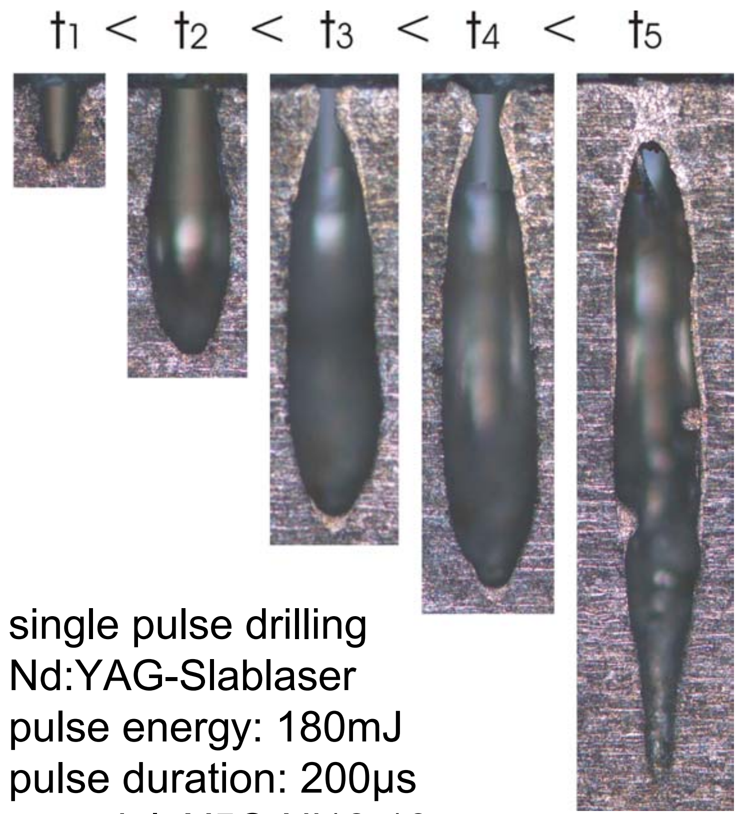
- **ablation rate**
- **...**

variation of parameters:
- pulse energy
- pulse duration
- temporal pulse shape
- focal position
- repetition rate
- ...

purposes:
- reduction of recast layers and closures
- cylindrical geometry of hole

=> parameters for percussion drilling

development of hole geometry during one pulse

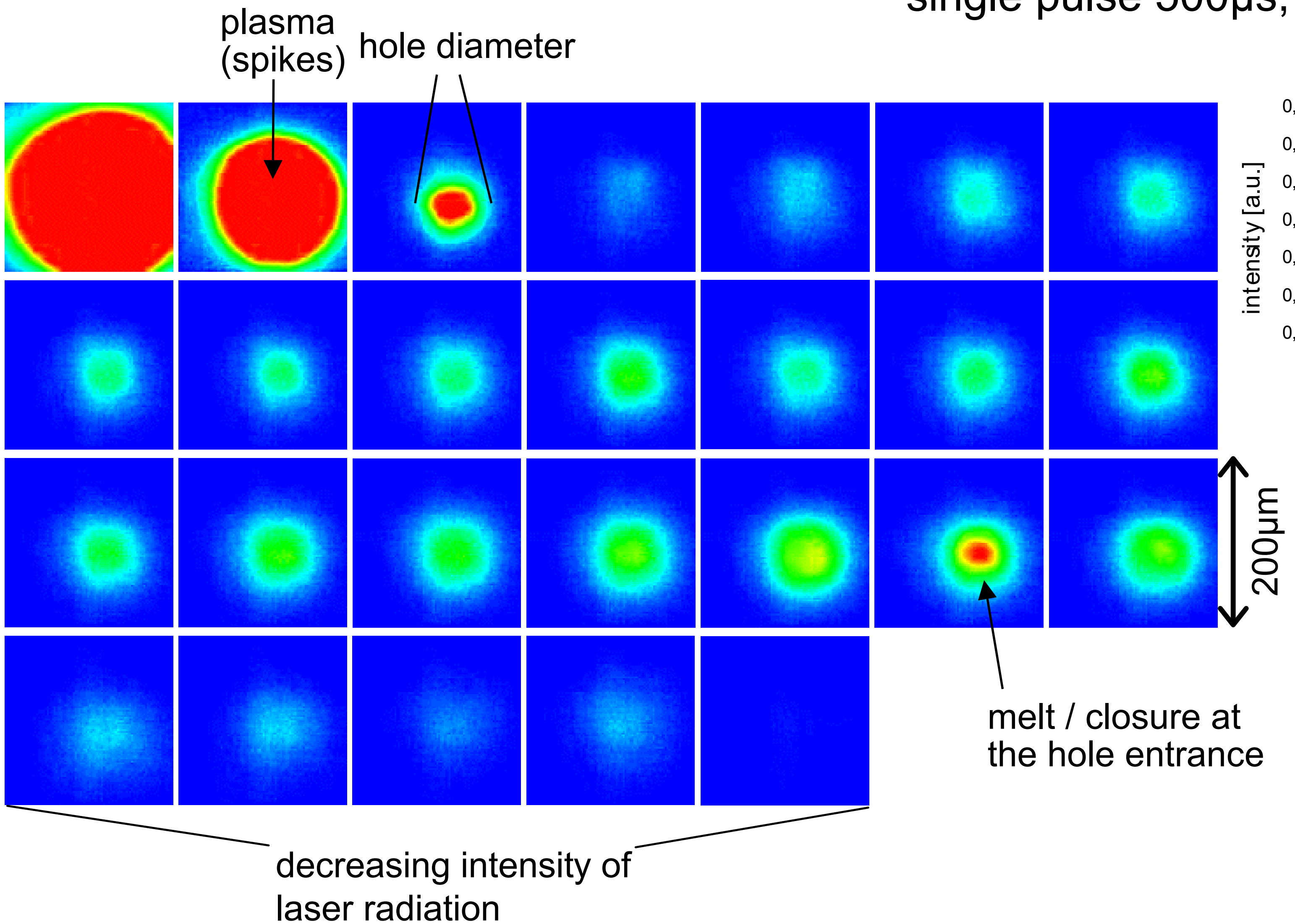


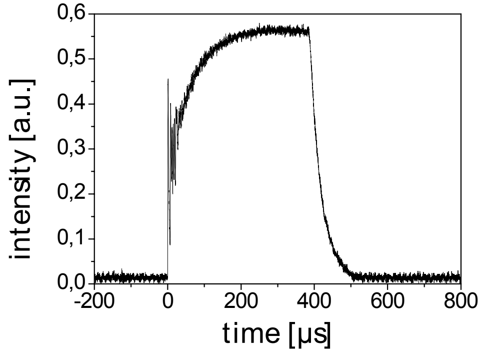

single pulse drilling
Nd:YAG-Slablaser
pulse energy: 180mJ
pulse duration: 200µs
material: X5CrNi18-10

**cross-section of single pulse drillings**

# Process analysis by high speed photography

single pulse 500µs, 500mJ, dt=20µs



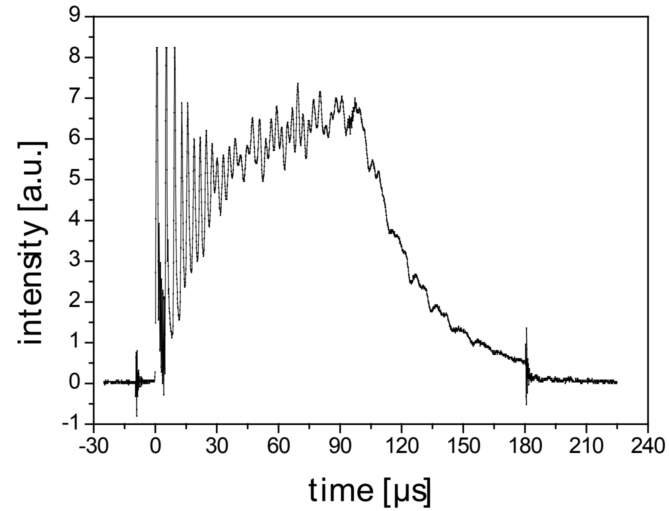



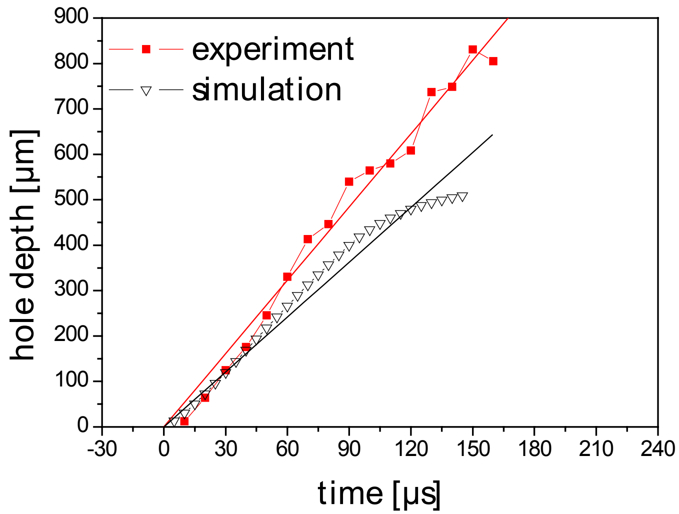

pulse shape

# Modeling and simulation

time scales of physical processes:
- beginning of melting and vapourisation
- time until meltflow becomes stationary

geometrical scales:
- hole depth
- depth where resolidification occurs
- hole diameter

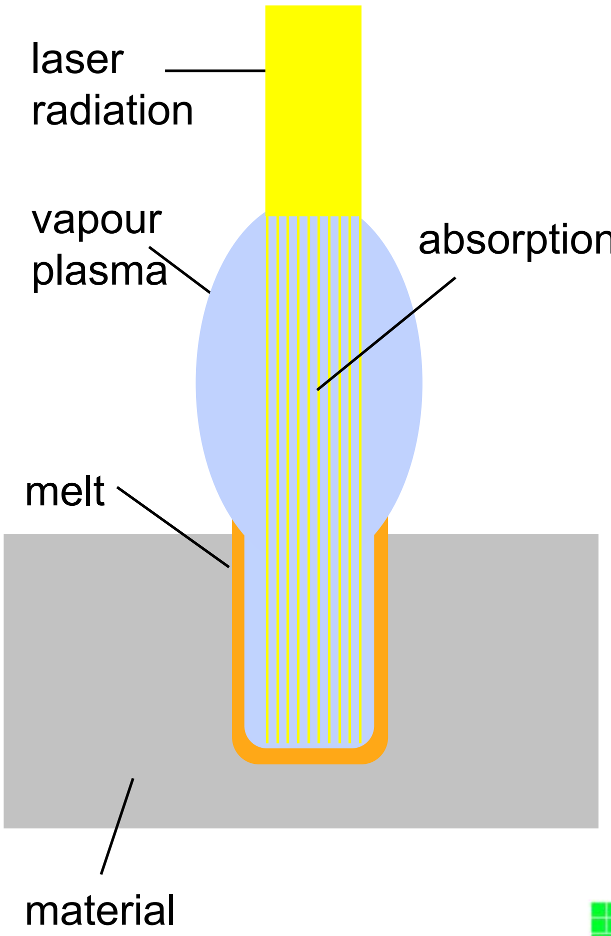


**Analysis of physical processes**

- absorption of laser radiation (vapour, plasma) at different wavelengths
- plasma formation and absorption of laser radiation at different pulse numbers and delays
- development of hole geometry depending on pulse numbers

$\Rightarrow$ find timescales and geometrical scales in comparison to drilling with µs-pulses



B: drilling experiments (metals (X5CrNi18 10, CMSX-4, Al, Cu), ceramics ($Si_3N_4$, AlN))

B1: single burst drilling

- variation of:
  - number of pulses (1,2,5,10,20,50,100)
  - different pulse delays
  - pulse energy
  - wavelength

B2: multi-burst drilling

- variation of:
  - number of burst (1,2,5,10,20,50,100)
  - number of pulses/burst (1,2,5,10)
  - different pulse and/or burst delays
  - pulse energy
  - wavelength

High-speed-photography of plasma dynamics

metallography, SEM and optical microscopy

# Pulsed Laser Deposition

Leonid Moiseev



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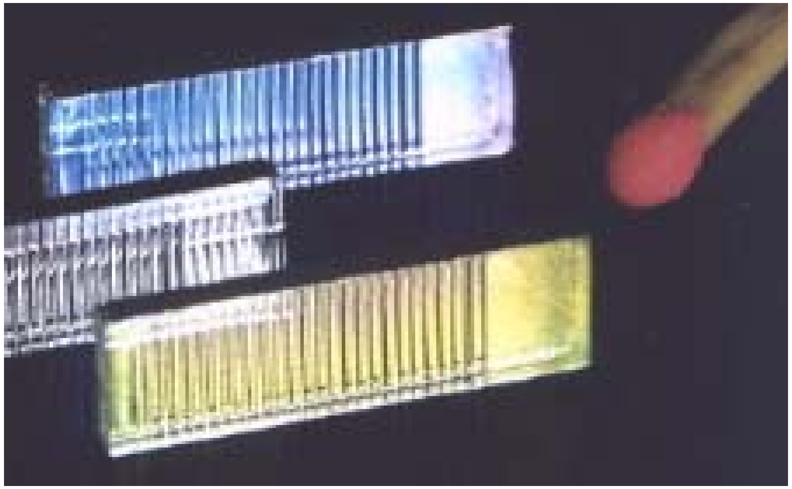
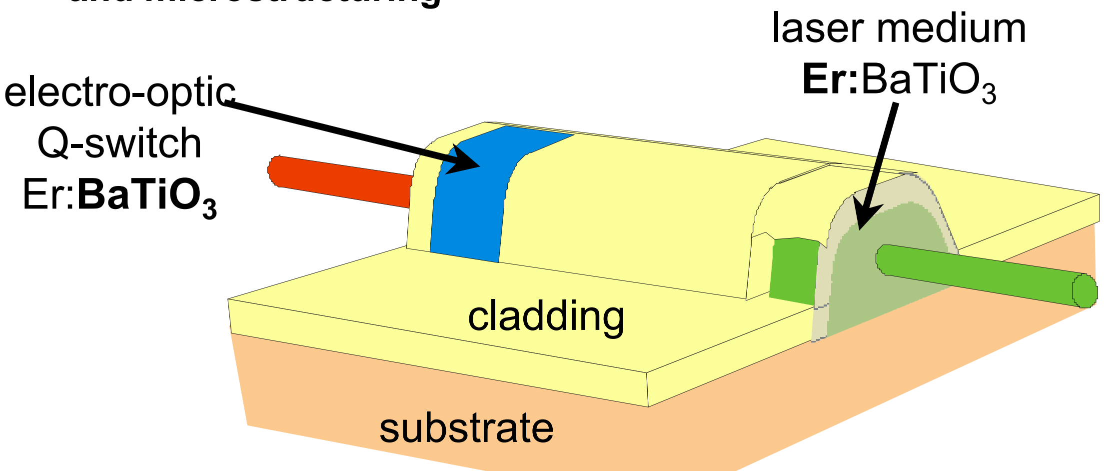
# Pulsed Laser Deposition

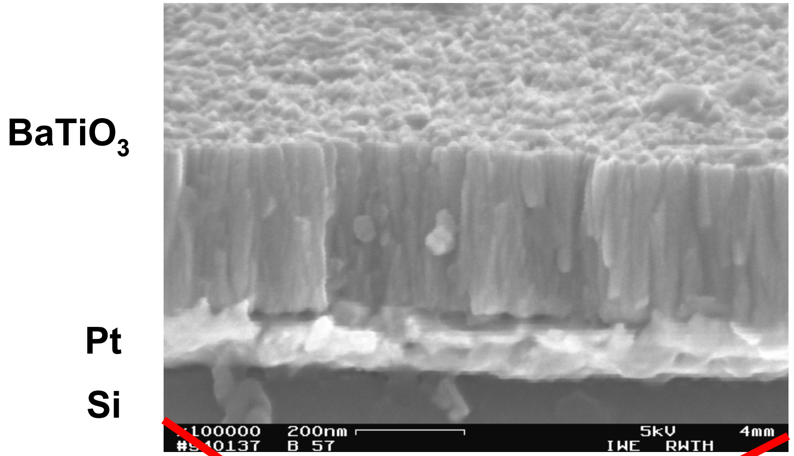
**Anti reflective coating ($ZrO_2$, $Al_2O_3$) on arrays of cylindrical lenses of PMMA**

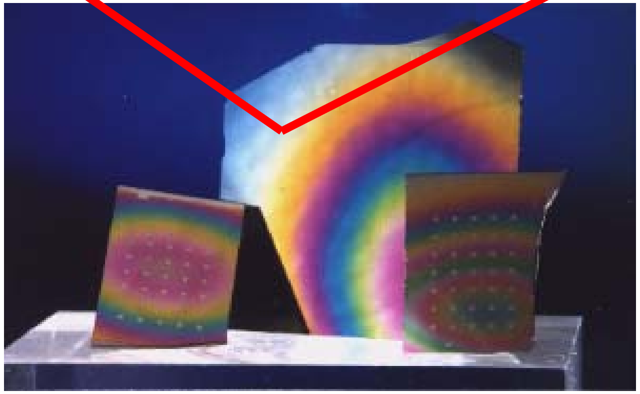


**Q-switch waveguide laser by PLD and microstructuring**




**Ferroelectric thin films ($BaTiO_3$, PZT)**



**$BaTiO_3$ thin films on Si/Pt**



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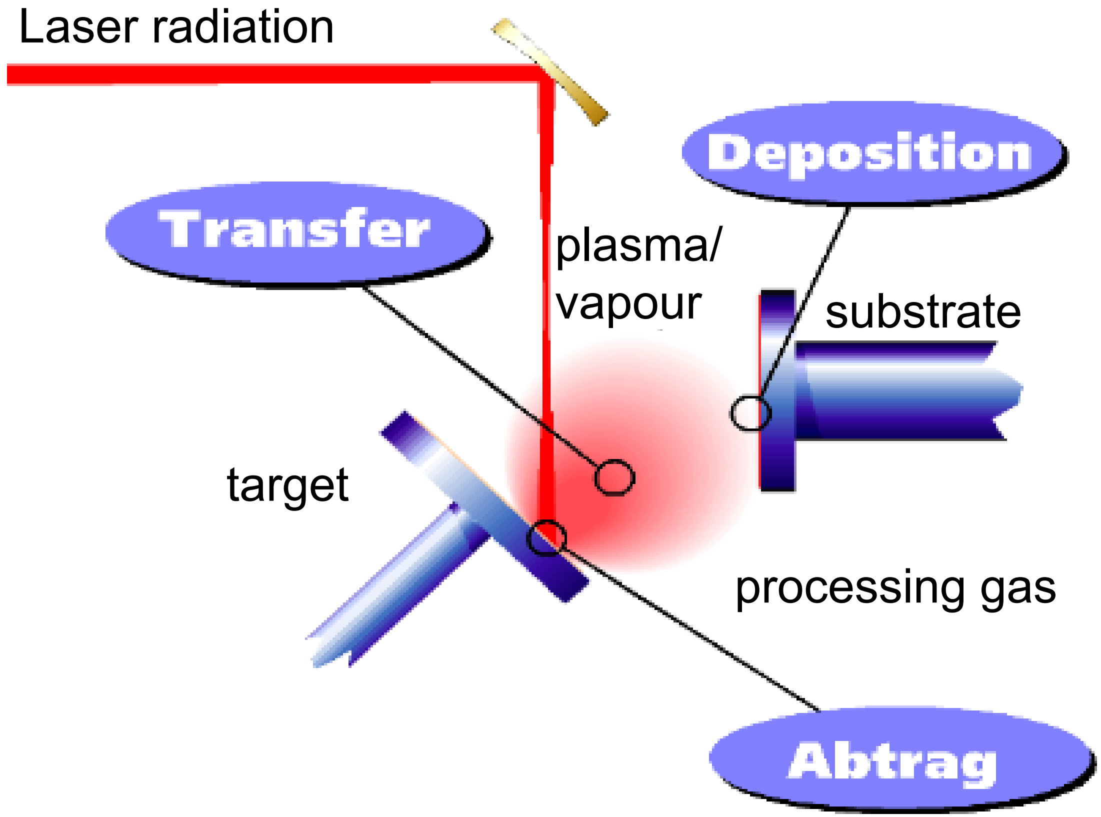
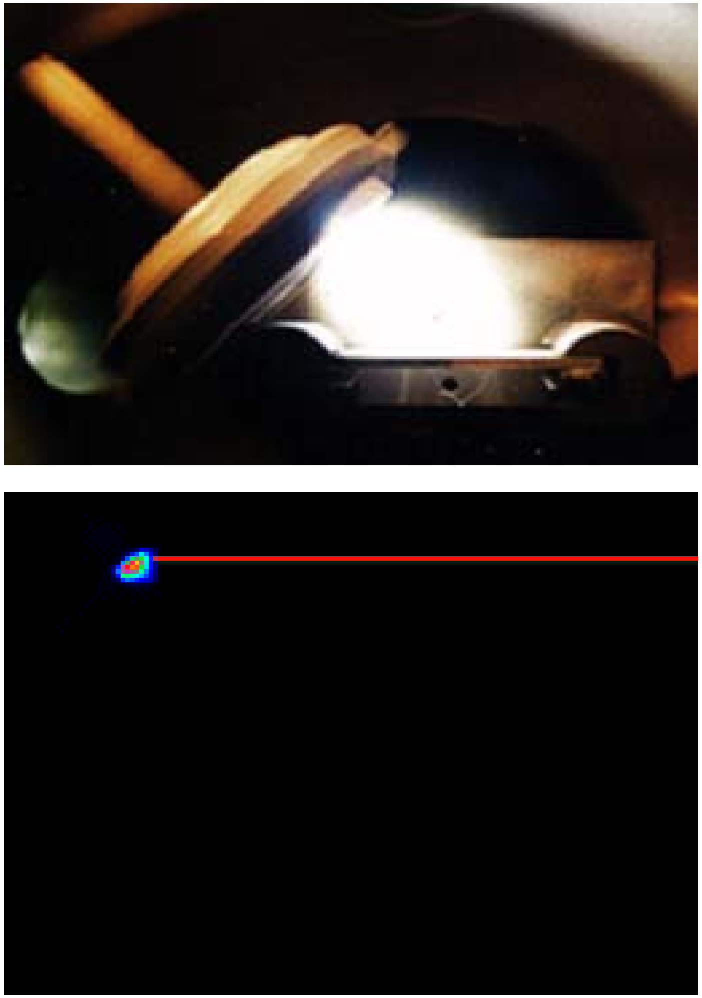
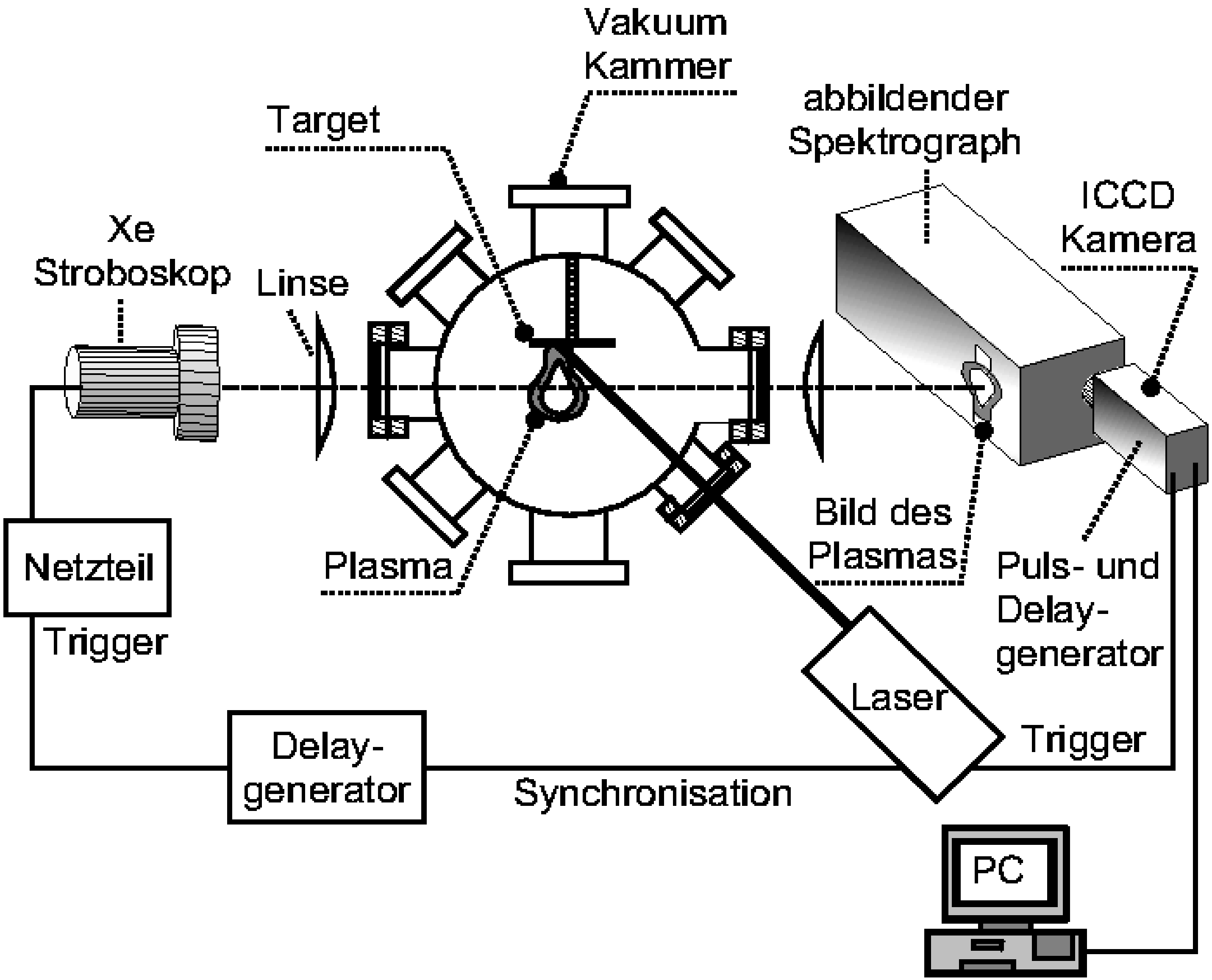


Plasma expansion during PLD

# Spectroscopy on laser-induced plasmas



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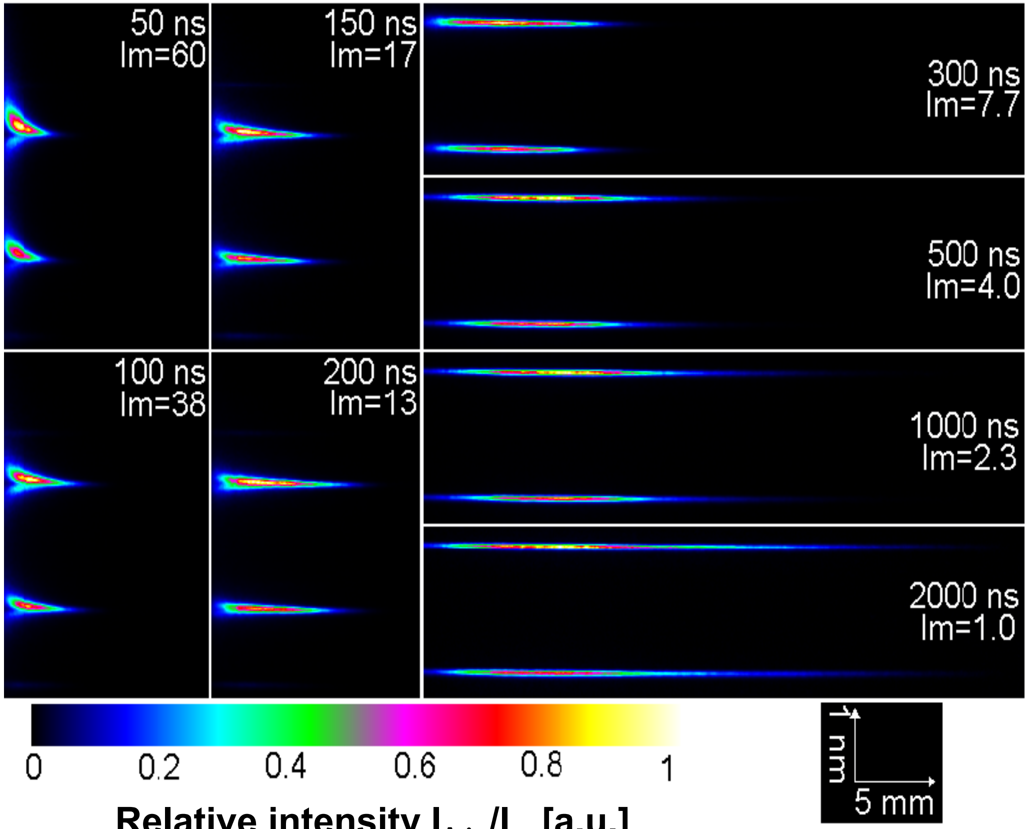
# Time-resolved plasma emission spectroscopy

**High speed photography with imaging spectrometer**
**Al lines at 395 nm during ablation of $Al_2O_3$ in $O_2$**

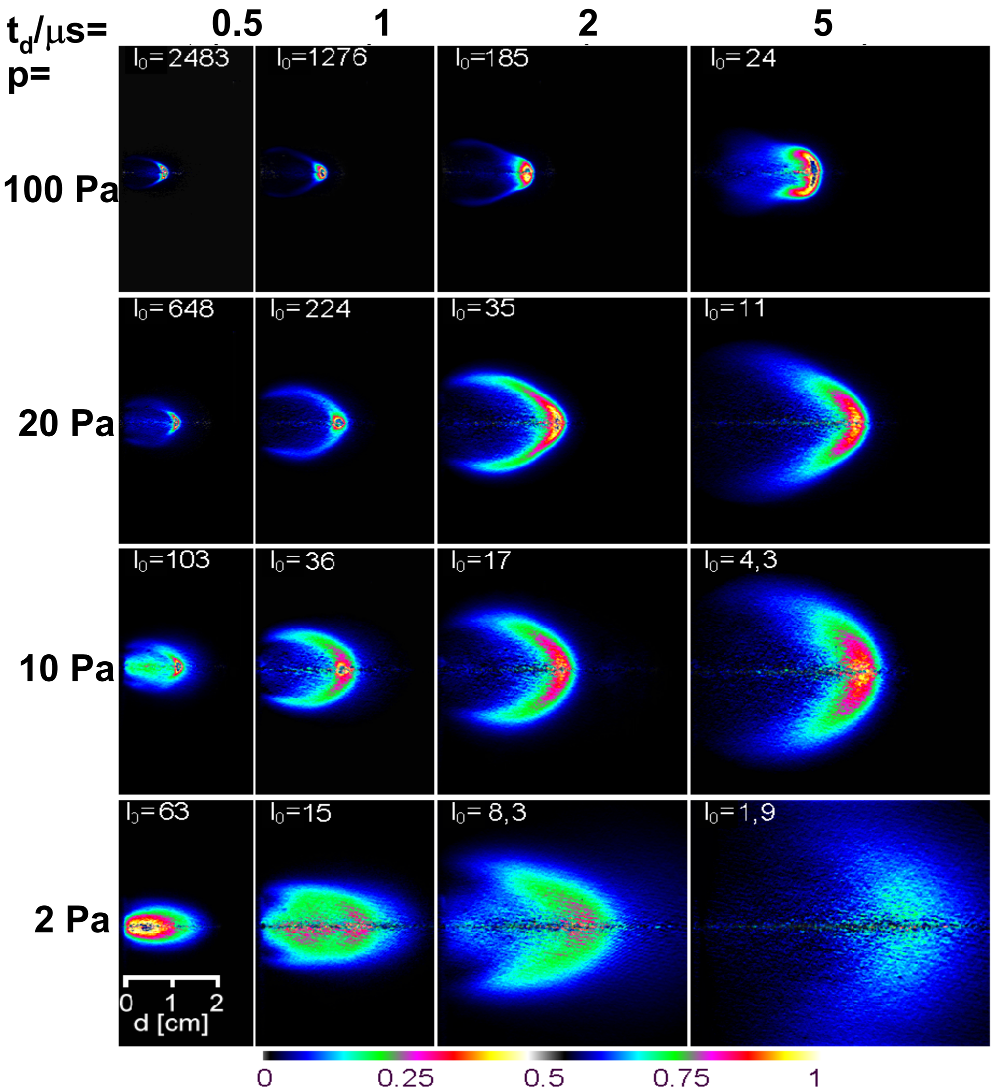



**Relative intensity $I_{A,\lambda}$ / $I_m$ [a.u.]**

$\Delta\lambda$: 1 nm

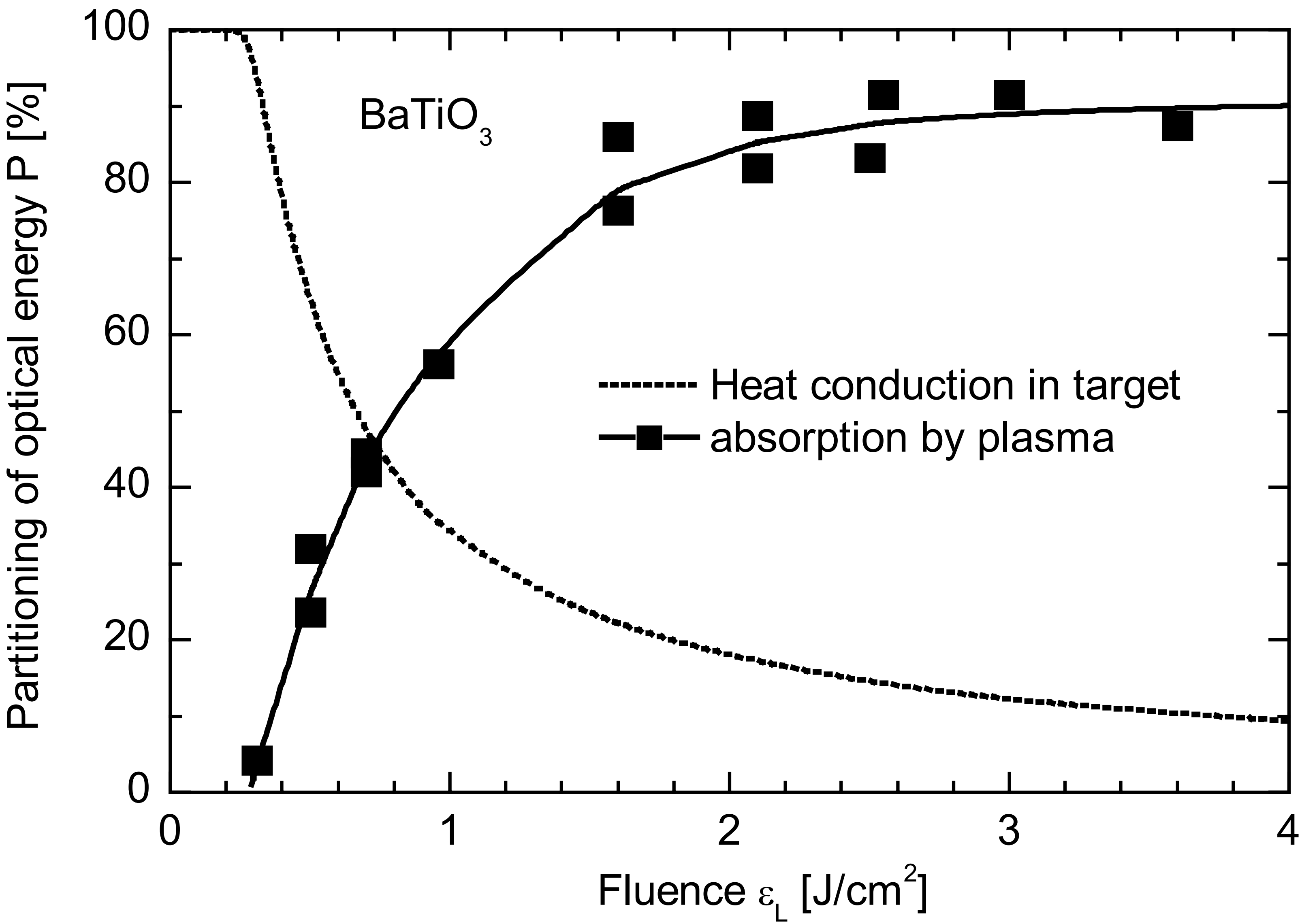
d=5 mm Distance

**High speed photography after Abel inversion**
**material: $Al_2O_3$, gas: $O_2$**



# Heat conduction in the target and absorption by the plasma





# Kinetic energy of the particles

## Model:

- **elastic collisions**

$$\langle E_{kin} \rangle_i = c_1 \frac{m_i}{1 + c_2 \frac{pr^3}{\varepsilon_L T}}, \text{ [1]}$$

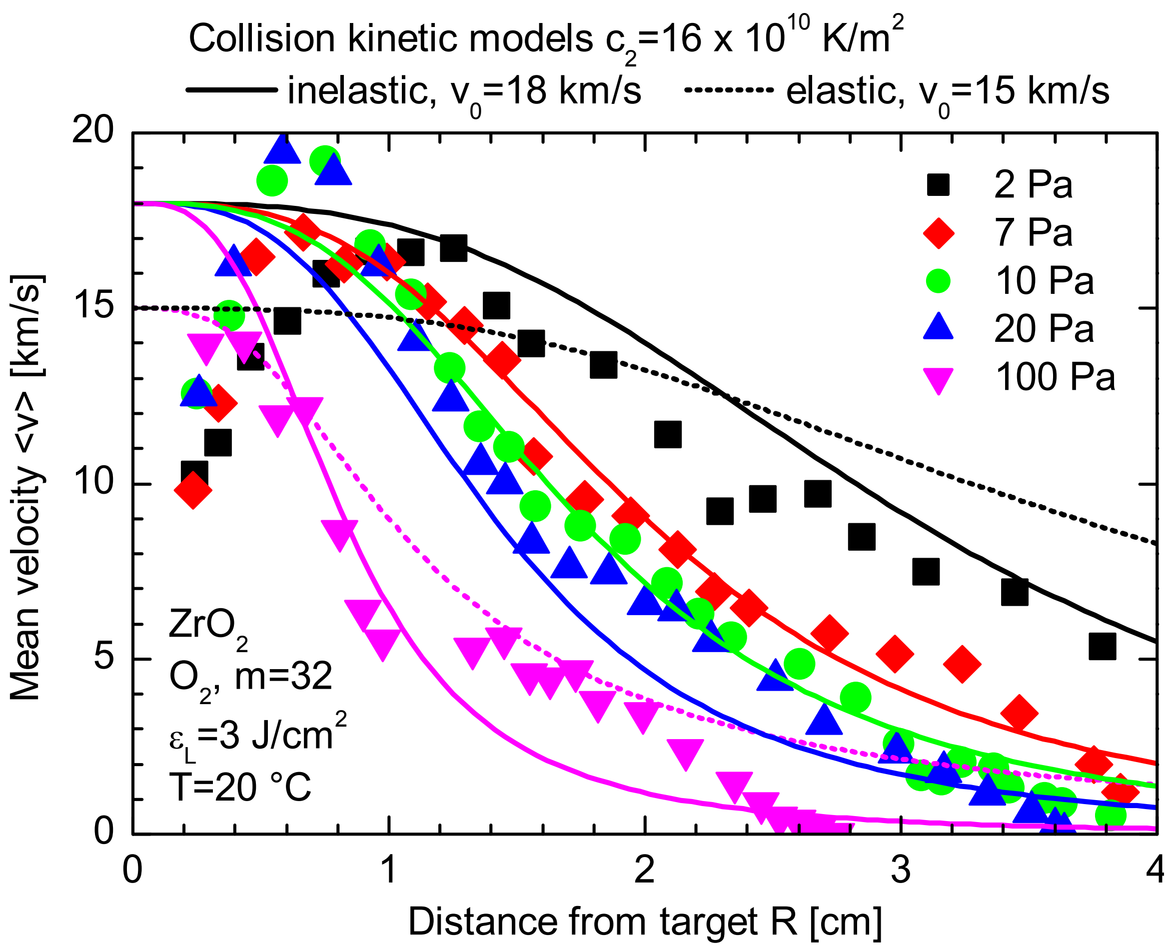
- **inelastic collisions (macroscopic)**

$$\langle E_{kin} \rangle_i = c_1 \frac{m_i}{\left(1 + c_2 \frac{pr^3}{\varepsilon_L T}\right)^2}$$

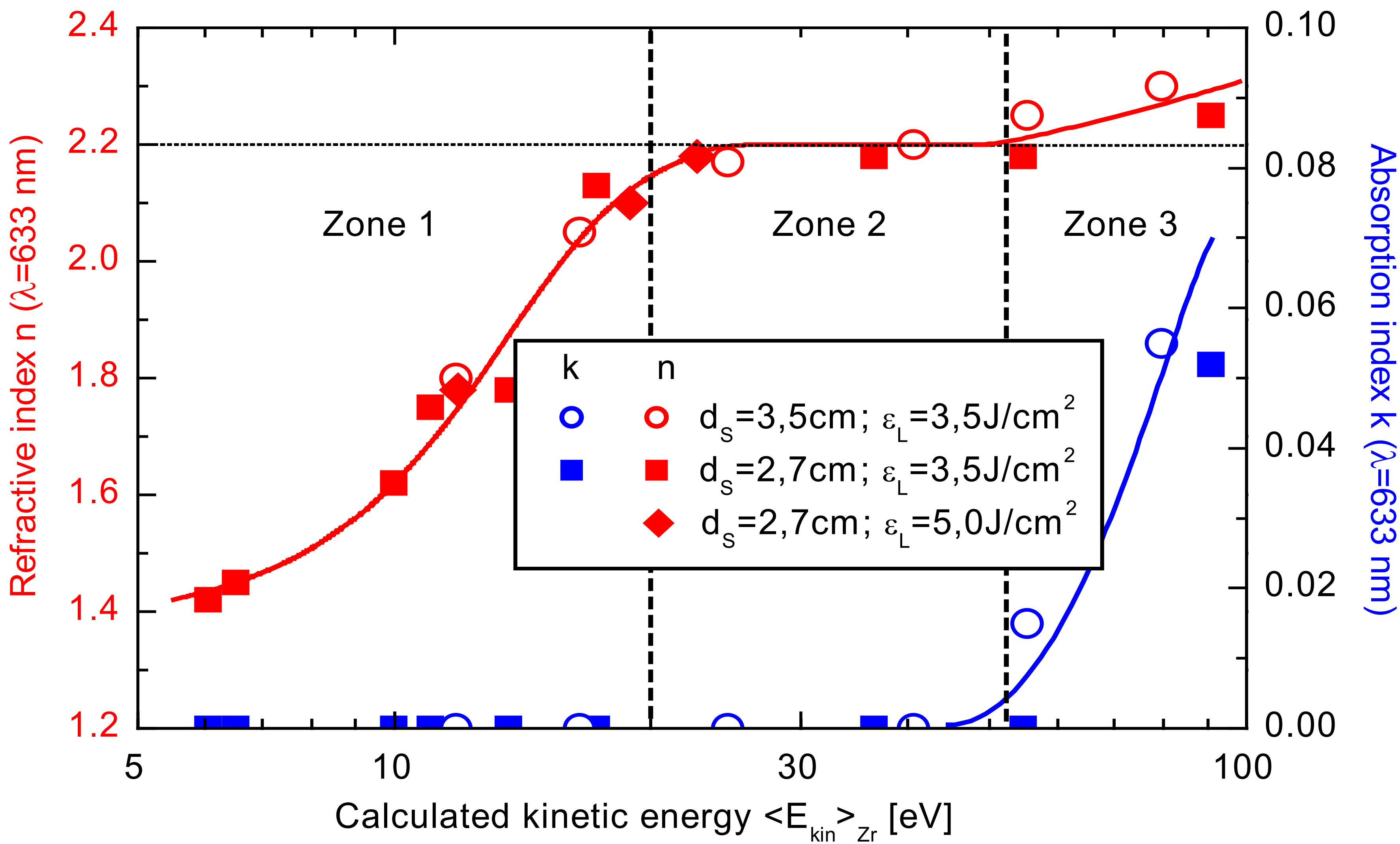
| material | elastic | inelastic | $c_2 / M_{Pg}$ |
|---|---|---|---|
| | $c_1$ [eV/u] | $c_1$ [eV/u] | |
| $Al_2O_3$ | $2{,}3 \pm 0{,}4$ | $4{,}1 \pm 0{,}8$ | $6{,}0 \pm 0{,}5$ |
| $ZrO_2$ | $1{,}2 \pm 0{,}2$ | $1{,}7 \pm 0{,}3$ | $5{,}0 \pm 0{,}5$ |
| $BaTiO_3$ | $0{,}9 \pm 0{,}2$ | $1{,}5 \pm 0{,}3$ | $2{,}5 \pm 0{,}3$ |

[1] Gottmann et. al.: (E-MRS 1997)
Surf. Coat. Technol. 100-101, (1998) p. 415

## Comparison with plume dynamics by iCCD:



# Ellipsometry: Refractive index of $ZrO_2$ films




$T_S$=20 °C
$\varepsilon_L$=3.5 J/cm²

**The bulk values n=2.2 and k=0 are achieved at <$E_{kin}$>=20 - 50 eV**

# Deposition Experiments at FEL

C: deposition experiments of oxides and fluorides

C1: ablation for plasma diagnostics

- optical emission and absorption spectroscopy
- variation of: - different pulse delays
  - pulse energy
  - wavelength

C2: pulsed laser deposition with pulse bursts

- measurement of deposition rate, optical and structural film properties and correlation with plasma parameters
- variation of: - number of pulses per burst
  - burst energy
  - wavelength

# Aim of all planned Experiments & Conclusion



## Analysis of physical processes ablation

- **process efficiency:** absorption of laser radiation in vapour/ plasma at different wavelengths and pulse energies,
- **kinetic energy of particles:** plasma expansion and absorption of laser radiation using different pulse numbers, delays and energy
- **correlation** of the physical processes with the resulting deposition/ablation rate and film properties
- **modelling** of the processes using the FEL-parameters

Find out **parameters** for

- the deposition of high quality films at high deposition rates (>1 $\mu m/s/cm^2$)
- the ablation/drilling with tailored pulse trains to precondition the surrounding getting melt-free structures

# Aachen and ILT



Rathaus

Carl der Grosse

Dom

ILT&LLT

Marktplatz

# Adaptation of processing parameters

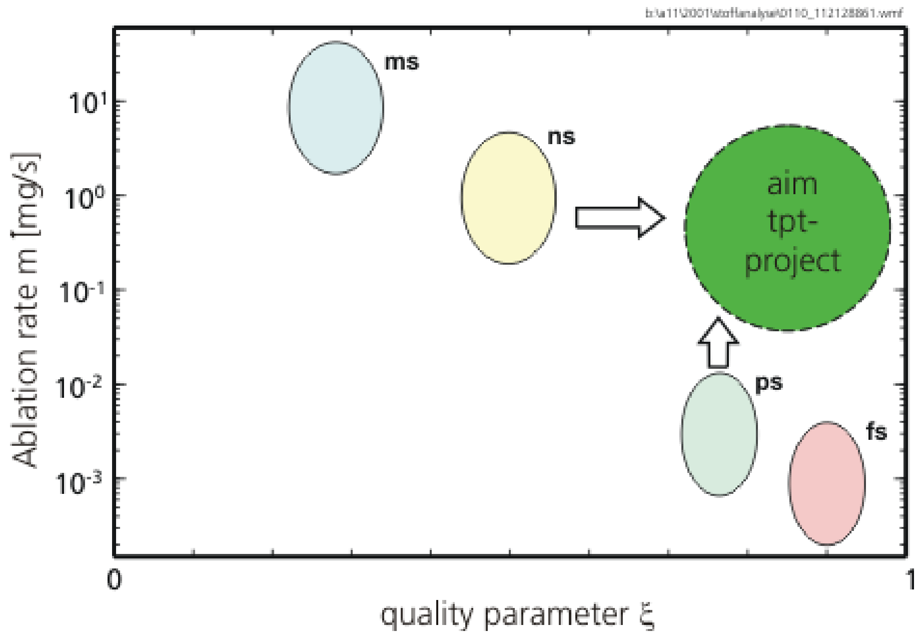
**ms-pulses:**

- high ablation rate
- lower quality

↔

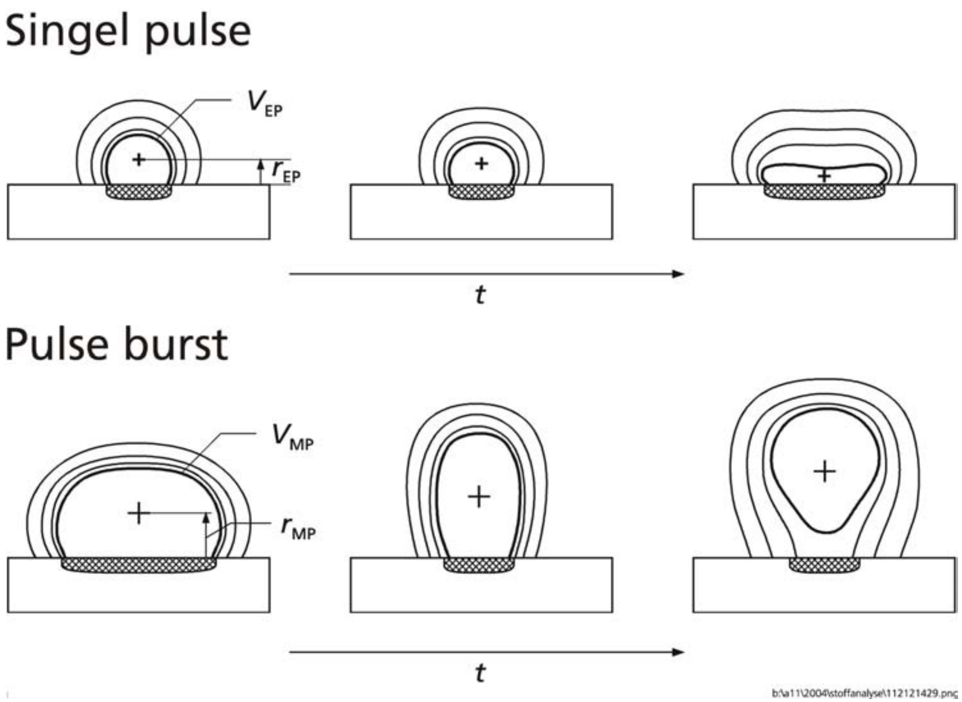
**fs-pulses:**

- lower ablation rate
- high quality




**tpt-project:**

- high ablation rate
- high quality




**Model for ablation process:**

- Following pulses again interact with the surface
- $V_{PB}$ >> $V_{SP}$, $m_{PB}$ >> $m_{SP}$
- $dr_{SP}/dt < 0$, $dr_{PB}/dt > 0$
- single pulse: spheric $\rightarrow$ discoid
- pulse burst: discoid $\rightarrow$ spheric

consequence of the precondition due to the previous pulses

Fraunhofer Institut Lasertechnik



RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

LEHRSTUHL FÜR LASERTECHNIK