Basics of ultrashort pulse laser micro-drilling

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Further questions?

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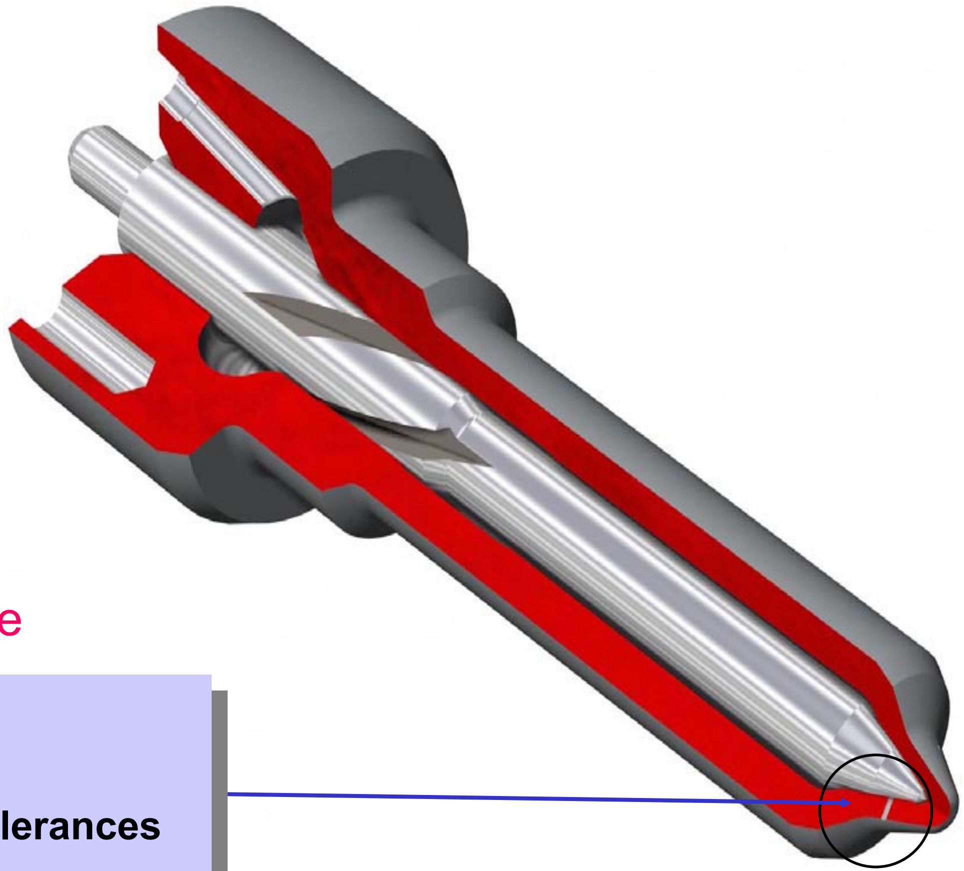
Outline

- Applications of micro holes
- Interaction of light and metals
- Interaction of light and ambient atmosphere
- Diagnostics of the process
- Percussion and helical drilling
- Optical concepts for helical drilling

High precision drilling

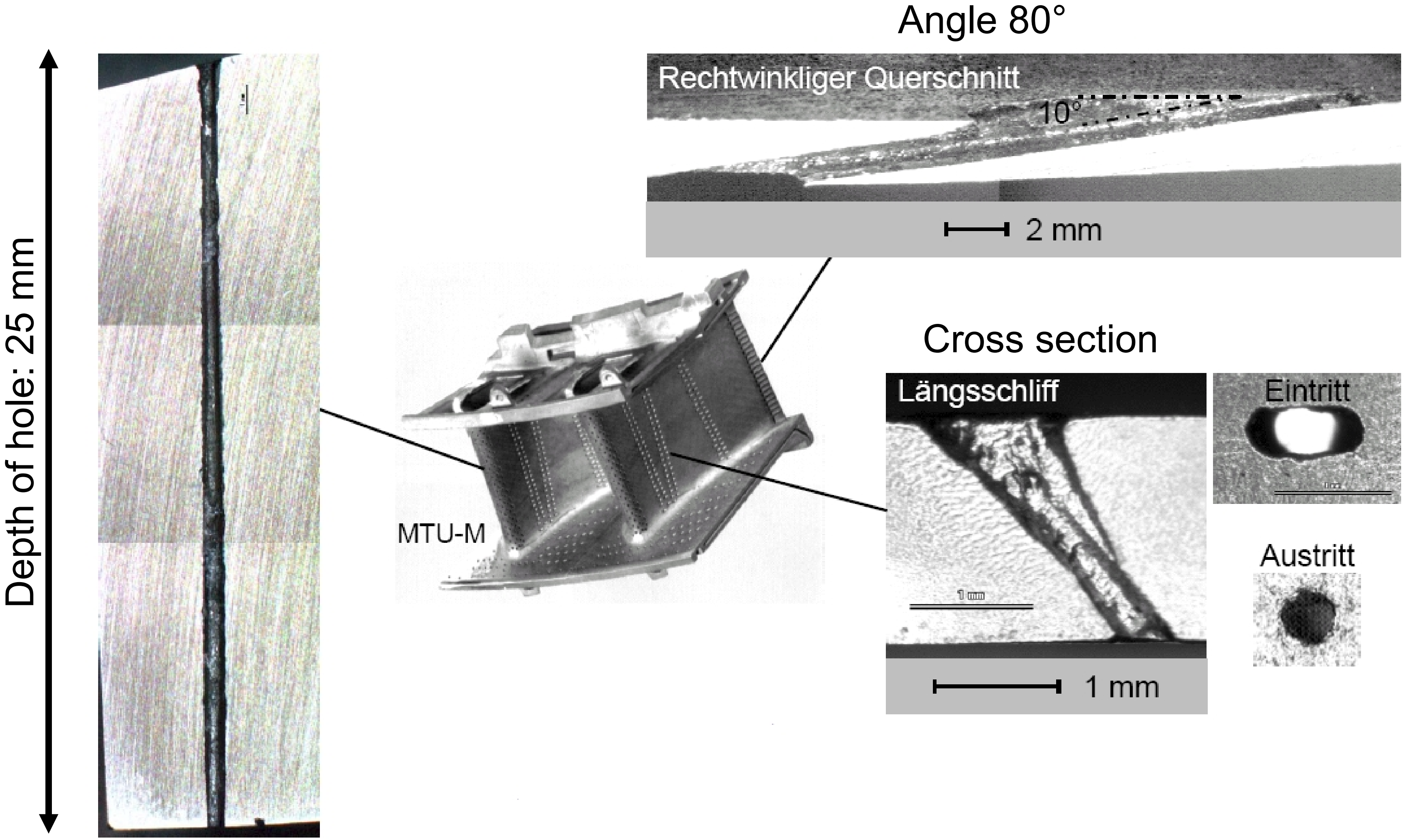
Example: Drilling of injection nozzles



Small hole

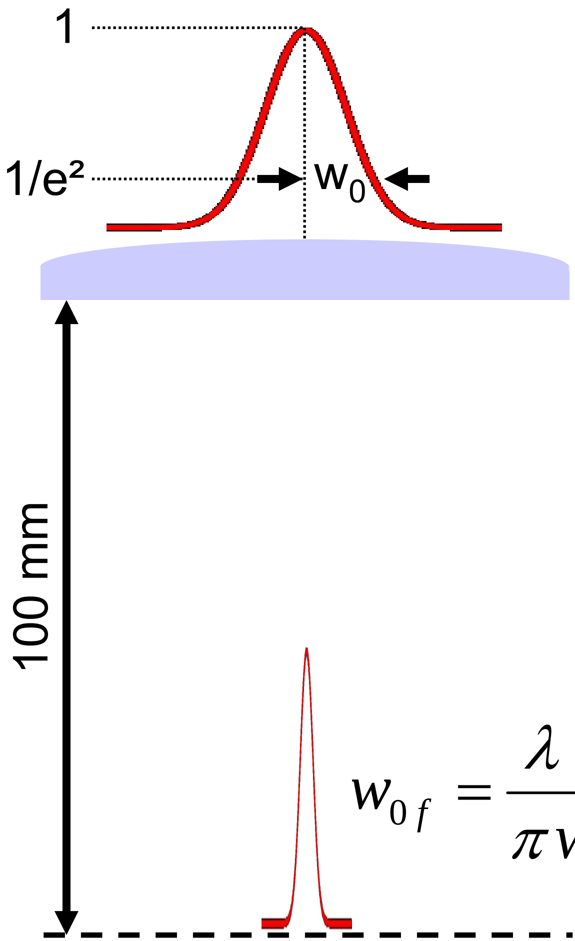
- 40 – 150 µm
- Sharp edges
- Minimal flow tolerances

Drilling of turbine blades



(Source: Daimler, Stuttgarter Lasertage 99)

Focussing of light (paraxial approximation)



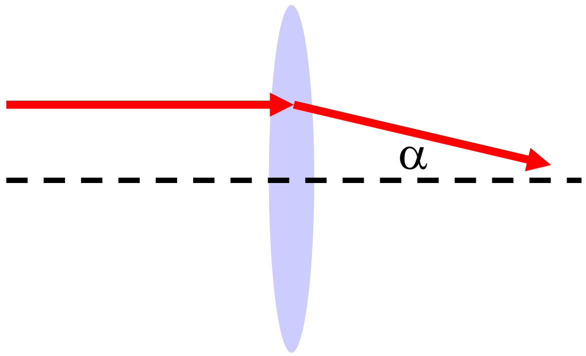
Incoming Intensity

lens
f = 100 mm

Focal plane

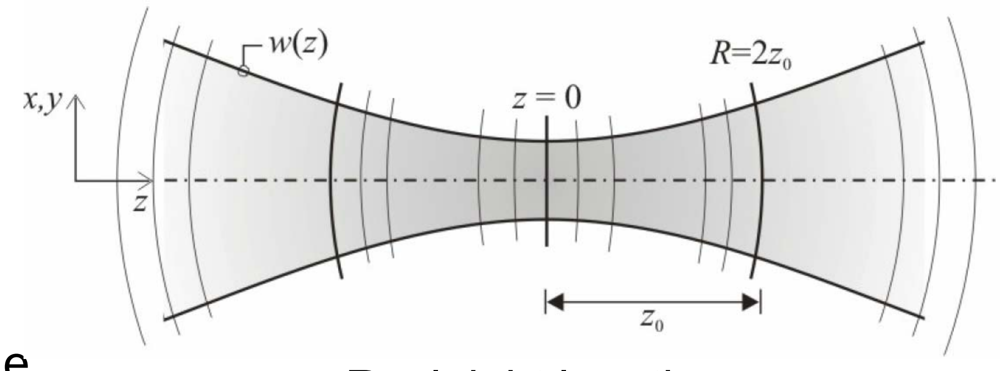
$$w_{0f} = \frac{\lambda f}{\pi w_0} M^2$$

M² ≥ 1: Diffraction number
λ : wavelength



Paraxial approximation:
sin α ≈ tan α ≈ α

Propagation in the focal region



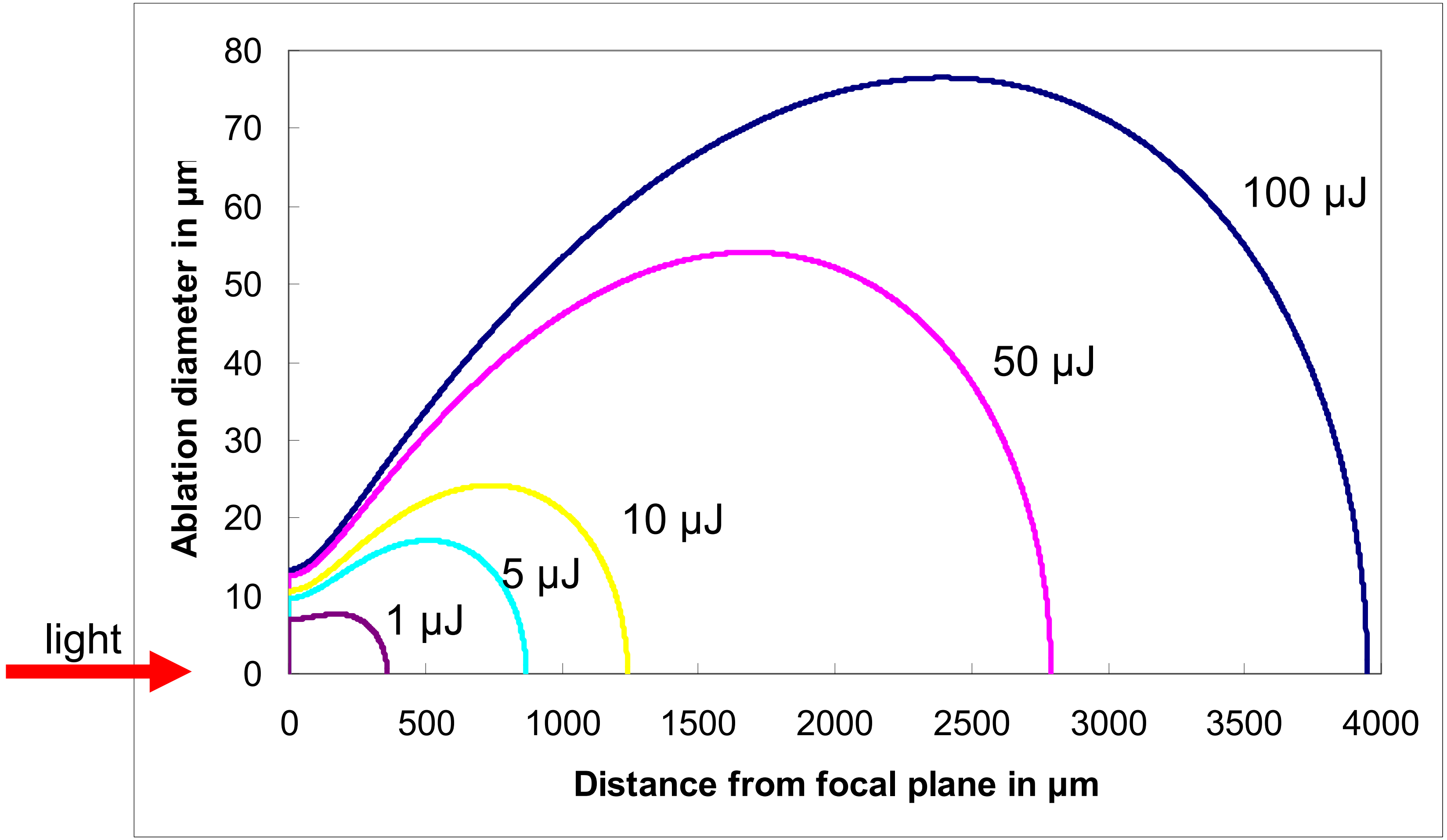
Rayleight length z_0:

$$w(z_0) = w_0\sqrt{2}$$

(Coming soon: New book from Thomas Graf!)

(SSOM Engelberg Lectures 19.3.09)

Theoretical ablation diameter



d_f = 15 µm λ = 1064 nm F_{thr} = 0.2 J/cm²

Why is the drilling channel narrow and deep and the „isophotes“ not?

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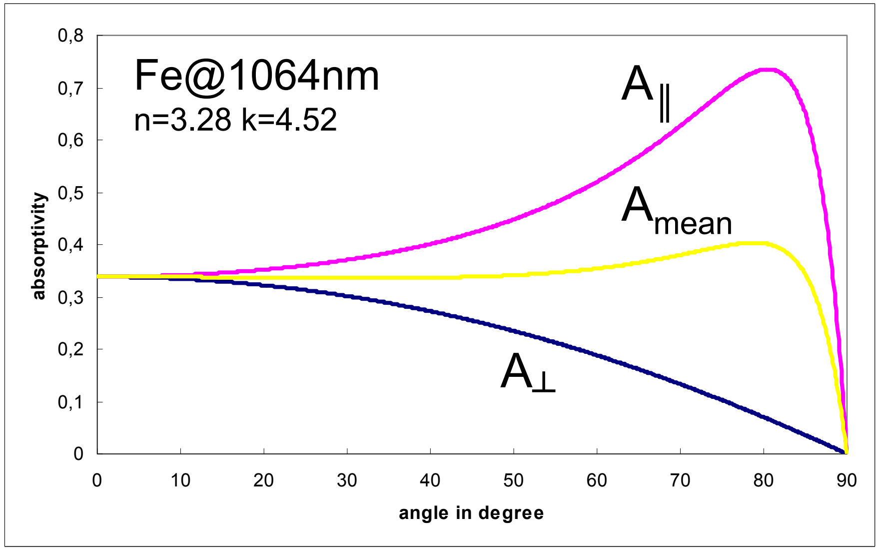
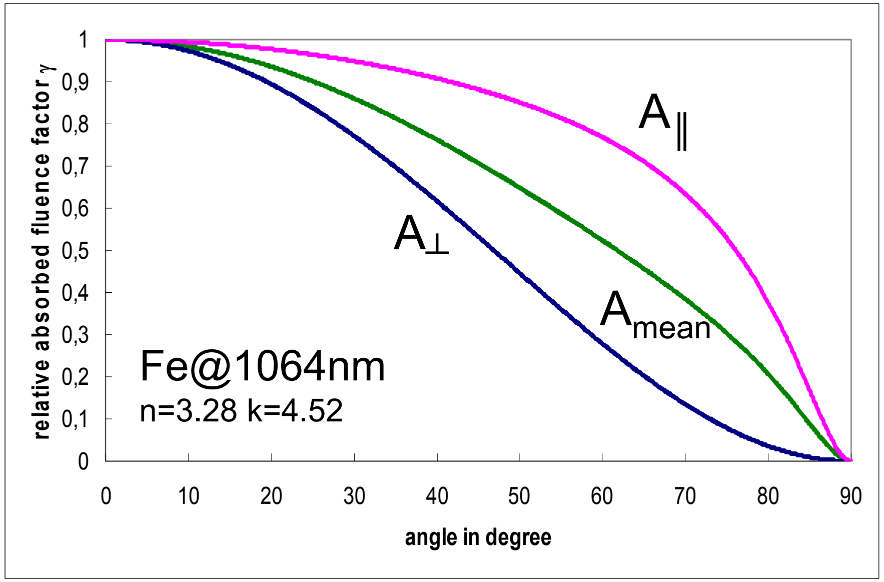
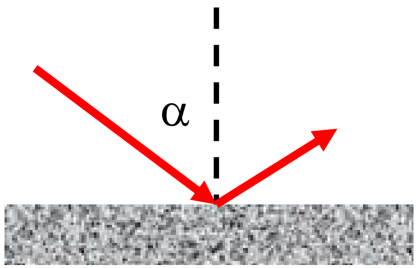
(SSOM Engelberg Lectures 19.3.09)

Absorption at metal surface





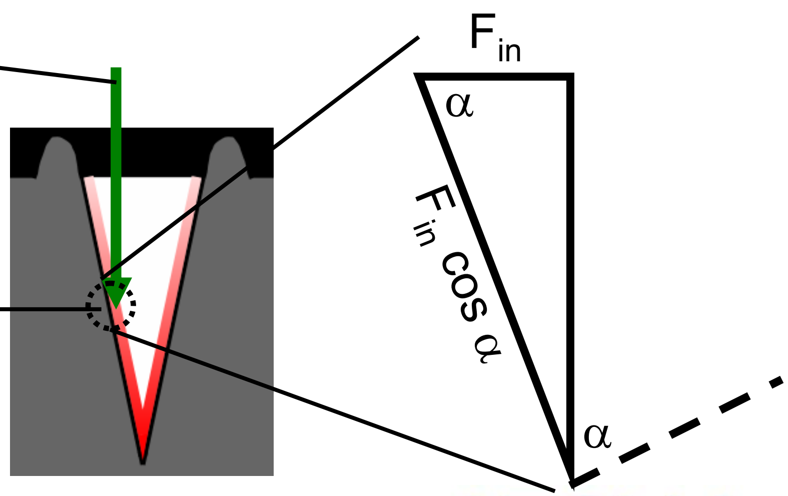
Fresnel absorptivity



Incoming fluence F_{in}

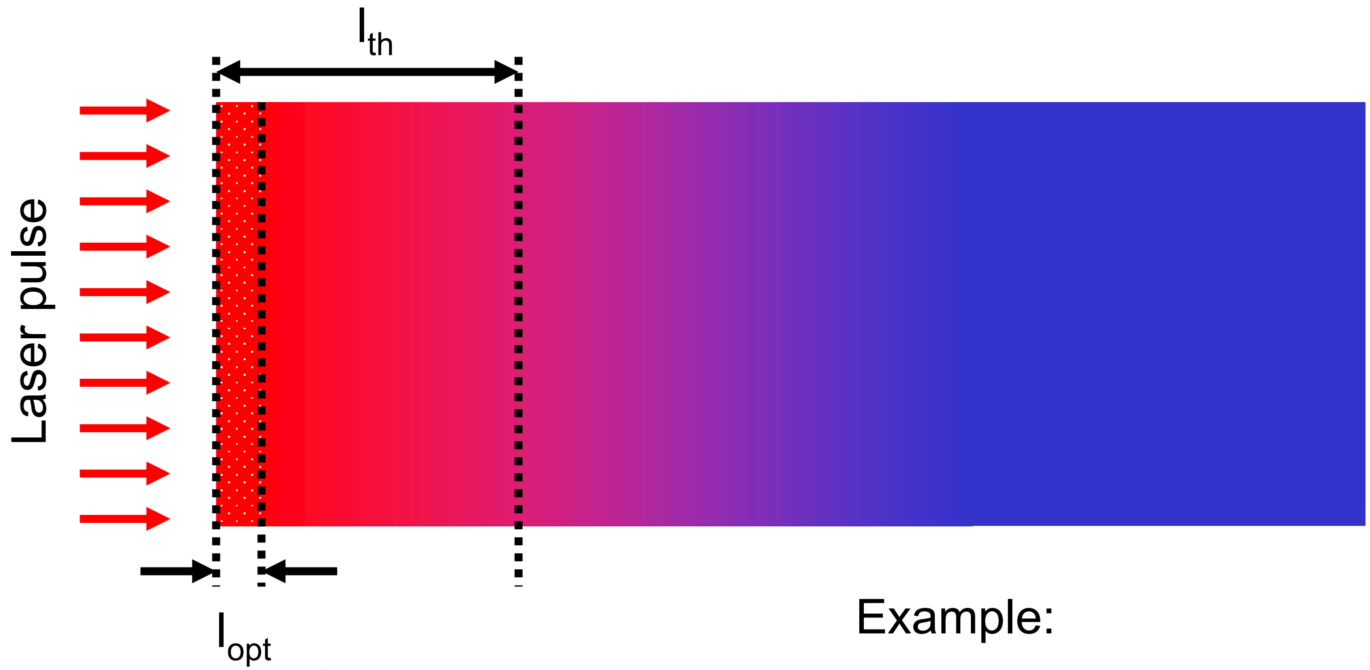
Absorbed fluence

$F_{abs} = F_{in} * A(0°) * \gamma(\alpha)$



(SSOM Engelberg Lectures 19.3.09)

Optical and thermal penetration depth



$$l_{opt} = \frac{\lambda}{4\pi k(\lambda)}$$

$$l_{th} = 2\sqrt{\kappa\tau}$$

Example:

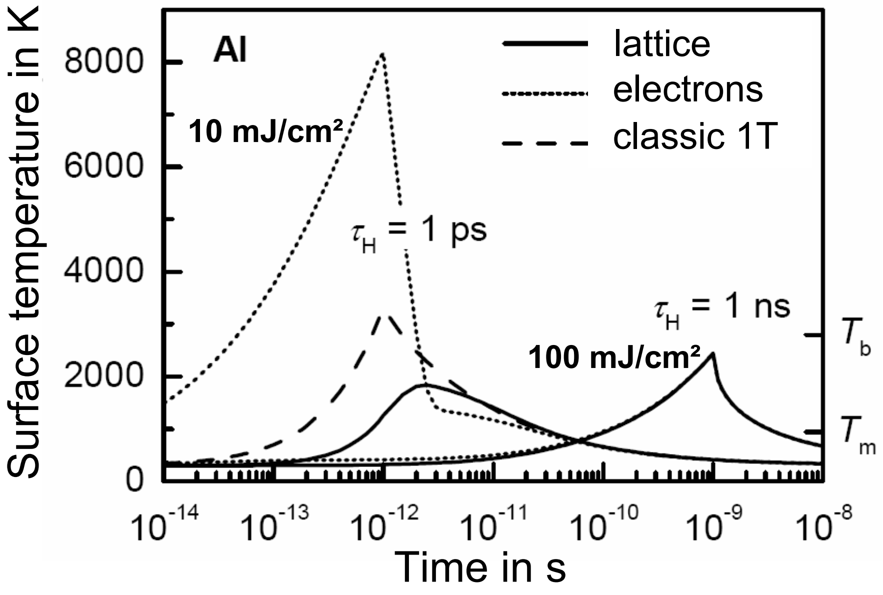
l_{opt}(Fe@1064nm) = 19 nm

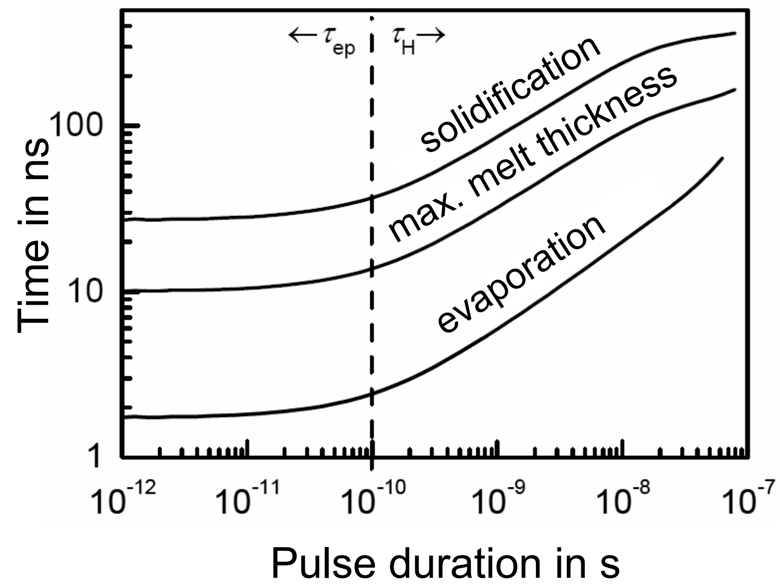
l_{th}(Fe@10ns) = 0.95 µm

For metals: thermal penetration depth >> optical penetration depth.

(SSOM Engelberg Lectures 19.3.09)

2-temperature model

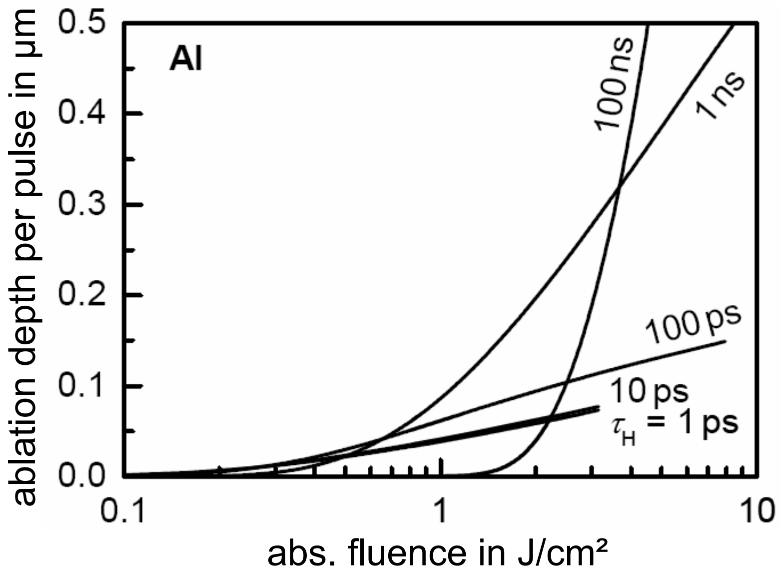


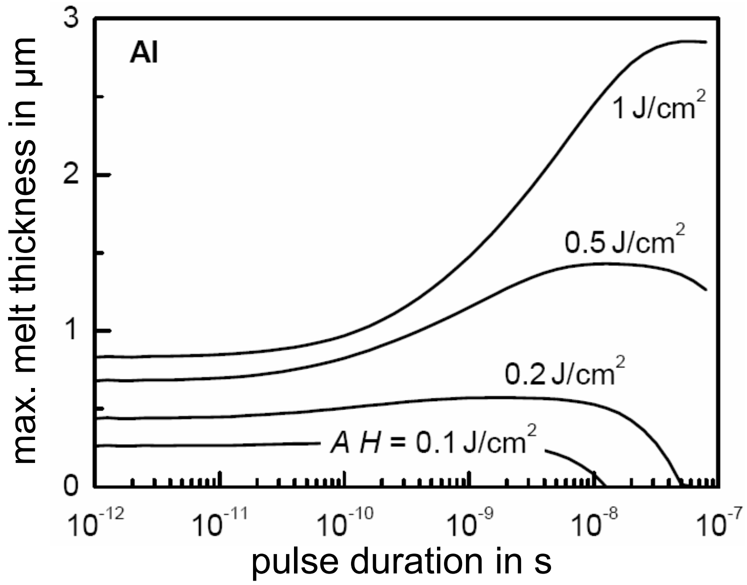


- For pulse duration much longer than electron-phonon relaxation time τ_{ep}
  ➔ thermal equilibrium of electrons and lattice
- For pulse duration in the order of electron-phonon relaxation time τ_{ep}
  ➔ heating of electrons, thermalization
- Aluminium τ_{ep} = 4.27 ps, Iron τ_{ep} = 3.5 ps, Copper τ_{ep} = 57.5 ps
- Evaporation time, max. melt thickness and solidification time converges to minimum value > 0

(Source: Andreas Ruf, PhD thesis, IFSW)

Theoretical results

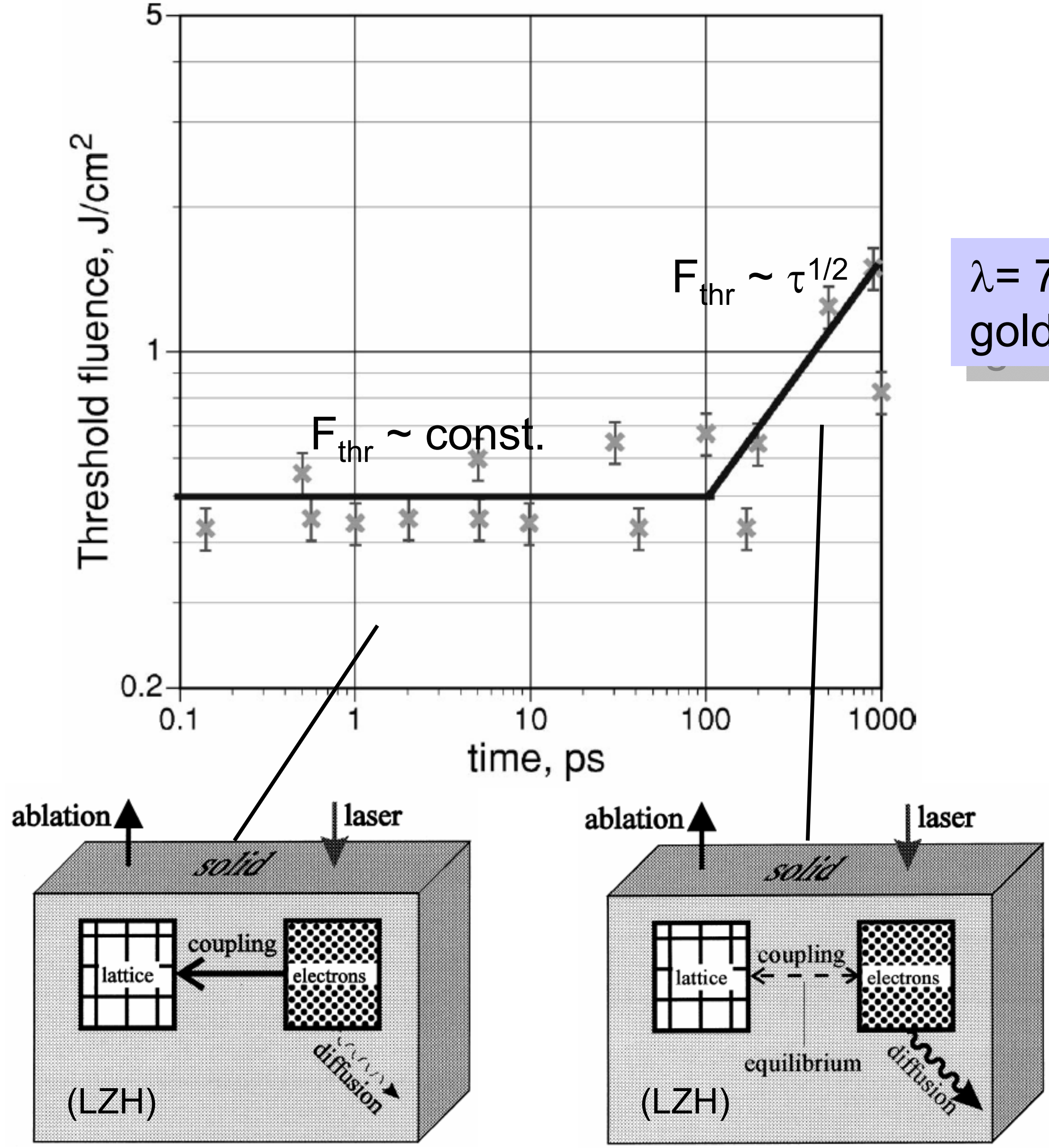




- For higher fluences (compared to ablation threshold)
  The ablation depth per pulse increases strongly with pulse duration
- For fluences near the threshold
  The ablation can be more efficient for shorter pulse durations
- The melt thickness does not tend to zero if pulse duration tends to zero
  ➔ Electron-phonon relaxation τ_{ep} defines lower limit
  ➔ A further decrease of pulse duration far below τ_{ep} not advantageous

(Source: Andreas Ruf, PhD thesis, IFSW)

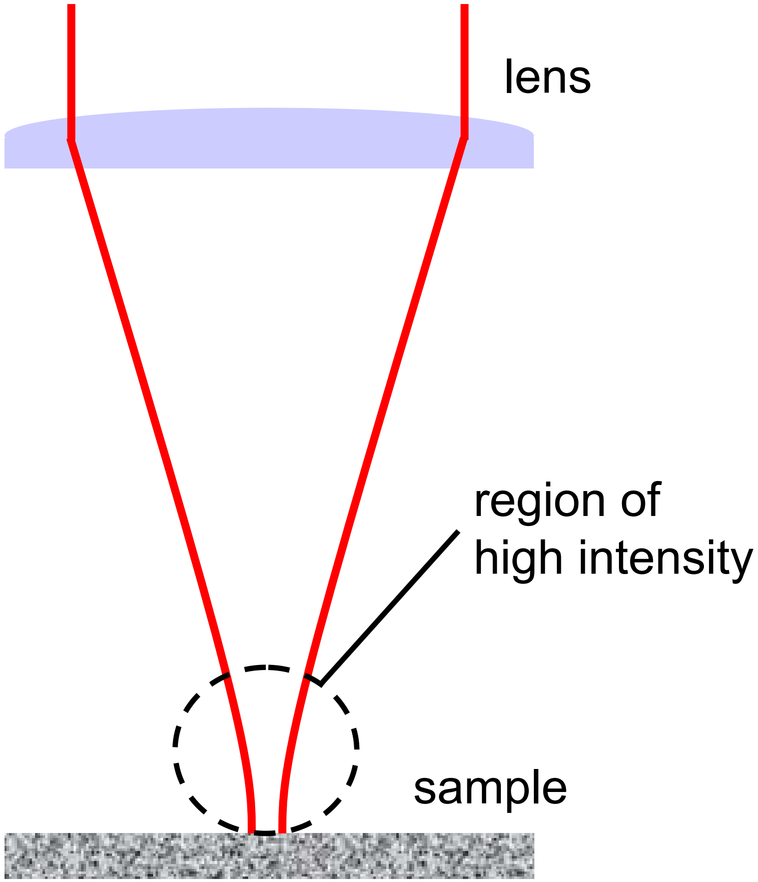
Ablation threshold



λ= 780 nm
gold

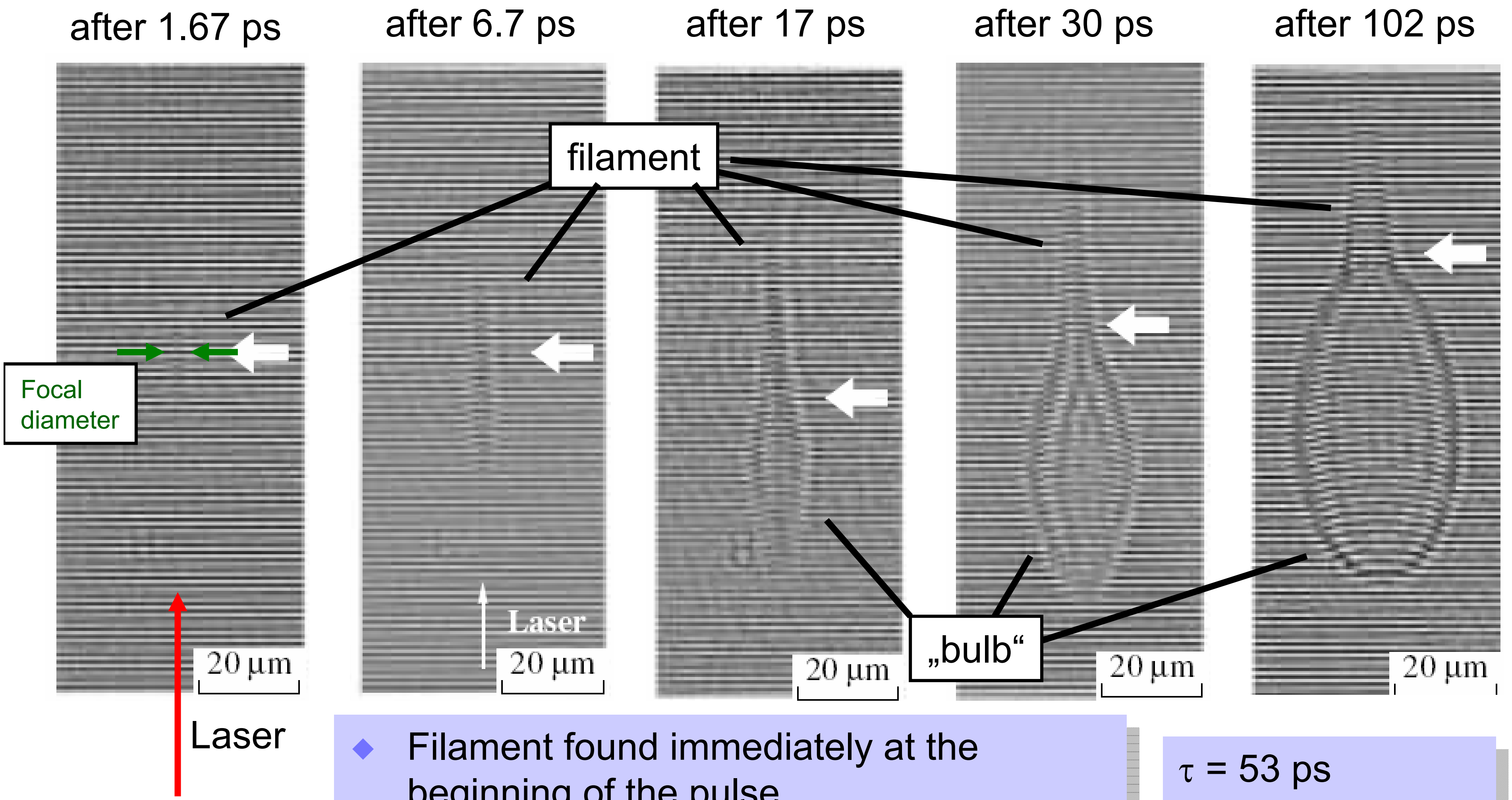
(Source: Gamaly et. al, Physics of Plasmas Vol. 9, No. 3, 2002, pp. 949) (SSOM Engelberg Lectures 19.3.09)

Interaction with ambient atmosphere



- Ultrashort pulses + focussing
  ➔ high intensities
- Example (rectangular pulse):
  E_p = 100 µJ τ = 1 ps d_f = 20 µm
  ➔ intensity = $10^{14}/\pi$ W/cm²
- Question: What can happen to the ambient gas atmosphere?

Air breakdown: Time resolved interferometric observation



- Filament found immediately at the beginning of the pulse
- „pumping“ of the plasma
  ➔ the plasma absorbs energy!

τ = 53 ps
λ = 1078 nm
I = 22*10^{14} W/cm²

(Source: Garnov et. al, Laser Physics Vol. 13, No. 3, 2003, pp.386)

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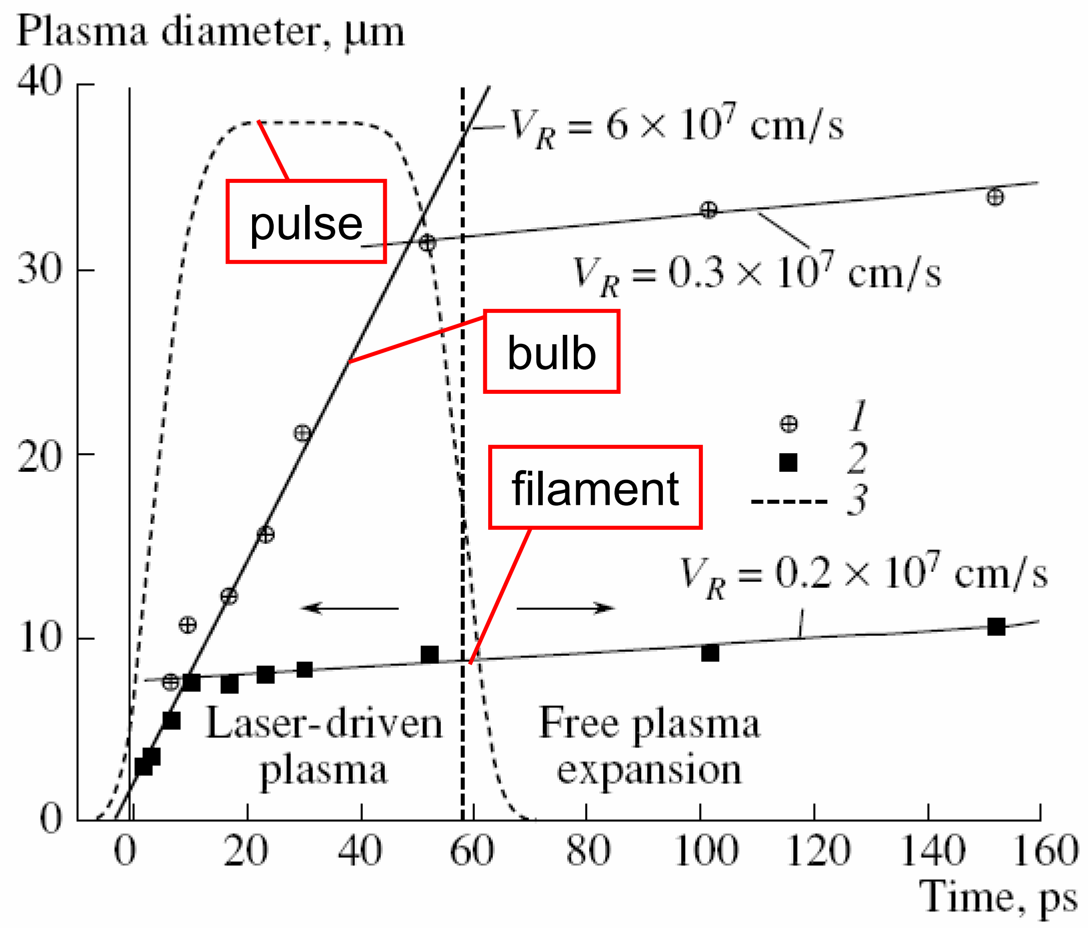
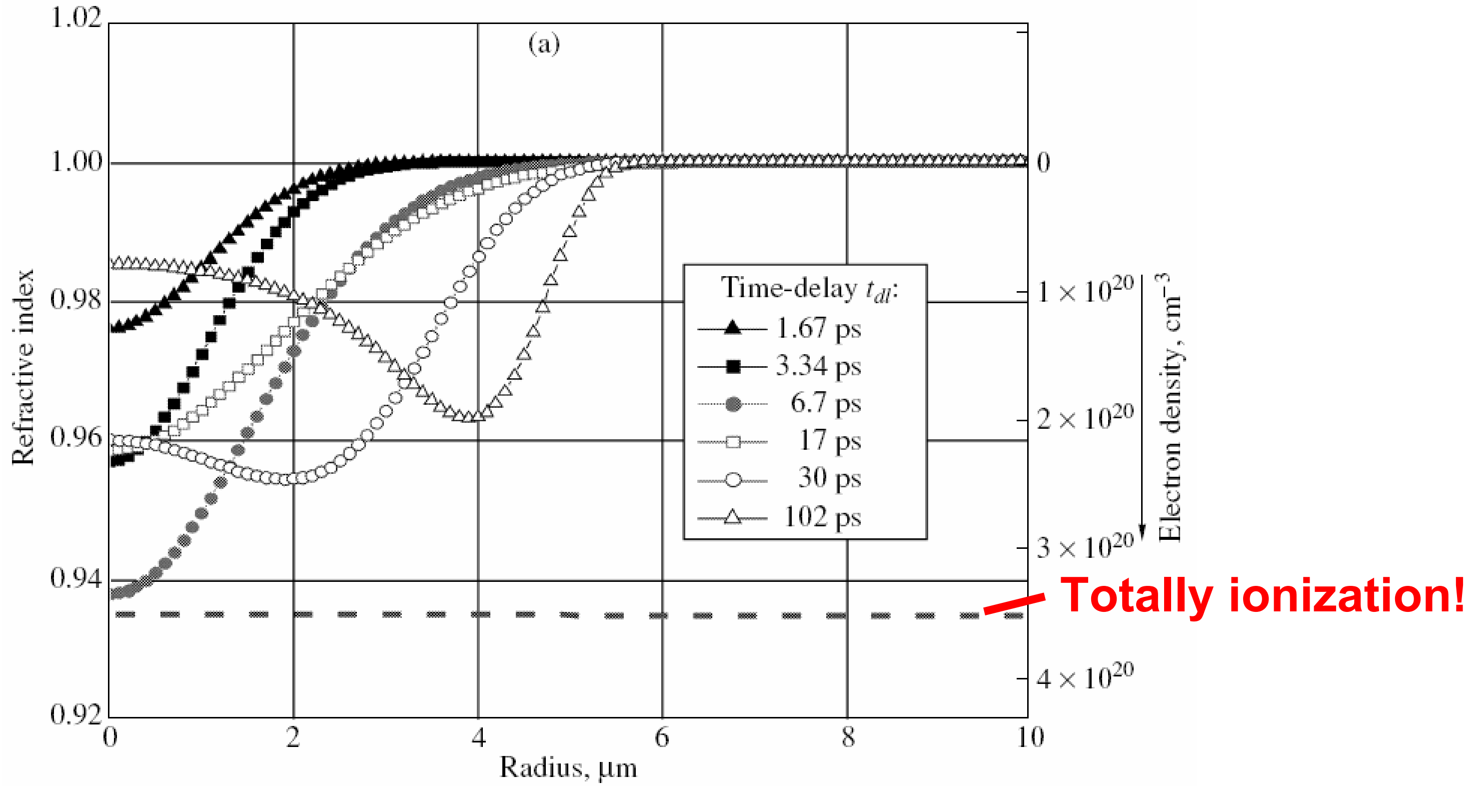
Air breakdown: Time resolved interferometric observation



- Expanding velocity of the plasma bulb during the pulse $6*10^7$ cm/s
  ➔ strong laser-plasma interaction
- Expanding speed decreases after the pulse
  ➔ free expansion

(Source: Garnov et. al, Laser Physics Vol. 13, No. 3, 2003, pp.386)

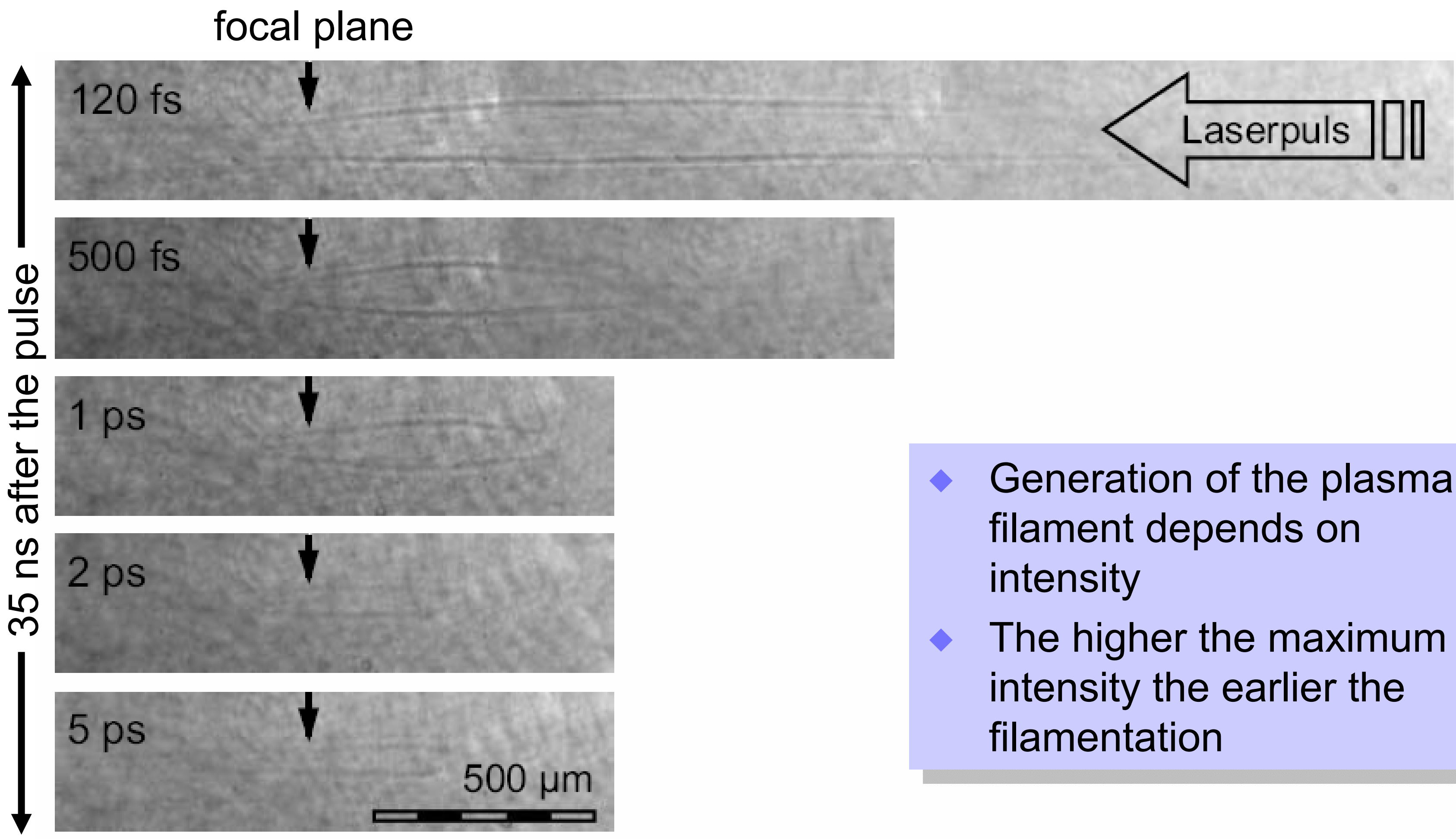
Air breakdown: electron density



- Air breakdown plasma consists of nearly totally ionized air
- Spatial profile of index of refraction
  ➔ plasma „lens" can affect beam profile

(Source: Garnov et. al, Laser Physics Vol. 13, No. 3, 2003, pp.386)

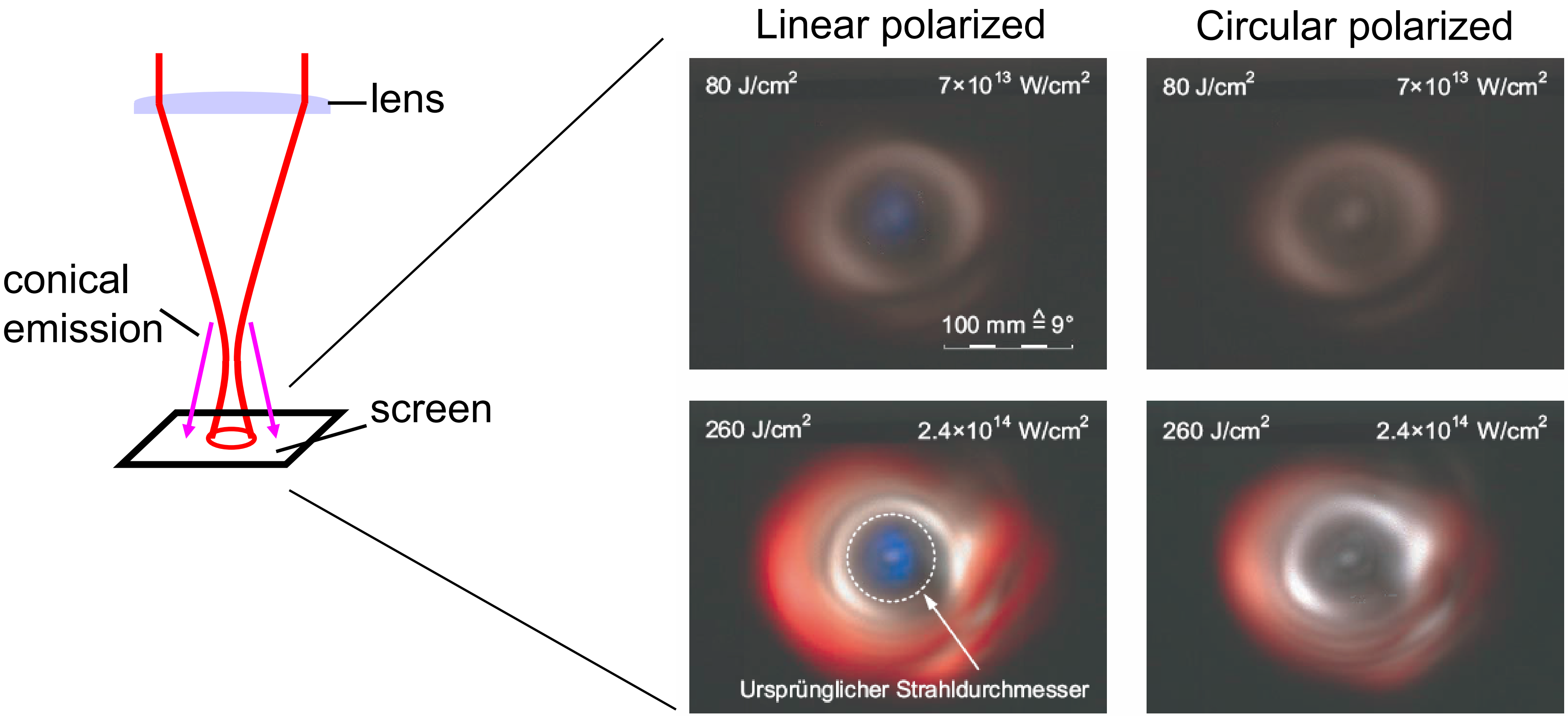
Air breakdown at diffent pulse durations



- Generation of the plasma filament depends on intensity
- The higher the maximum intensity the earlier the filamentation

(Source: Breitling et. al, Proc. SPIE 5339, pp. 49-63)

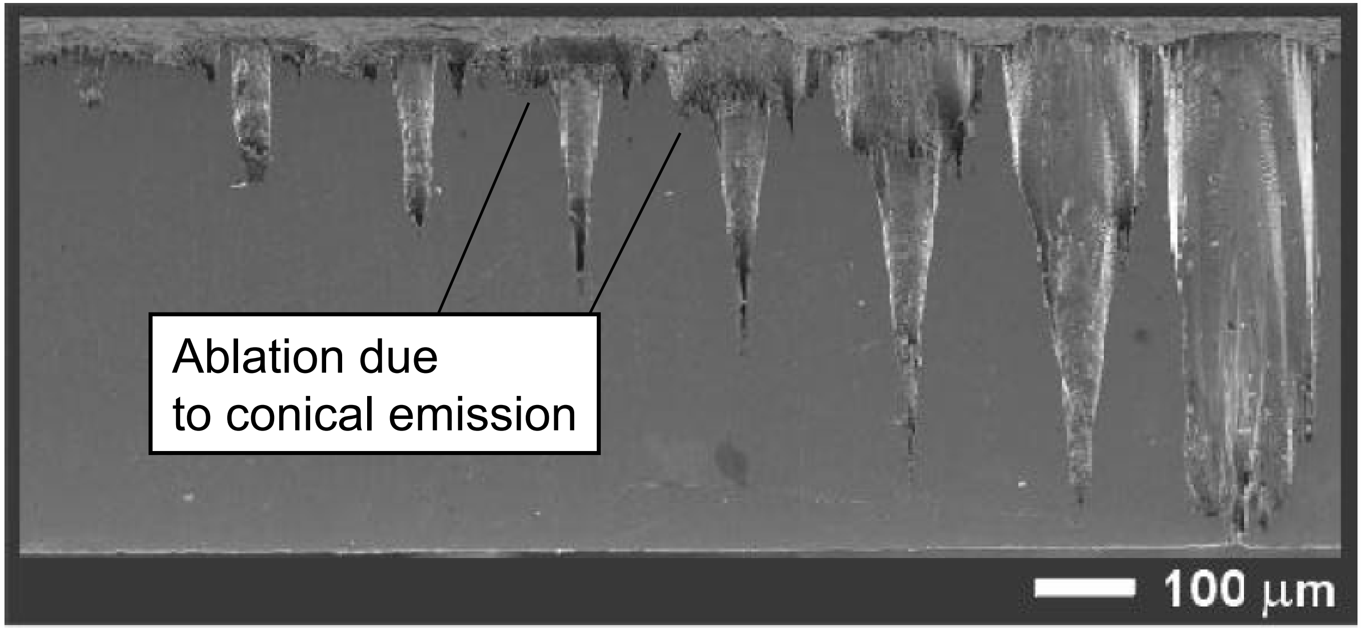
Implifications of ionization of the ambient gas



- Conical emission starts in from of the focal plane
- Intensity dependence evident
- The pulse energy is partly „scattered“ into an increased solid angle

(Source: Klimentov et. al, Breitling et. al., Proc. of LAT2002)

Practical implifications of conical emission

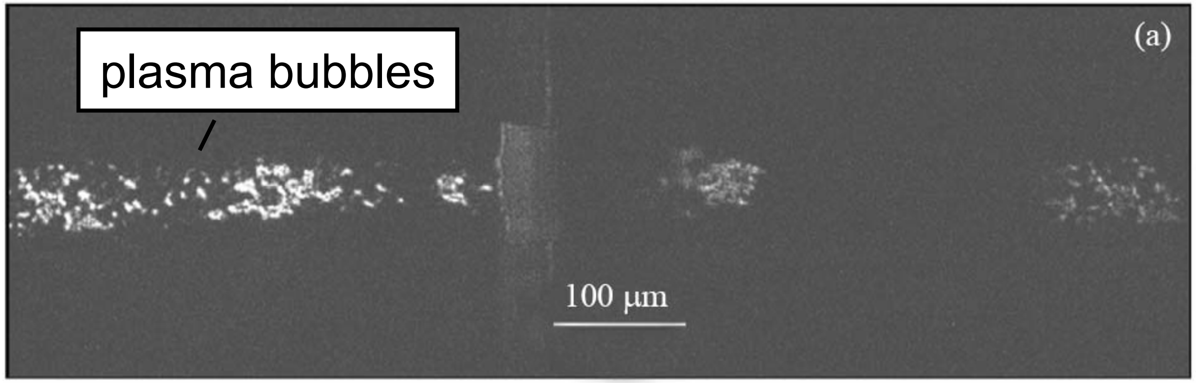


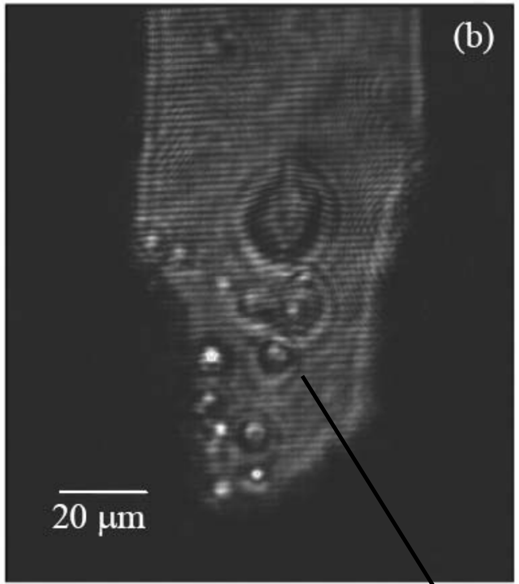
λ = 800 nm
τ = 130 fs
F = 80 J/cm²

- Ablation outside the „normal“ ablation diameter
- The scattered power due to conical emission reduces precision at high fluences

(Source: Klimentov et. al, Breitling et. al., Proc. of LAT2002)

Particles as sources for plasma



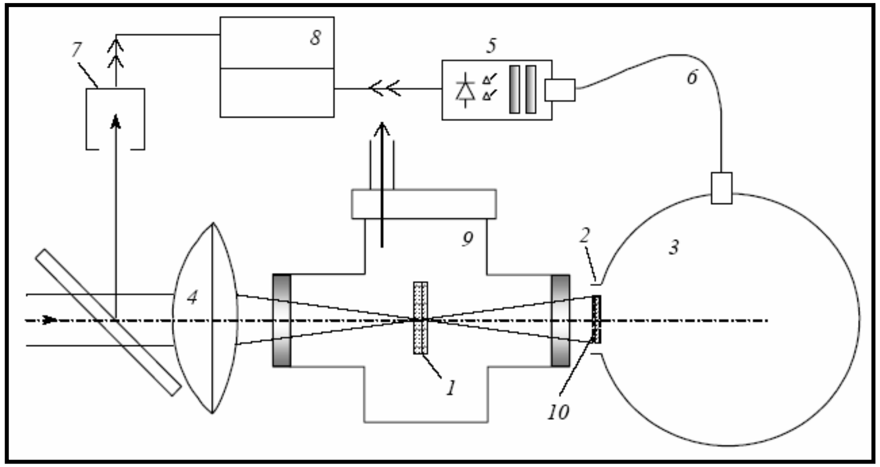


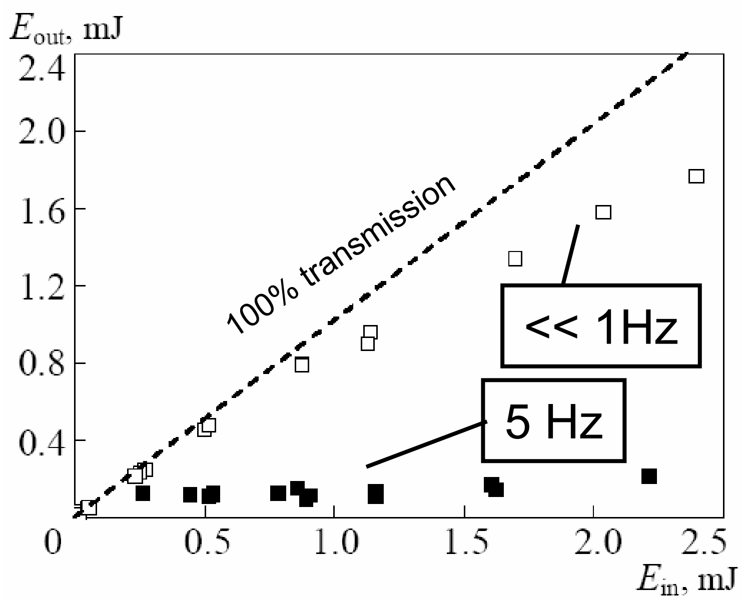
- Particles act as origins of plasma expansion
- Particles reduce the threshold of ionization

(Source: Klimentov et. al, Physics of wave phenomena, Vol. 15 No. 1, pp. 1-11, 2007)

Absorption inside particle generated plasma

- Transmission through channel depends on repetition rate
  ➔ particle-ignited plasma absorbs
- Transmitted energy independent from source energy
  ➔ The higher the intensity the stronger the plasma absorption



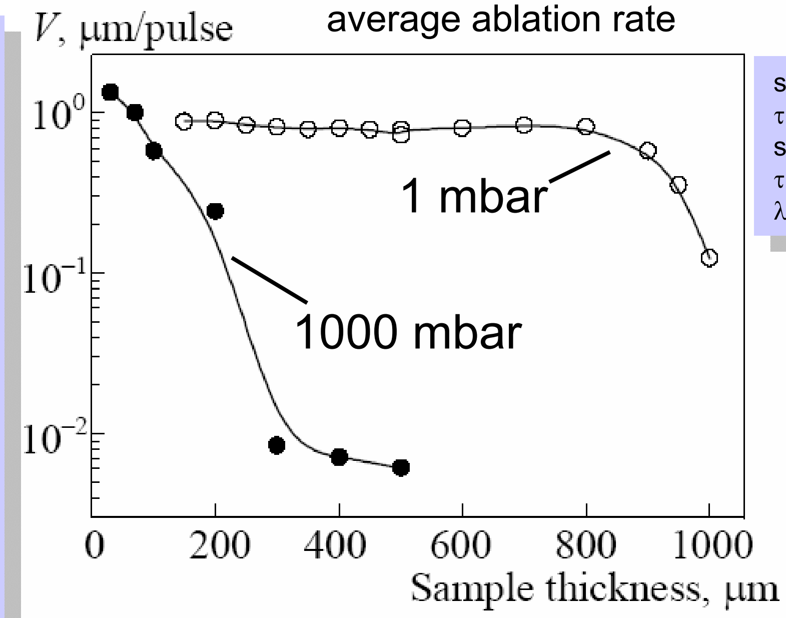


τ = 300 ps
$l_{channel}$ = 500 µm
F = 80 J/cm²
λ = 1078 nm

(Source: Klimentov et. al, Physics of wave phenomina, Vol. 15 No. 1, pp. 1-11, 2007) erg Lectures 19.3.09)

Absorption inside particle generated plasma

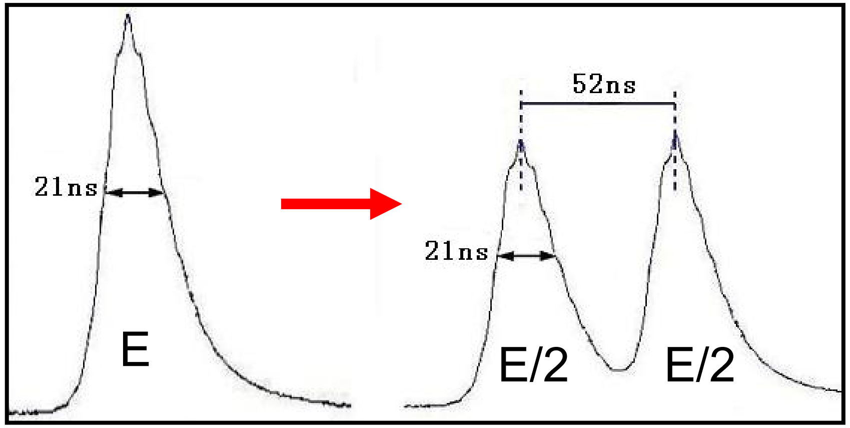
- Transmission through channel depends on repetition rate
  ➔ particle-ignited plasma absorbs
- Transmitted energy independent from source energy
  ➔ The higher the intensity the stronger the plasma absorption
- The mean ablation rate depends strongly on the pressure of the ambient air
  ➔ The lower the pressure, the lower the density of gas ions, the lower the plasma electron density

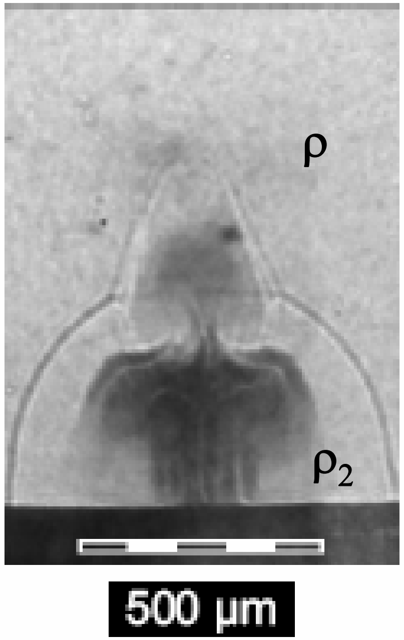


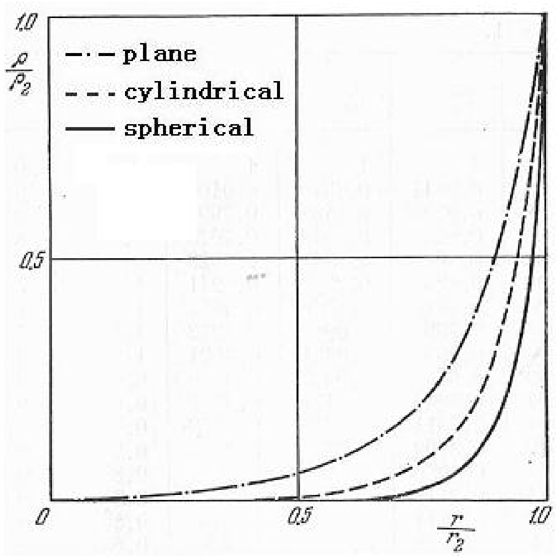
steel
τ= 300 ps
$sample_l$ = 500 µm
τF = 80 J/cm²
λ = 1078 nm

(Source: Klimentov et. al, Physics of wave phenomina, Vol. 15 No. 1, pp. 1-11, 2007)

Temporal beam shaping to improve drilling speed



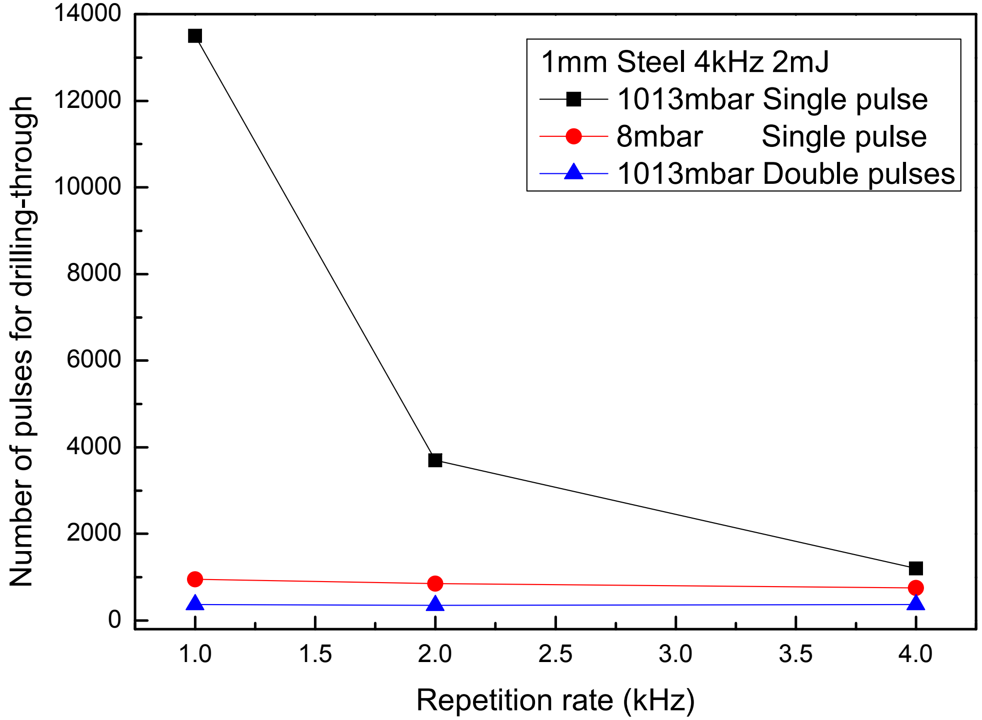




- Nanosecond pulse was devided into double pulse
- A shock wave appears due to the first pulse
- Inside the shock wave the gas density is low

(Source: Wang, Michalowski et. al., Optics&Laser Tech. Vol. 41, pp. 148-152, 2009)

Temporal beam shaping to improve drilling speed

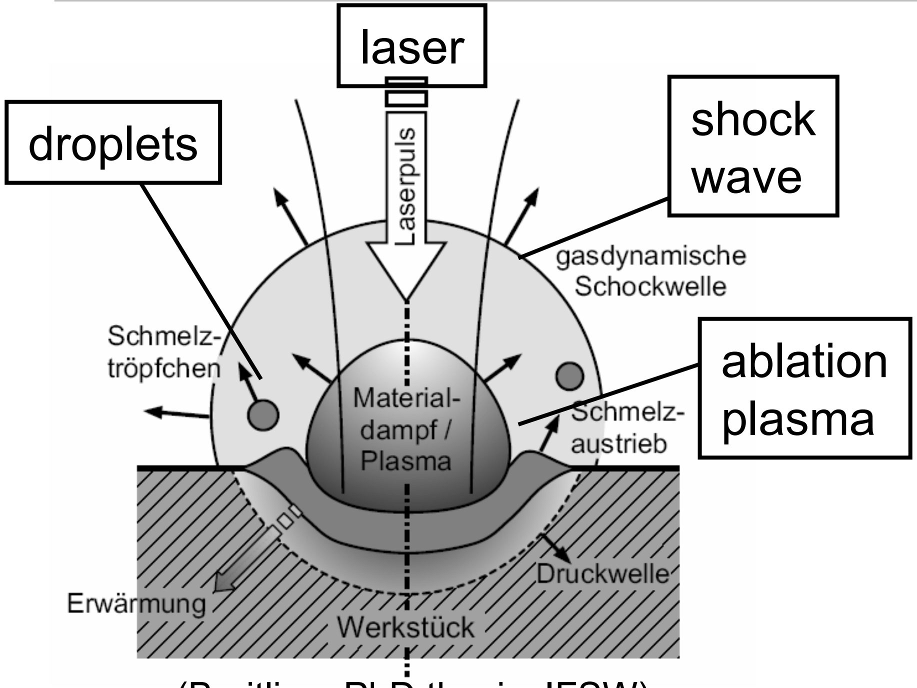


- Nanosecond pulse was devided into double pulse
- A shock wave appears due to the first pulse
- Inside the shock wave the gas density is low
- The number of pulses for drilling through is reduced significantly using double pulses even at low repetition rate
- At vacuum conditions the effect is much less pronounced

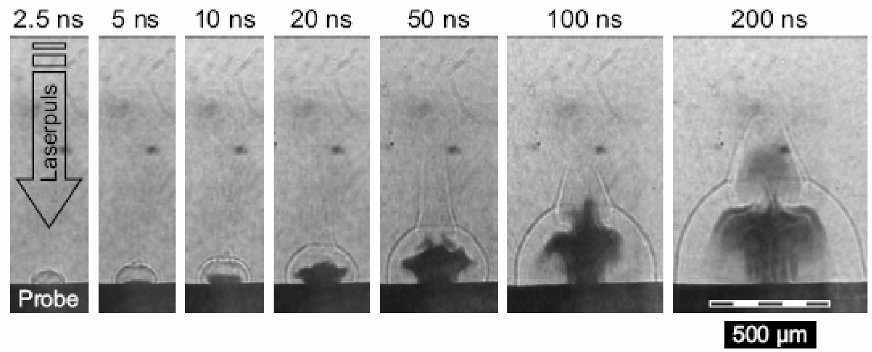
➔ „Double pulse effect“ has to do with plasma avoidance

(Source: Wang, Michalowski et. al., Optics&Laser Tech. Vol. 41, pp. 148-152, 2009)

Processes which occur because of laser ablation (metals)



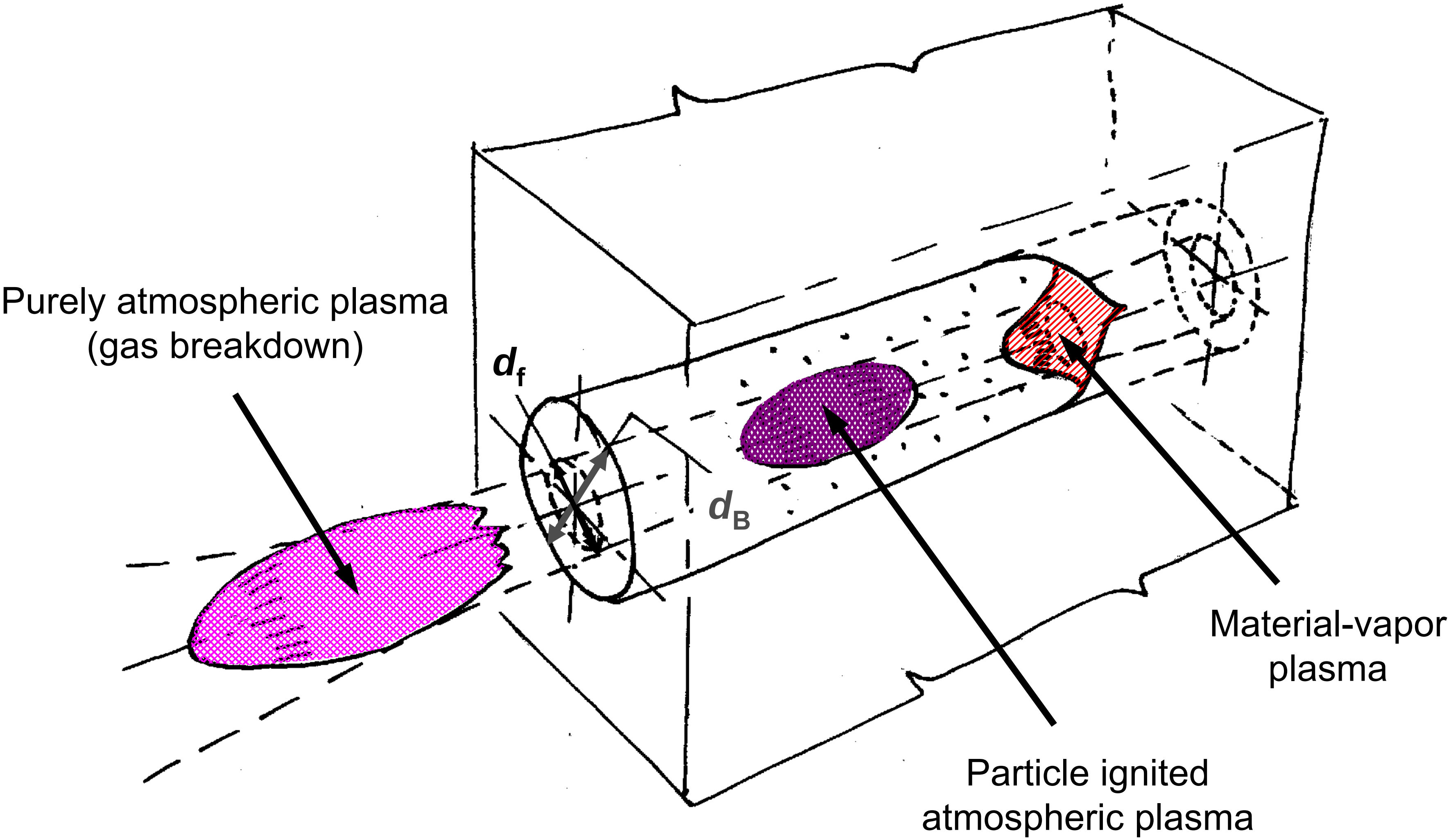
(Breitling, PhD thesis, IFSW)



- The pulse energy is coupled to the electrons inside the metal
- The electrons thermalize with the lattice
- The temperature increases rapidly (< 1ns)
- The material melts and partially evaporates nearly instantaneous
- Shock waves, an evaporation plasma, an evaporation plume, droplets and melt expulsion are generated

(Source: Breitling et. al., Proc. of LAT 2002, SPIE 5121, pp. 24-33)

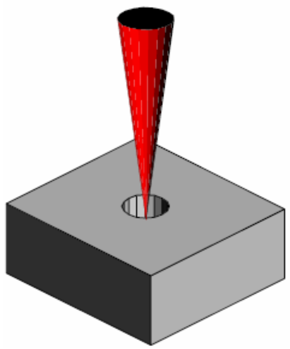
Types of plasma for laser drilling

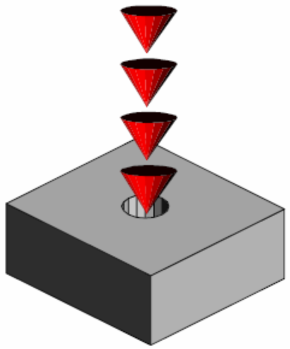


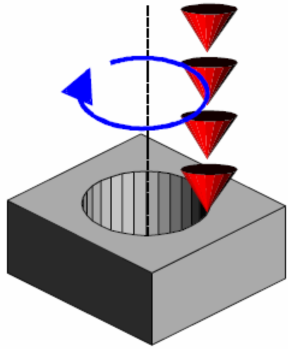
(Source: Proc. of 2nd Intl. Workshop Hirschegg 2001)

Drilling strategies

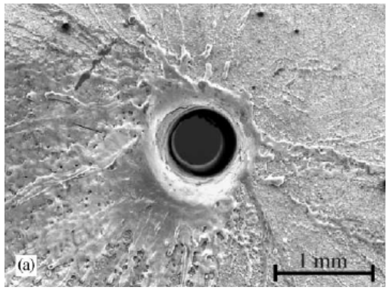
single pulse	percussion drilling	helical drilling



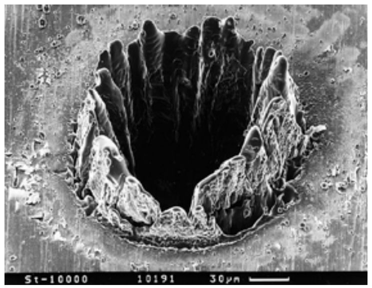




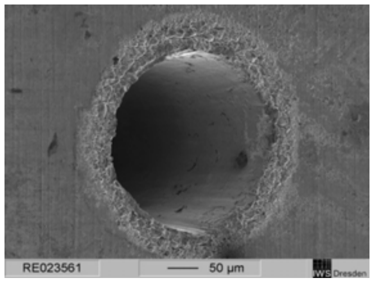
1 mm



100 µm



200 µm



Question:

Why is precision better for helical drilling?

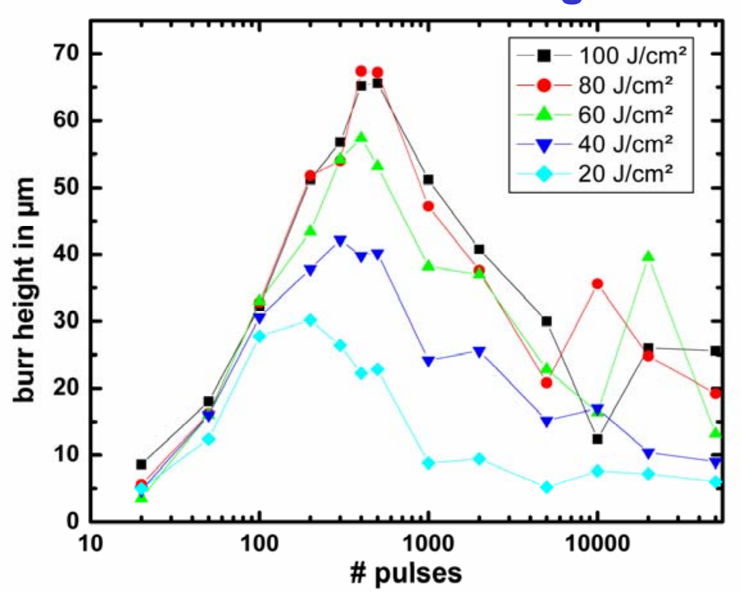
single pulse
- Long pulses ~ ms
- Numerous holes / sec
- Much melt recast
- Not very reproducible

percussion drilling
- Shorter pulses possible
- Simple process engineering
- Reduced melt recast
- Better reproducible

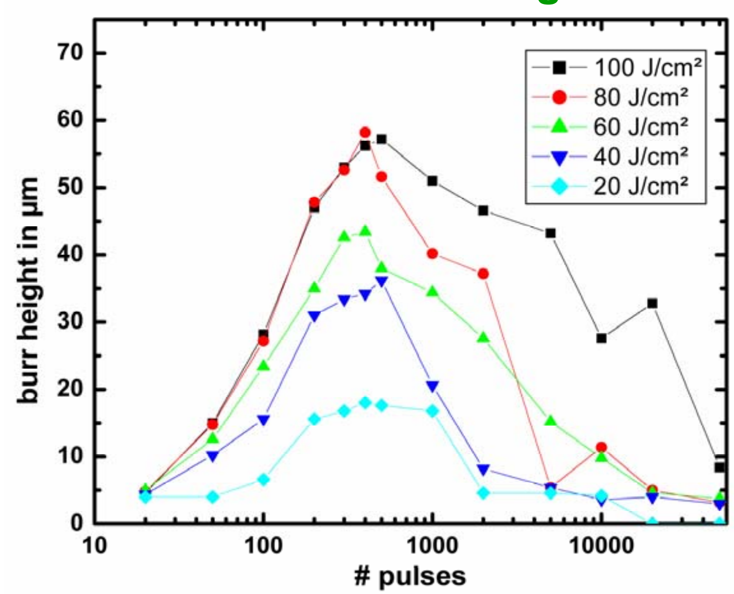
helical drilling
- Complex process engineering
- Avoidance of melt recast possible
- Best reproducibility

Post process diagnostics of melt transport: burr formation

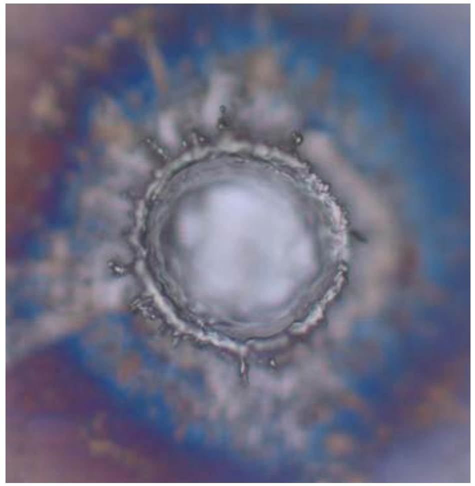
Percussion drilling



Helical drilling



- Burr formation:
  Beginning of drilling
- Maximum burr height:
  smaller for helical drilling
- Burr reduction:
  Longer processing time
- Fluence ↓ → burr height ↓



(Source: Michalowski et. al., Proc. of Stuttgarter Lasertage 2008)

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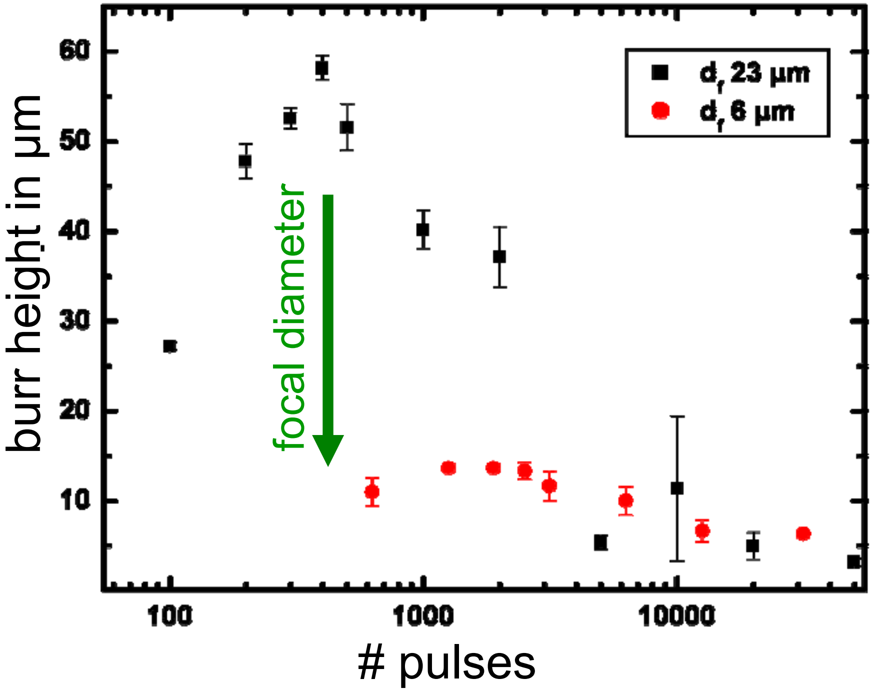
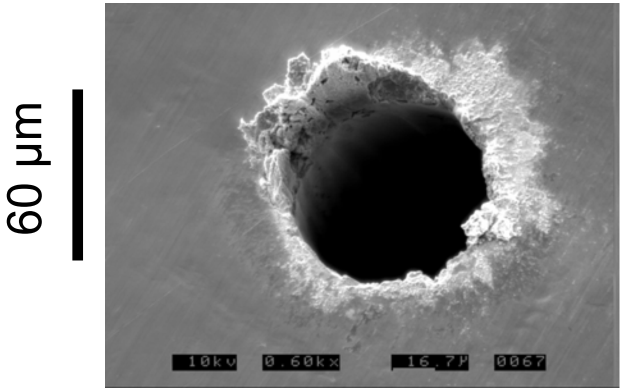
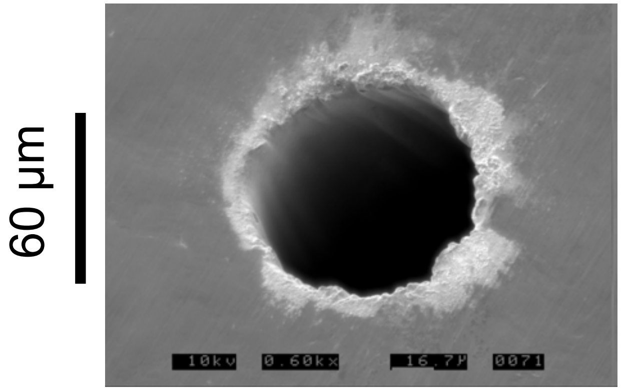
Drilling parameters to reduce burr height



Smaller focal diameter



+ simple strategy

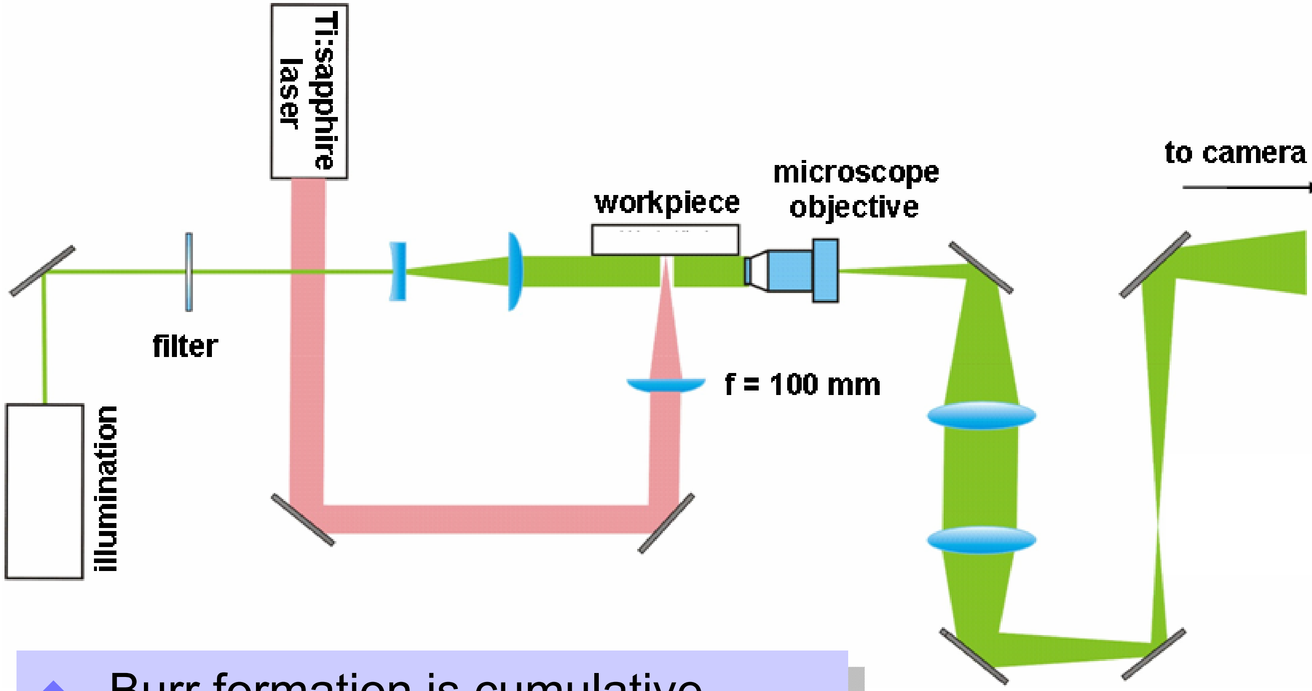


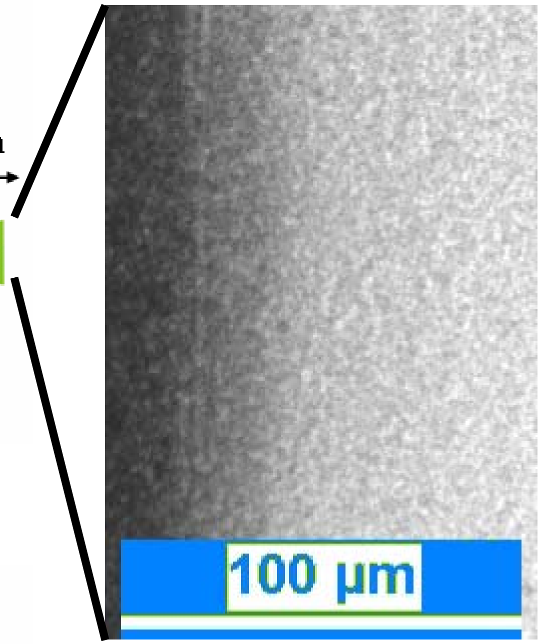
(helical drilling)

- Scaling down focal diameter
  → Reduction of burr
- Simple energy strategy further reduces burr

(Source: Michalowski et. al., Proc. of Stuttgarter Lasertage 2008)

In process diagnostics: burr formation





Helical drilling

- Burr formation is cumulative process
- Burr is destabilized for longer processing
- No further burr formation for deep hole

Question:
No further melt ejection?

In process diagnostics: droplet ejection

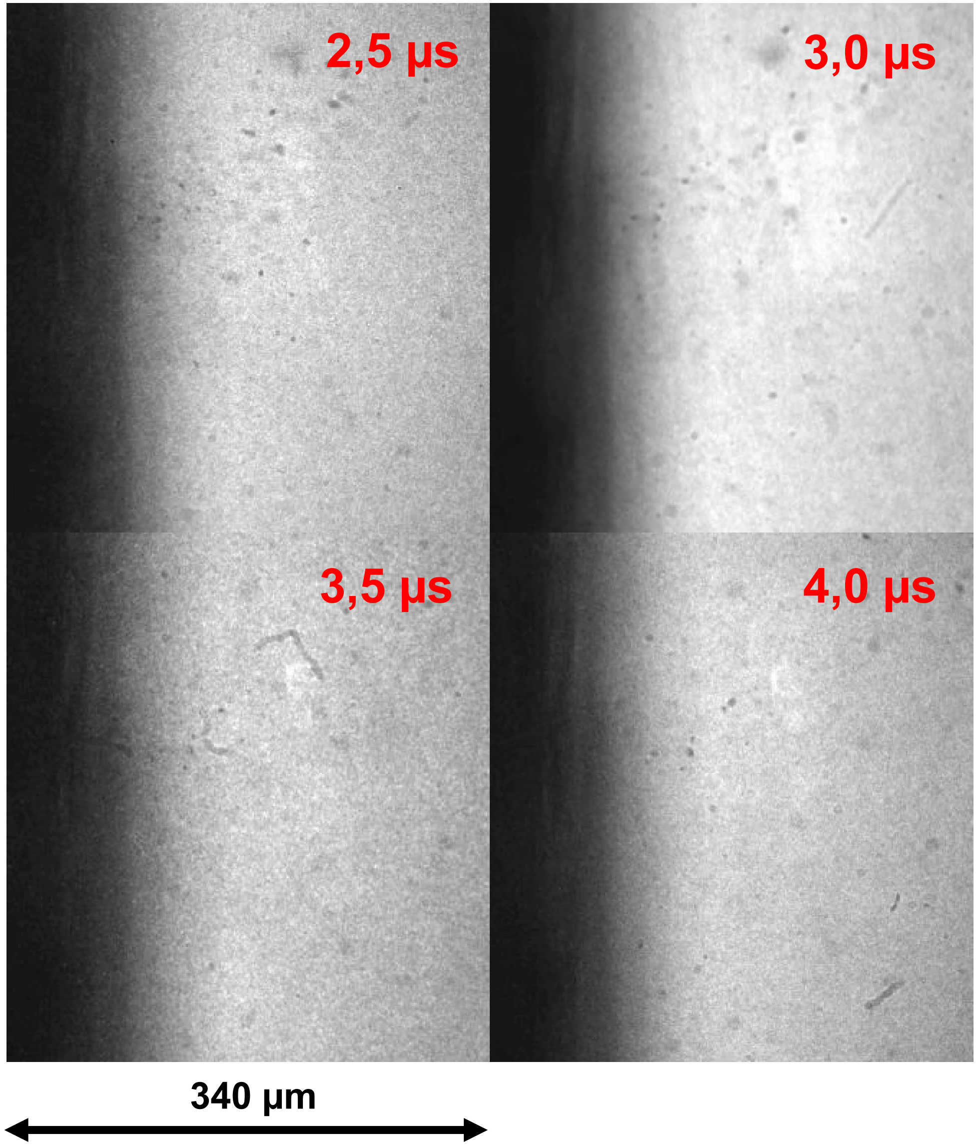
Experiment

- Time resolved high speed filming for droplet tracing
- Frame rate 2 MHz

Observation

- Burr formation stops
  Droplet ejection continues
- Big droplets observed for deeper drilling channel

Question:
Where are droplets generated?



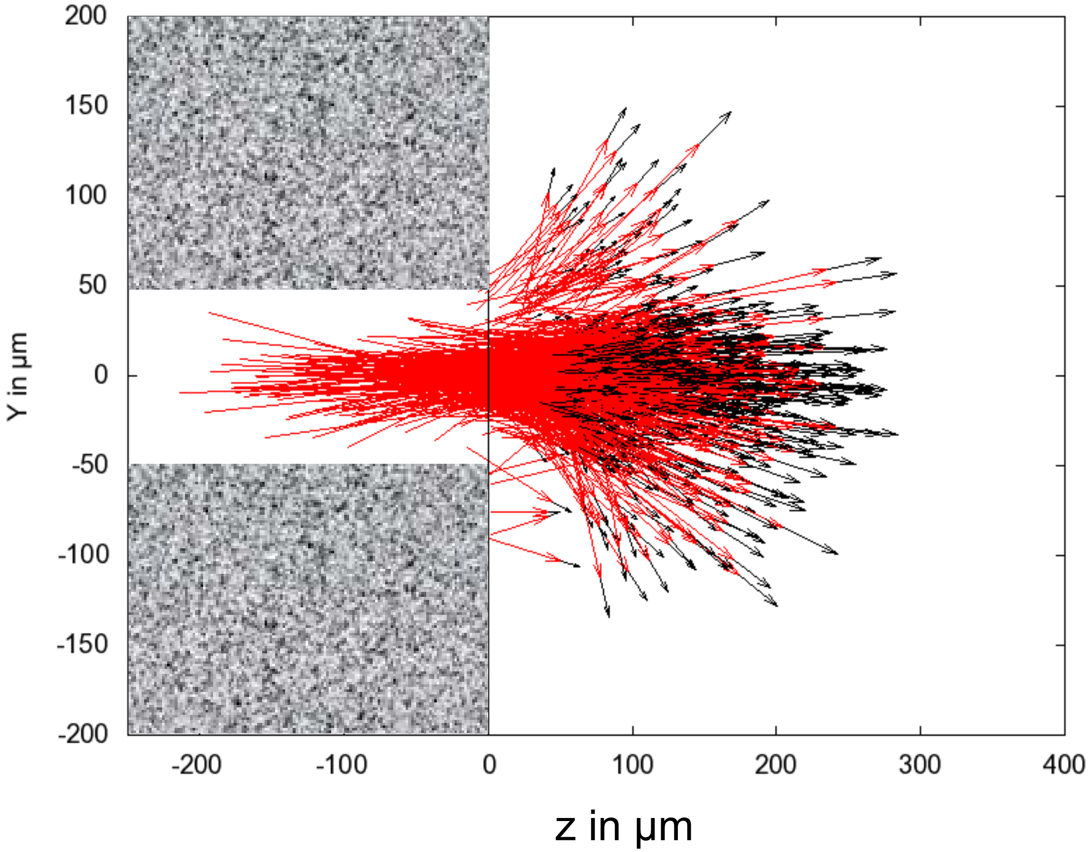
(SSOM Engelberg Lectures 19.3.09)

In process diagnostics: droplet ejection

Observation

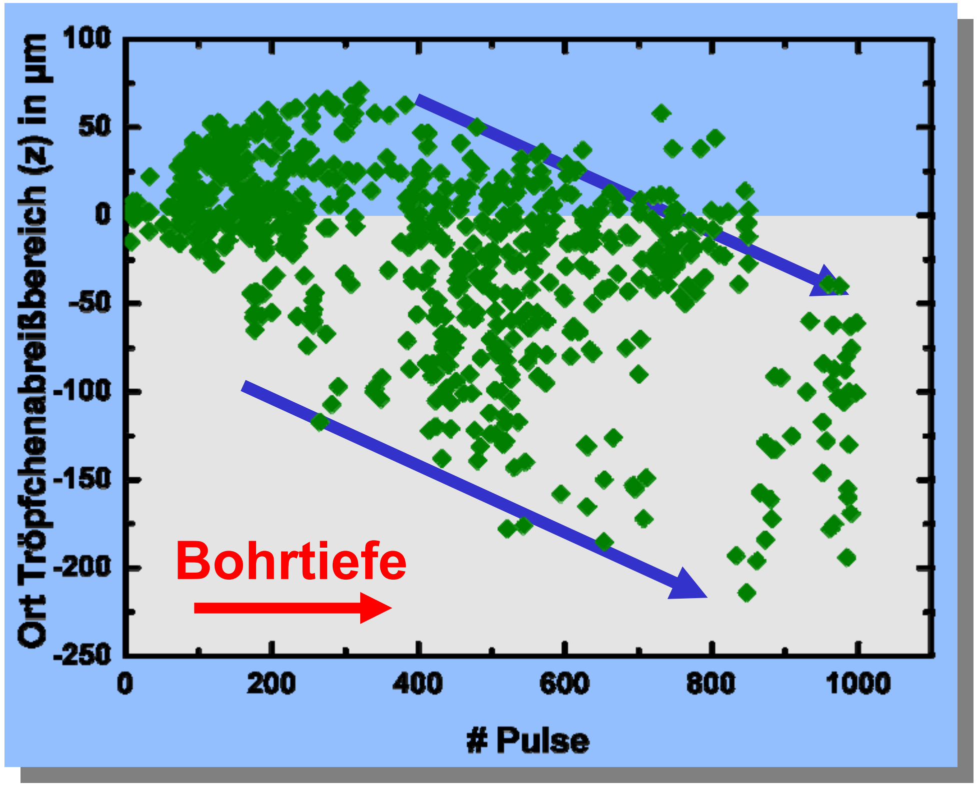
- Droplet traces can be visualized
- Most droplets in surface normal direction
- Droplet velocity (v_z) unchanged during observation
- Droplet origin deep inside the channel

Estimation of droplet origin

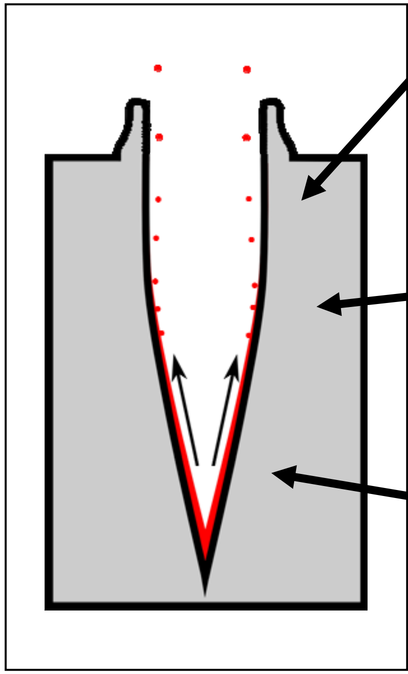


(SSOM Engelberg Lectures 19.3.09)

Estimation of droplet origin

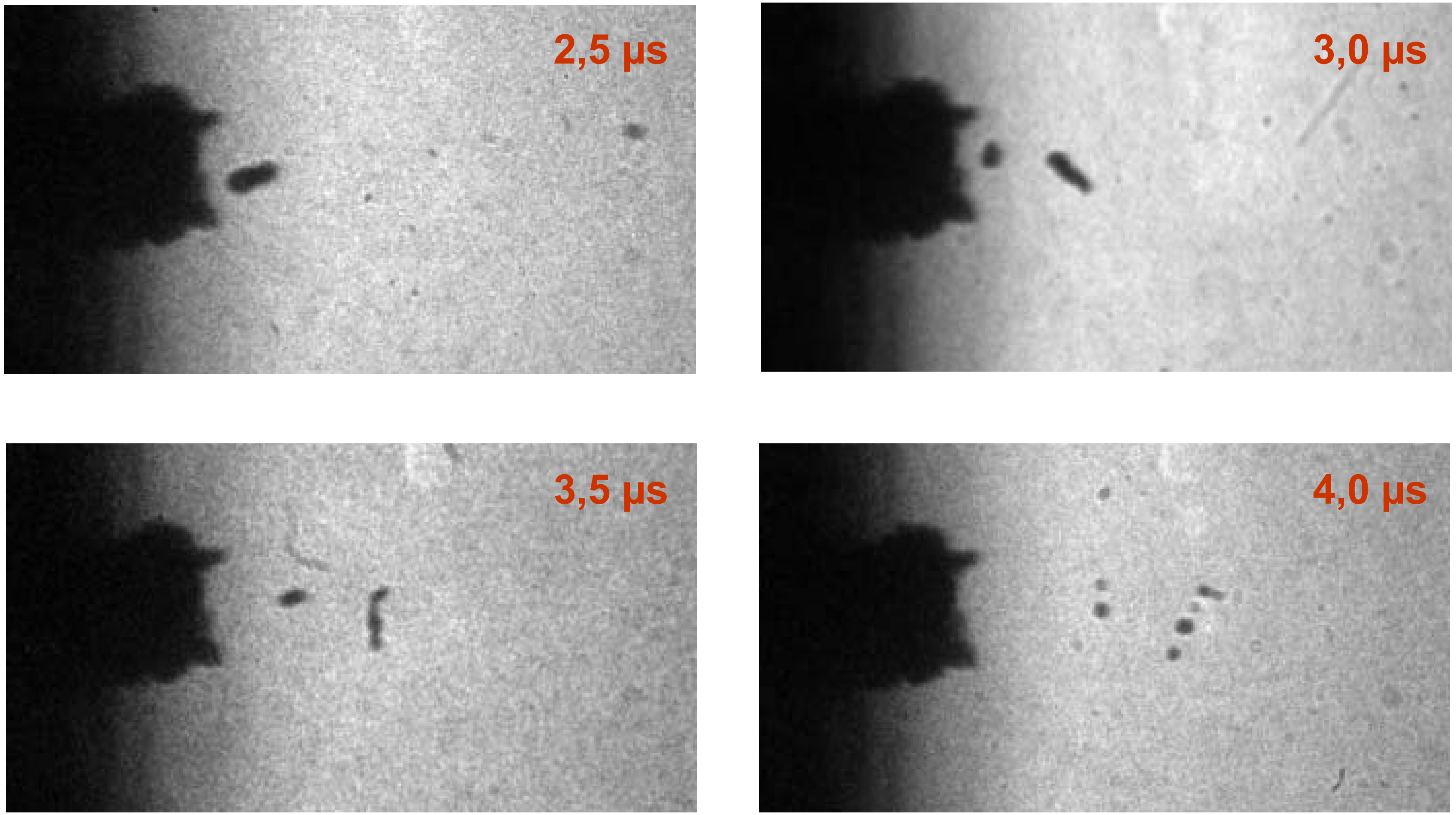


Model representation



- Melt film: Limited flow distance
- In upper region droplet release
- Droplet speed ≈ 80 m/s

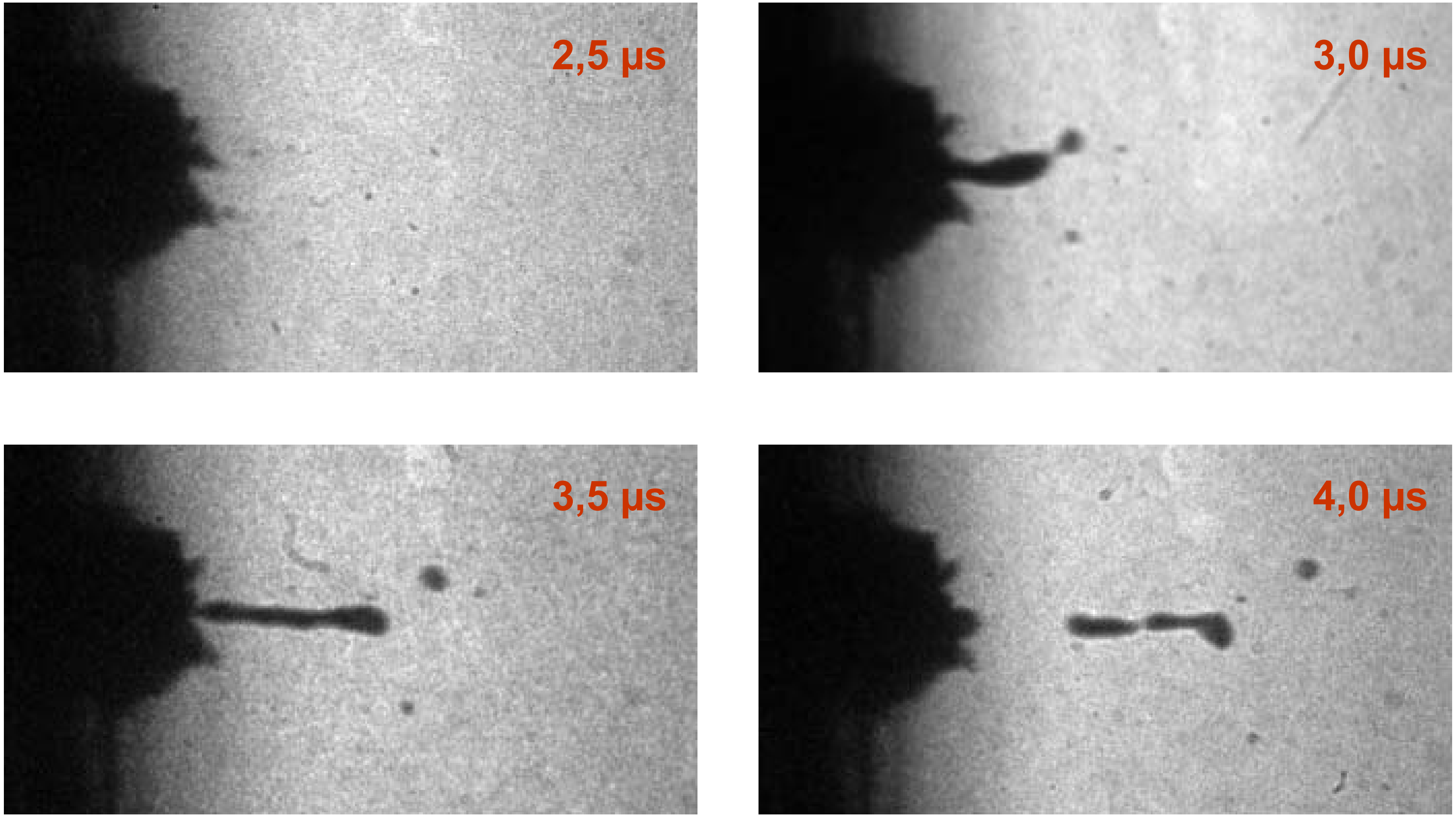
Droplets rotate and break ➔ still liquid phase



IFSW

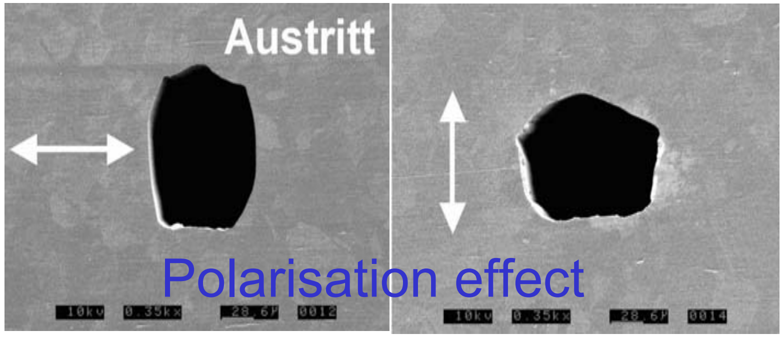
(SSOM Engelberg Lectures 19.3.09)

Surface tension evident ➔ liquid phase



(SSOM Engelberg Lectures 19.3.09)

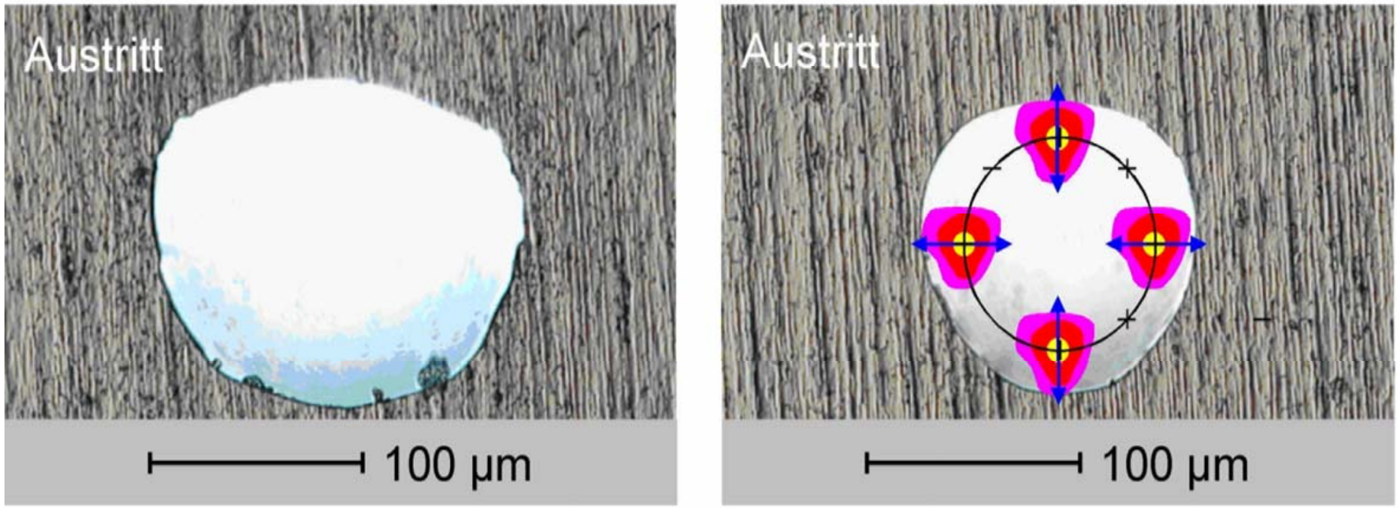
Cylindricity: Influence of polarisation and beam profile



- Polarization has effect on hole shape
- Circular or rotated polarization improves geometry
- Nevertheless because of a not rotational symmetric beam profile the hole will not become cylindric

Linear polarization

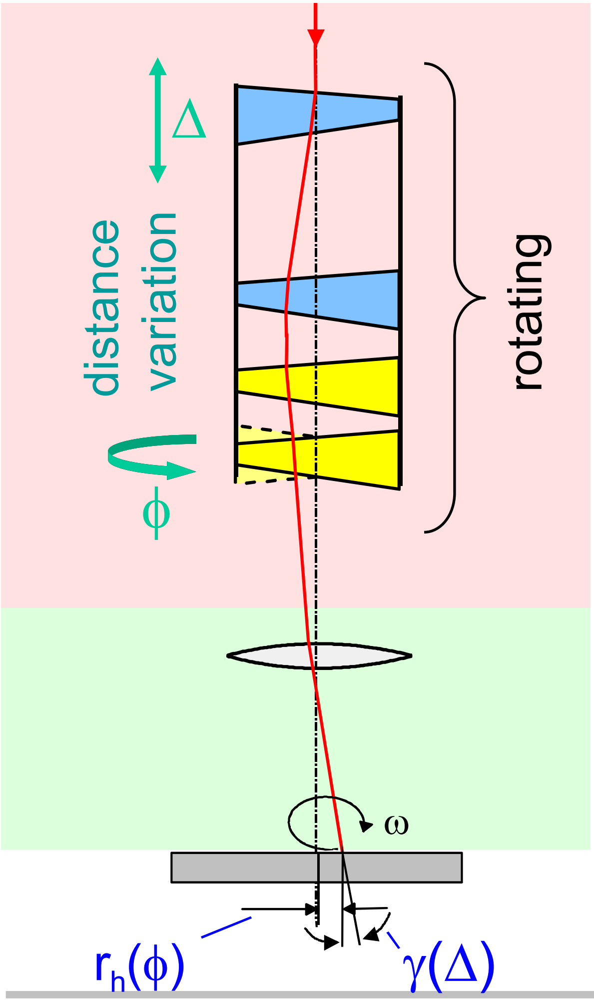
rotated polarization

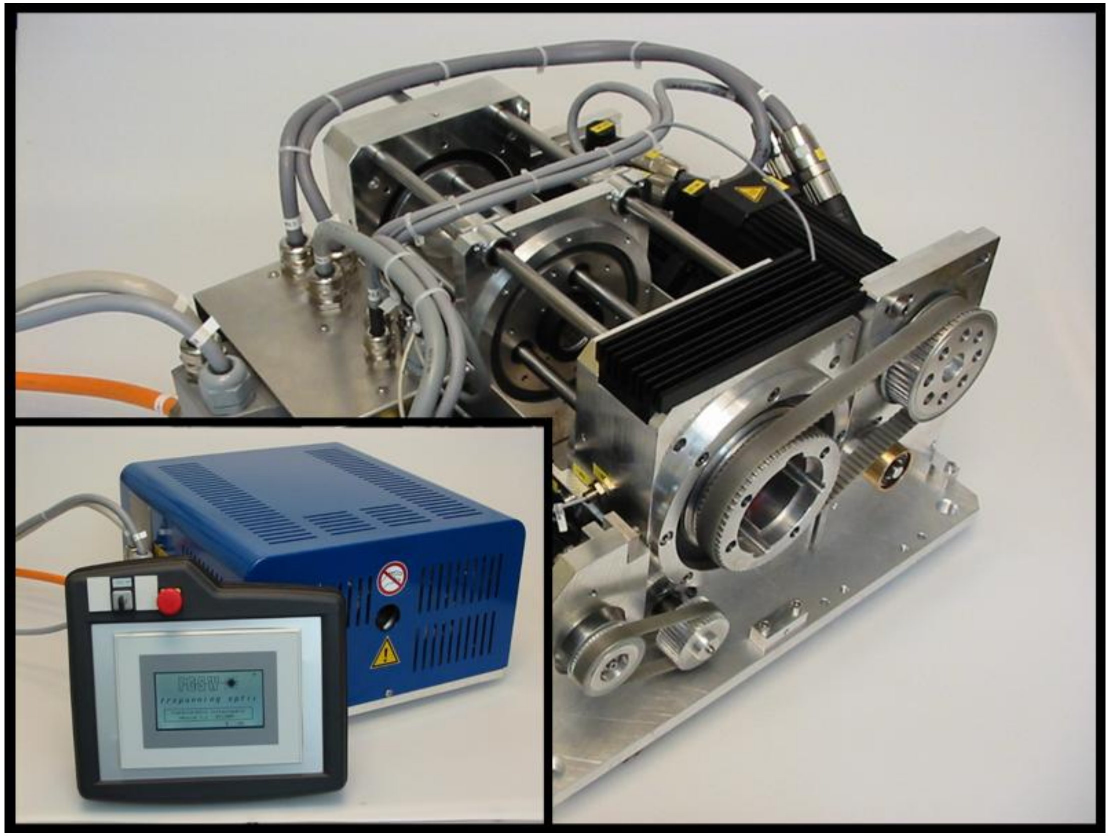


(SSOM Engelberg Lectures 19.3.09)

Helical Drilling Optics with rotation wedges

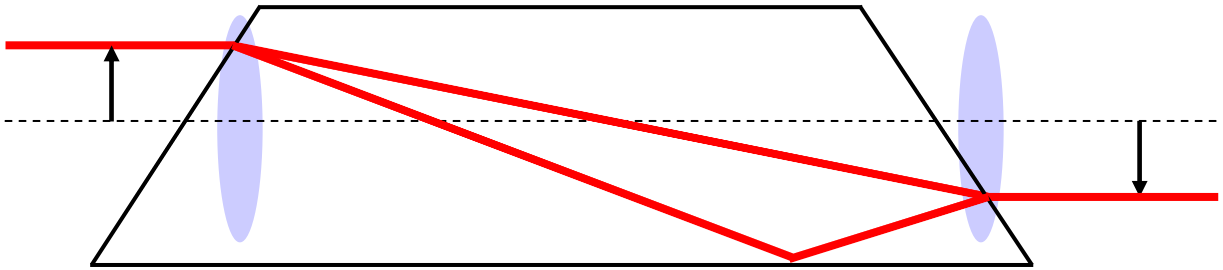
- To control the inclination angle and the diameter of the helical drilling path the wedge distance and relative rotation angle is adjusted during operation.

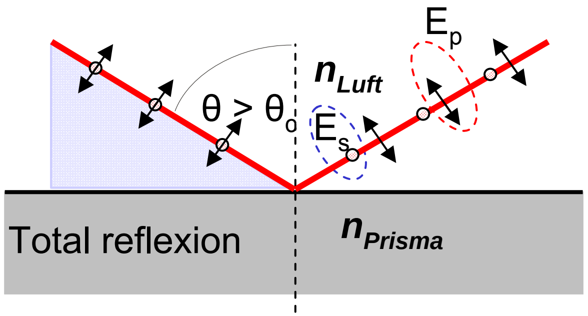




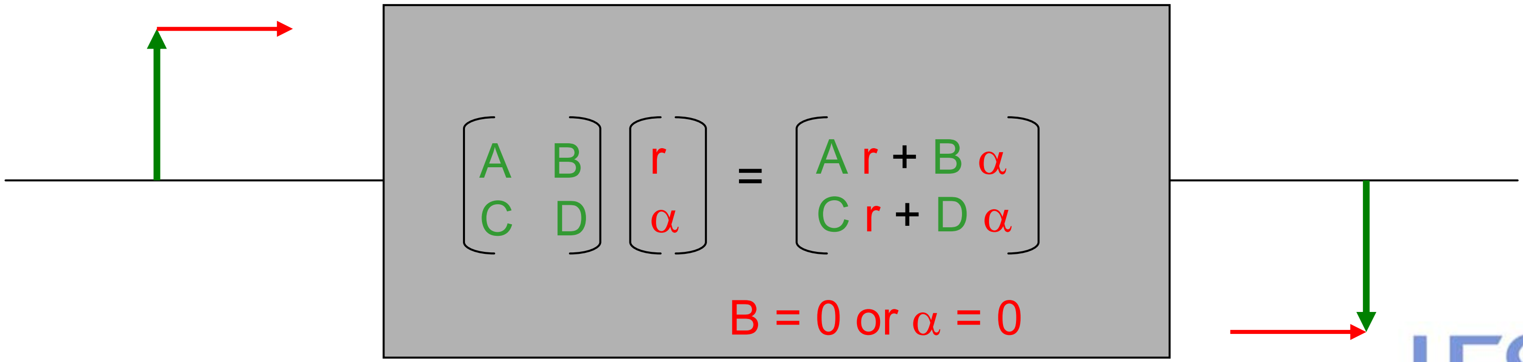
Principle: Beam rotation

Dove prism
Telescope





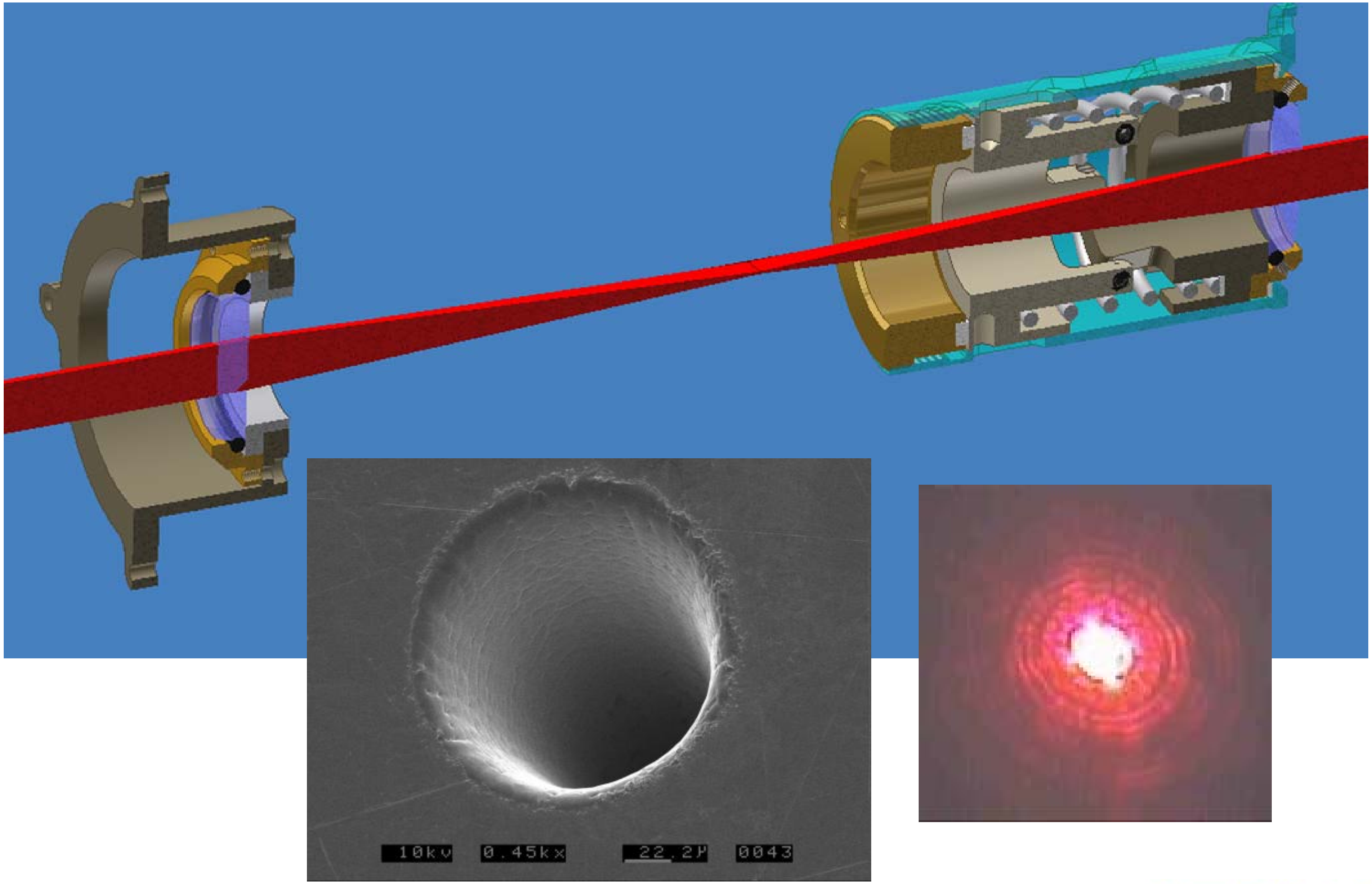
For a laser beam we only need:



$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} r \\ \alpha \end{pmatrix} = \begin{pmatrix} A\,r + B\,\alpha \\ C\,r + D\,\alpha \end{pmatrix}$$

$B = 0$ or $\alpha = 0$

Coming soon: New helical drilling optics



(τ = 160 ns, Stahl)

Summary

- Because of the fresnel equations and because the light hits the wall at an effective angle of incidence close to 90°
  ➔The drilling channel results with „parallel“ walls
- Pulses shorter than the electron-phonon relaxation time of the metal do not further improve the quality.
- At high intensities (~10^{13} W/cm²) an air breakdown occurs.
  ➔This plasma absorbs light.
  ➔Conical emission occurs which reduces the precision.
- Particles in the ambient air (and inside the channel) decrease the threshold for breakdown.
- Double pulses can increase the ablation rate. The mean effect is the avoidance of particle ignited atmosperic plasma.
- The burr occurs only during the first stage of drilling and originates from the expulsion of a melt film. Later on melt expulsion from the hole consists of liquid droplets.

Summary

- The hole cylindricity is improved by using radial symmetric polarization.
- The intensity distribution has also an effect to the cylindricity.
  ➔ Using a poor beam, not only the position but also the profil must be rotated.
- A new concept of a helical drilling optics was presented.

Some solutions to avoid unwanted plasma effects during drilling:

- Usage of shorter wavelength, because plasma absorption ~ λ^2
  (Demonstrated experimentally at the IFSW/FGSW)
- Decreasing of air density (e.g. IFSW-aerodynamic window)
- Using processing gases with high ionization threshold (e.g. helium)
  (Demonstrated experimentally at the IFSW)

Thank you for your interest!