



# Laser Ablation

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## Fundamentals & Applications

**Samuel S. Mao**

Department of Mechanical Engineering  
University of California at Berkeley

Advanced Energy Technology Department  
Lawrence Berkeley National Laboratory

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# Laser Ablation

## What is “Laser Ablation”?

Mass removal by coupling laser energy to a target material

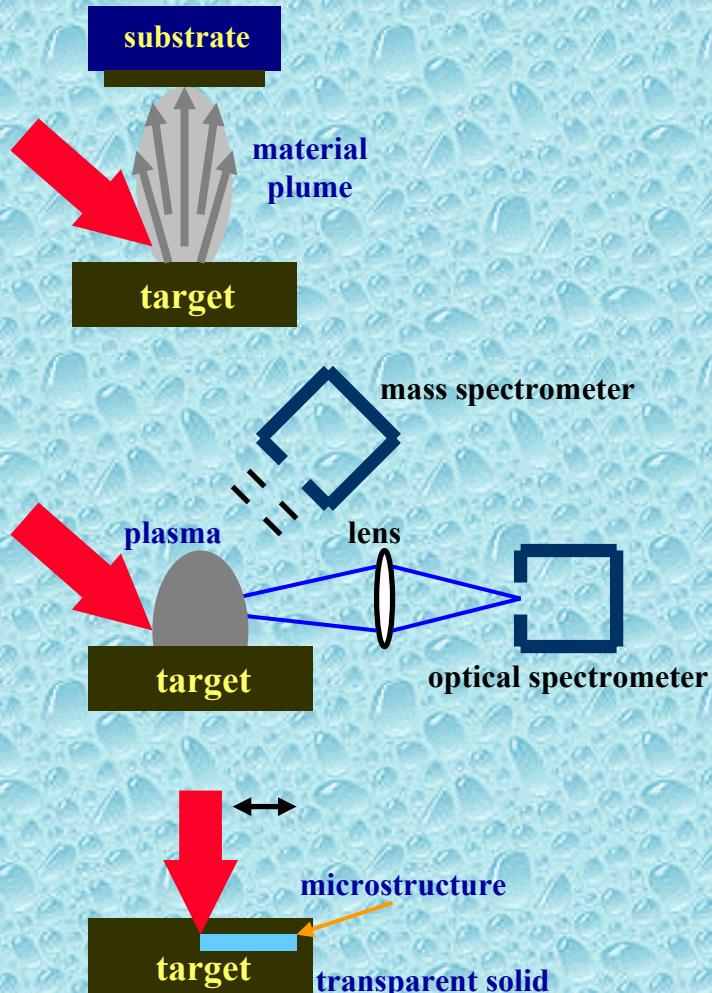


laser ablation

# Is it important?

## ☞ Film deposition

- \* oxide/superconductor films
- \* nanocrystals/nanotubes



## ☞ Materials characterization

- \* semiconductor doping profiling
- \* solid state chemical analysis

## ☞ Micro structuring

- \* direct wave guide writing
- \* 3D micro fabrication

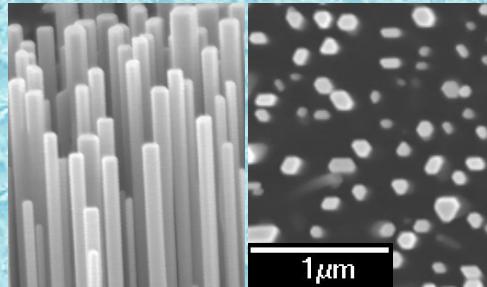
**laser ablation**

# Is it important?



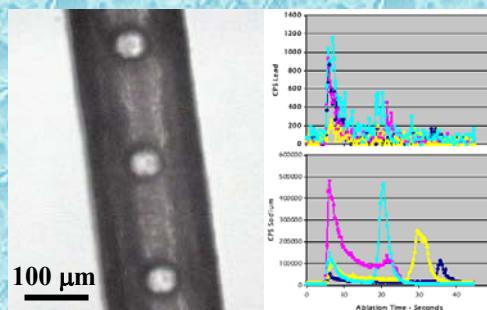
## ☞ Film deposition

- \* oxide/superconductor films
- \* nanocrystals/nanotubes



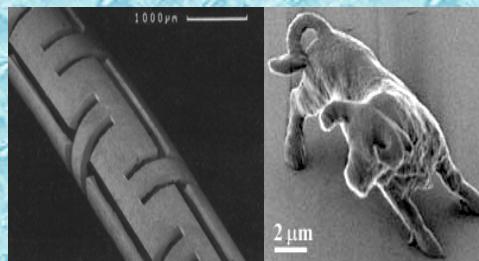
## ☞ Materials characterization

- \* semiconductor doping profiling
- \* solid state chemical analysis



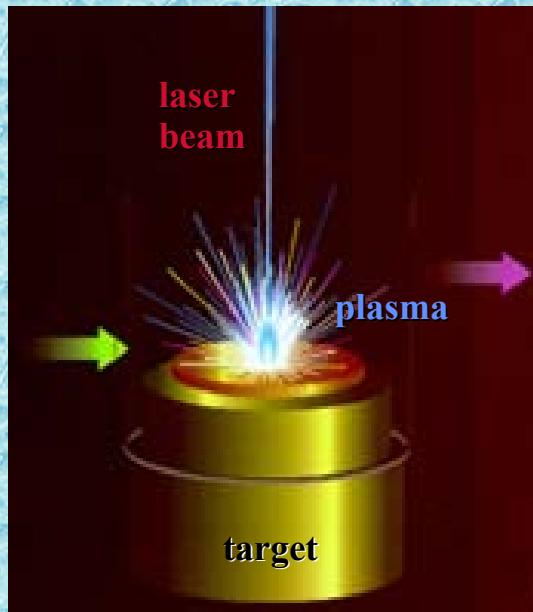
## ☞ Micro structuring

- \* direct wave guide writing
- \* 3D micro fabrication



laser ablation

# Do we really understand?



**“Laser ablation ... is still largely unexplored at the fundamental level.”**

J. C. Miller & R. F. Haglund,  
*Laser Ablation and Desorption*  
(Academic, New York, 1998)



# Laser Ablation

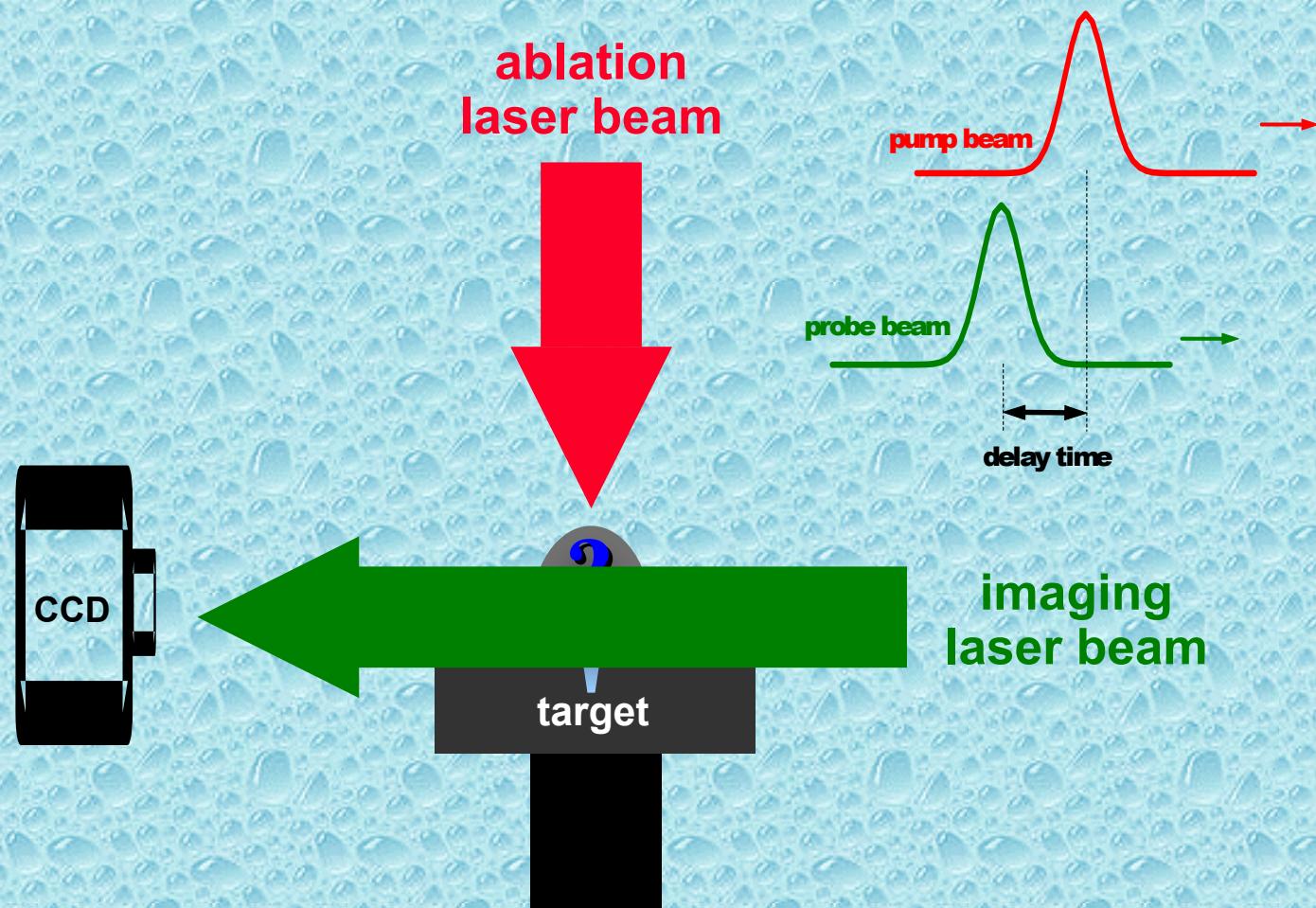
☞ What is happening?





# Experiments - ultrafast imaging

## ☞ Pump-probe technique

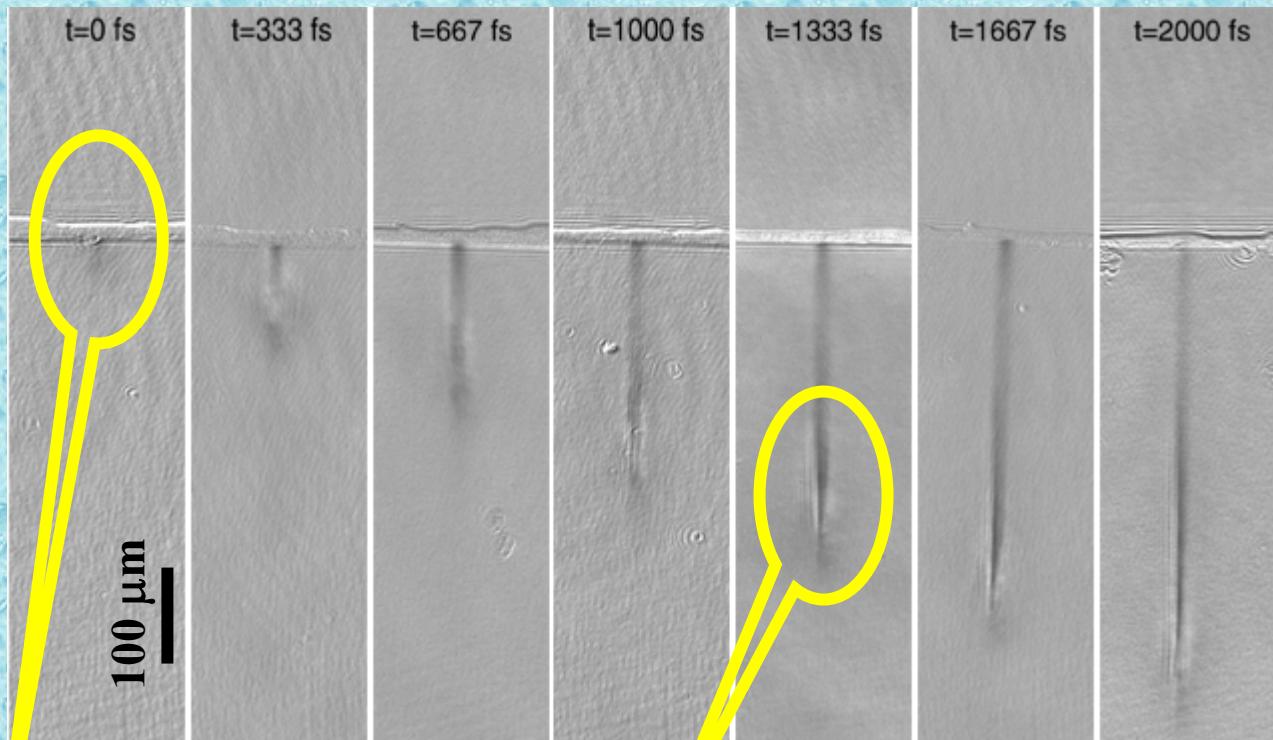


$1 \text{ fs} = 10^{-15} \text{ s}$

# Femtosecond Time Scale

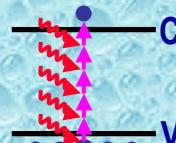


air  
glass



100 fs, 800 nm  
 $E = 30 \mu\text{J}$

electronic excitation  
e-h plasma



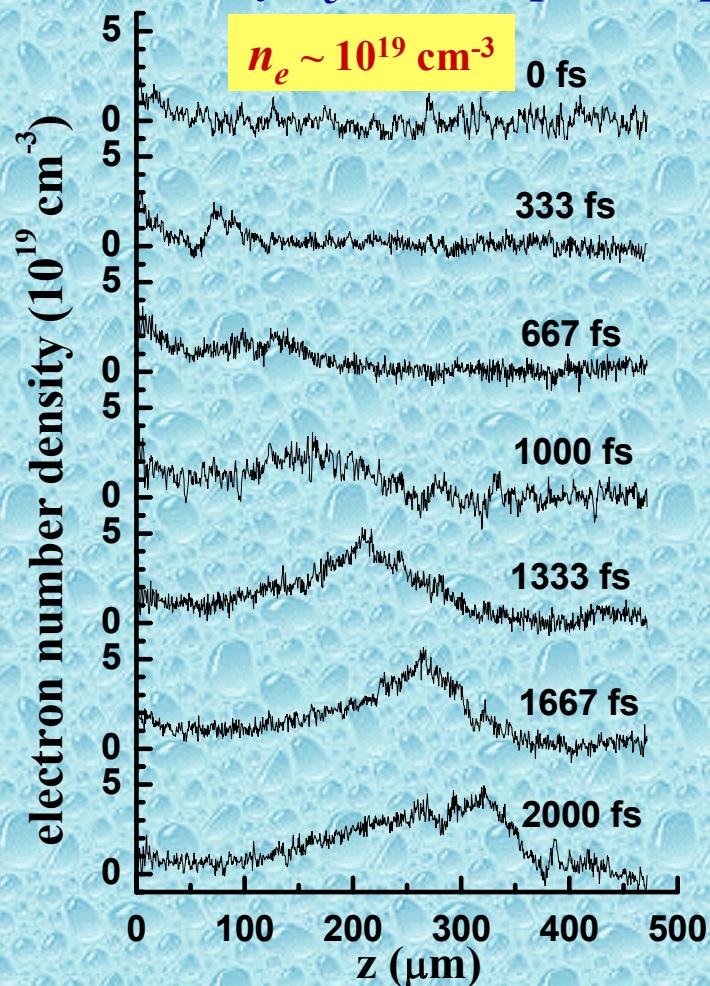
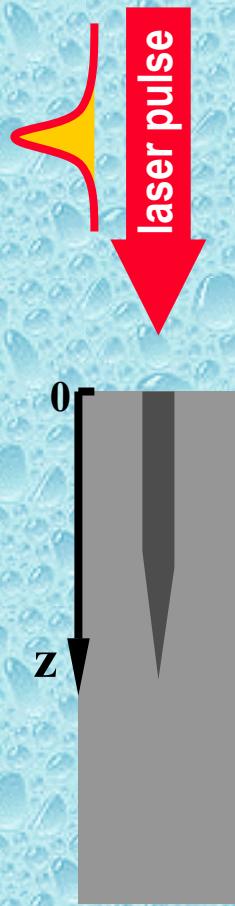
self-focusing





# Femtosecond Time Scale

- ☛ Electron number density  $n_e$  – time/space dependence



- Transmittance (probe beam)

$$\frac{I_d}{I_0} = e^{-\alpha d}$$

- Absorption coefficient

$$\alpha = \frac{\tau}{nc} \frac{\omega_p^2}{1 + \omega^2 \tau^2}$$

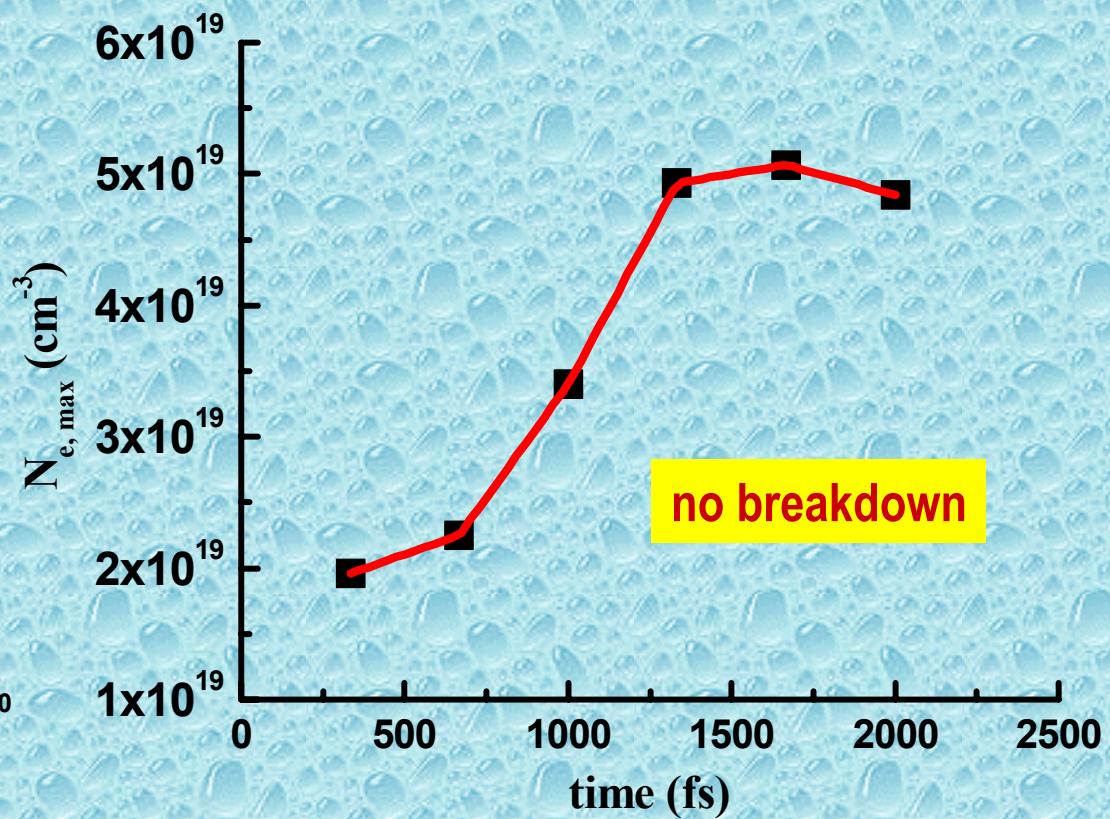
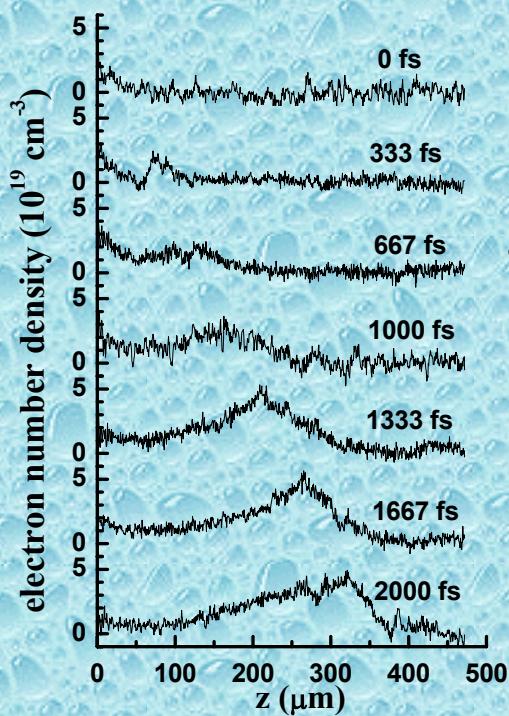
- Plasma frequency

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$



# Femtosecond Time Scale

☞ Peak electron number density  $n_e$  - time dependence



flattened peak electron number density

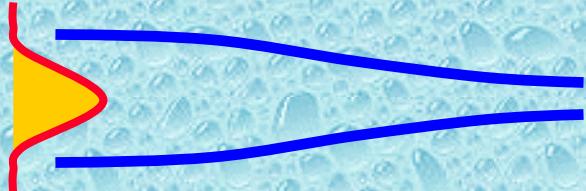
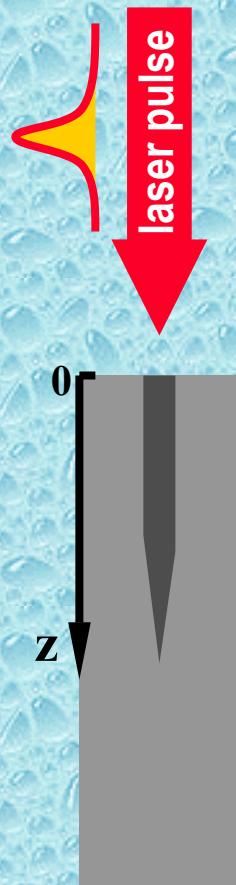


# Femtosecond Time Scale

## ☞ Fundamental processes

### ✓ Nonlinear optics

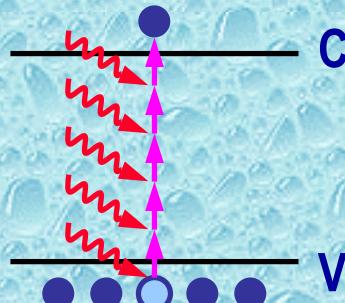
Self-focusing - intensity dependence of refractive index



positive refractive index change

### ✓ Nonlinear absorption

Electronic excitation - interband absorption



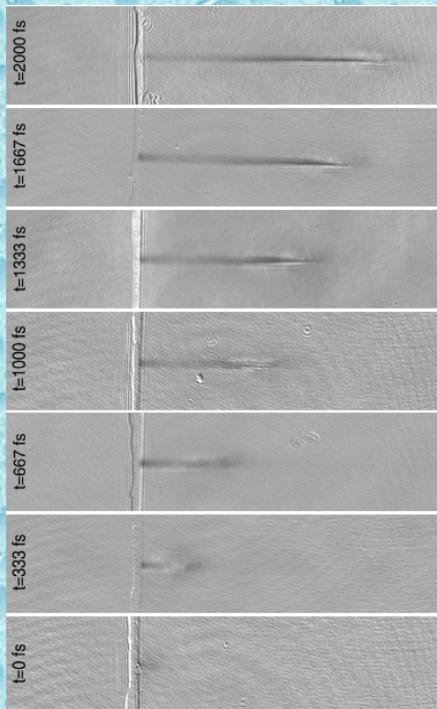
negative refractive index change

suppress self-focusing

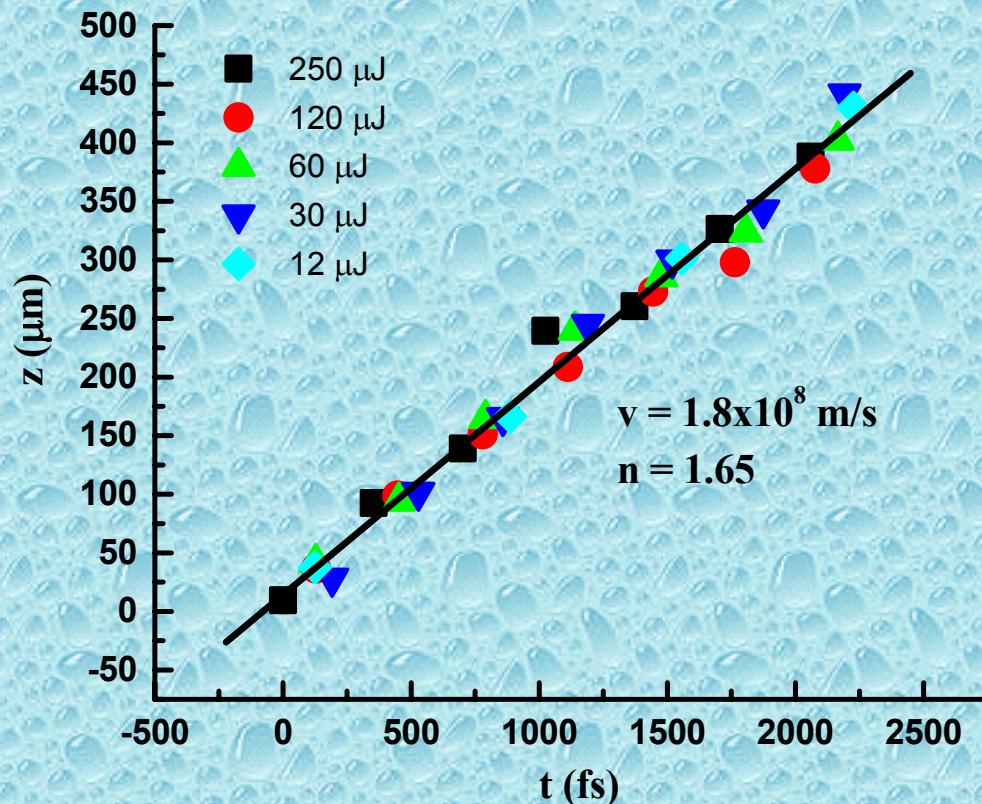


# Femtosecond Time Scale

## Propagation of electronic excitation in glass



100 fs, 800 nm  
 $E = 30 \mu J$

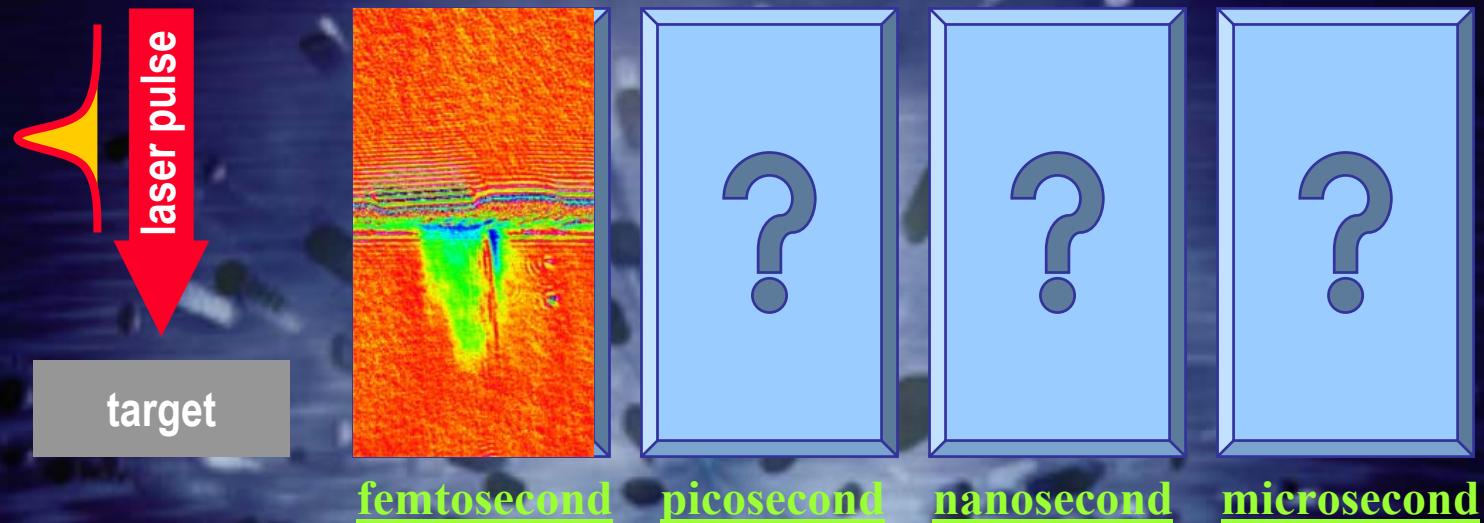


[Appl. Phys. A 79, 1695–1709 (2004)]



# Laser Ablation

☞ What is happening?

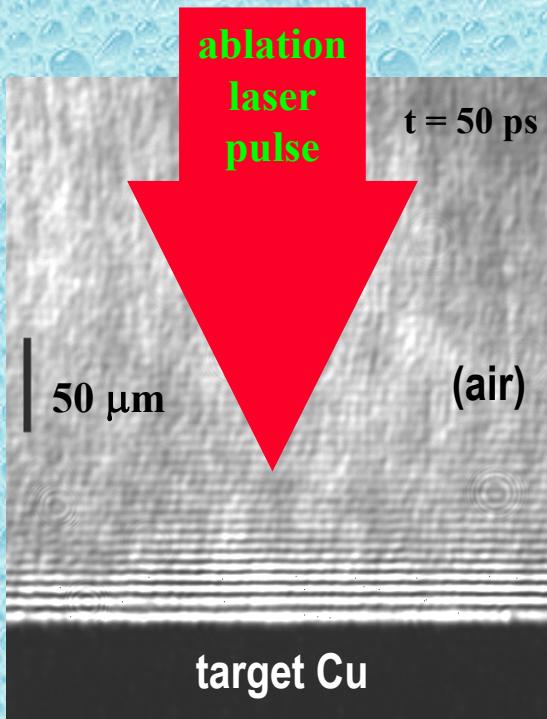


$$1 \text{ ps} = 10^{-12} \text{ s}$$

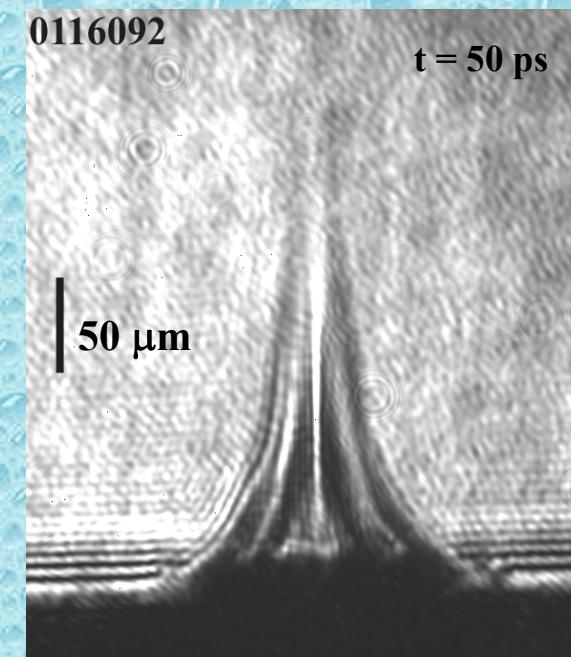


# Picosecond Time Scale

## ☞ Picosecond imaging



(laser pulse: 35 ps, fluence: **60 J/cm<sup>2</sup>**)

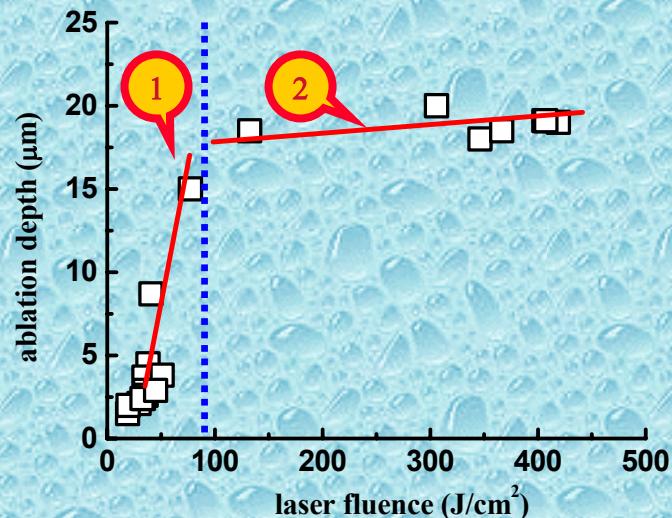
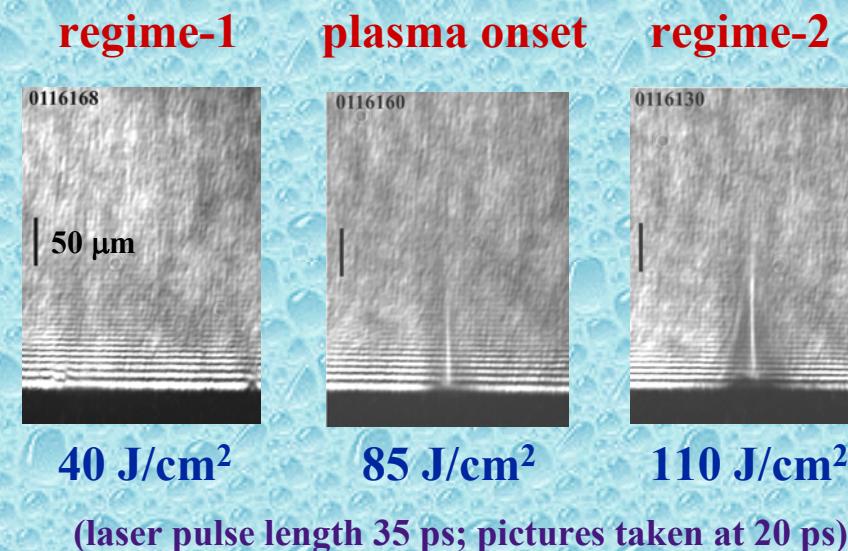


(laser pulse: 35 ps, fluence: **90 J/cm<sup>2</sup>**)



# Picosecond Time Scale

## ☞ Threshold behavior



✓ Threshold for picosecond plasma formation – same as the threshold for ablation efficiency reduction:

~  $85 \text{ J}/\text{cm}^2$  (laser fluence)

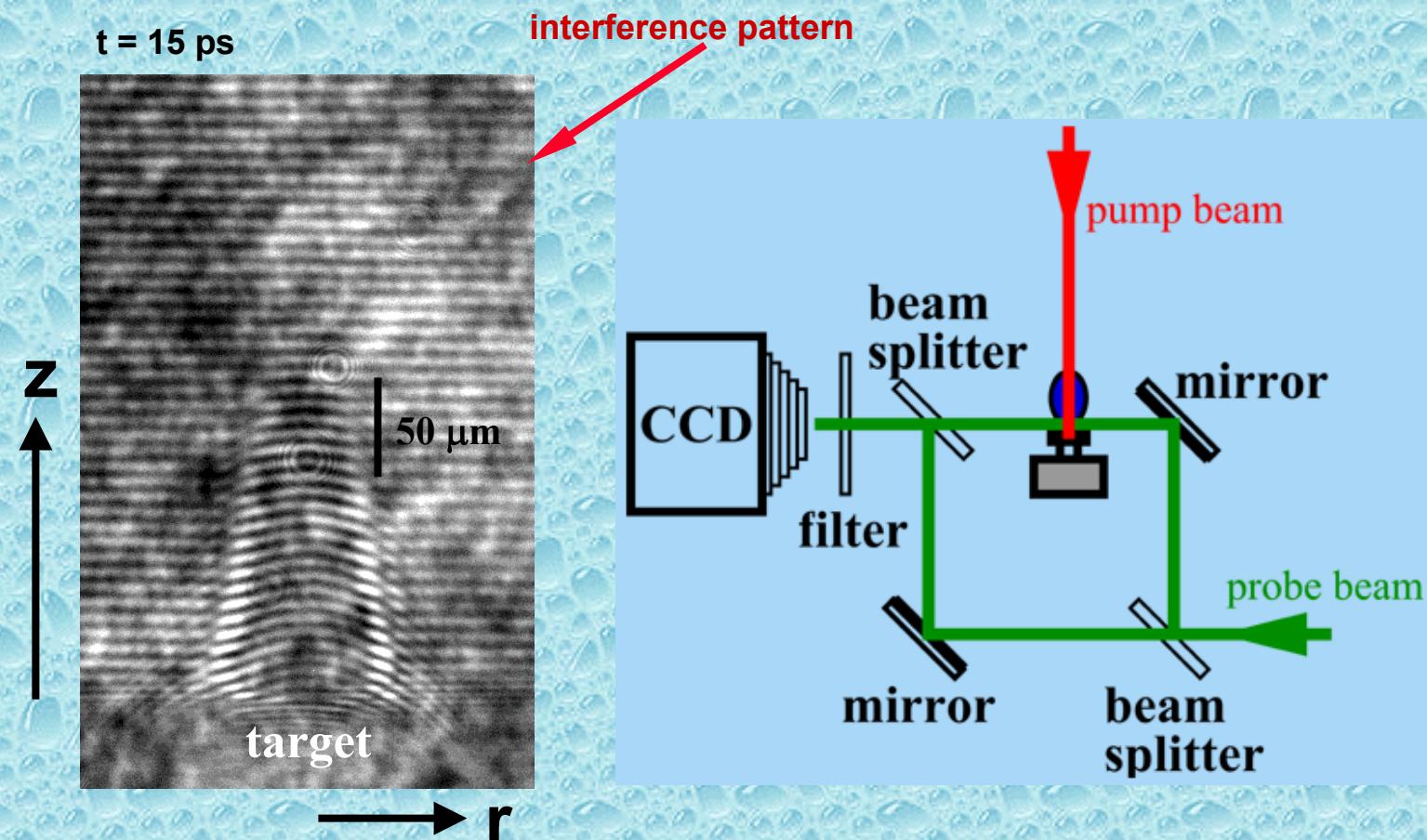
~  $10^{12} \text{ W}/\text{cm}^2$  (power density)

(threshold for direct laser-induced air breakdown: ~  $10^{13} \text{ W}/\text{cm}^2$ )



# Picosecond Time Scale

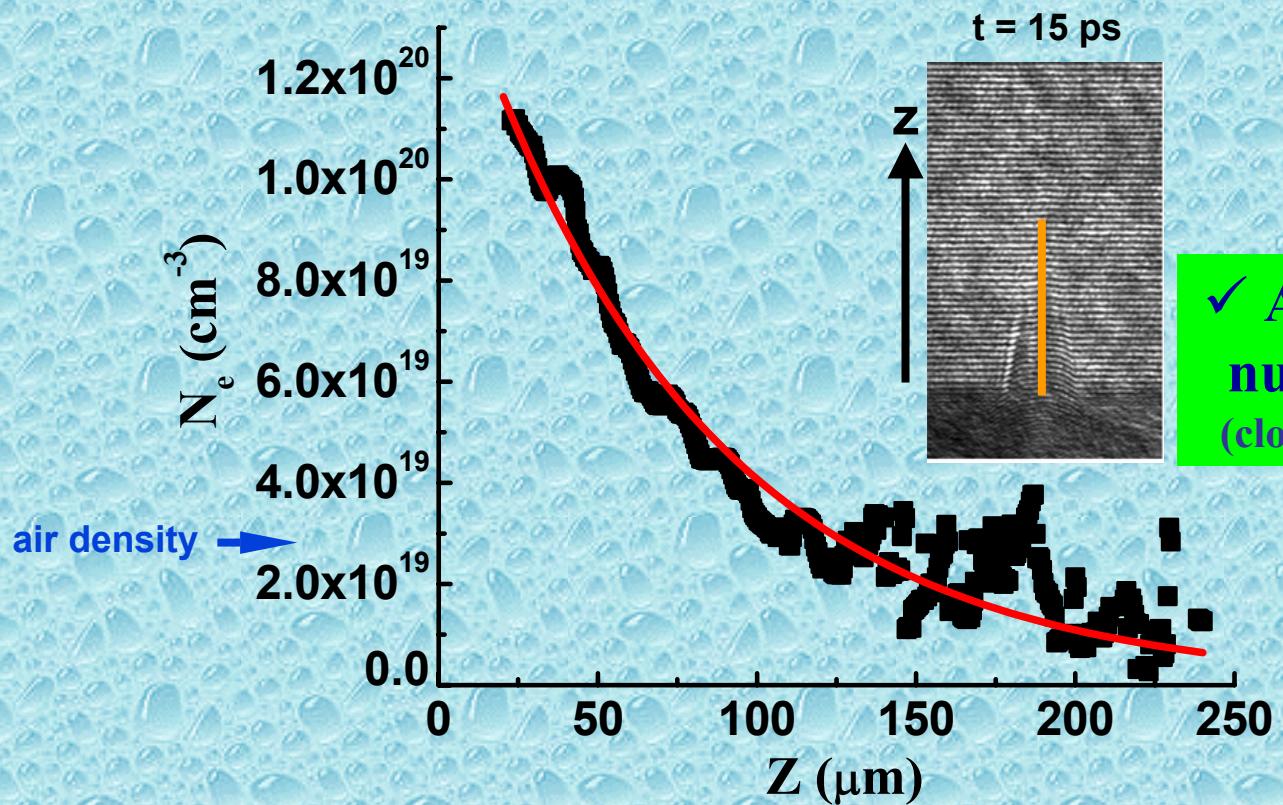
## Ultrafast interferometry





# Picosecond Time Scale

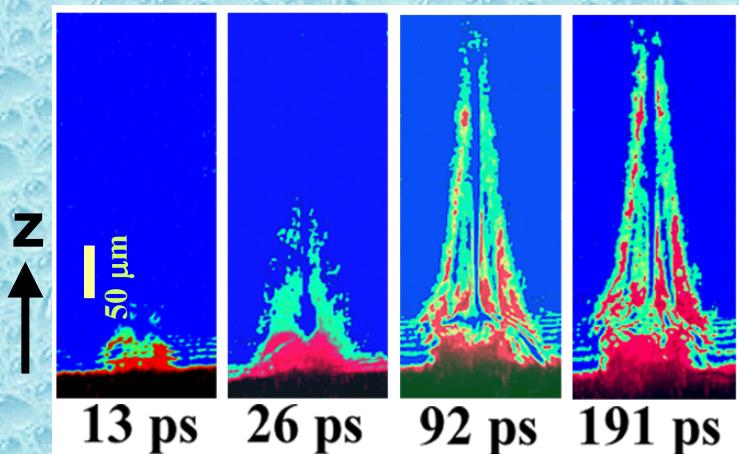
## ☞ Electron number density





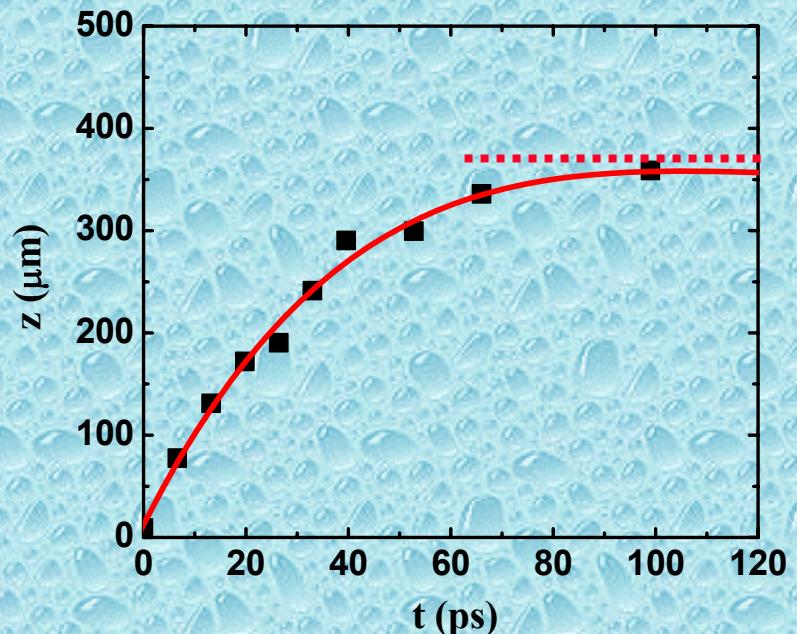
# Picosecond Time Scale

## ⌚ Longitudinal (z) expansion



(laser energy: 10 mJ)

longitudinal plasma extent vs. time



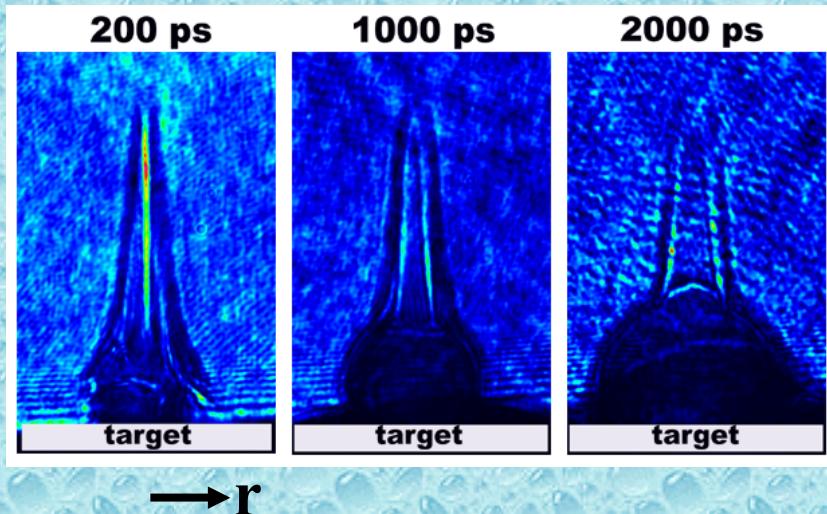
✓ longitudinal expansion is suppressed ( $t > 50$  ps)!



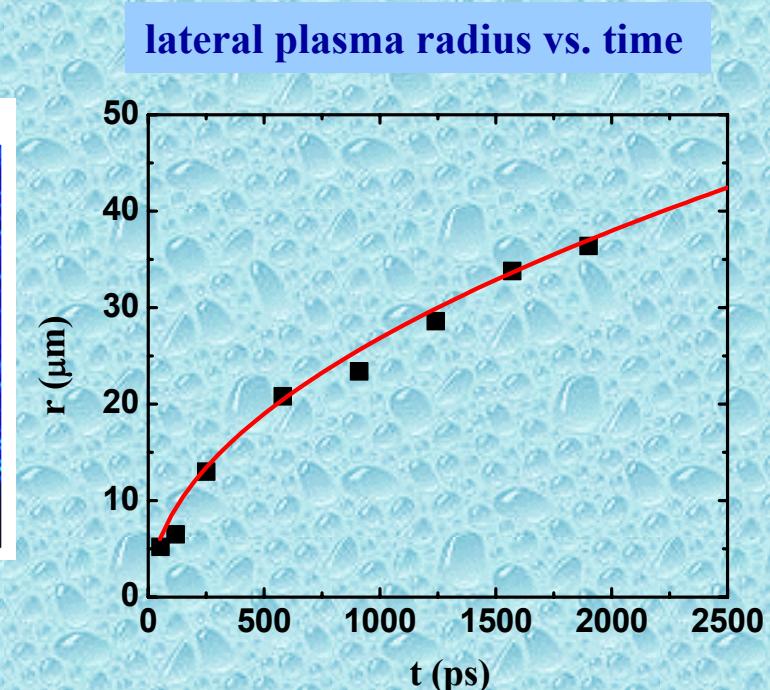
# Picosecond Time Scale

☞ Lateral ( $r$ ) expansion

( $t > 50$  ps: expansion only in lateral direction)



(laser energy: 10 mJ)

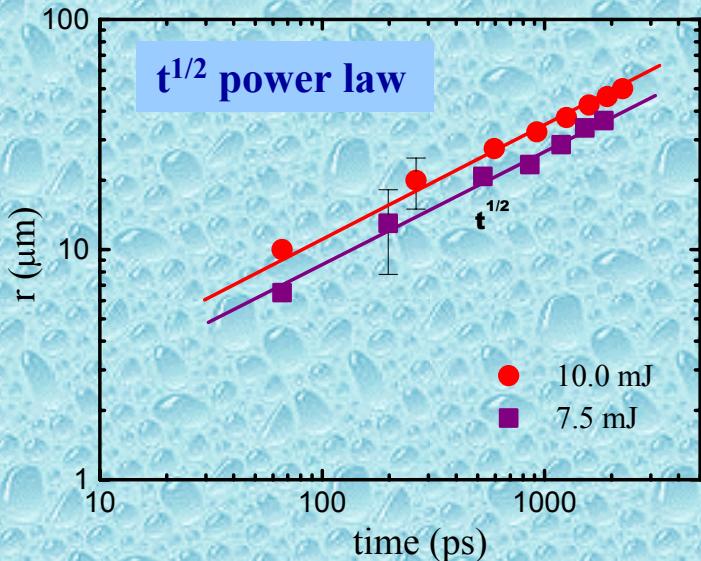


✓ lateral expansion follows a power law!



# Picosecond Time Scale

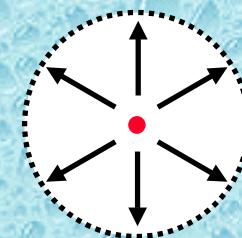
## ☞ Energy deposition to picosecond plasma



similarity relation

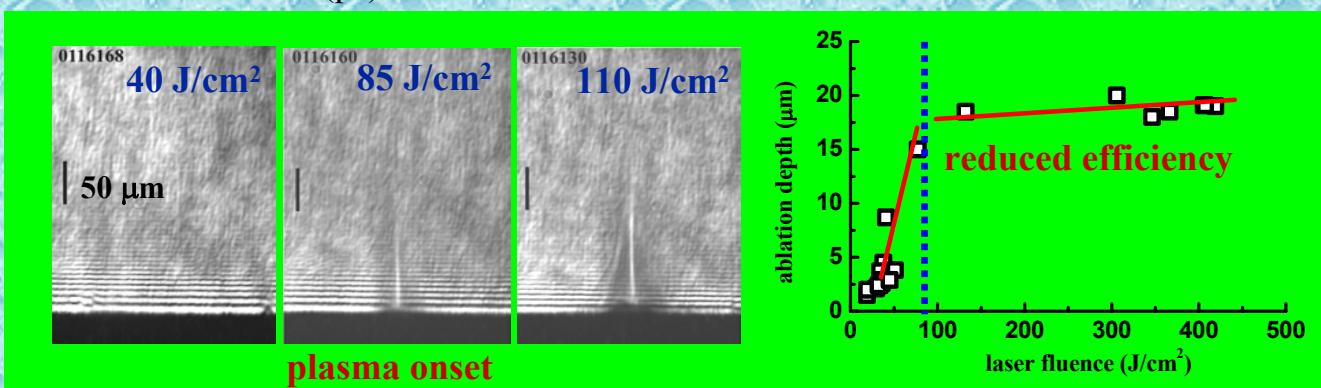
(2D blast wave - line energy source)

$$r \propto \left( \frac{E}{\rho_0} \right)^{1/4} t^{1/2}$$



$E$ : energy deposition density (laser axis)

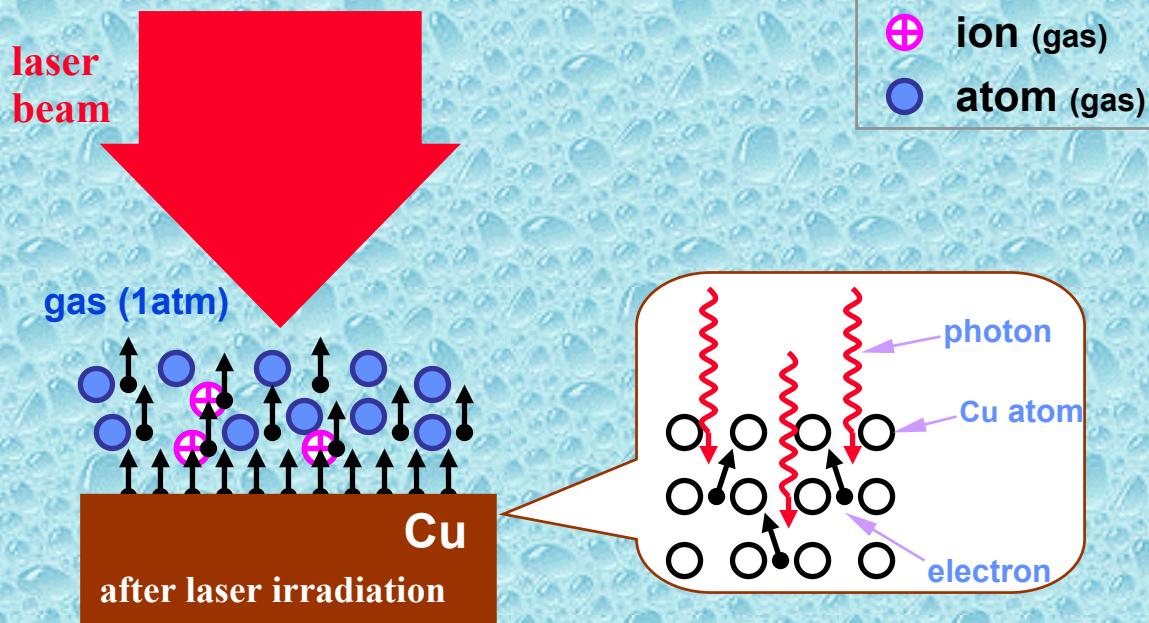
$\rho_0$ : ambient gas (air) density





# Picosecond Time Scale

## Theoretical model (laser-solid-gas interaction)



✓ **laser heating of target (metal)**

↔ electron heating - absorption of laser energy  
lattice heating - electron-phonon collisions

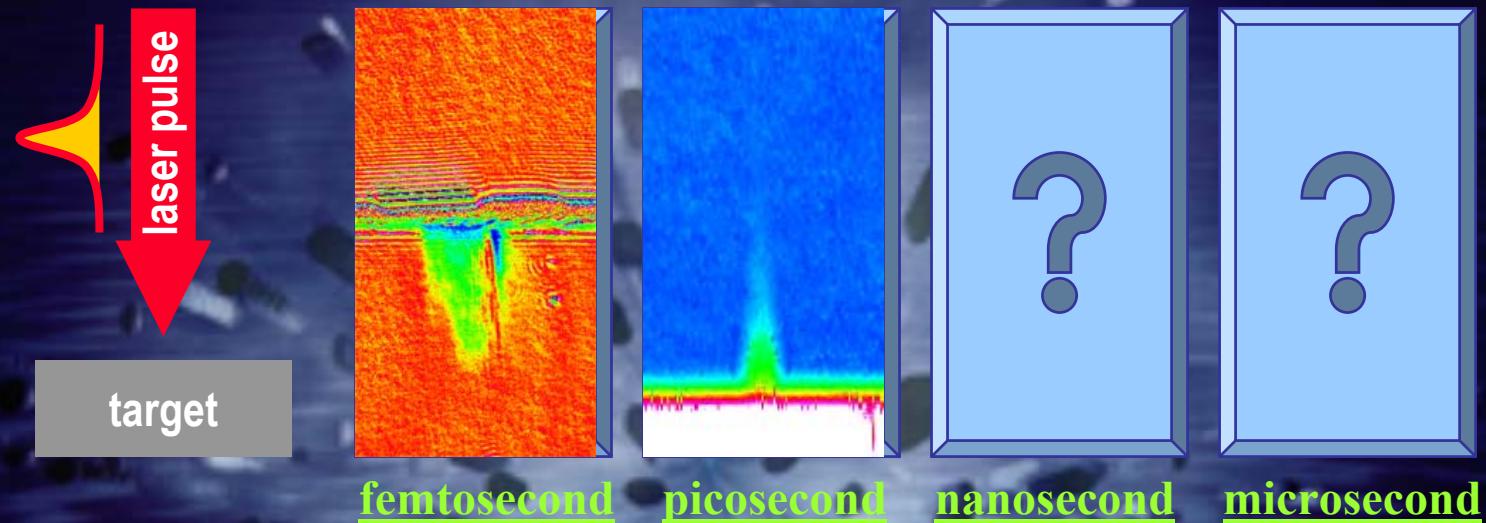
✓ **plasma development above target**

↔ surface electron emission (seed)  
impact ionization of gas



# Laser Ablation

☞ What is happening?



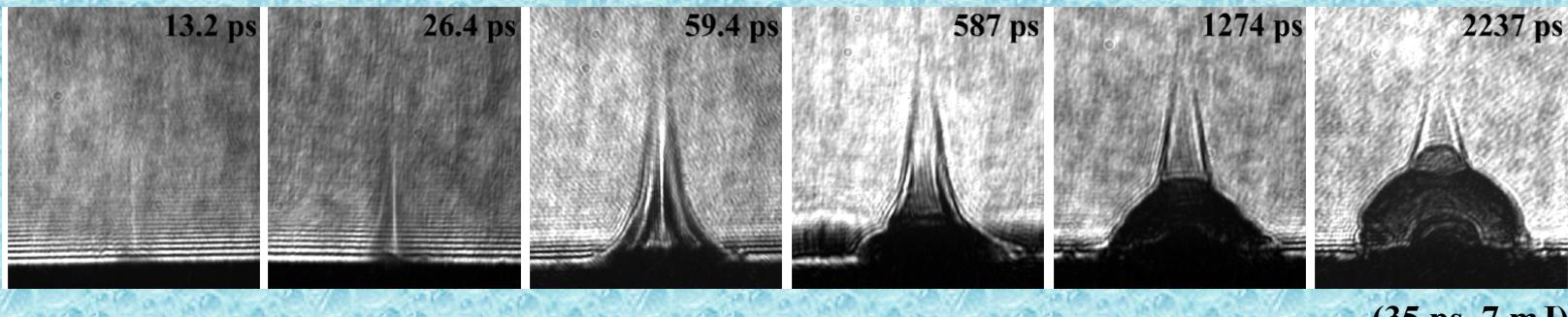
$$1 \text{ ns} = 10^{-9} \text{ s}$$

# Nanosecond Time Scale



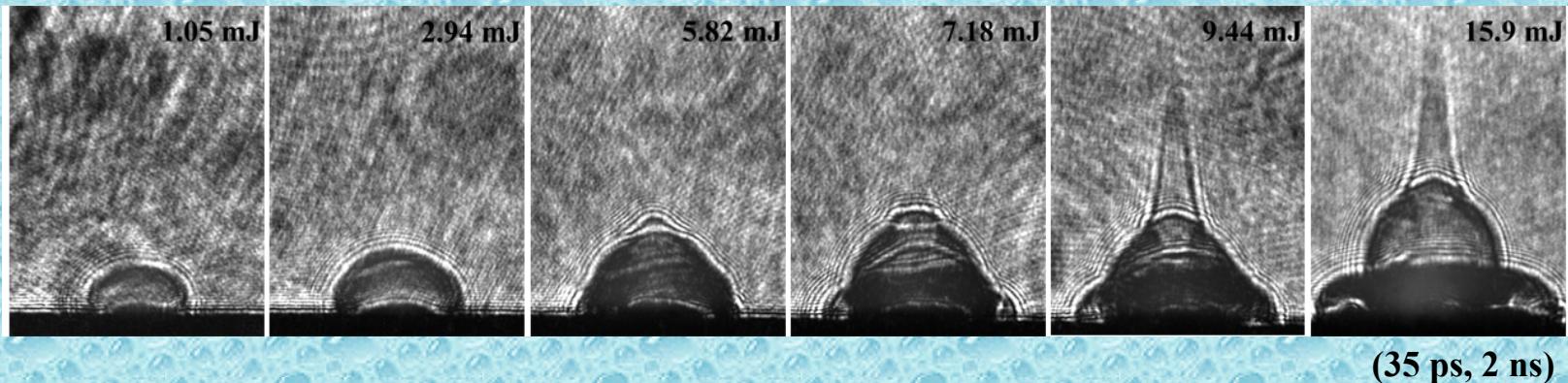
☞ Plasma evolution – picosecond to nanosecond

● time dependence



(35 ps, 7 mJ)

● laser energy dependence



(35 ps, 2 ns)



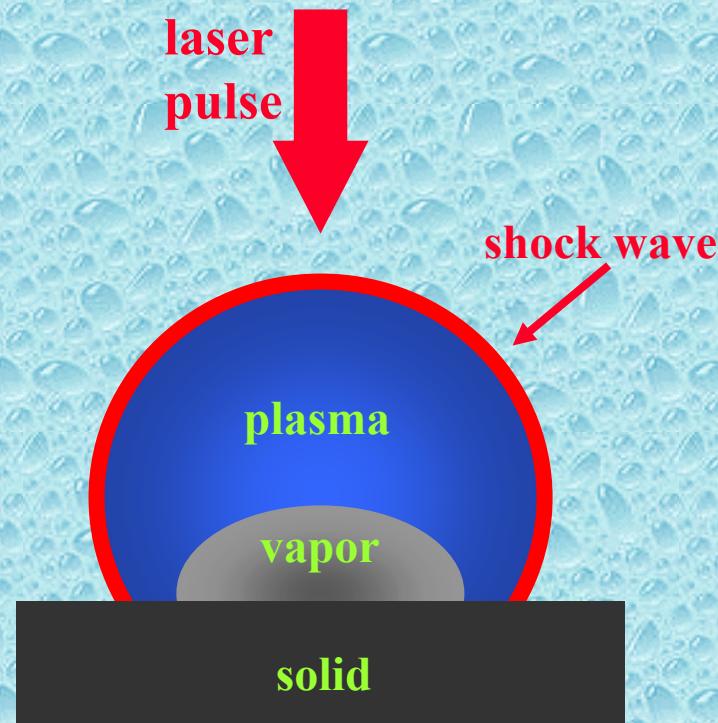
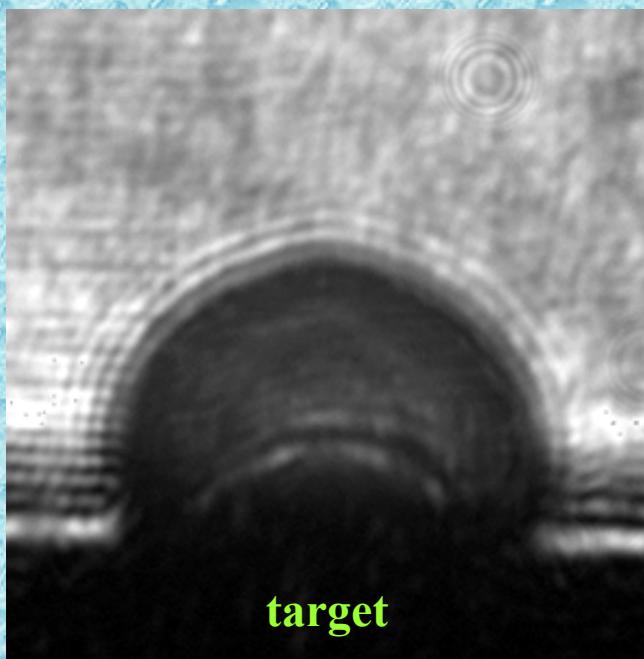
# Nanosecond Time Scale

## ☞ Plasma development

**plasma advancement:**

$\sim 10^6 \text{ cm/s}$

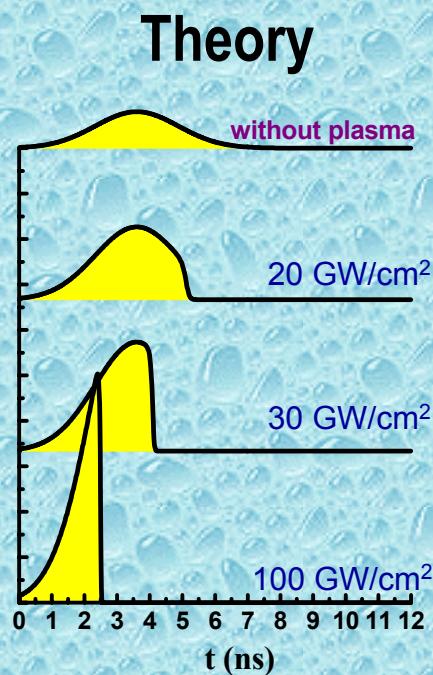
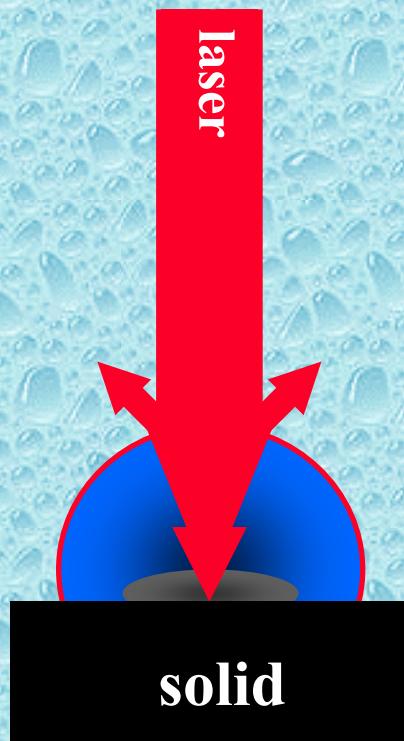
$\sim 10 \mu\text{m}$  every 1 ns (1000 ps)



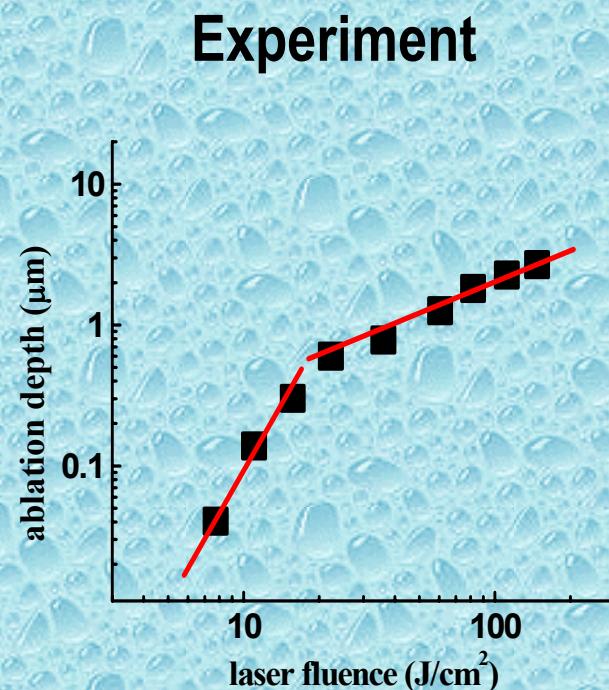


# Nanosecond Time Scale

## ☞ Plasma shielding – nanosecond



3 ns, 1064 nm laser ablation of Si  
(single pulse)

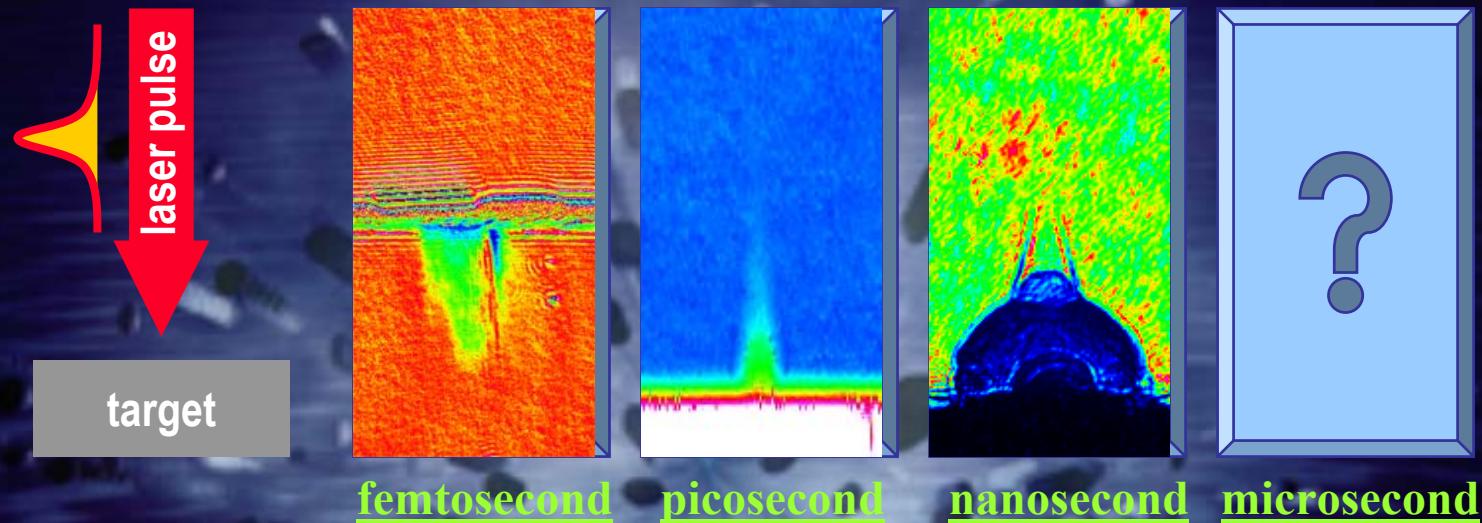


25 ns, 248 nm laser ablation of Cu  
(single pulse, in air, 100 μm spot diameter)



# Laser Ablation

☞ What is happening?



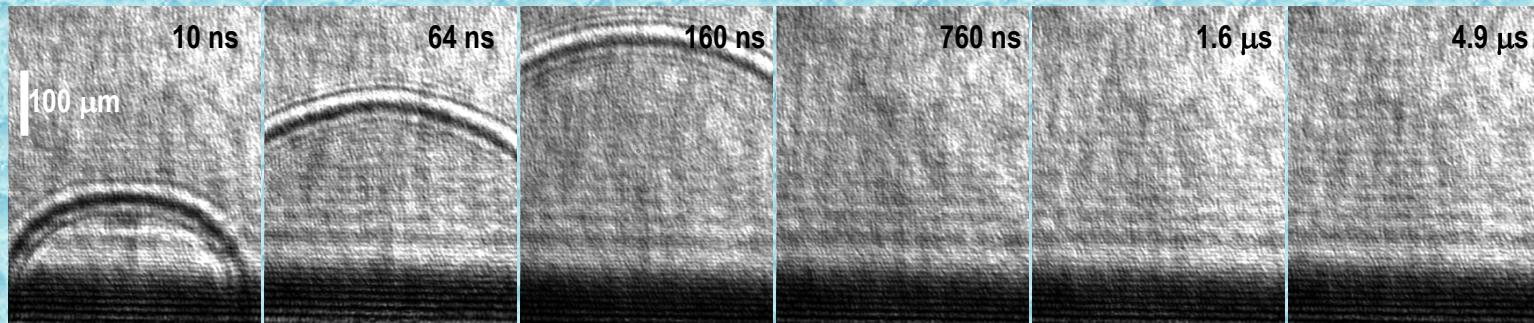
$$1 \mu\text{s} = 10^{-6} \text{ s}$$

# Microsecond Time Scale



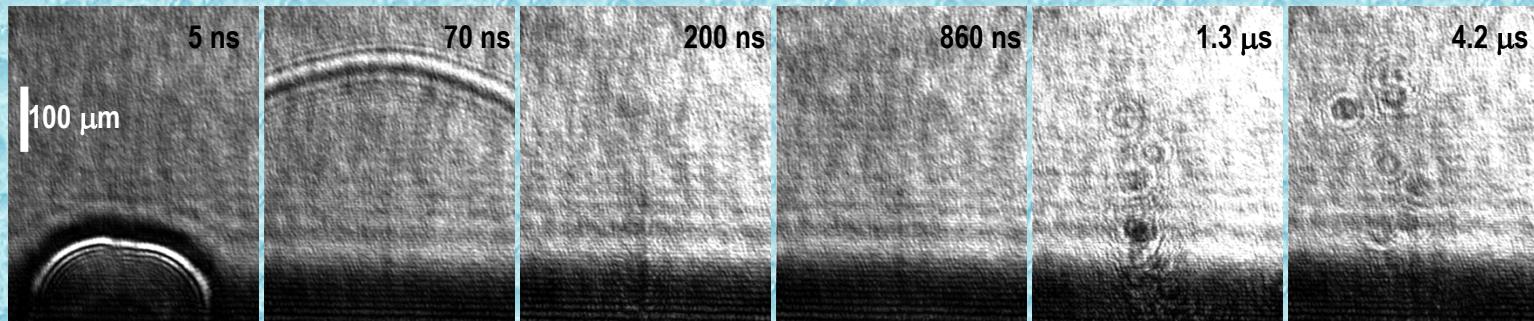
## ☞ Plume evolution

### ● below threshold



(3 ns,  $1.8 \times 10^{10} \text{ W/cm}^2$ )

### ● above threshold

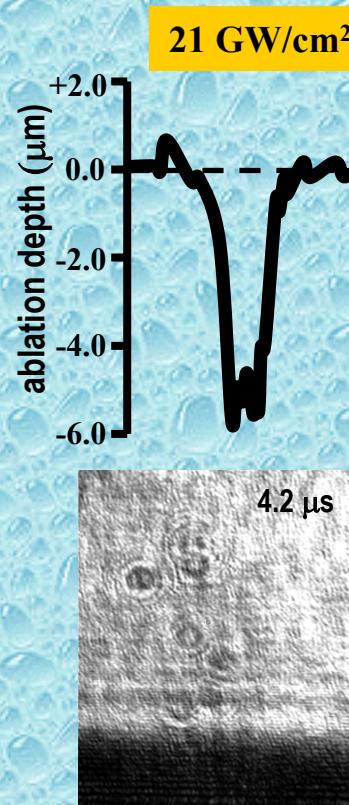
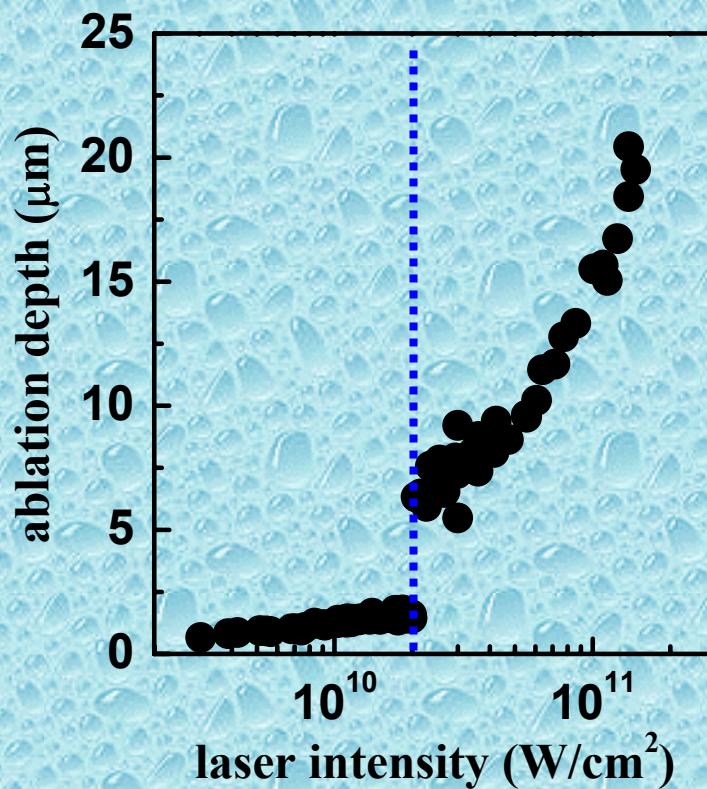
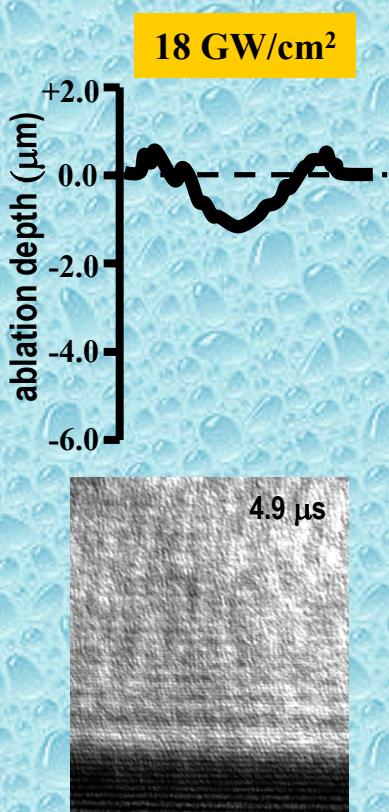


(3 ns,  $2.1 \times 10^{10} \text{ W/cm}^2$ )



# Microsecond Time Scale

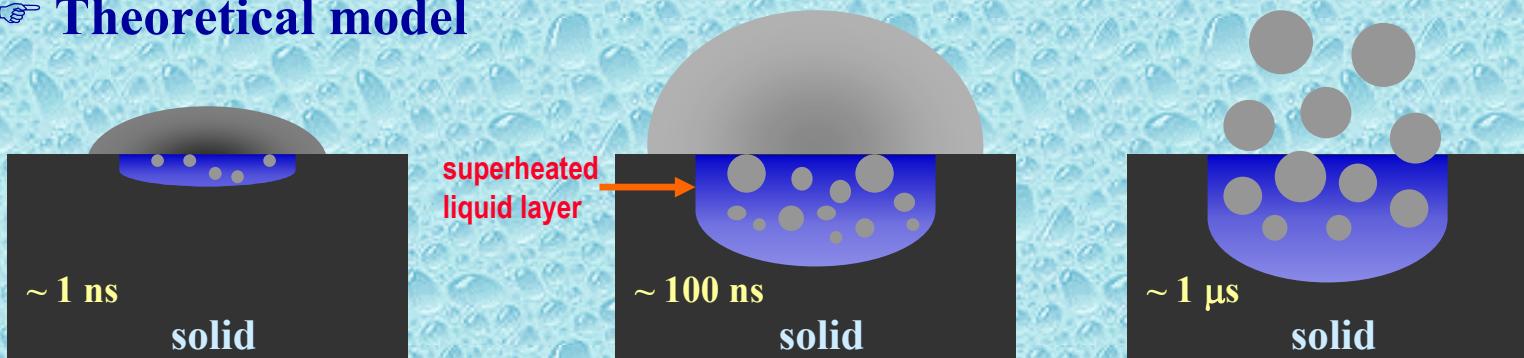
## ☛ Threshold behavior





# Microsecond Time Scale

## ☞ Theoretical model



- **Normal vaporization** (Hertz-Knudsen equations)

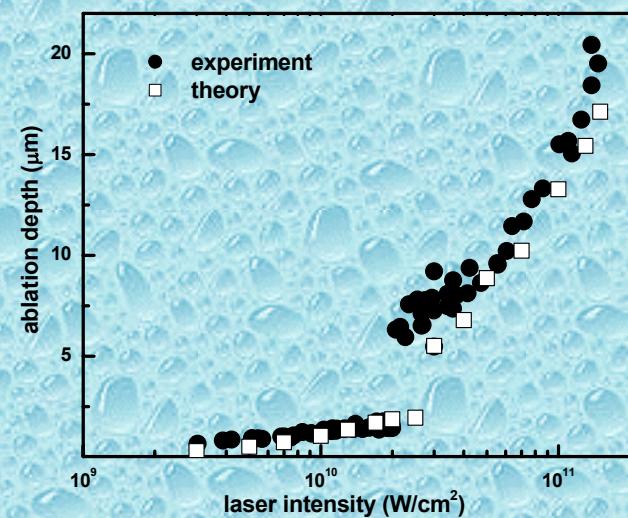
$$\left. \frac{\partial x}{\partial t} \right|_{x=0} = \beta p_b \frac{m}{\rho} (2\pi m k_B T)^{-1/2} \exp\left[\frac{L_{ev} m}{k_B} \left(\frac{1}{T_b} - \frac{1}{T}\right)\right]$$

ablation below threshold: normal evaporation

- **Explosive boiling** (heat diffusion –  $T_{max} \sim T_c$ )

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \alpha I_{laser} \exp(-\alpha x)$$

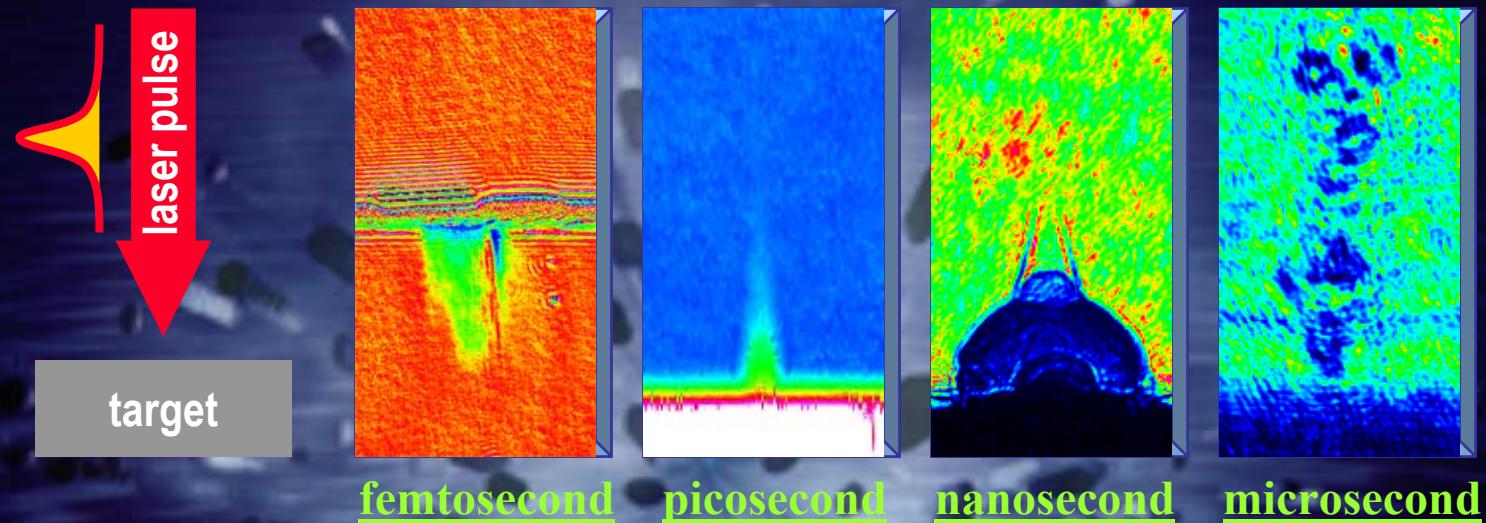
ablation above threshold: normal evaporation and explosive boiling





# Laser Ablation

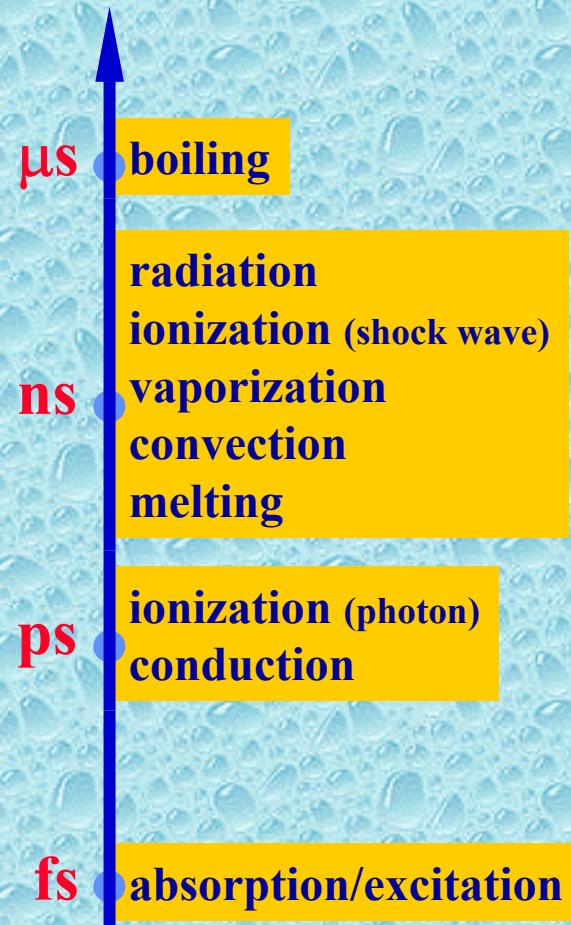
☞ What is happening?





# Laser Ablation

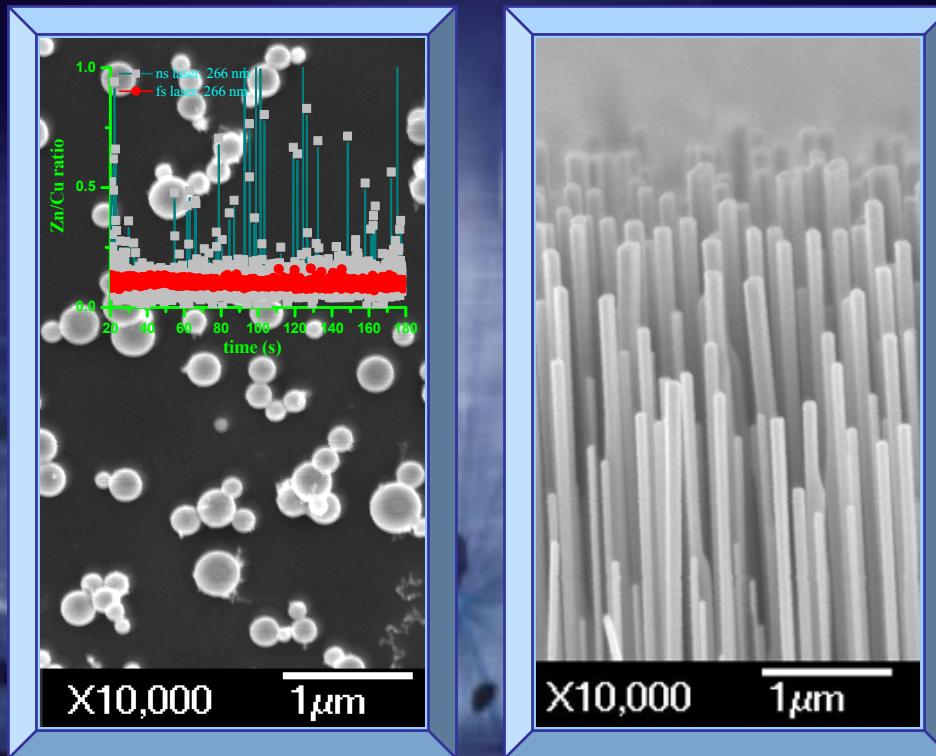
## ☞ Fundamental processes





# Laser Ablation

## Applications



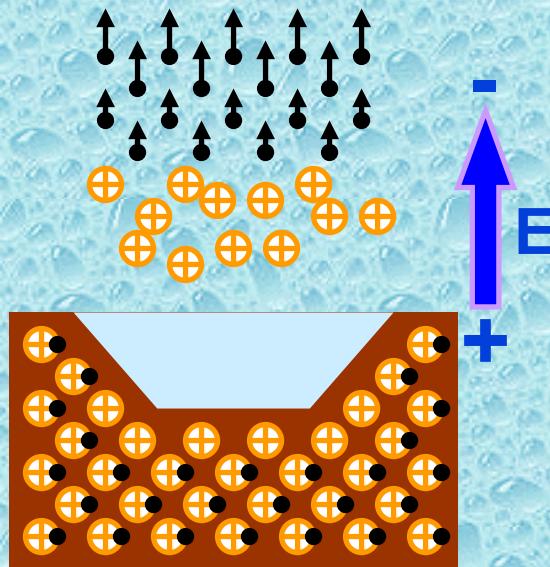
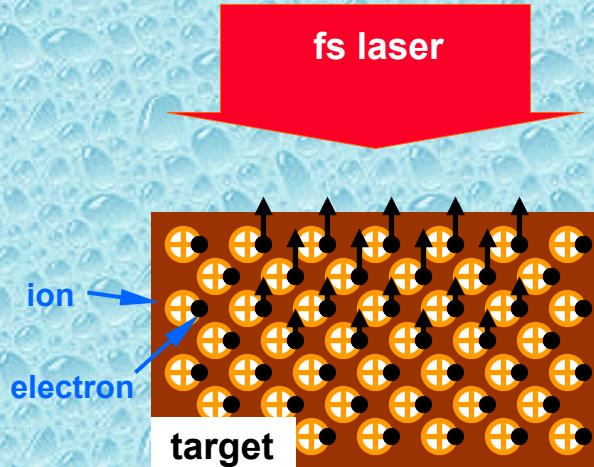
micro-analysis

nano-material



# Applications of *Ultrafast* Laser Ablation

- ☞ Ultrafast laser ablation ( $\tau_{\text{pulse}} < t_{\text{thermal}}$ ) – FEL capability!
  - Non-thermal ablation regime



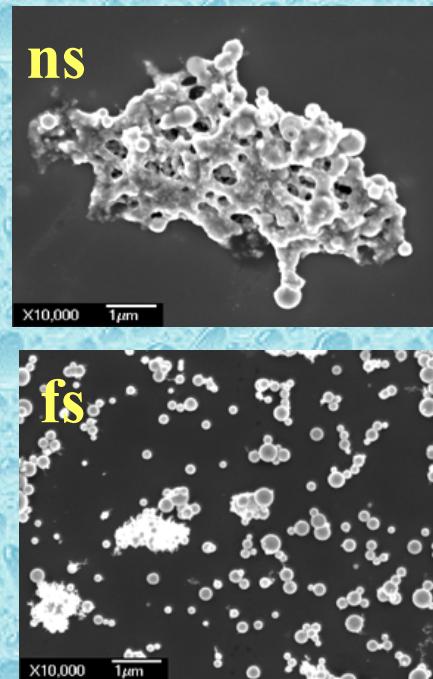
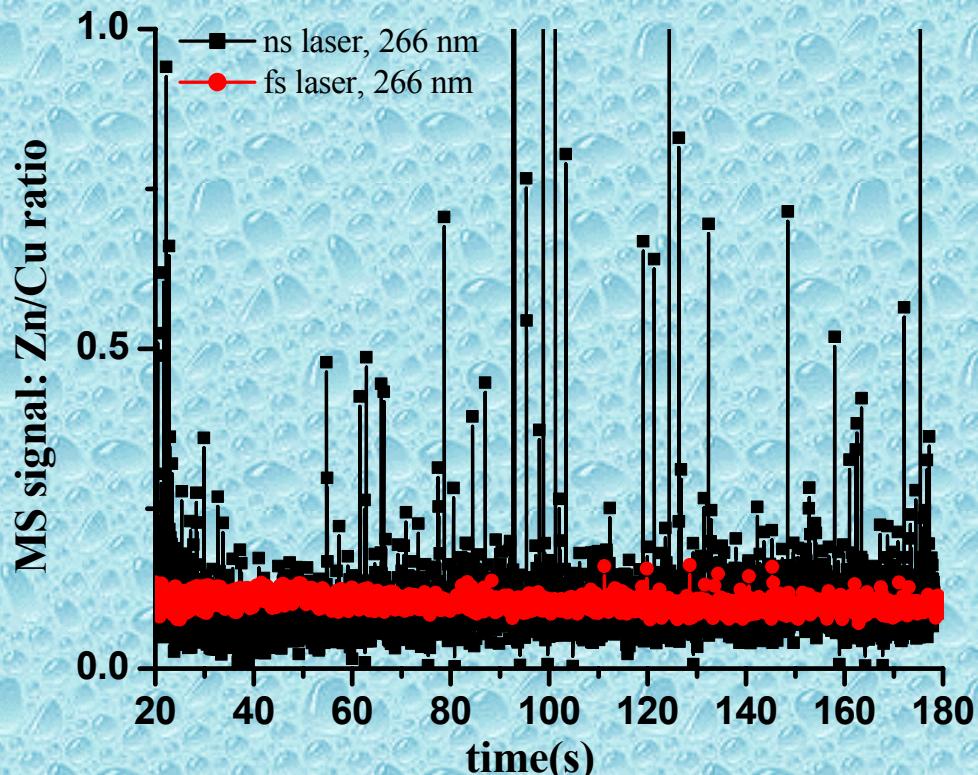
- ✓ Reduced dependence on thermal properties
- ✓ Reduced larger cluster particles generation



# Applications of *Ultrafast* Laser Ablation

## ☞ Micro Analysis

The problem of nanosecond laser ablation



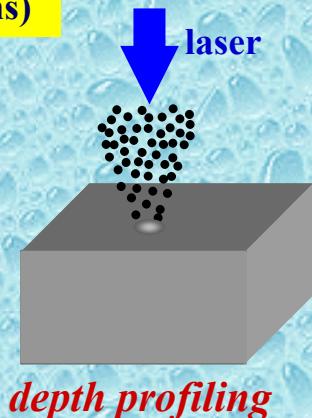
Mass Spectrometry - Laser ablation of brass (CuZn alloy)



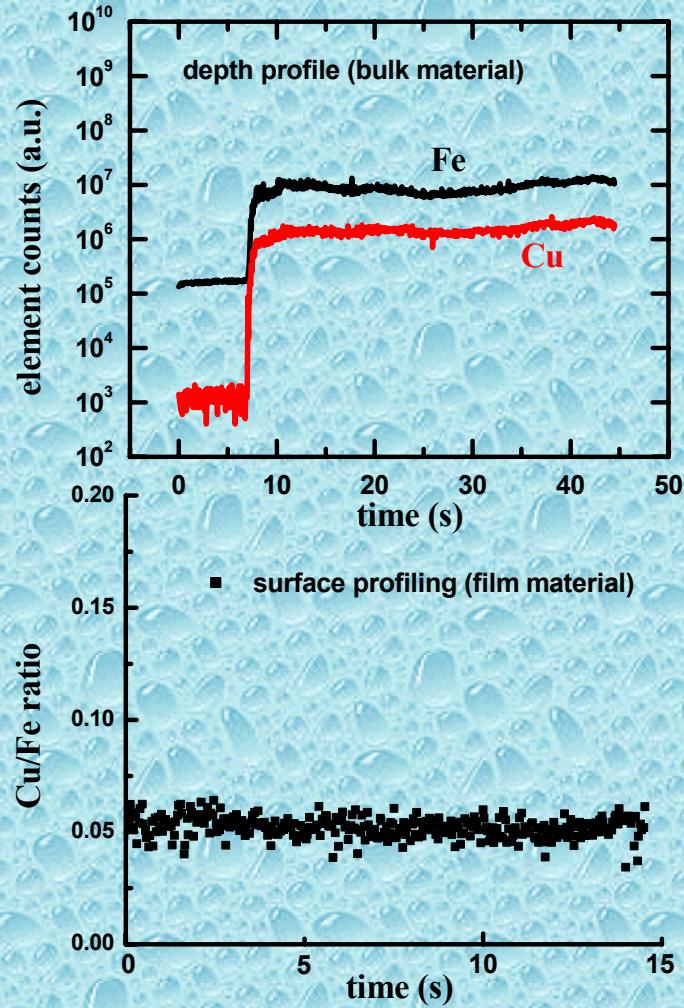
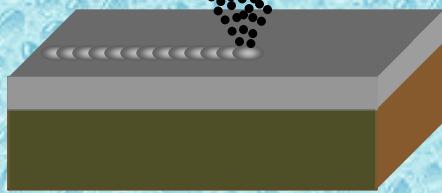
# Micro-Analysis Application

New magnetic film material  
(data storage applications)

sputtering target



deposited film

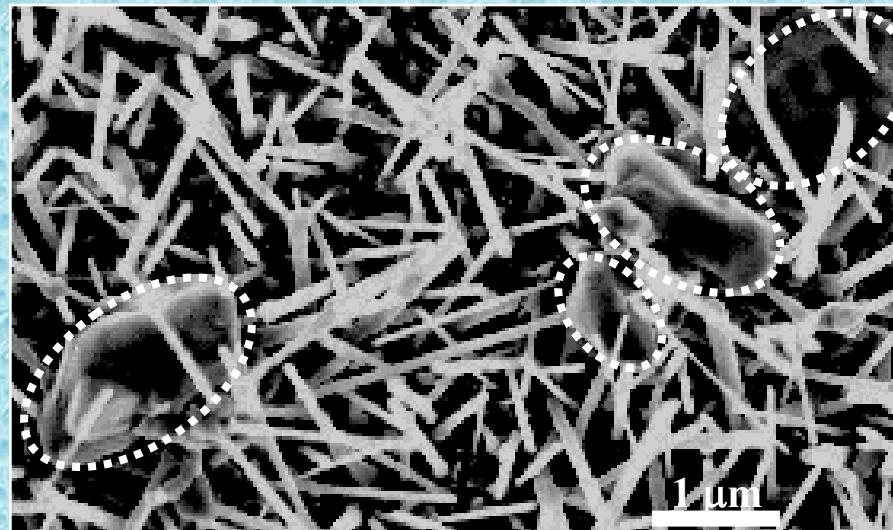
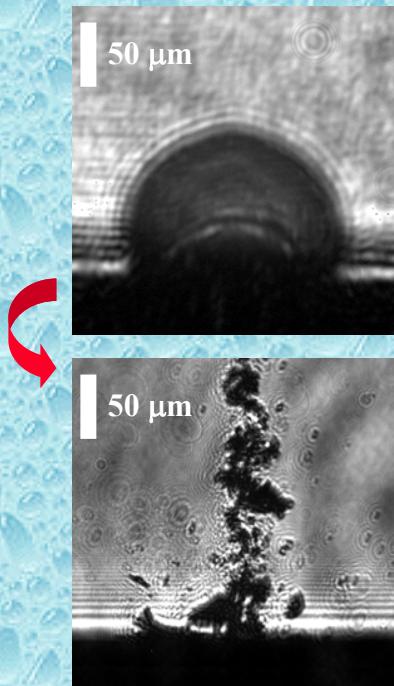




# Applications of *Ultrafast* Laser Ablation

## Nano Material

The problem of nanosecond laser ablation

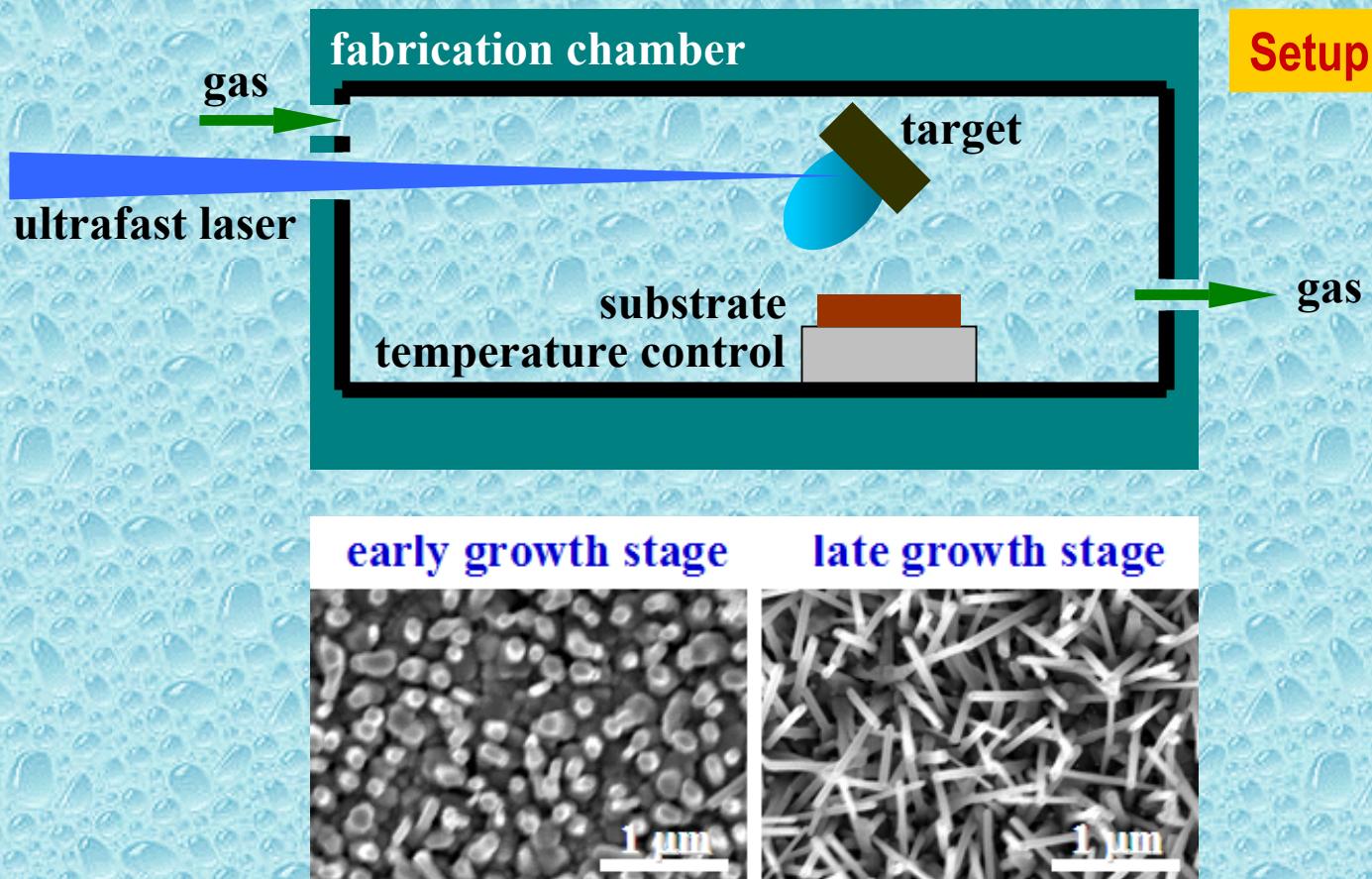


Nanowires with large particles



# Nano-Material Application

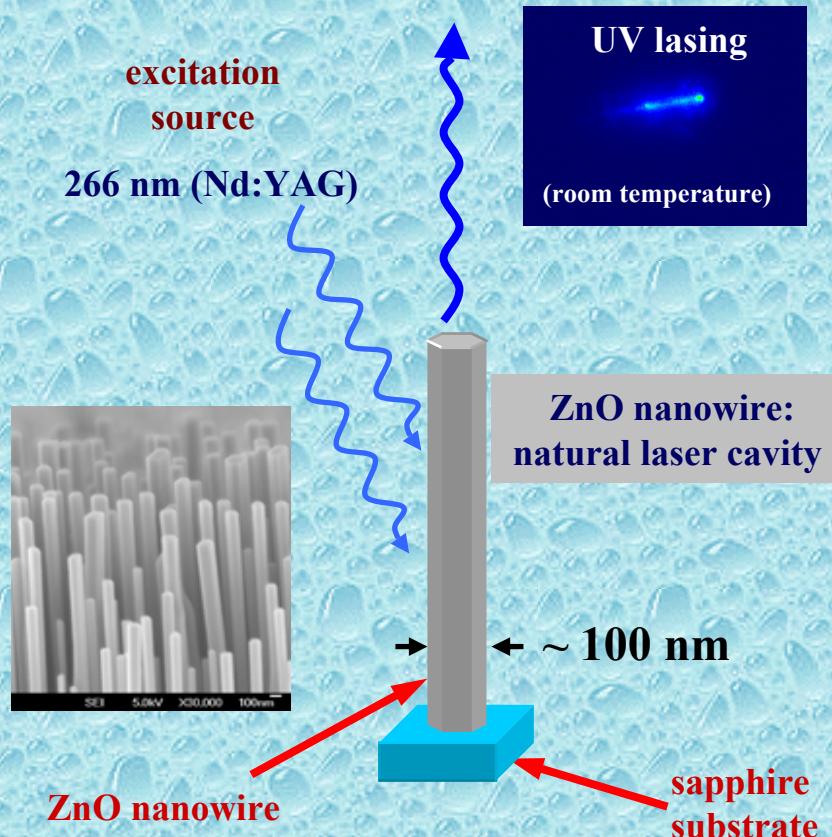
## ☞ Pulsed laser deposition – ZnO nanowire growth



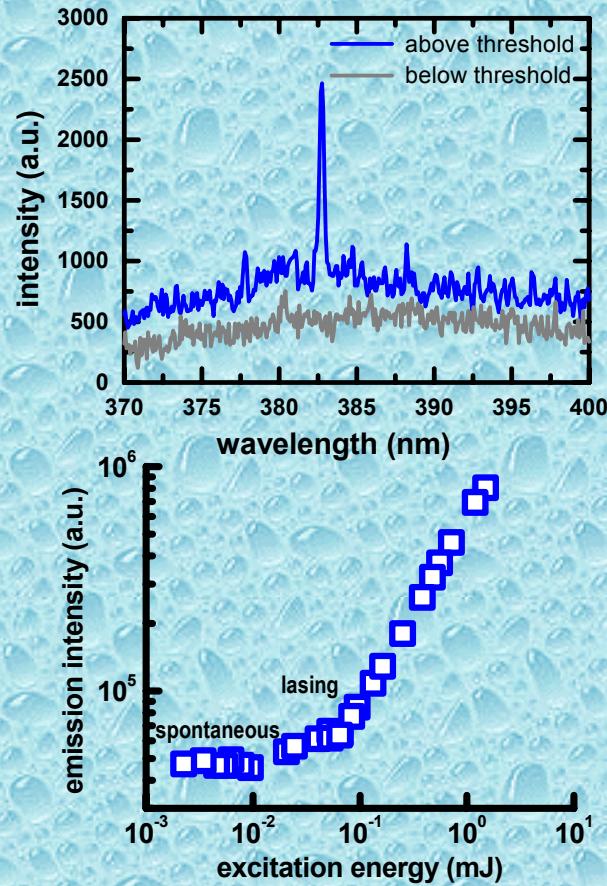


# Nano-Material Application

## ☞ Nanowire nanolaser



## ☞ Nanolaser spectra



[Science 292 (2001) 1897]



# Acknowledgements

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U. S. Department of Energy

Yanfeng Zhang  
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Richard Russo  
Xianglei Mao