ON THE MODELING OF DOUBLE PULSE LASER ABLATION OF METALS

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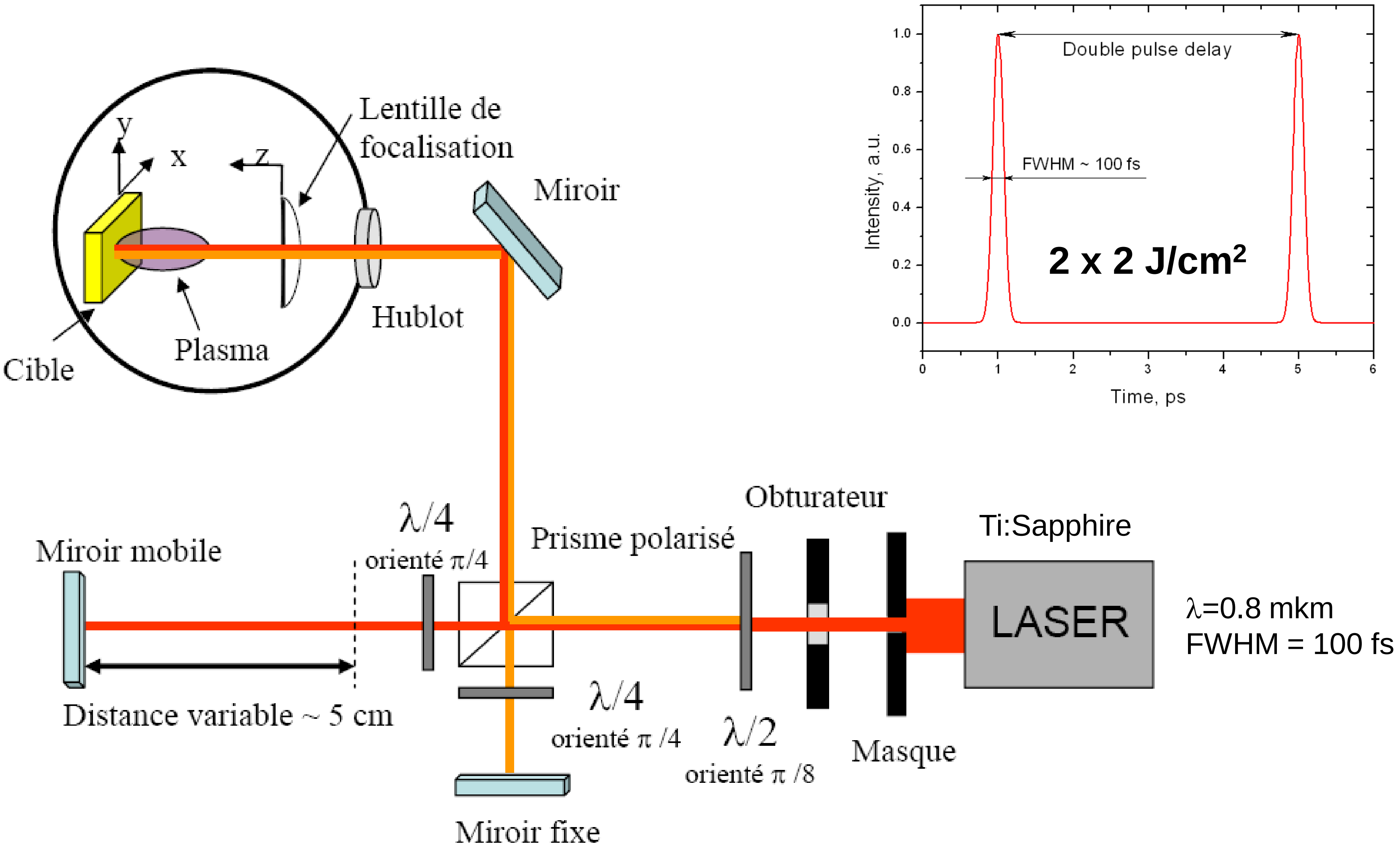
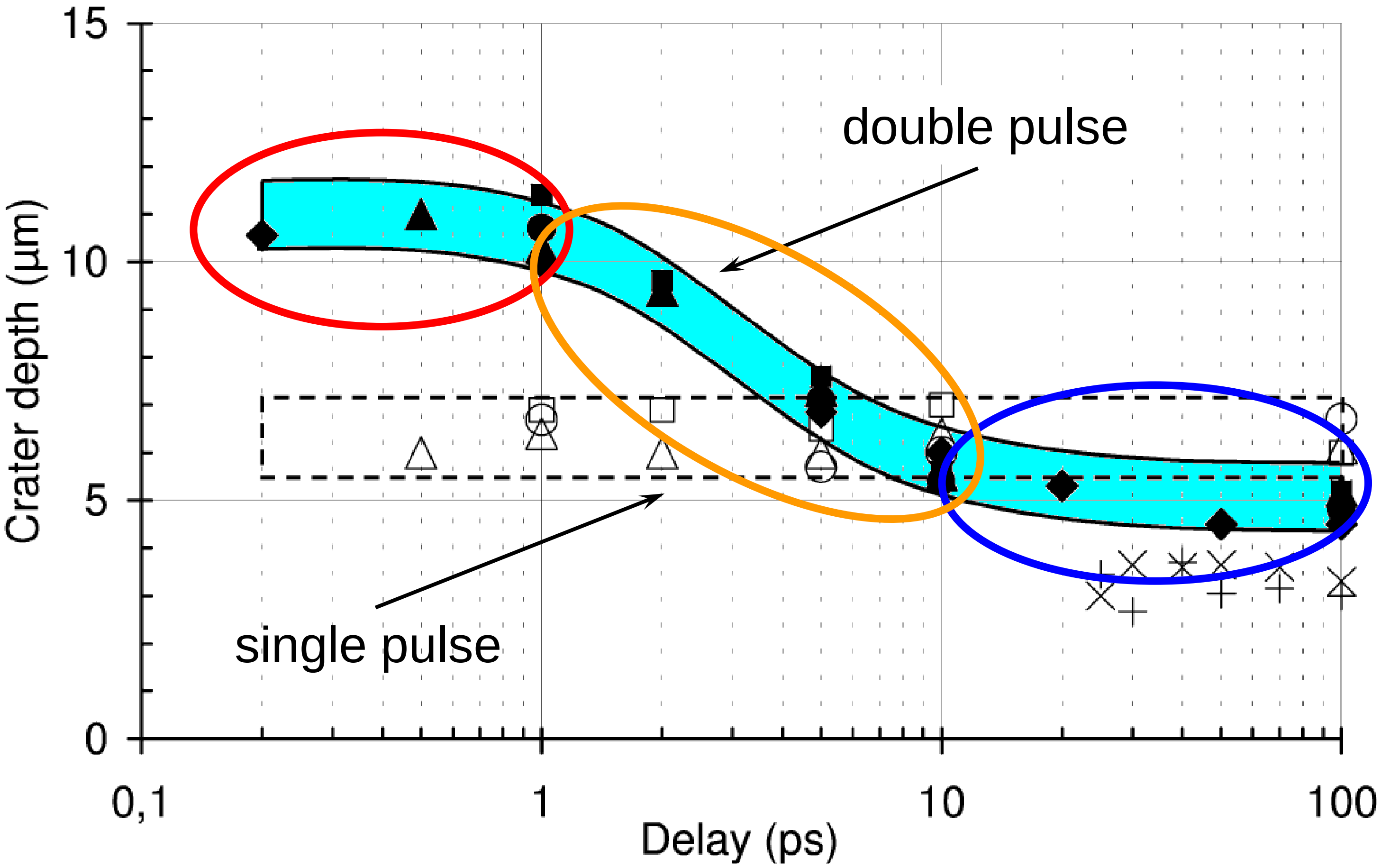
Outline

- Motivation
- Set-up configuration
- Double pulse experiments
- Numerical model
  - Basic equations
  - Transport properties
  - Equation of state
  - Fragmentation effects
- Preliminary results
- Summary

Double pulse set-up

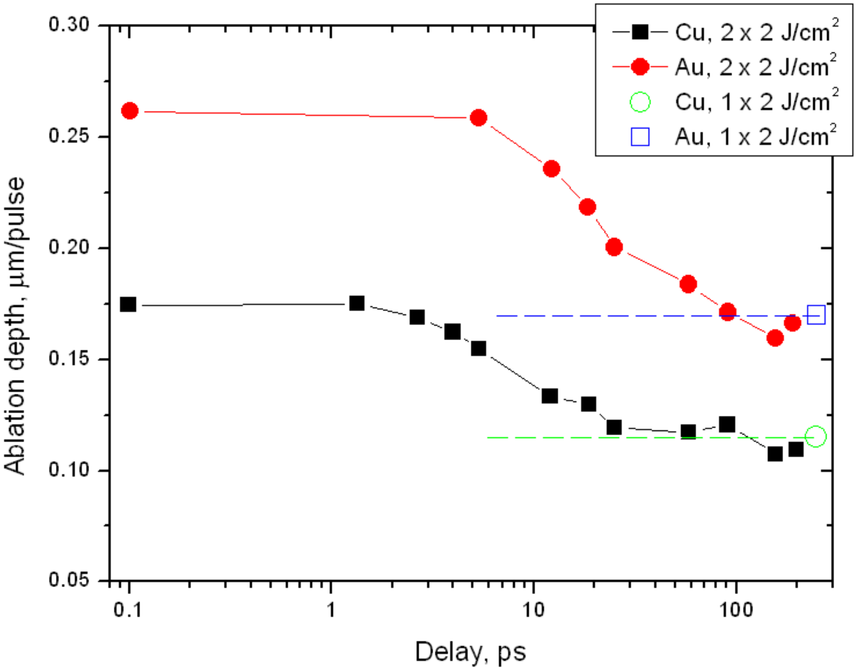


Experiment: single & double pulses, Cu

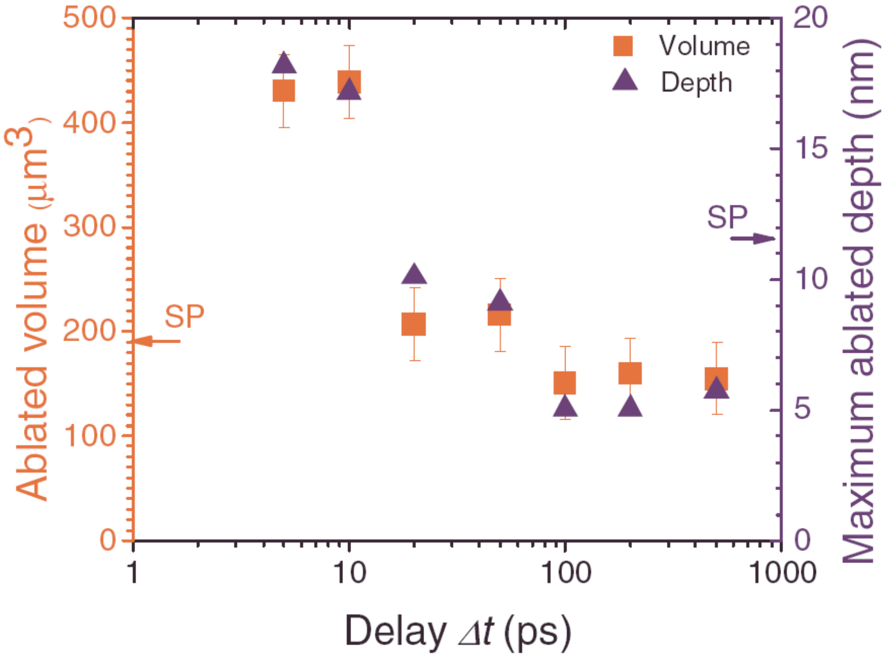


A.Semerok & C. Dutouquet *Thin Solid Films* **453 – 454** (2004)

Experiment: single & double pulses



J. Hermann & S. Noël, LP3 (2008)



T. Donnelly *et al.* J. Appl. Phys. **106**, 013304 2009

Two-temperature multi-material Eulerian hydrodynamics

Basic equations

$$\frac{\partial f^\alpha}{\partial t} + \nabla\cdot(f^\alpha \mathbf{u}) = \frac{f^\alpha \overline{K}_S}{K_S^\alpha}\nabla\cdot\mathbf{u}$$

$$\frac{\partial(f^\alpha\rho^\alpha Z^\alpha)}{\partial t} + \nabla\cdot(f^\alpha\rho^\alpha Z^\alpha\mathbf{u}) = f^\alpha m_i^\alpha S^\alpha$$

$$\frac{\partial(f^\alpha\rho^\alpha)}{\partial t} + \nabla\cdot(f^\alpha\rho^\alpha\mathbf{u}) = 0$$

$$\frac{\partial(\overline{\rho}\mathbf{u})}{\partial t} + \nabla\cdot(\overline{\rho}\mathbf{u}\otimes\mathbf{u}) + \nabla\overline{P} = 0$$

$$\frac{\partial}{\partial t}\left[f^\alpha\rho^\alpha\left(E_e^\alpha + \frac{|\mathbf{u}|^2}{2}\right)\right] + \nabla\cdot\left[f^\alpha\rho^\alpha\left(E_e^\alpha + \frac{|\mathbf{u}|^2}{2}\right)\mathbf{u}\right] + \frac{f^\alpha\rho^\alpha}{\overline{\rho}}\nabla\overline{P}\cdot\mathbf{u} =$$

$$-\overline{P}_e\frac{f^\alpha\overline{K}_S}{K_S^\alpha}\nabla\cdot\mathbf{u} - \boxed{f^\alpha Q_{ei}^\alpha} + \boxed{Q_L^\alpha} + \boxed{\frac{f^\alpha\rho^\alpha C_e^\alpha}{\overline{\rho}\overline{C}_e}\nabla\cdot(\overline{\kappa}_e\nabla\overline{T}_e)} + \boxed{f^\alpha Q_J^\alpha} + \boxed{f^\alpha Q_{rad}^\alpha}$$

$$\frac{\partial(f^\alpha\rho^\alpha E_i^\alpha)}{\partial t} + \nabla\cdot(f^\alpha\rho^\alpha E_i^\alpha\mathbf{u}) = -\overline{P}_i\frac{f^\alpha\overline{K}_S}{K_S^\alpha}\nabla\cdot\mathbf{u} + \boxed{f^\alpha Q_{ei}^\alpha}$$

$$\boxed{\begin{array}{c} F_i^\alpha(\rho, T_i) \Rightarrow E_i^\alpha, C_i^\alpha, P_i^\alpha, K_{iS}^\alpha \\ F_e^\alpha(\rho, T_e) \Rightarrow E_e^\alpha, C_e^\alpha, P_e^\alpha, K_{eS}^\alpha \end{array}}$$

Mixture model

$$\sum_\alpha f^\alpha = 1$$

$$\overline{\rho} = \sum_\alpha f^\alpha\rho^\alpha$$

$$\overline{C}_e = \frac{1}{\overline{\rho}}\sum_\alpha(f^\alpha\rho^\alpha C_e^\alpha)$$

$$1/\overline{K}_S = \sum_\alpha(f^\alpha/K_S^\alpha)$$

$$\overline{P} = \sum_\alpha\frac{f^\alpha P^\alpha}{K_S^\alpha}\Bigg/\sum_\alpha\frac{f^\alpha}{K_S^\alpha}$$

$$\overline{\rho}\overline{C}_e/\overline{\kappa}_e = \sum_\alpha(f^\alpha\rho^\alpha C_e^\alpha/\kappa_e^\alpha)$$

$$\overline{T} = \sum_\alpha f^\alpha\rho^\alpha C^\alpha T^\alpha\Bigg/\sum_\alpha f^\alpha\rho^\alpha C^\alpha$$

Transport properties

$$\nu = \min(\nu_{met}, \nu_{pl}, \nu_{max})$$

$$\nu_{met} = \boxed{A_1}\frac{k_B T_i}{\hbar} + \boxed{A_2}\frac{k_B T_e^2}{\hbar T_F}$$

$$\nu_{pl} = \frac{4\sqrt{2\pi} n_e Z e^4}{3\sqrt{m_e}(k_B T_e)^{3/2}}\Lambda$$

$$\nu_{max} = \frac{\sqrt{v_F^2 + k_B T_e/m_e}}{r_0}$$

$$\varepsilon = \xcancel{\boxed{\varepsilon_{bb}}} + 1 - \frac{\omega_{pl}^2}{\omega_L(\omega_L + i\nu)}$$

on melting

$$\gamma_{ei} = \boxed{A_3}\frac{3 m_e n_e \nu}{m_i}$$

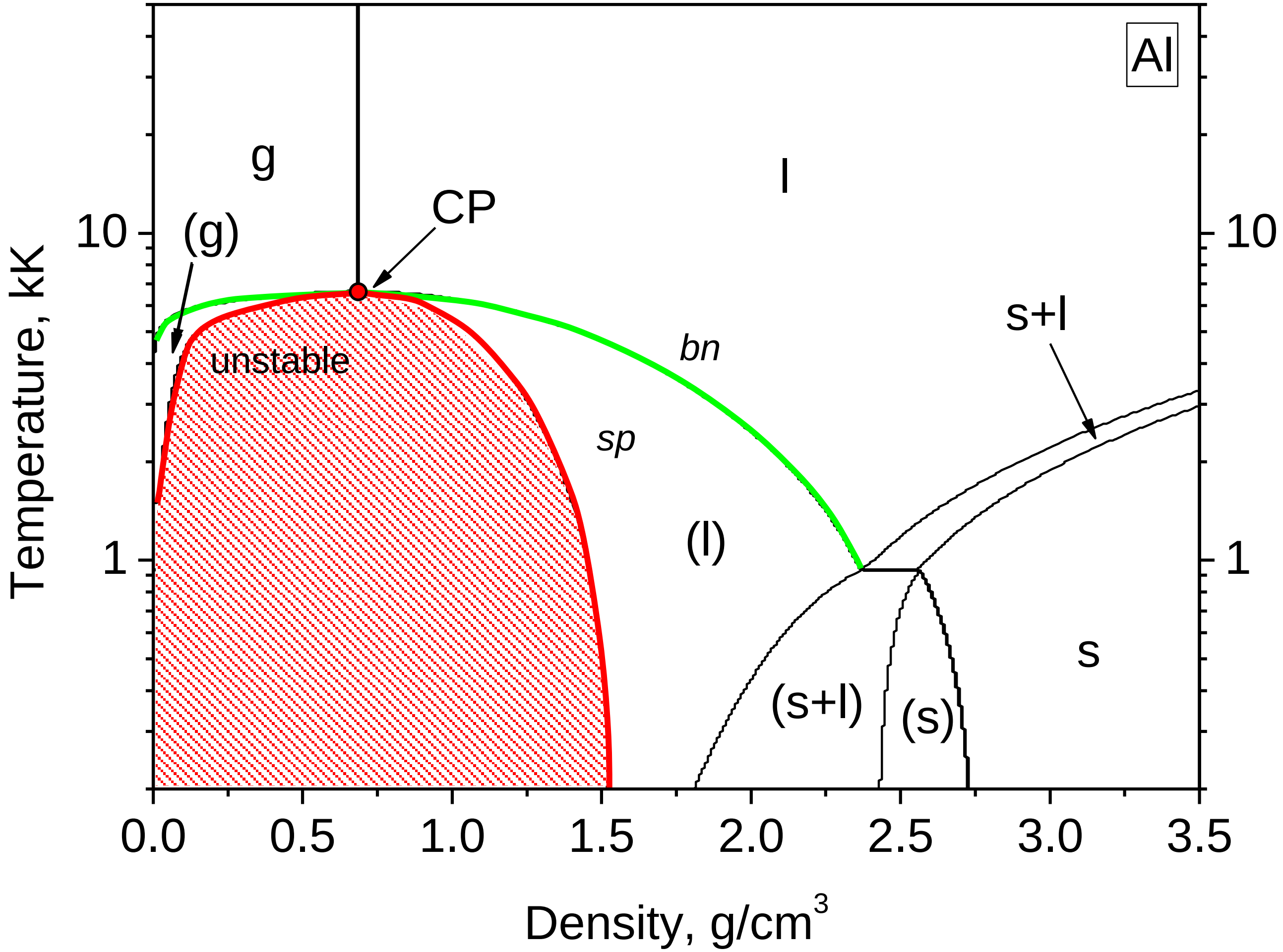
$$\chi = \boxed{A_4}\frac{k_B^2 n_e T_e}{m_e \nu}$$

K. Eidmann *et al.* Phys. Rev. E **62**, 1202 (2000)

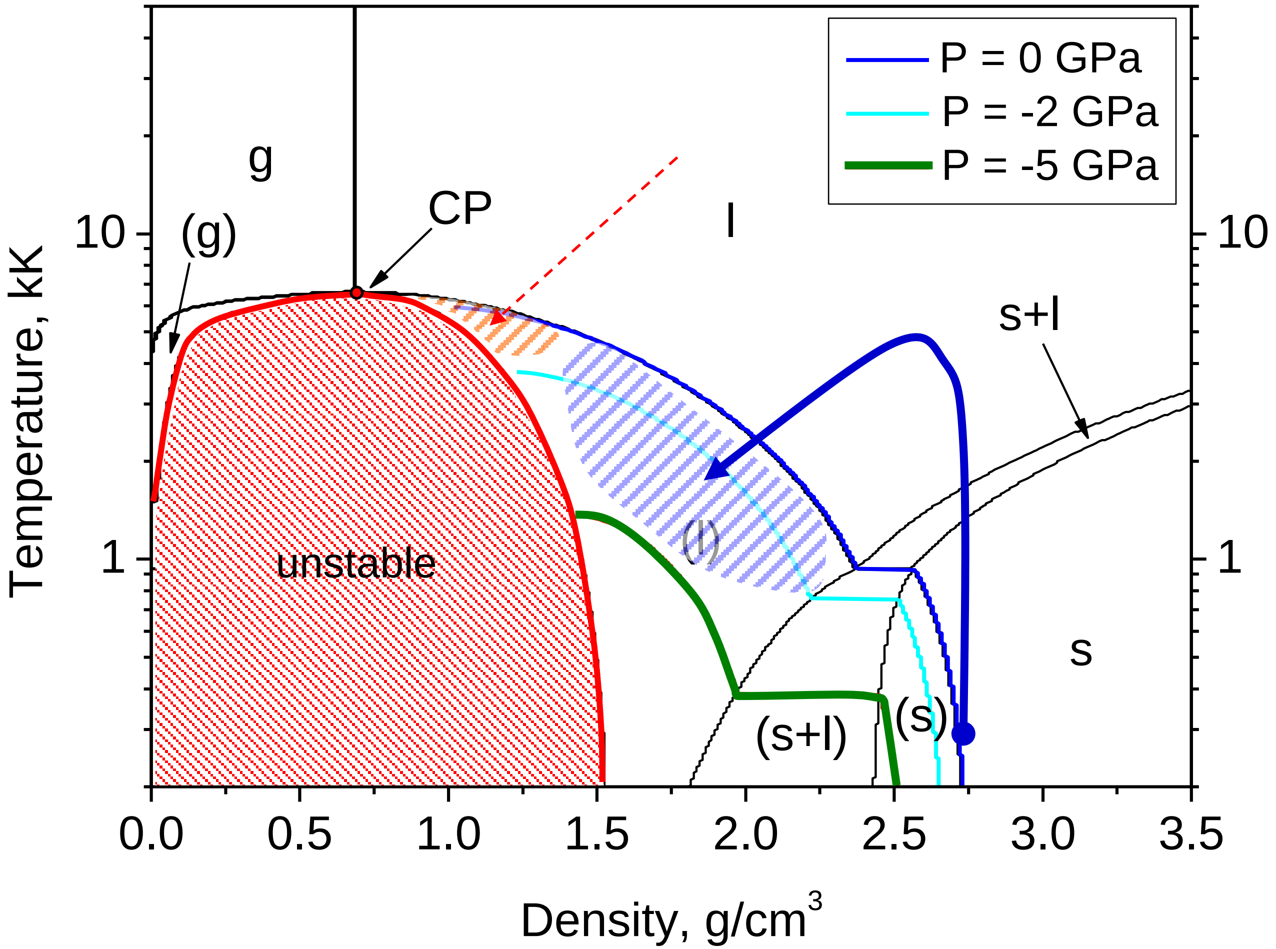
Handbook of optical constants of solids, E. Palik *et al.*

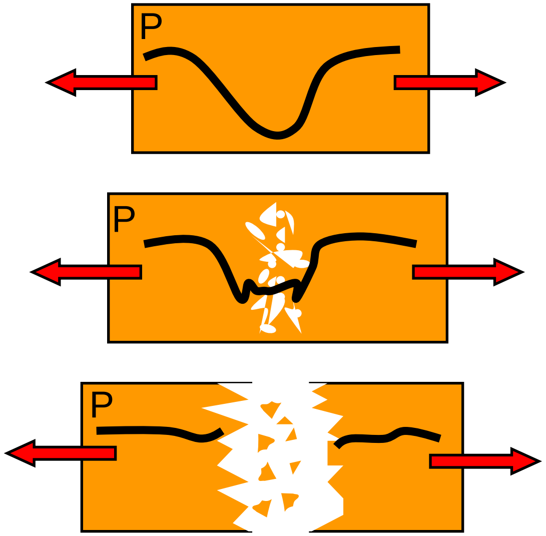
	λ_L, mkm	n	k	$\varepsilon_1 = n^2 - k^2$	$\varepsilon_2 = 2nk$	R
Cu	0.83	0.260	5.26	-27.60	2.74	0.964
Cu	1.24	0.433	8.46	-71.38	7.33	0.976
Au	0.83	0.188	5.39	-29.02	2.03	0.975
Au	1.24	0.372	8.77	-76.77	6.52	0.981

Two-temperature semi-empirical EOS



Mechanical spallation (cavitation)





liquid + voids

Time to fracture is governed by the confluence of voids

Spallation criteria

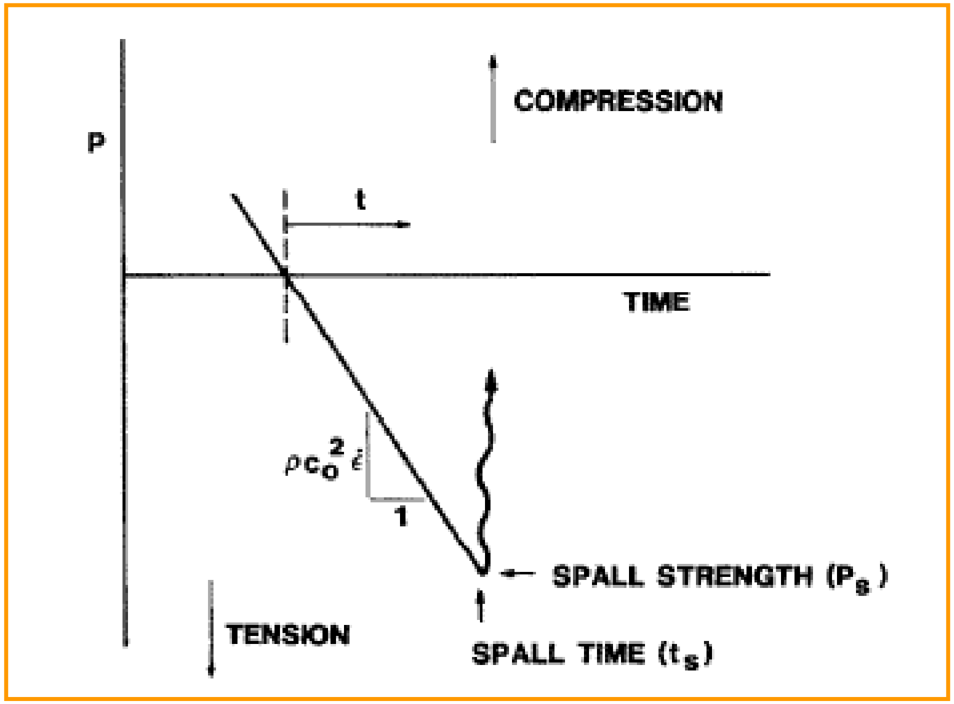
Strain rate $\dot{\varepsilon}$ in laser experiments is up to 10^{10} s^{-1}

Energy minimization

$$P_s = (6\rho^2 c^3 \sigma \dot{\varepsilon})^{1/3}$$

$$t_s = (6\sigma / \rho \dot{\varepsilon}^2 c^3)^{1/3}$$

$$\sigma = \sigma_0 (1 - T/T_c)^{1.25}$$

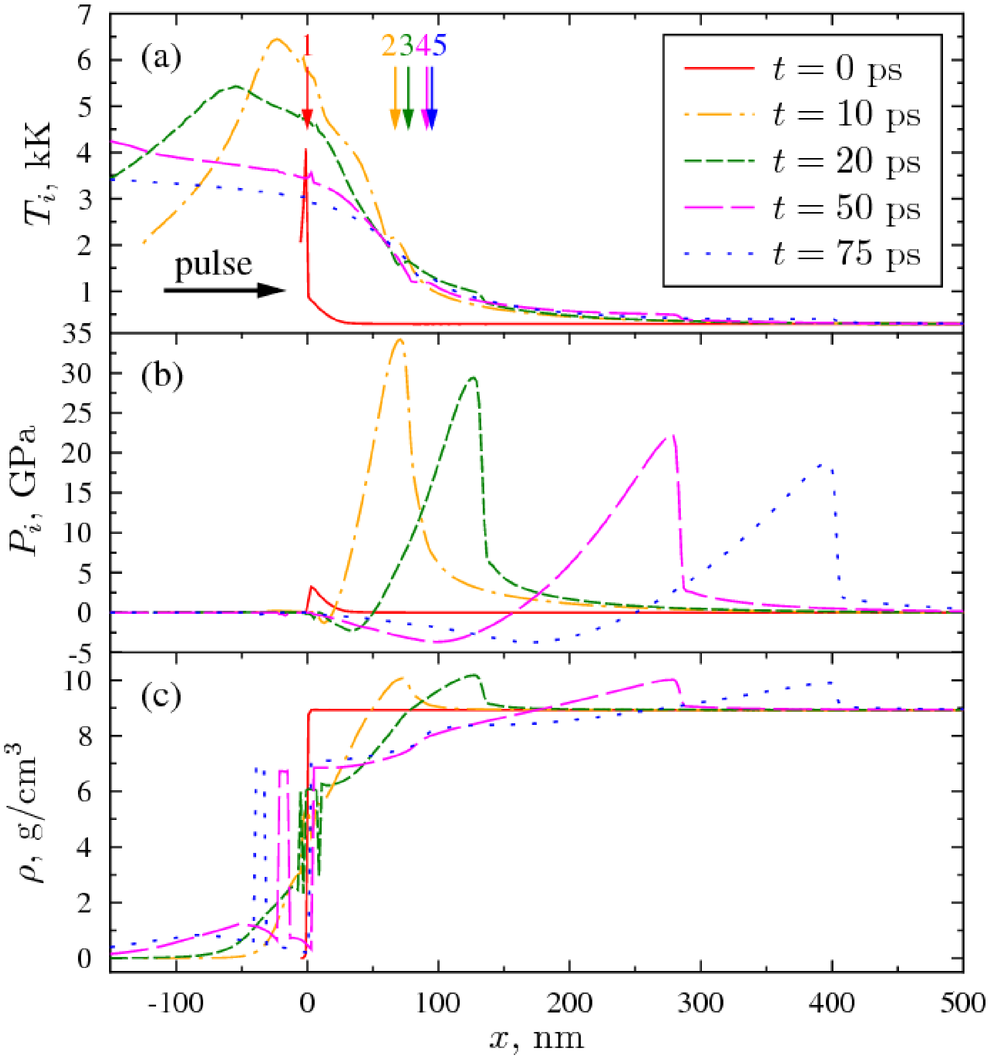


D. Grady, J. Mech. Phys. Solids **36**, 353 (1988).

Basic features of the model

- Multi-material hydrodynamics (several substances + phase transitions)
- Two-temperature model (Te $\neq$ Ti)
- Two-temperature equations of state
- Wide-range models of el-ion collisions, permittivity, heat conductivity (ν, ε, χ)
- Model of laser energy absorption (Helmholtz)
- Model of ionization & recombination (metals)

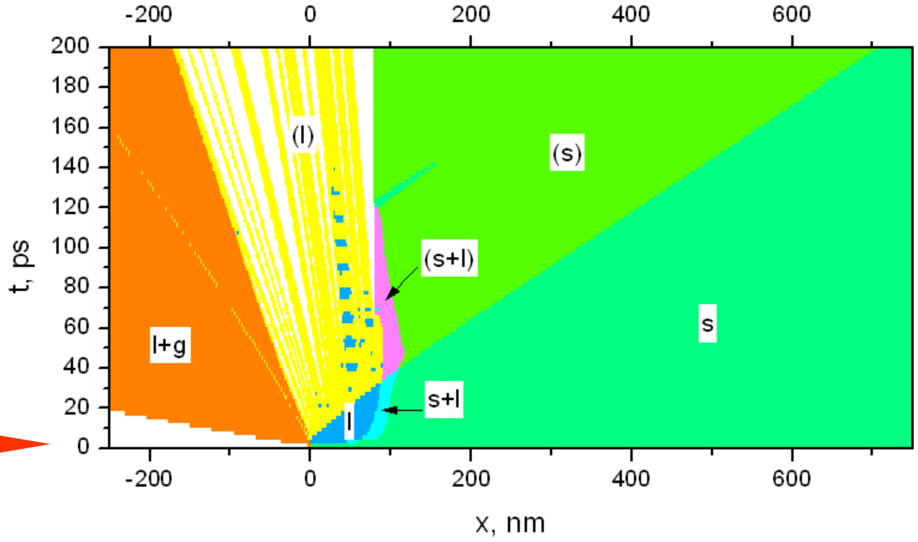
Simulation: single pulse



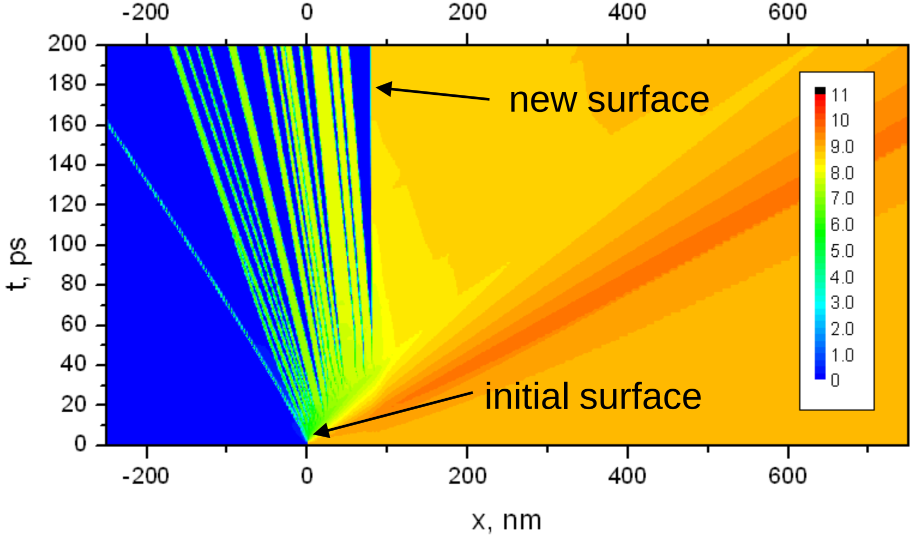
Simulation: *x-t* diagram of Cu, F=1.2 J/cm^2

phase states

laser pulse



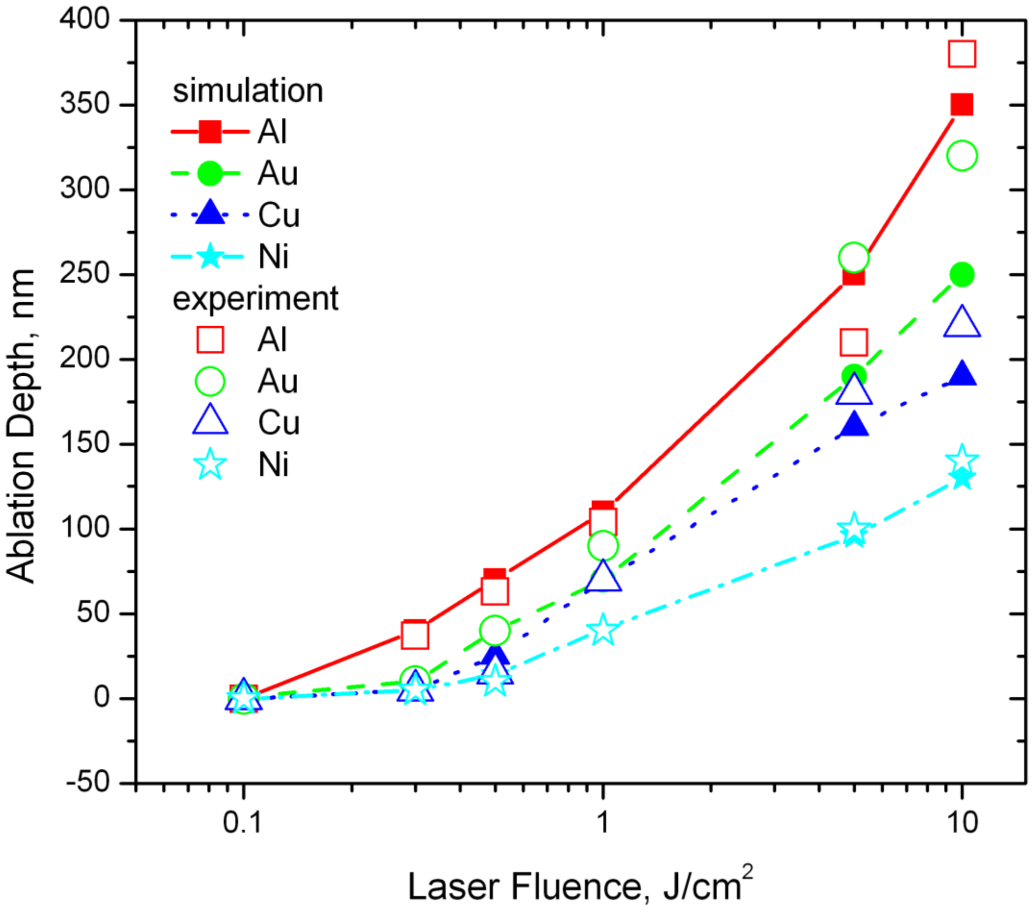
density



new surface

initial surface

Ablation depth vs. fluence



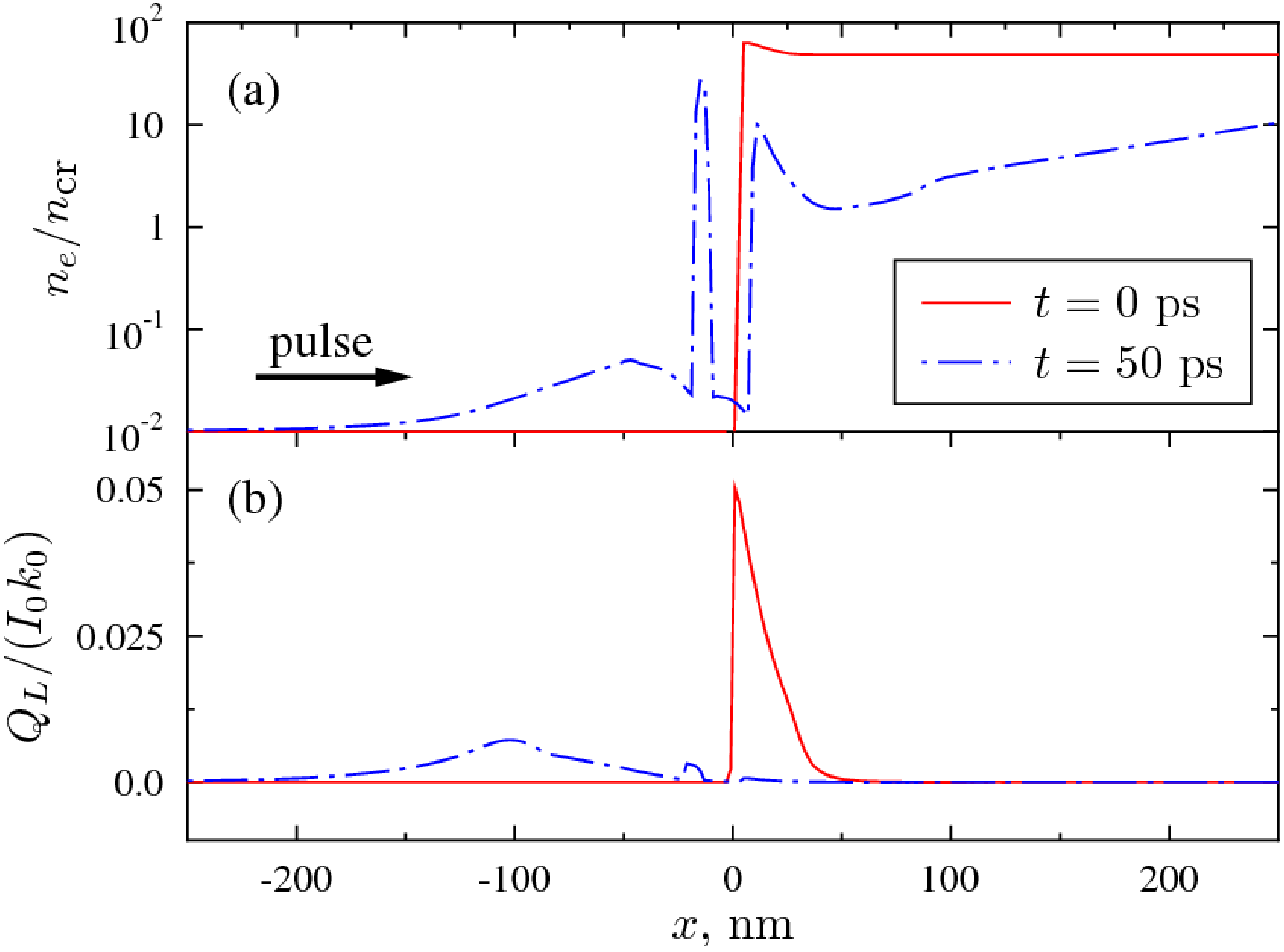
Experiment:

M. Hashida *et al.* SPIE Proc. **4423**, 178 (2001).

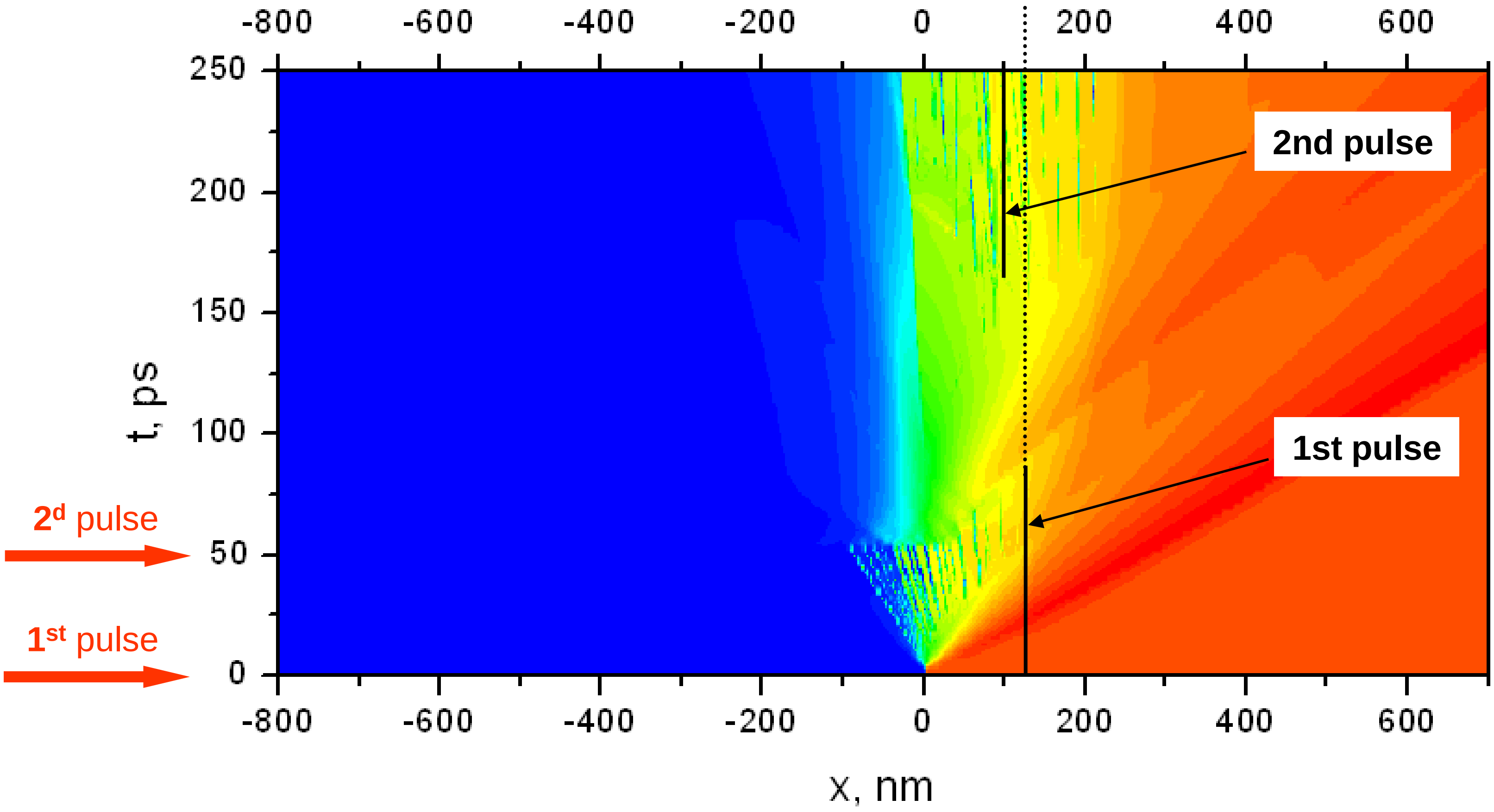
J. Hermann *et al.* Laser Physics **18**(4), 374 (2008).

M.E. Povarnitsyn *et al.*, Proc. SPIE 7005, 700508 (2008)

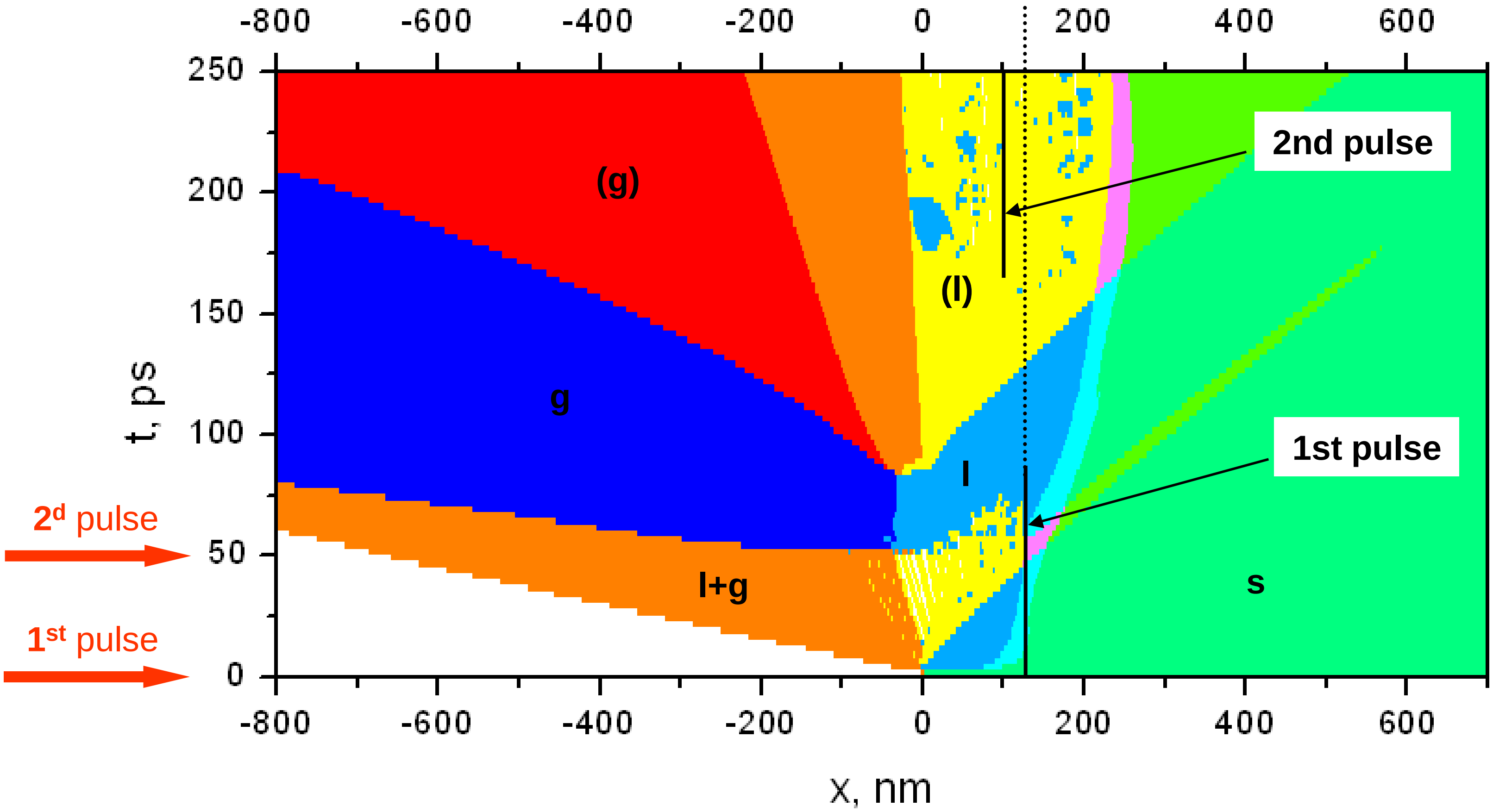
Simulation: double pulse with τ_{delay}=50ps



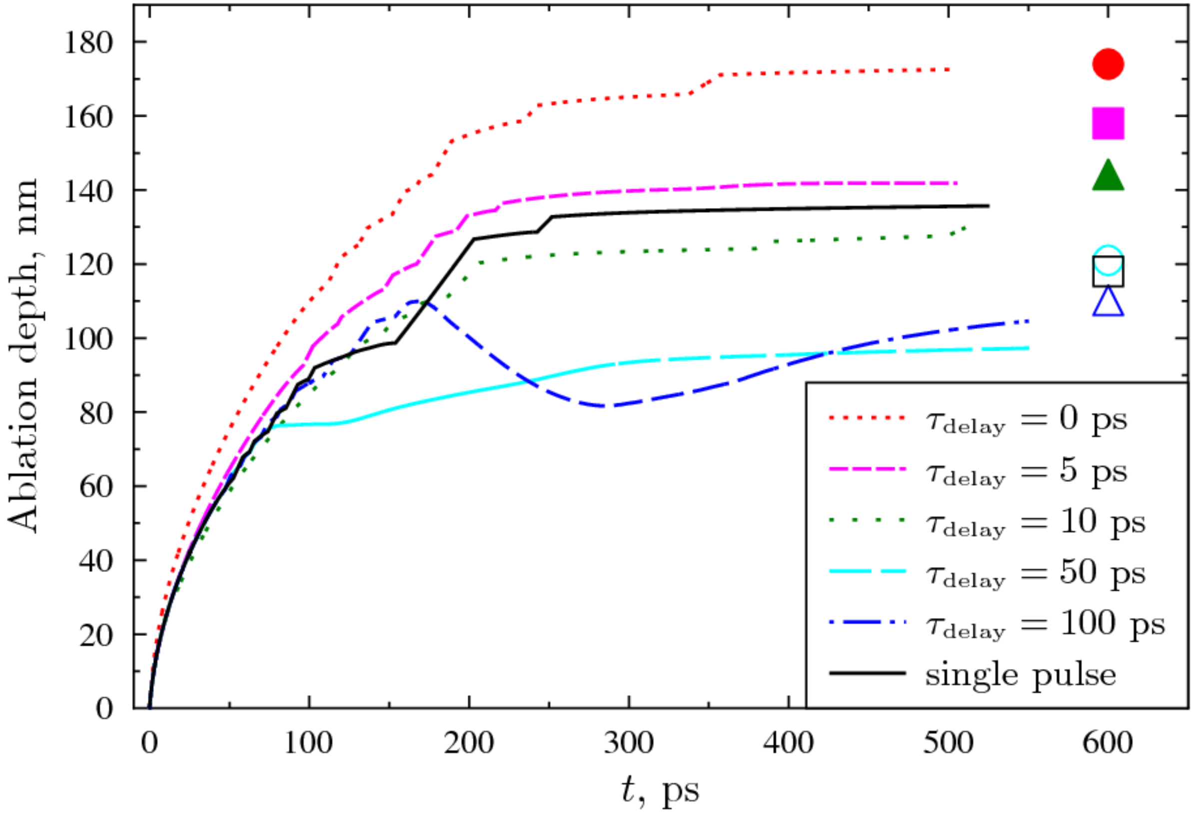
Simulation: delay 50 ps, density of Cu



Simulation: delay 50 ps, phase states of Cu



Simulation: single & double pulse 2×2 J/cm^2



$$\Delta_{\rm abl}(t) = \rho_0^{-1} \int_0^t (\rho u)|_{x=0} dt'$$

Summary

- Model describes ablation depth for single and double pulse experiments in the range 0.1 – 10 J/cm^2.

- For long delays the second pulse interacts with the nascent ablation plume (in liquid phase).

- Reheating of the nascent ablation plume results in suppression of the rarefaction wave.

- Back deposition of substance caused buy the second pulse is the reason of even less crater depth for double pulses with long delay.

Thank you for your attention!