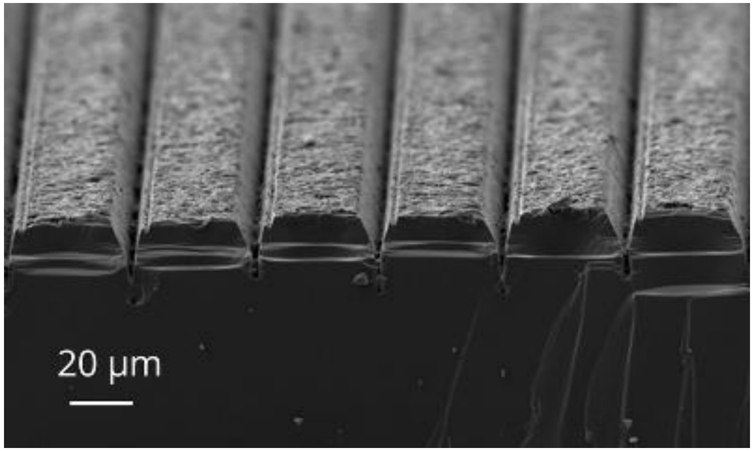
Гидродинамическое моделирование воздействия лазерных импульсов умеренной интенсивности на вещество с помощью широкодиапазонных моделей теплофизических свойств

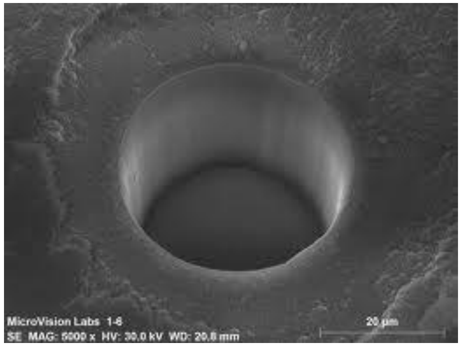
М. Поварницын

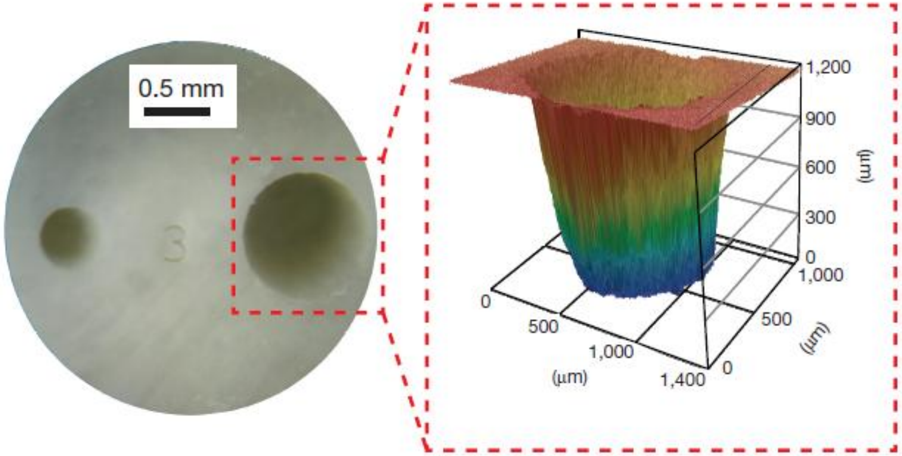
ОИВТ РАН
povar@ihed.ras.ru

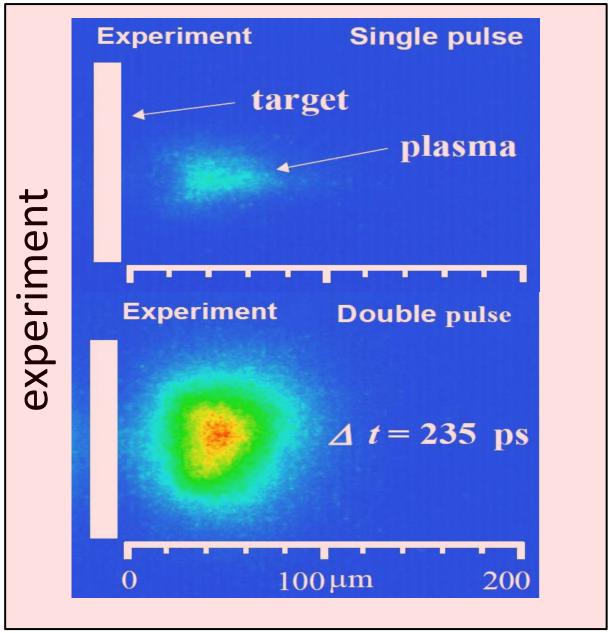
ОБЪЕДИНЕННЫЙ
ИВТАН

Мотивация: сверление, спектроскопия, наночастицы, преплазма







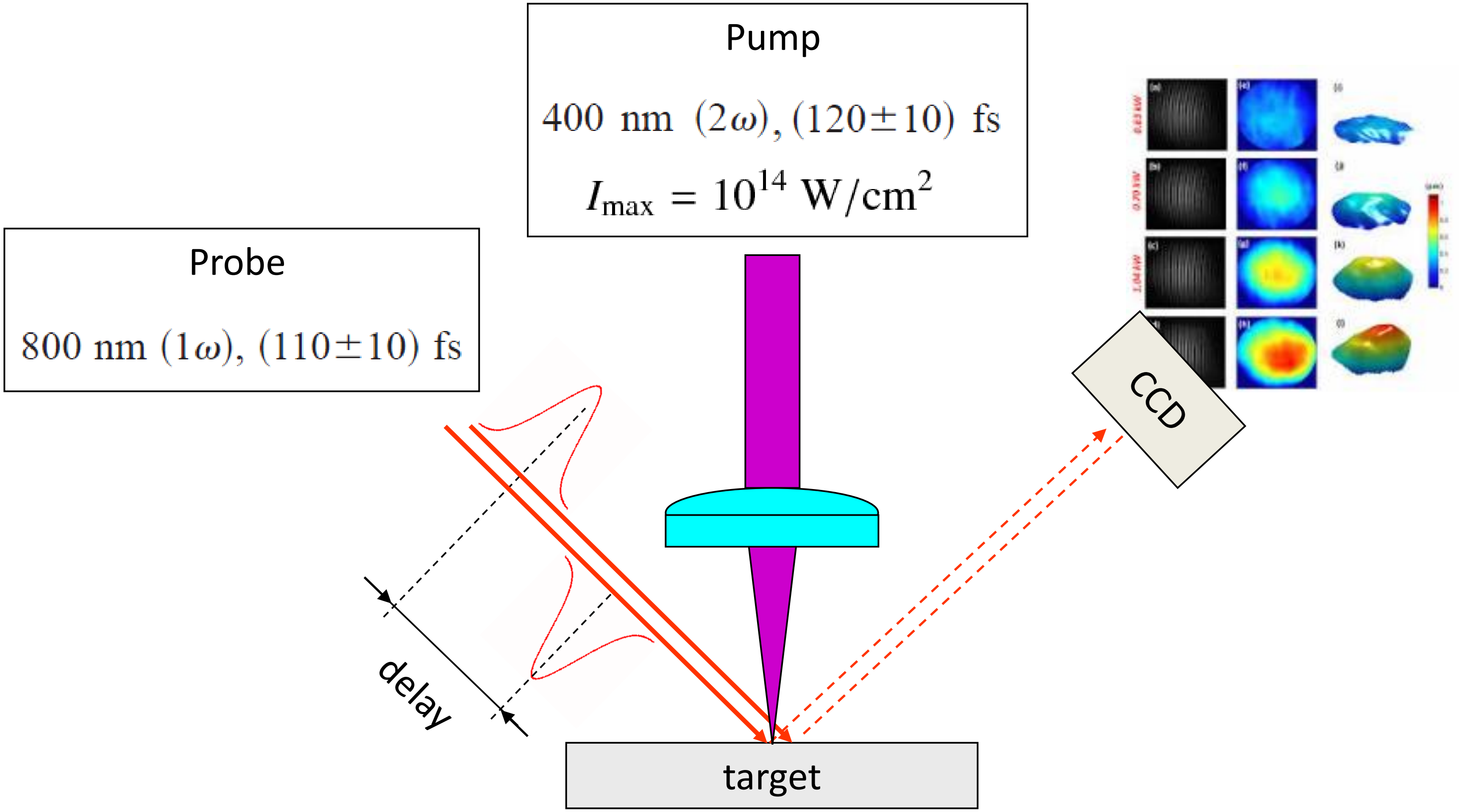


Model

- Two-temperature hydrodynamics
- Helmholtz wave equation
- Wide-range multi-phase equation of state
- Wide-range permittivity and conductivity

Povarnitsyn et al. Appl. Surf. Sci. **258**, 9480 (2014)

Pump-probe technique



Pump

400 nm (2ω), (120$\pm$10) fs

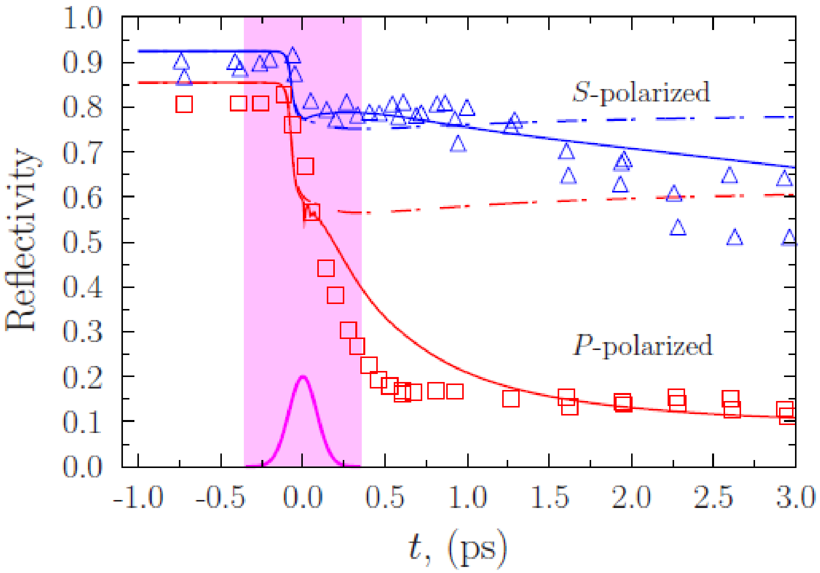
$I_{\max} = 10^{14}$ W/cm^2

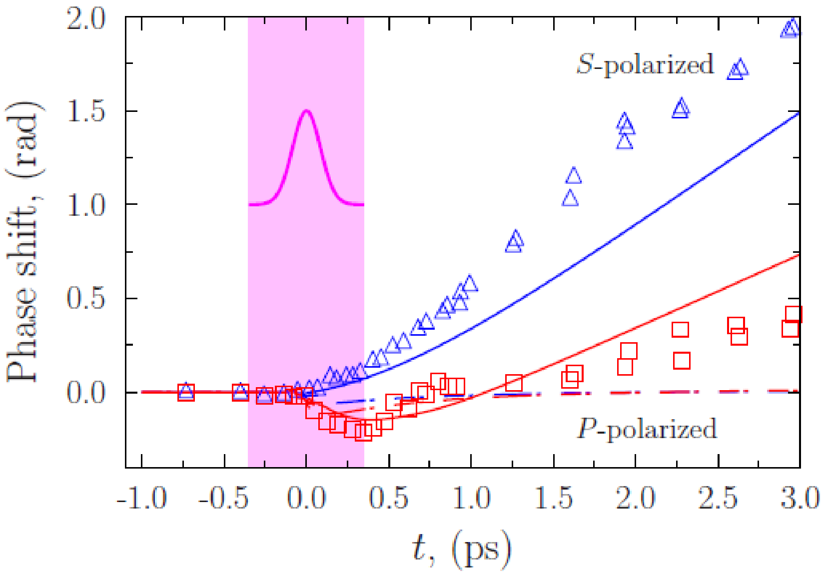
Probe

800 nm (1ω), (110$\pm$10) fs

Widmann *et al.* Phys. Plasmas 8 (2001)

Моделирование *s*- и *p*-поляризованных импульсов



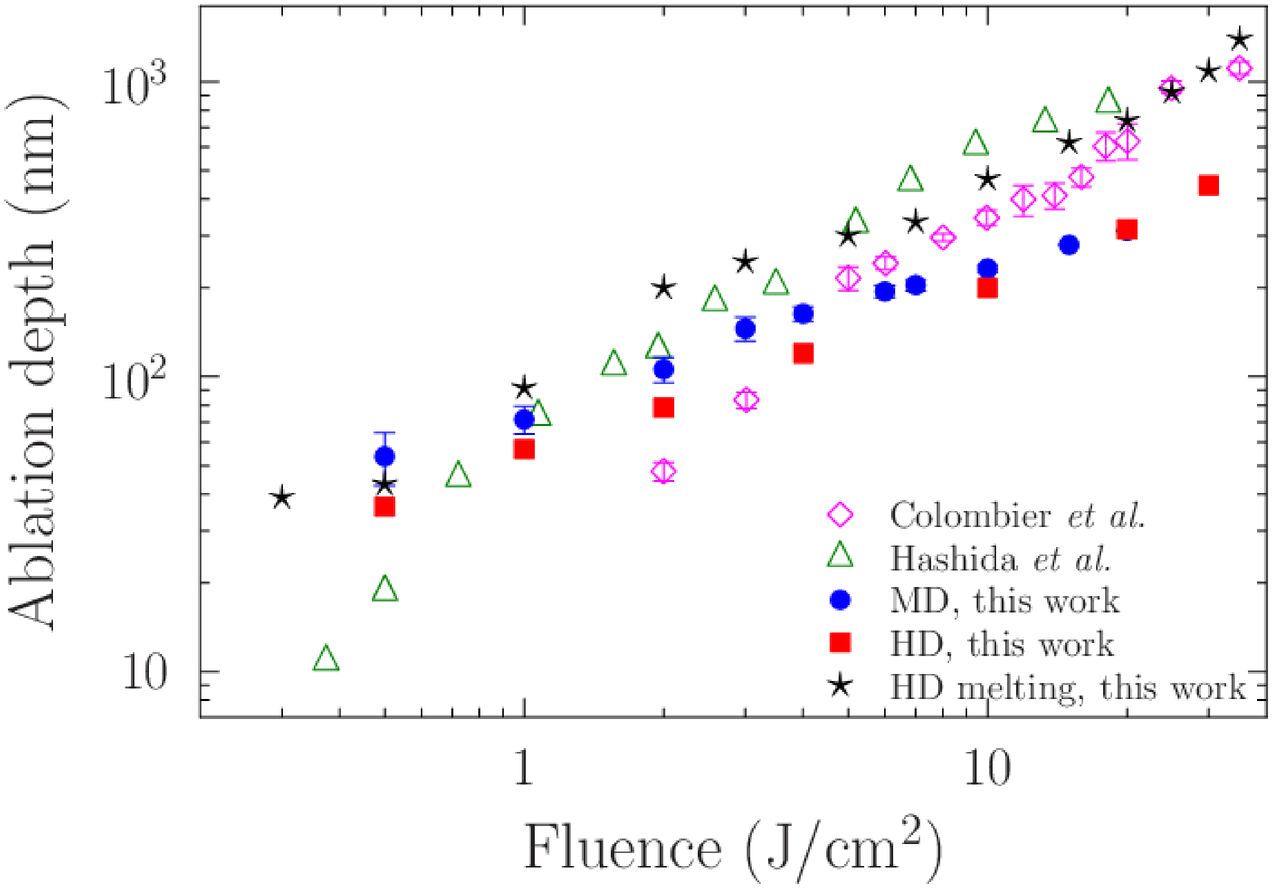


Отражение s- и p-поляризованных импульсов

Сдвиг фазы s- и p-поляризованных импульсов

Povarnitsyn *et al.*, Appl. Surf Sci. 258 (2012)

Depth vs Fluence for 800 nm, 100 fs pulse, Al



M. Povarnitsyn *et al.* Appl. Surf. Sci., 357 (2015)

Ablation efficiency

Aluminum

$E_{sub} \approx 12$ kJ/g

$F = 10$ J/cm^2

$\rho = 2.7$ g/cm^3

$\Delta_{max} \approx 3$ µm

$\Delta_{exp} \approx 300$ nm

800 nm, 100 fs

Effectiveness ≈ 10%

LETTER

doi:10.1038/nature18619

Ablation-cooled material removal with ultrafast bursts of pulses

Can Kerse[1], Hamit Kalaycıoğlu[2], Parviz Elahi[2], Barbaros Çetin[3], Denizhan K. Kesim[1], Önder Akçaalan[1], Seydi Yavaş[4], Mehmet D. Aşık[5], Bülent Öktem[6], Heinar Hoogland[7,8], Ronald Holzwarth[7] & Fatih Ömer Ilday[1,2]

The use of femtosecond laser pulses allows precise and thermal-damage-free removal of material (ablation) with wide-ranging scientific[1–5], medical[6–11] and industrial applications[12]. However, its potential is limited by the low speeds at which material can be removed[1,9–11,13] and the complexity of the associated laser technology. The complexity of the laser design arises from the need to overcome the high pulse energy threshold for efficient ablation. However, the use of more powerful lasers to increase the ablation rate results in unwanted effects such as shielding, saturation and collateral damage from heat accumulation at higher laser powers[6,13,14]. Here we circumvent this limitation by exploiting ablation cooling, in analogy to a technique routinely used in aerospace engineering[15,16]. We apply ultrafast successions (bursts) of laser pulses to ablate the target material before the residual heat deposited by previous pulses diffuses away from the processing region. Proof-of-principle experiments on various substrates demonstrate that extremely high repetition rates, which make ablation cooling possible, reduce the laser pulse energies needed for ablation and increase the efficiency of the removal process by an order of magnitude over previously used laser parameters[17,18]. We also demonstrate the removal of brain tissue at two cubic millimetres per minute and dentine at three cubic millimetres per minute without any thermal damage to the bulk[9,11].

Ablation is the evaporative removal of a material when its temperature

a critical value. Because the ablated material is physically carried

energy contained in the ablated mass is also removed,

temperature of the remaining material.

ablation cooling, which has been

tection during the atmos-

minimal mass

is not

time, τ_0, is proportional to δ^2/α, where δ is the depth or the lateral radius (whichever dimension is smaller) of the section of the material to be ablated and α is its thermal diffusivity. For a train of N pulses, the temperature of the target surface that is encountered by the $(n+1)$th pulse is given by $T_{n+1}=T_n+\delta T$, where $\delta T=\Delta T/\sqrt{1+\tau_R/\tau_0}$ is the small net increase in target temperature by a single pulse and τ_R is inverse of the repetition rate. Ablation occurs when the temperature exceeds a critical value T_c. For the traditional regime of ultrafast ablation, the repetition rate is low ($\tau_R \gg \tau_0$) and each pulse must be energetic enough to cause ablation ($\Delta T > T_c - T_0$, where T_0 is the initial surface temperature). The ablation-cooled regime corresponds to $\tau_R \lesssim \tau_0$. In this regime, the energy of the individual pulses can be lower than the ablation threshold because temperature builds up from pulse to pulse and ablation starts after the mth pulse in the train, where $m=(T_c-T_0-\Delta T+\delta T)/\delta T$. The volume of the ablated material is given by $V_{\text{ablated}}=\beta[N-u(T_c-T_0-\Delta T)m]E_p u(N-m)$, where β is a proportionality factor and u is the Heaviside (unit step) function. The thermal energy that diffuses into the bulk of the target owing to cooling between the pulses is

$$E_{\text{heat}}=\alpha(T_c-T_0)\left(1-\frac{1}{\sqrt{1+\tau_R/\tau_0}}\right)(N-m)E_p+\alpha(\Delta T-\delta T)mE_p.$$

For the traditional regime, this result reduces to $\lim_{\tau_R\to\infty} E_{\text{heat}}=\alpha(T_c-T_0)NE_p$.

The toy model makes two main predictions for the ablation-cooled regime—both are confirmed by numerical solutions of the heat diffusion equation (see Supplementary Information section 2 for details) as well as the experiments described below. The first is that increasing the repetition rate reduces the heating of surrounding regions (Fig. 1b, c and Supplementary Fig. 1). Because less of the deposited laser energy is lost to heat diffusion ($\lim_{\tau_R\to 0} E_{\text{heat}}=0$), the ablation effi-

is higher than for the traditional regime (Supplementary Fig. 3).

states that the pulse energy can be decreased if the num-

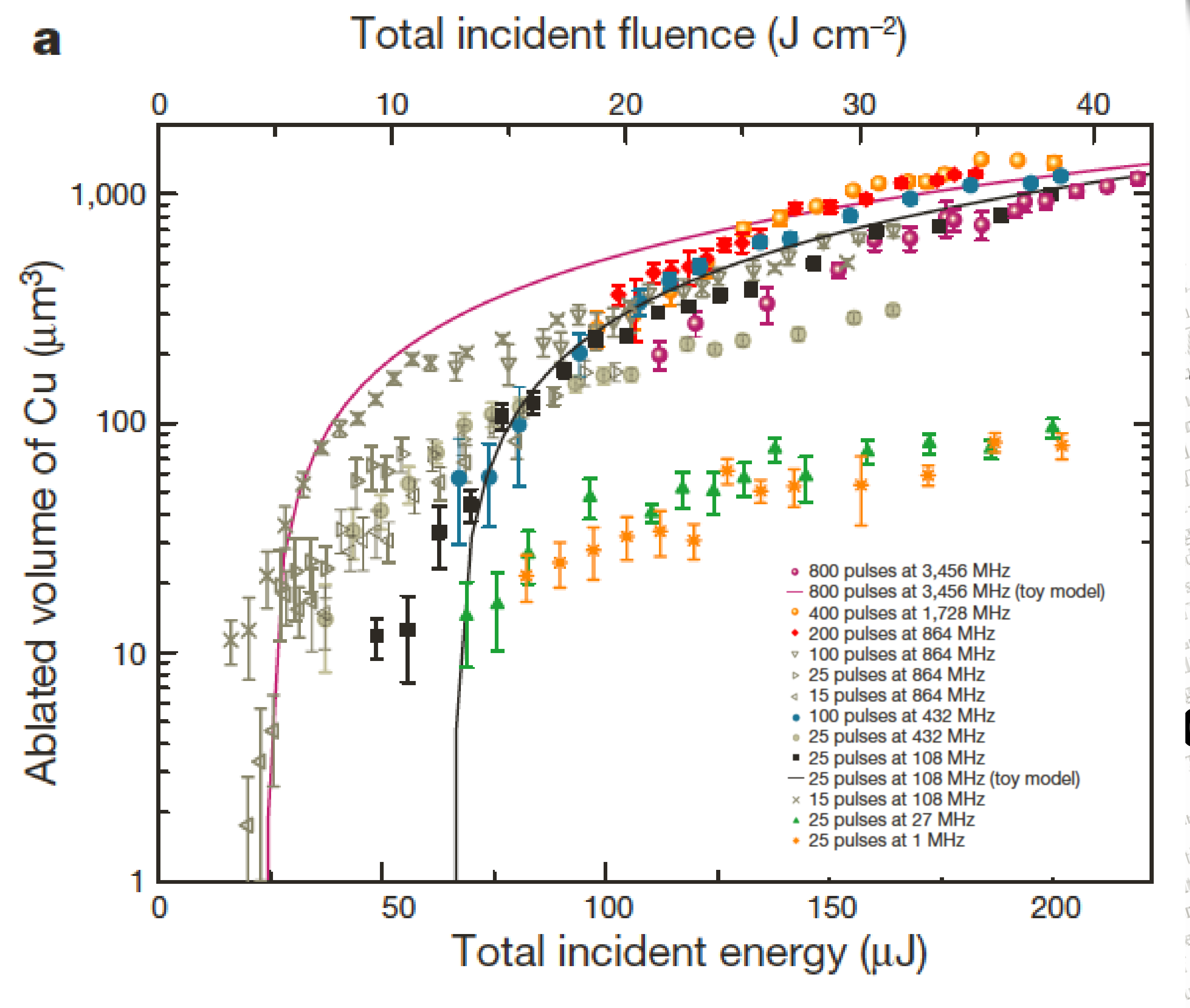
ltaneously increased in proportion, without a

lation efficiency (Fig. 1d). This is nec-

-cooled regime, because

ma and ejected par-

vent effi-



z (290 ps)

0 pulses

C. Kerse *et al.*, Nature 537, 84 (2016)

APPLIED PHYSICS LETTERS **112**, 051603 (2018)

Simulation of ultrafast bursts of subpicosecond pulses: In pursuit of efficiency

Mikhail E. Povarnitsyn,[1] Pavel R. Levashov,[1,2] and Dmitry V. Knyazev[1,3]
[1]*Joint Institute for High Temperatures RAS, Izhorskaya 13 Bldg 2, Moscow 125412, Russia*
[2]*Tomsk State University, 36 Lenin Prospekt, Tomsk 634050, Russia*
[3]*Moscow Institute of Physics and Technology, 9 Institutskiy per., Dolgoprudny, Moscow Region 141700, Russia*

(Received 7 November 2017; accepted 14 January 2018; published online 31 January 2018)

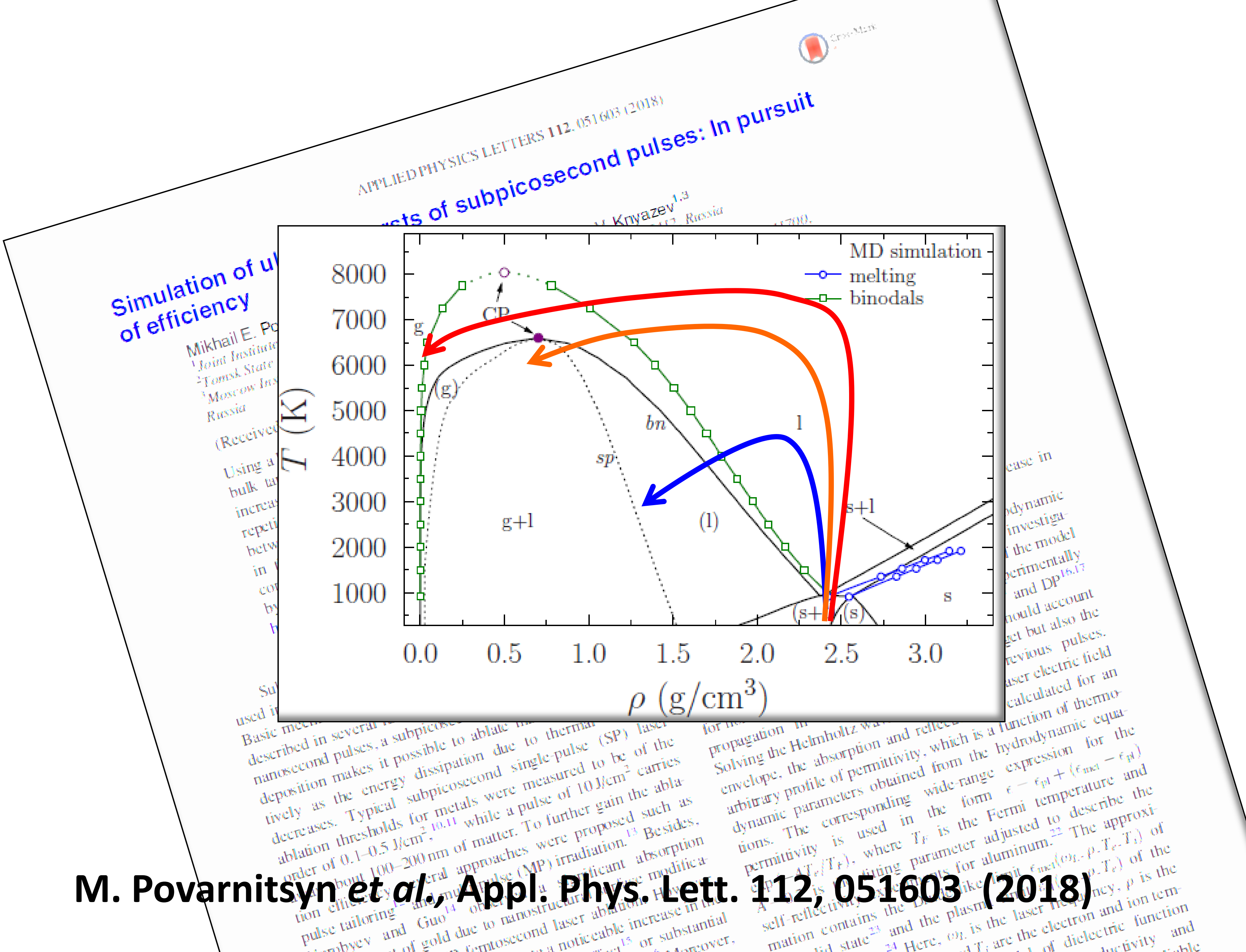
Using a hydrodynamic two-temperature model, we simulate multi-pulse laser ablation of an aluminum bulk target. The results of modeling demonstrate that the effectiveness of the multi-pulse ablation increases an order of magnitude in comparison to a single-pulse ablation of the same energy, while the repetition rate grows up to several GHz because the material surface does not cool down substantially between successive pulses. To prevent the shielding and suppression effects, the fluence of each pulse in the burst should have a subthreshold value to avoid the generation of slow moving ablated condensed-phase nanolayers. The obtained results are consistent with recent experiments on ablation by ultrafast bursts of ultrashort pulses. *Published by AIP Publishing.*

https://doi.org/10.1063/1.5012758

Subpicosecond laser processing of materials is widely used in scientific,[1,2] medical,[3,4] and industrial applications.[5,6] Basic mechanisms of ultrashort ablation of metals have been described in several fundamental papers.[7–9] In comparison to nanosecond pulses, a subpicosecond timescale of laser energy deposition makes it possible to ablate materials more effectively as the energy dissipation due to thermal diffusion decreases. Typical subpicosecond single-pulse (SP) laser ablation thresholds for metals were measured to be of the order of 0.1–0.5 J/cm^2,[10,11] while a pulse of 10 J/cm^2 carries away about 100–200 nm of matter. To further gain the ablation efficiency, several approaches were proposed such as pulse tailoring[12] and multi-pulse (MP) irradiation.[13] Besides,
robyev and Guo[14] observed a significant absorption
t of gold due to nanostructural surface modifica-
femtosecond laser ablation. However,
a noticeable increase in the
effect[15] or substantial
Moreover,

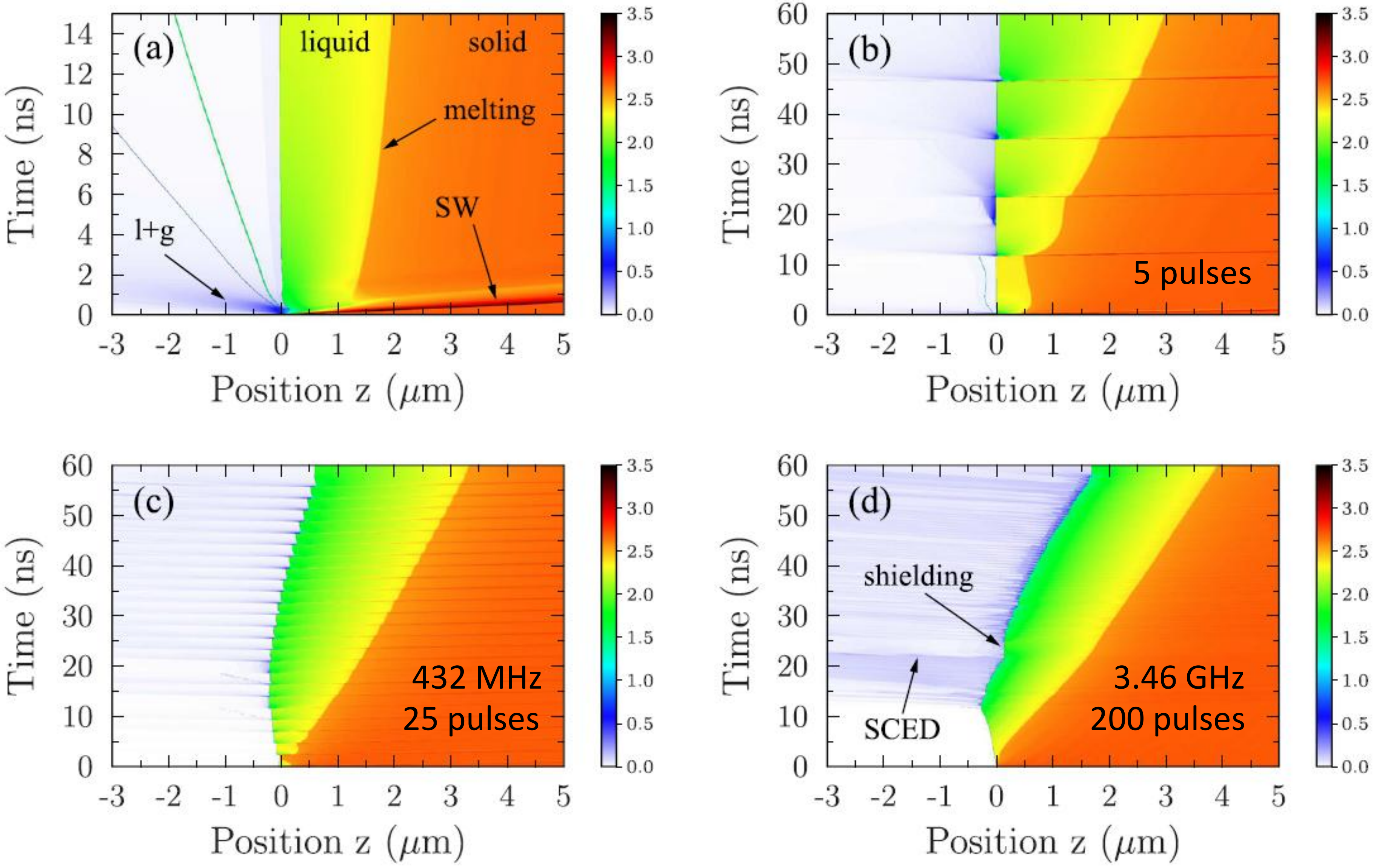
study mechanisms responsible for such a record increase in ablation efficiency.

A one-dimensional two-temperature hydrodynamic model[21] was developed and previously used for the investigation of SP and DP ablation of metals. The validity of the model was confirmed by comparison with the experimentally obtained ablation depth for several metals in SP[11] and DP[16,17] regimes. In the case of MP ablation, the model should account for not only the laser light interaction with a target but also the propagation in the plume generated by previous pulses. Solving the Helmholtz wave equation for the laser electric field envelope, the absorption and reflection are calculated for an arbitrary profile of permittivity, which is a function of thermodynamic parameters obtained from the hydrodynamic equations. The corresponding wide-range expression for the permittivity is used in the form $\epsilon = \epsilon_{pl} + (\epsilon_{met} - \epsilon_{pl})$ $\exp(-AT_e/T_F)$, where T_F is the Fermi temperature and $A = 0.2$ is the fitting parameter adjusted to describe the self-reflectivity experiments for aluminum.[22] The approximation contains the Drude-like limit $\epsilon_{met}(\omega_L, \rho, T_e, T_i)$ of the
lid state[23] and the plasma limit $\epsilon_{pl}(\omega_L, \rho, T_e)$ of the
[24] Here, ω_L is the laser frequency, ρ is the
and T_i are the electron and ion tem-
of dielectric function
ductivity and

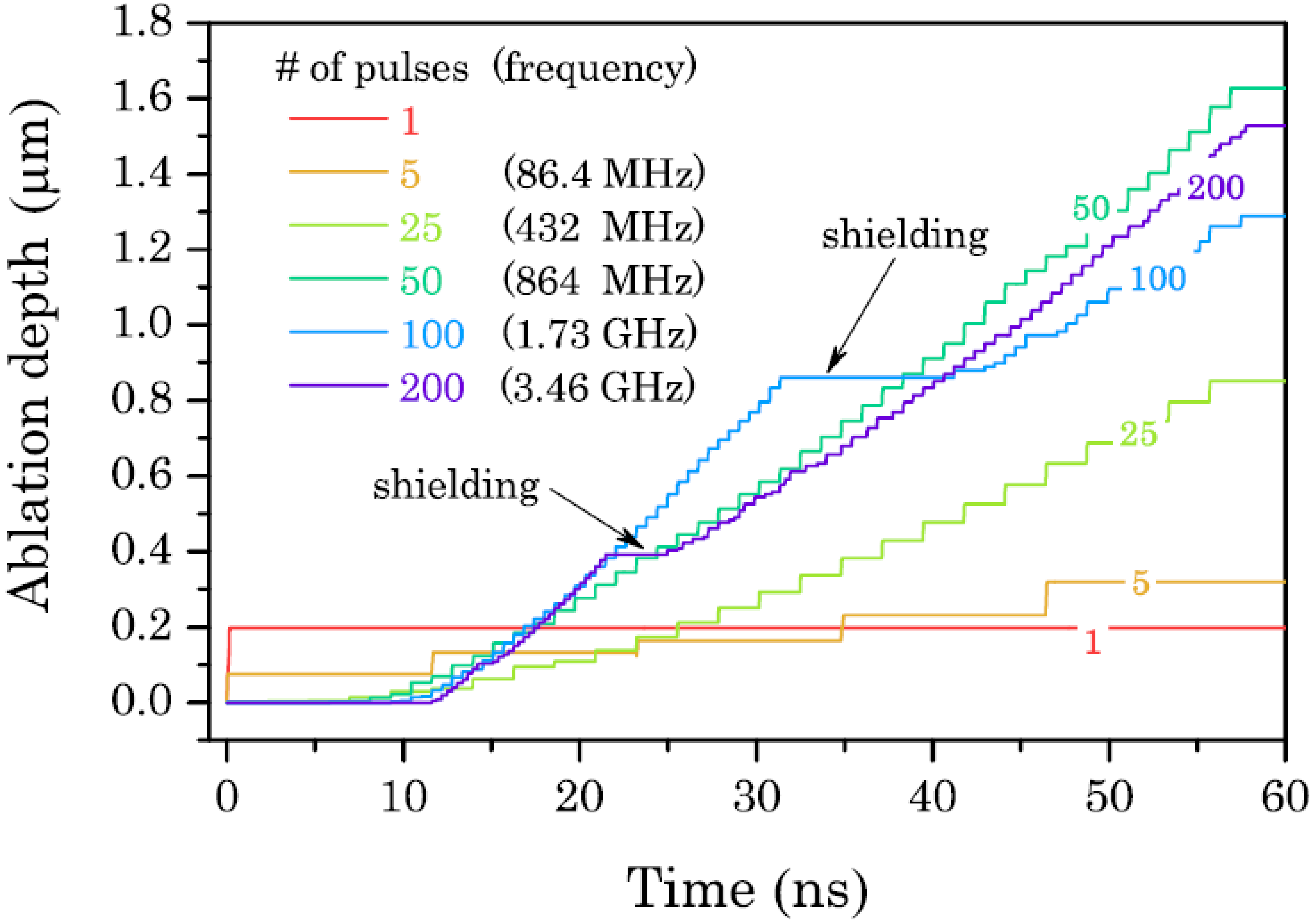


M. Povarnitsyn *et al.*, Appl. Phys. Lett. 112, 051603 (2018)

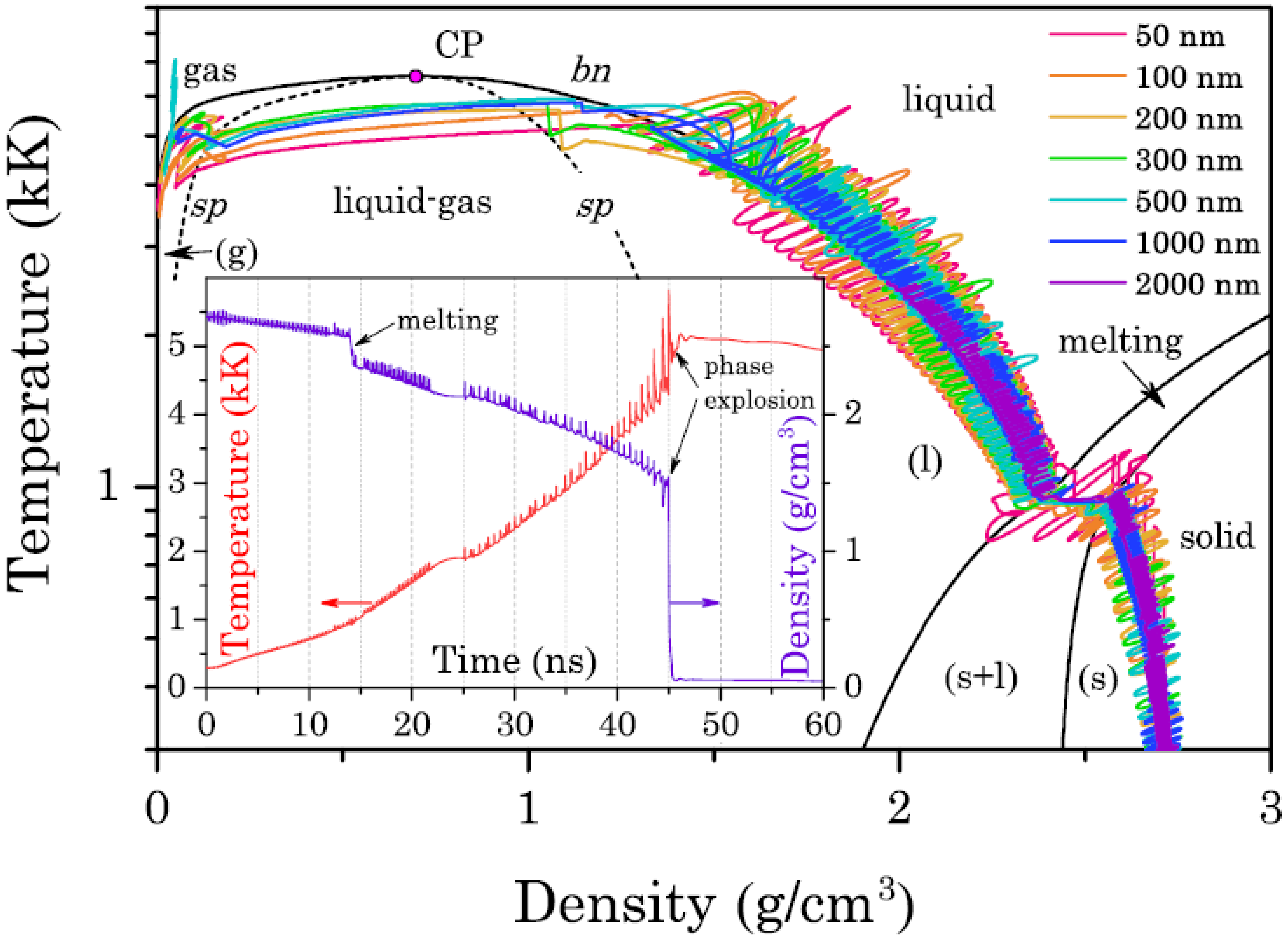
Al; 1, 5, 25 and 200 pulses, 20 J/cm^2



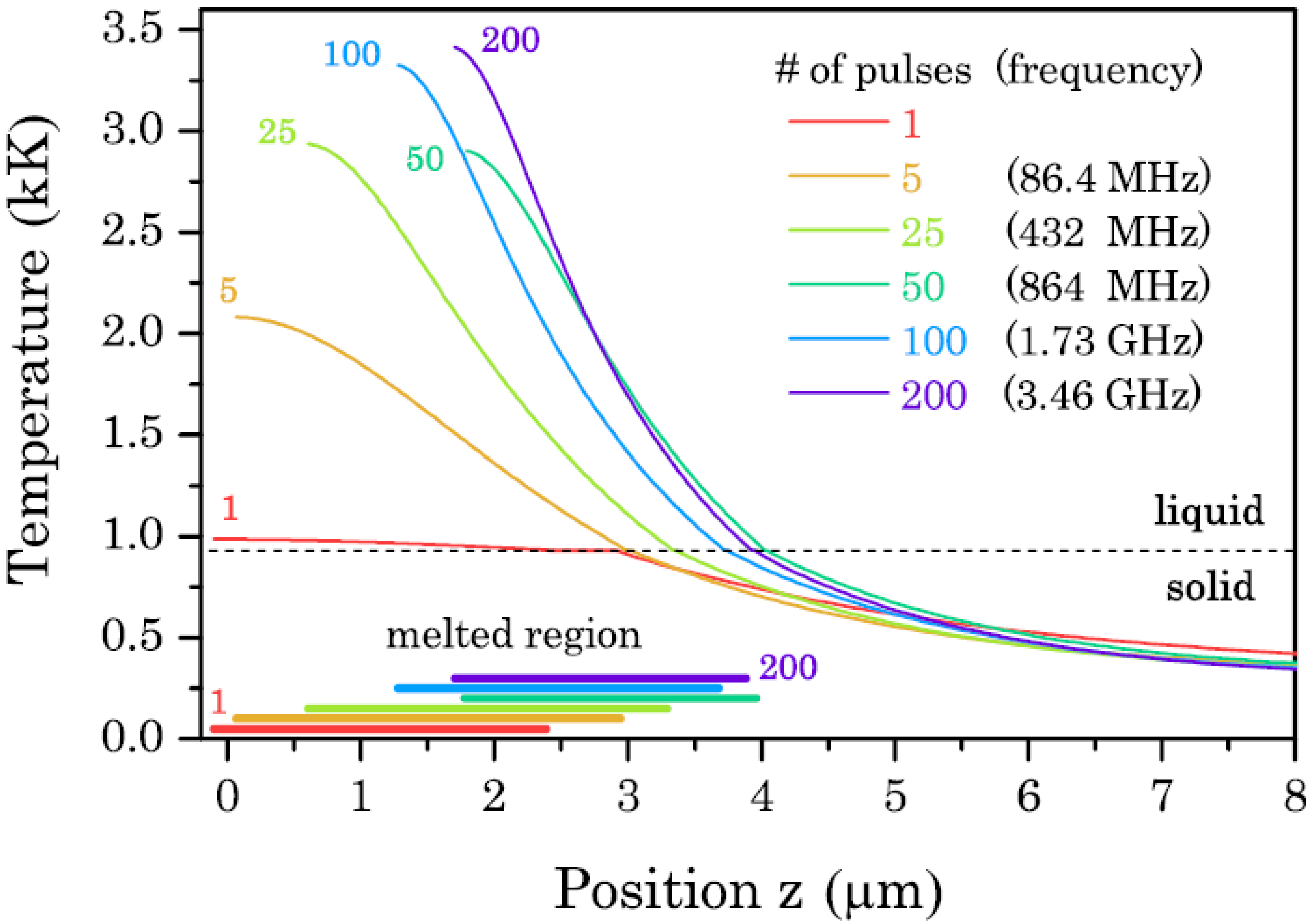
Ablation rate, 20 J/cm^2



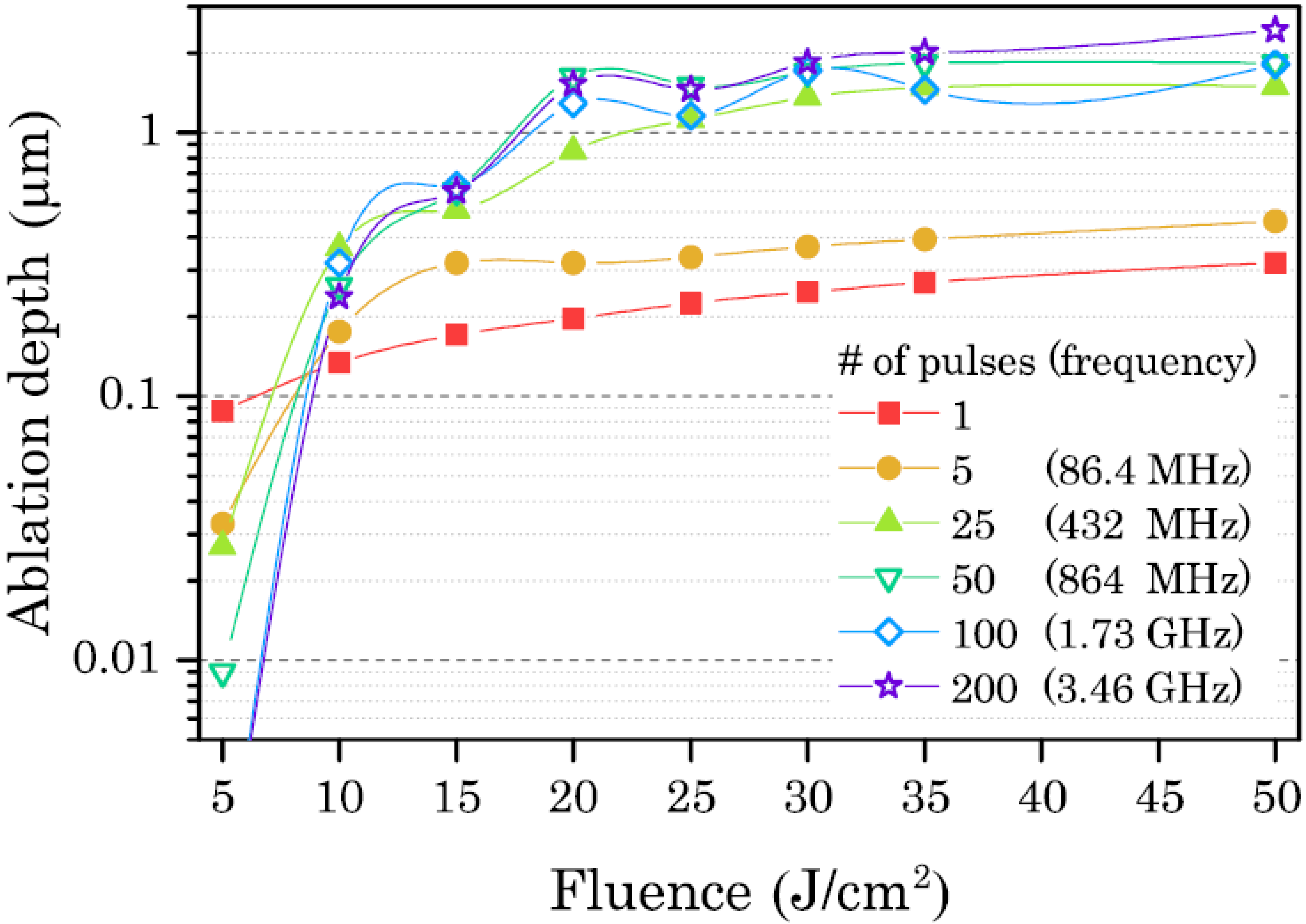
200-pulse ablation



Temperature inside the target at 60 ns



Ablation depth vs. Fluence



Conclusions

- Multi-pulse ablation: rate increases with the intraburst repetition rate growth
- Material surface does not cool down substantially between successive pulses
- To prevent the shielding and suppression: the fluence of each pulse in the burst has a sub-threshold value
- Multiple pulses can guide thermodynamic trajectories along the binodal to the critical point
- Optical and transport properties in liquid-gas region?