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Repetition-rate dependent femtosecond laser ablation of fused silica at high fluences in air

Xiao Jia
Clemson University

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Xiao Jia (Ph.D. Student)
Adviser: Dr. Xin Zhao, Assistant Professor
Department of Mechanical Engineering, Clemson University

Motivation

- Great potential of ultrashort laser in **high-precision micromachining** for dielectric materials with ultrahigh intensity.
- **Fundamental mechanisms** of ultrashort laser ablation (USLA) in dielectric materials remain underexplored in wide range of laser pulse energy, pulse number, and repetition rate.
- **High-repetition-rate manufacturing** significantly enhances productivity and cost-efficiency.

Intellectual Merit and Broader Impacts

- **Temperature-based ablation criterion** provides decent prediction on ablation behavior and crater dimensions during USLA of dielectric materials.
- Better understanding of underlying physics facilitates improvement of **micromachining** in dielectric materials.
- **Numerical simulation** has higher flexibility and cost efficiency in study of more complicated processes than in experiments.

Experiments

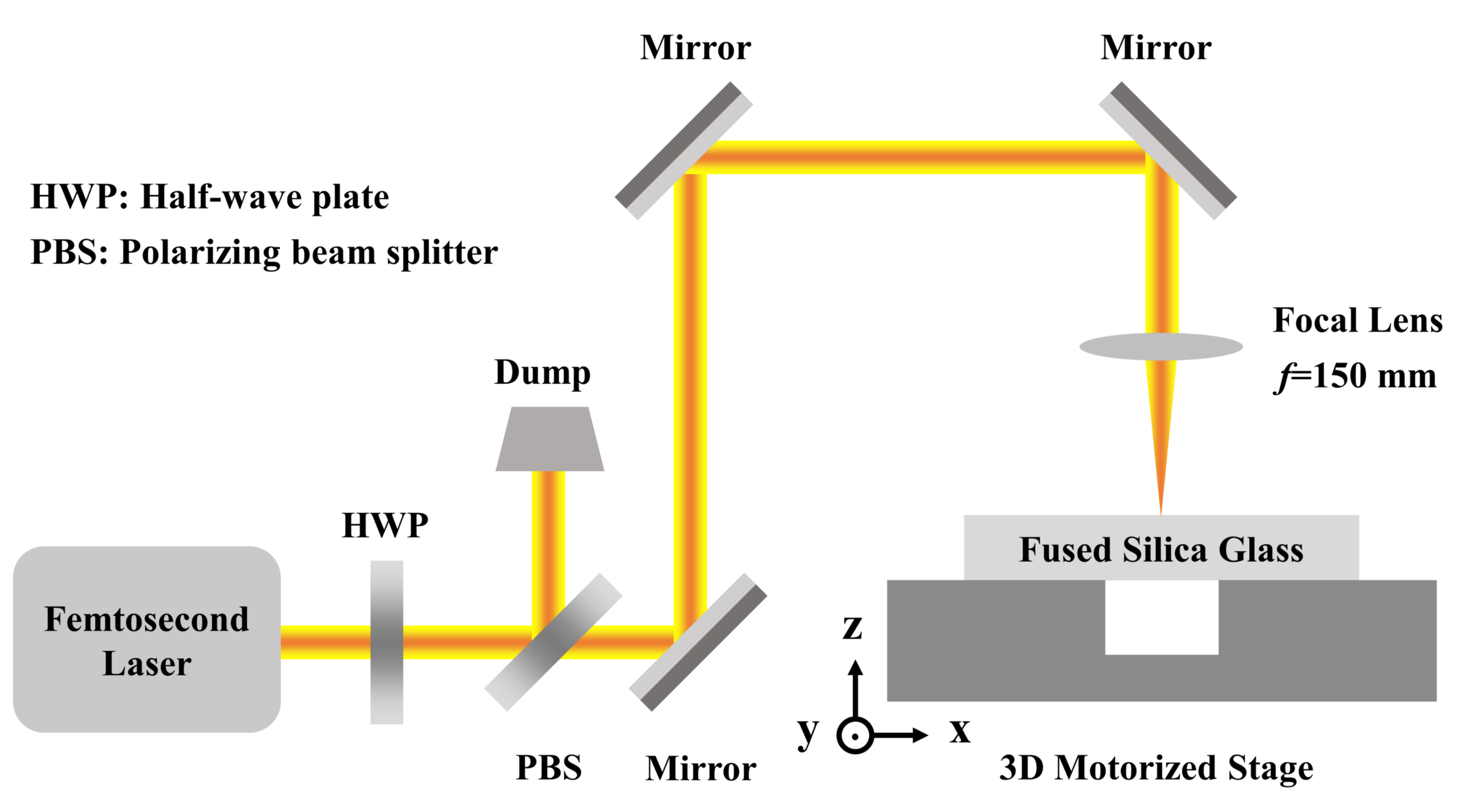

FIG 1 Experimental setup of femtosecond laser ablation in fused silica.

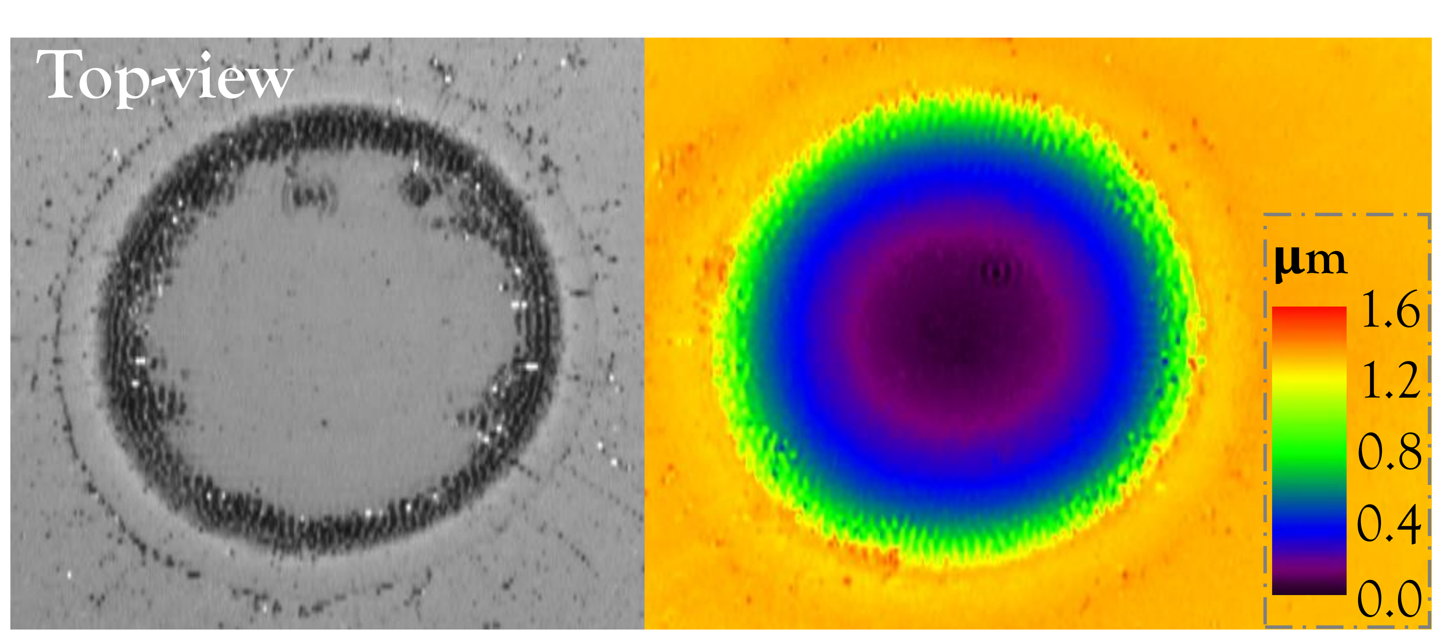

FIG 2 Morphology of ablation crater from 3D laser microscope.

Numerical Modeling

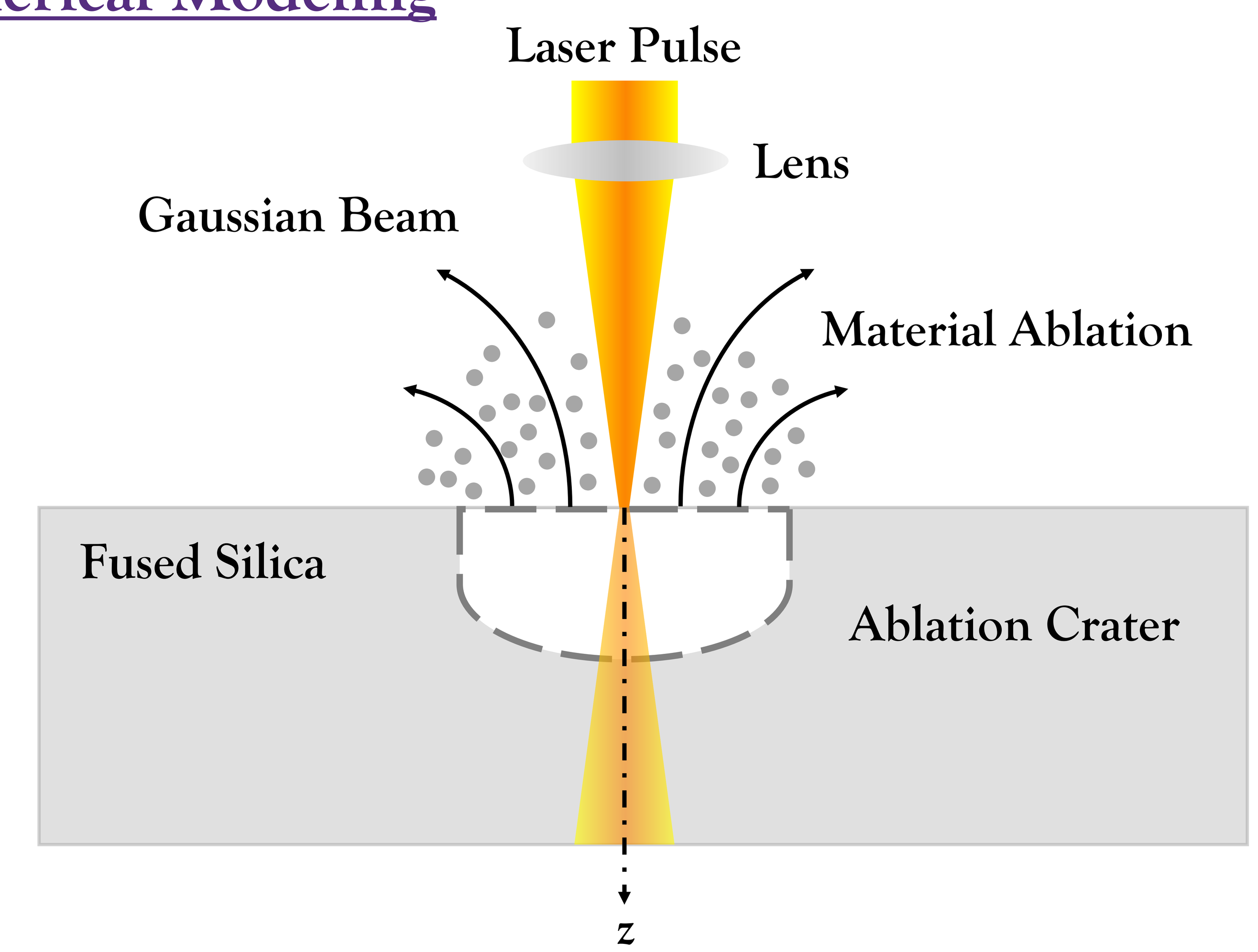

FIG 3 Schematic illustration of **ultrashort laser ablation.**

Two-Temperature Model (TTM)

$$\frac{\partial}{\partial t}(C_e T_e) = \nabla \cdot (K_e \nabla T_e) - G(T_e - T_l) + S$$

$$\frac{\partial}{\partial t}(C_l T_l) = \nabla \cdot (K_l \nabla T_l) + G(T_e - T_l)$$

T – Temperature
C - heat capacity
K - heat conductivity
S - laser source
G - electron-phonon coupling strength
e, l - electron and lattice

Plasma Model

$$\frac{\partial n_e}{\partial t} + \frac{1}{e}\frac{\partial J}{\partial z} = S_e - L_e$$

n - Electron number density
J – electronic flux
S – electron generation
L – electron loss

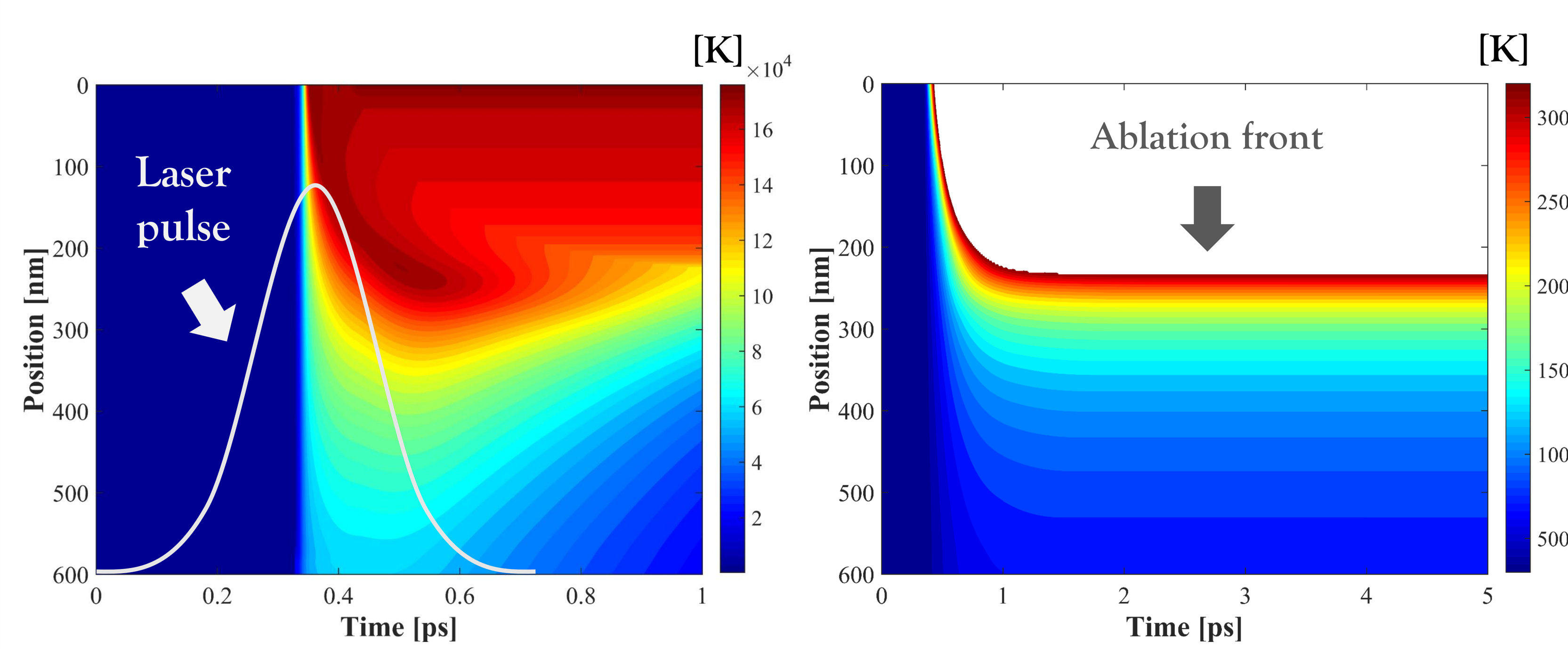

FIG 4 Temporal and spatial evolution of electron (left) and lattice (right) temperature in fused silica with a 6 J/cm², 190 fs, 1030 nm single pulse.

Acknowledgements

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For More Information Please Contact
Xiao Jia at xiaoj@g.clemson.edu

Air Plasma Defocusing

Beam defocusing by air plasma ***enlarges*** crater diameter and ***shrinks*** ablation depth.

Gaussian (Not good for high energy): *Mismatch* of Measurement and Prediction

Real (Good): *Match* of Measurement and Prediction

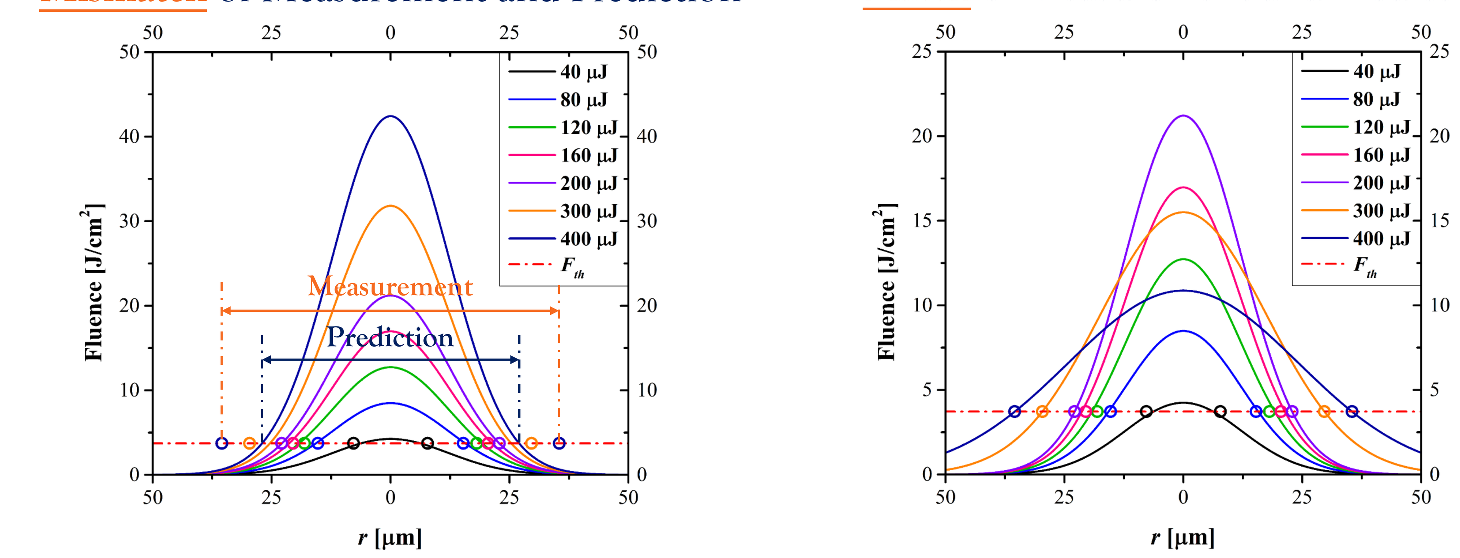

FIG 5 Predicted diameter without (left) and with (right) plasma defocusing effect.

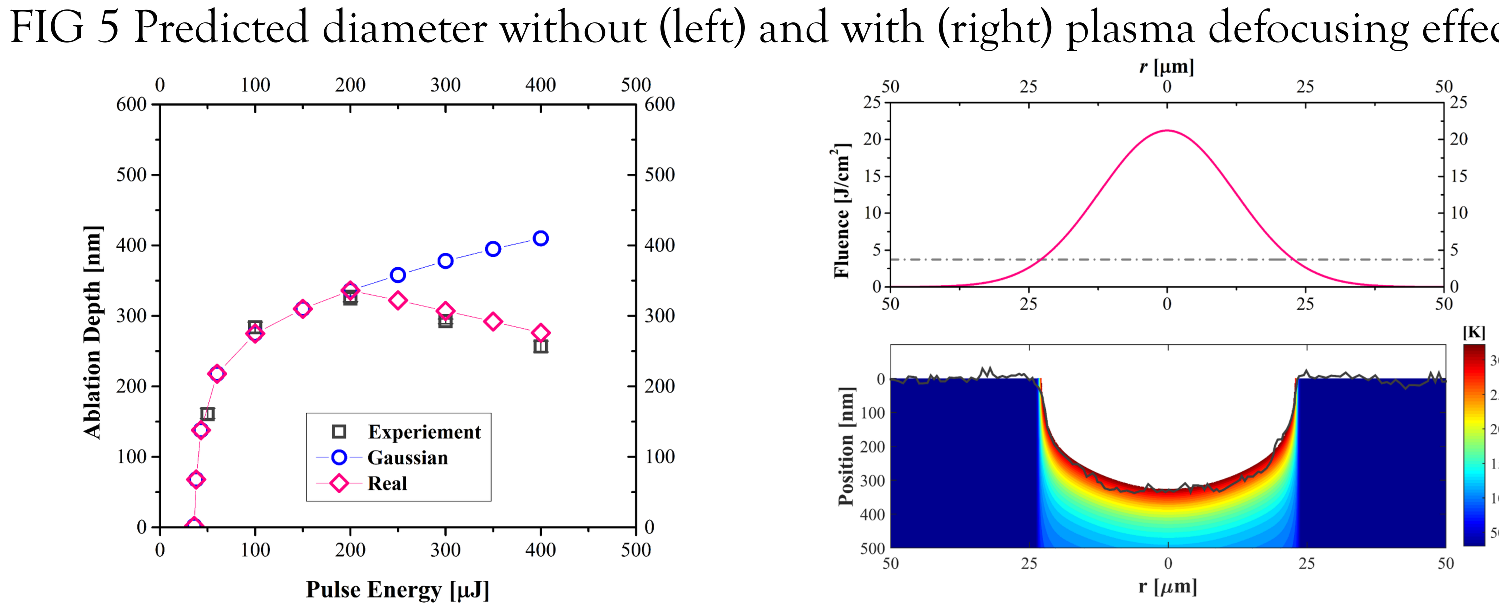

FIG 6 1D prediction of ablation depth and 2D representation of crater shape.

Ablation Enhancement

Thermal accumulation effect at 10 kHz ***doubles*** the machining speed at single-pulse.

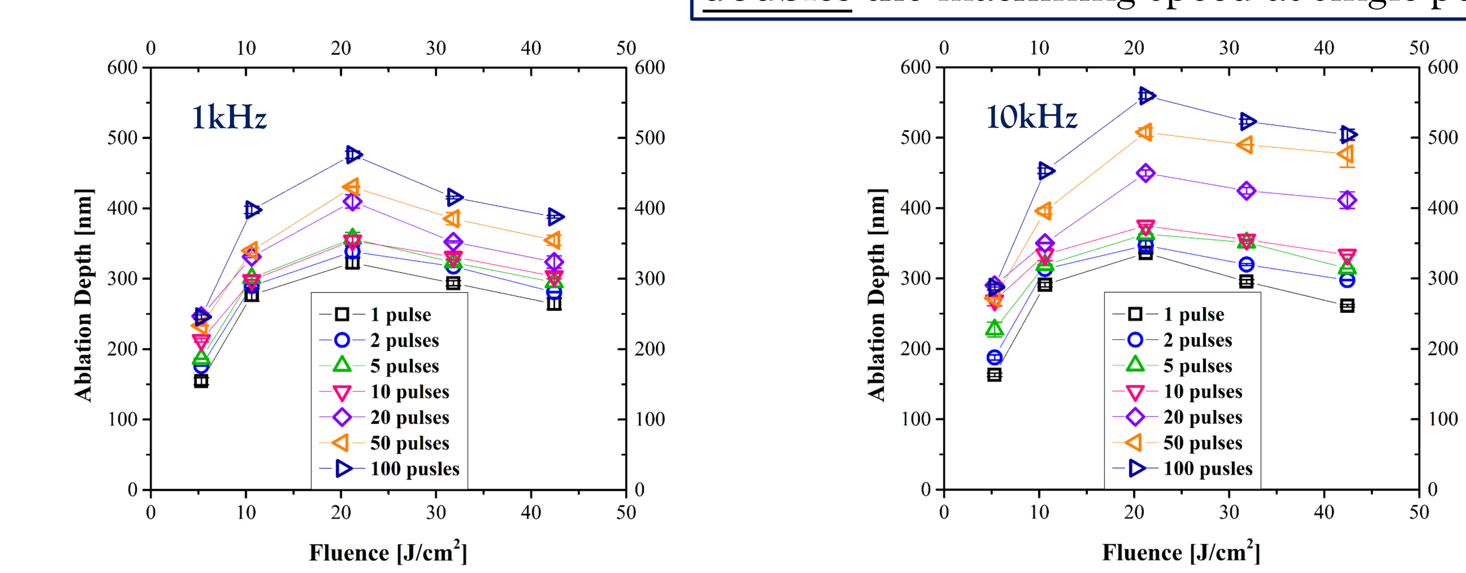

FIG 7 Measured depth (per pulse) vs. fluence at 1 kHz (left) and 10 kHz (right).

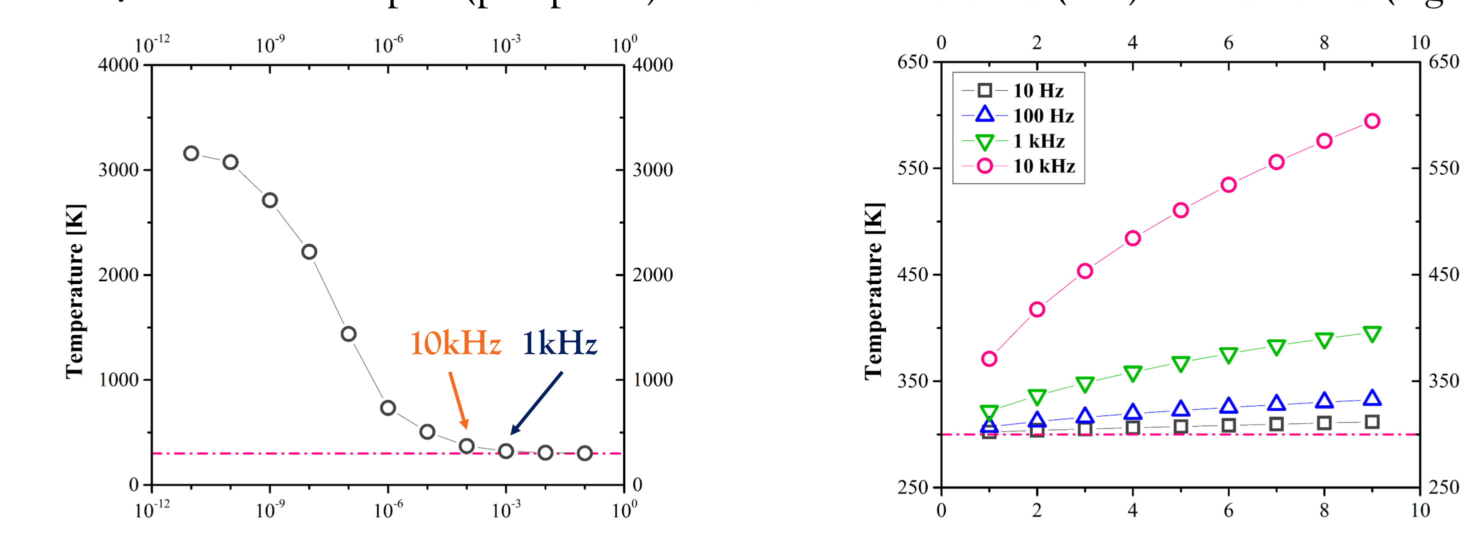

FIG 8 Temperature evolution with single (left) and multiple (right) pulses.

Conclusions

- ***Air plasma defocusing*** becomes prominent above 20 J/cm² (200 μJ), expanding crater diameter and reducing ablation depth.
- ***Thermal accumulation effect*** significantly enhances ablation at laser pulse repetition rate over 10 kHz.