

Atmospheric plume dynamics of a picosecond infrared laser with applications in surgery and biodiagnostics with mass spectrometry



E.Y.H. Lin^{1,2}, F. Busse¹, A. Krutilin¹, S.W. Epp¹, R.J.D. Miller^{1,3}

¹Max Planck Institute of the Structure and Dynamics of Matter, Hamburg, Germany, ²Faculty of Applied Science, University of British Columbia, Vancouver, Canada, ³Department of Physics and Chemistry, University of Toronto, Toronto, Canada

Introduction

In principle, lasers allow surgery at the single cell limit. But in practice, shock waves and thermal damage pose problems. A picosecond infrared laser (PIRL) can be tuned to excite the O-H stretching vibration of water, utilizing a regime termed desorption by impulsive vibrational excitation (DIVE)¹. This results in ablation processes faster than thermal exchange of energy and shock wave formation and avoids plasma formation or ionizing radiation effects. Intact functional biological entities are preserved and can be extracted and used for biodiagnostics^{2,3}.

The ablation results in a plume, which consists of a shock front and material ejections. Here, we present experiments that investigate the underlying vaporization processes under room temperature and standard pressure.

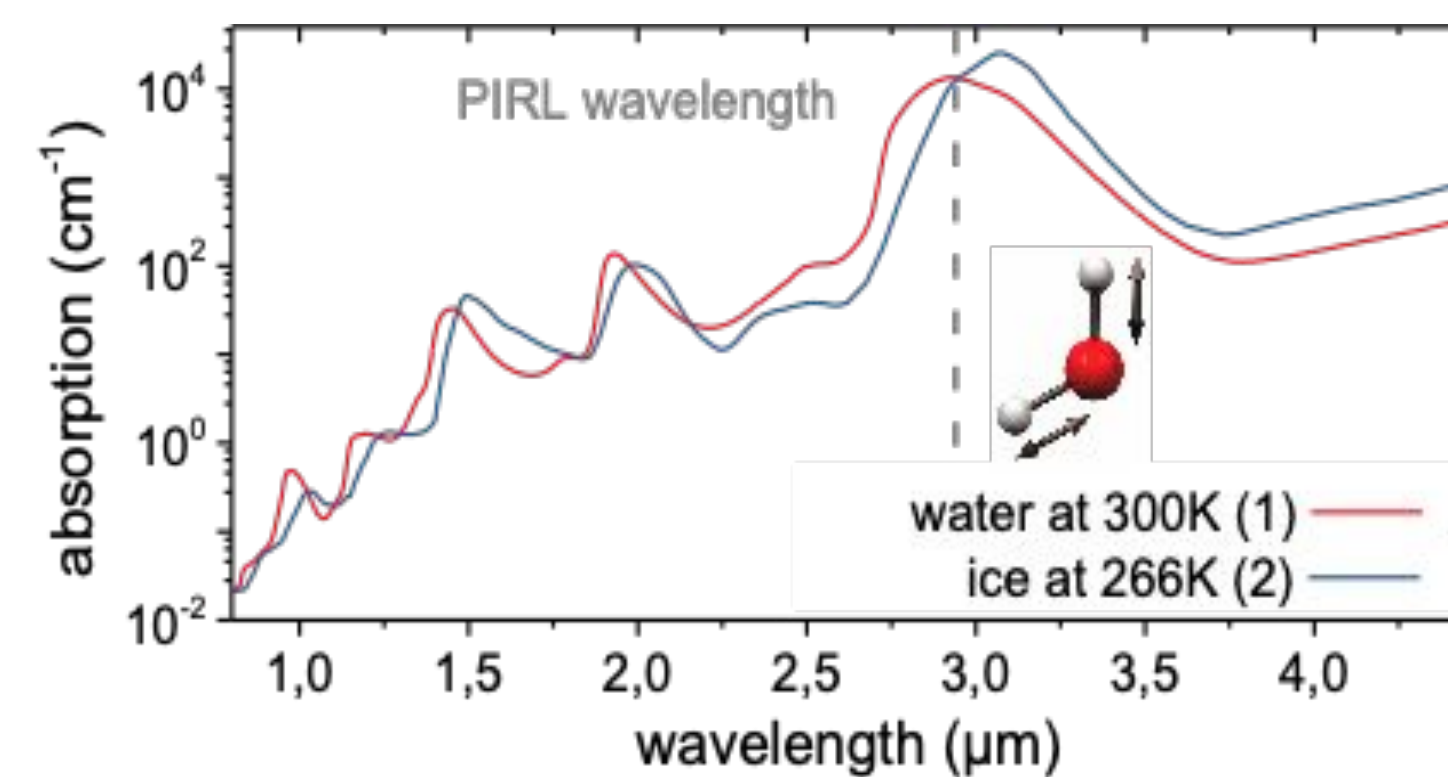


Figure: Absorption spectrum of water.

Experiments

Single-shot bright-field images were captured with varying delays after each pulse to capture plume growth over time.

Liquid Droplet Ablation

Liquid droplets were suspended from a steel syringe. The PIRL was focused onto the surface of each droplet, ablating normal to the surface.

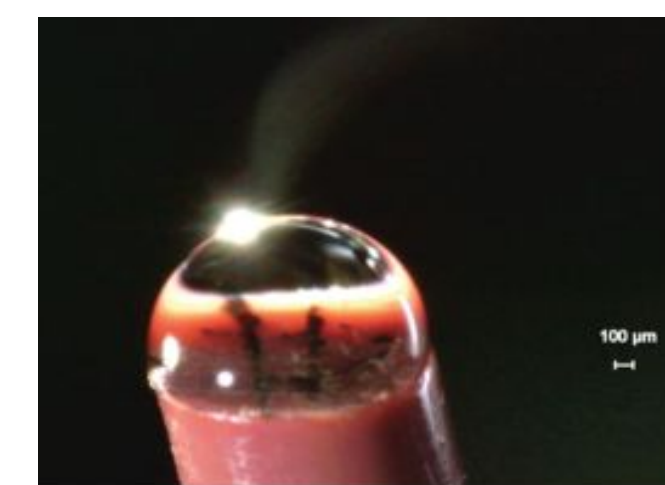
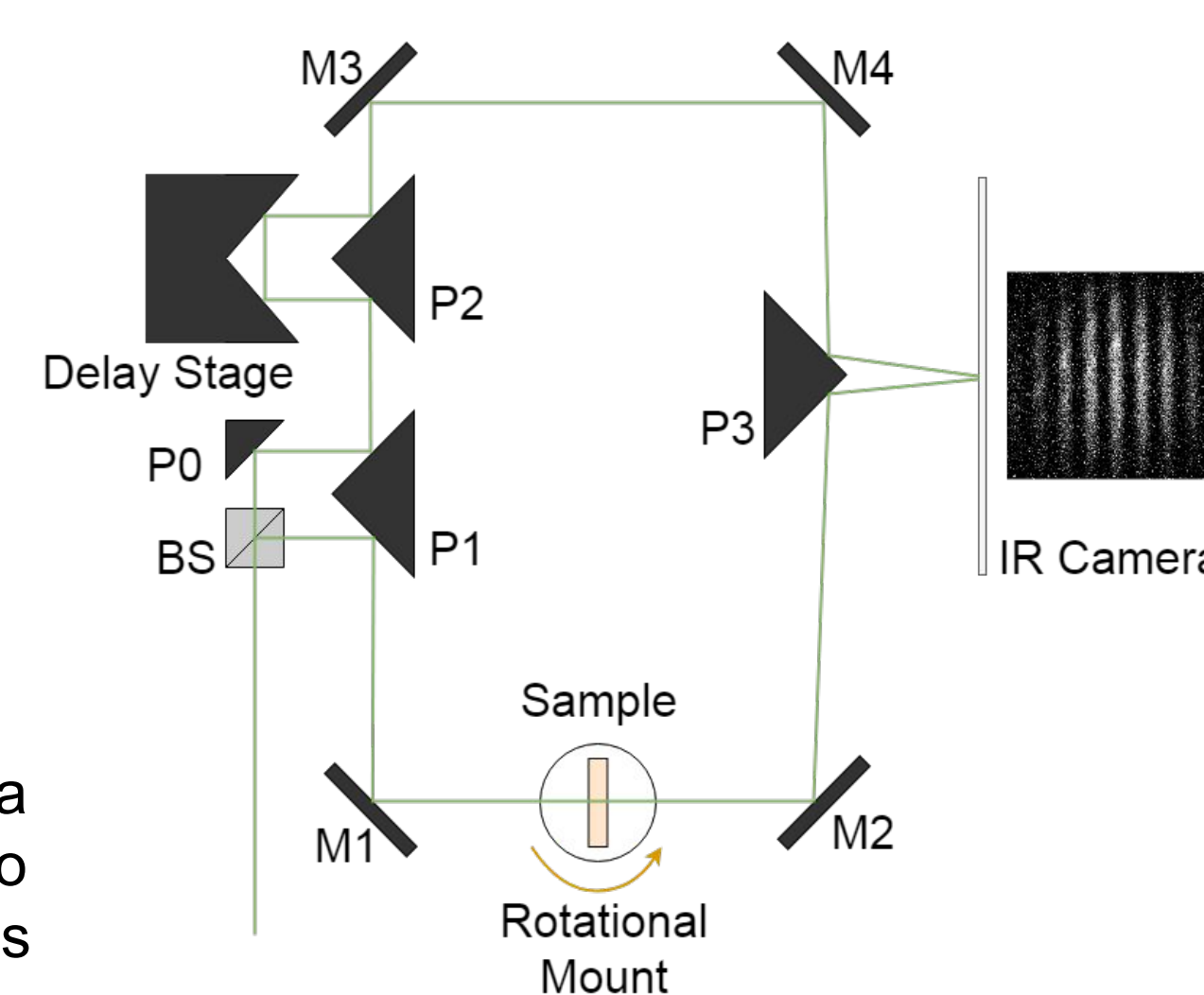


Figure: Droplet undergoing 1kHz PIRL-DIVE ablation. Scale bar shown is 100 μm. Lu Y. et al, *Anal. Chem.* 2018.

Free-Standing Thin Film Ablation

Vertically suspended films of water were ablated normal to the surface. An interferometer was incorporated to measure the thicknesses of each film simultaneously with the ablation processes.

Figure: Optical interferometer. Built with a 1.5μm continuous, tunable laser, it is able to measure free-standing thin film thicknesses and refraction indices.



Results

Plume Dynamics of Liquid Droplets

We investigate the ablation dynamics initiated by DIVE under atmospheric conditions for different materials. Water was chosen for its abundance in intramolecular and intermolecular hydrogen bonds. For acetone, intramolecular hydrogen bonds are unlikely while weak intermolecular ones are possible. Toluene has no hydrogen bonds and is nonpolar.

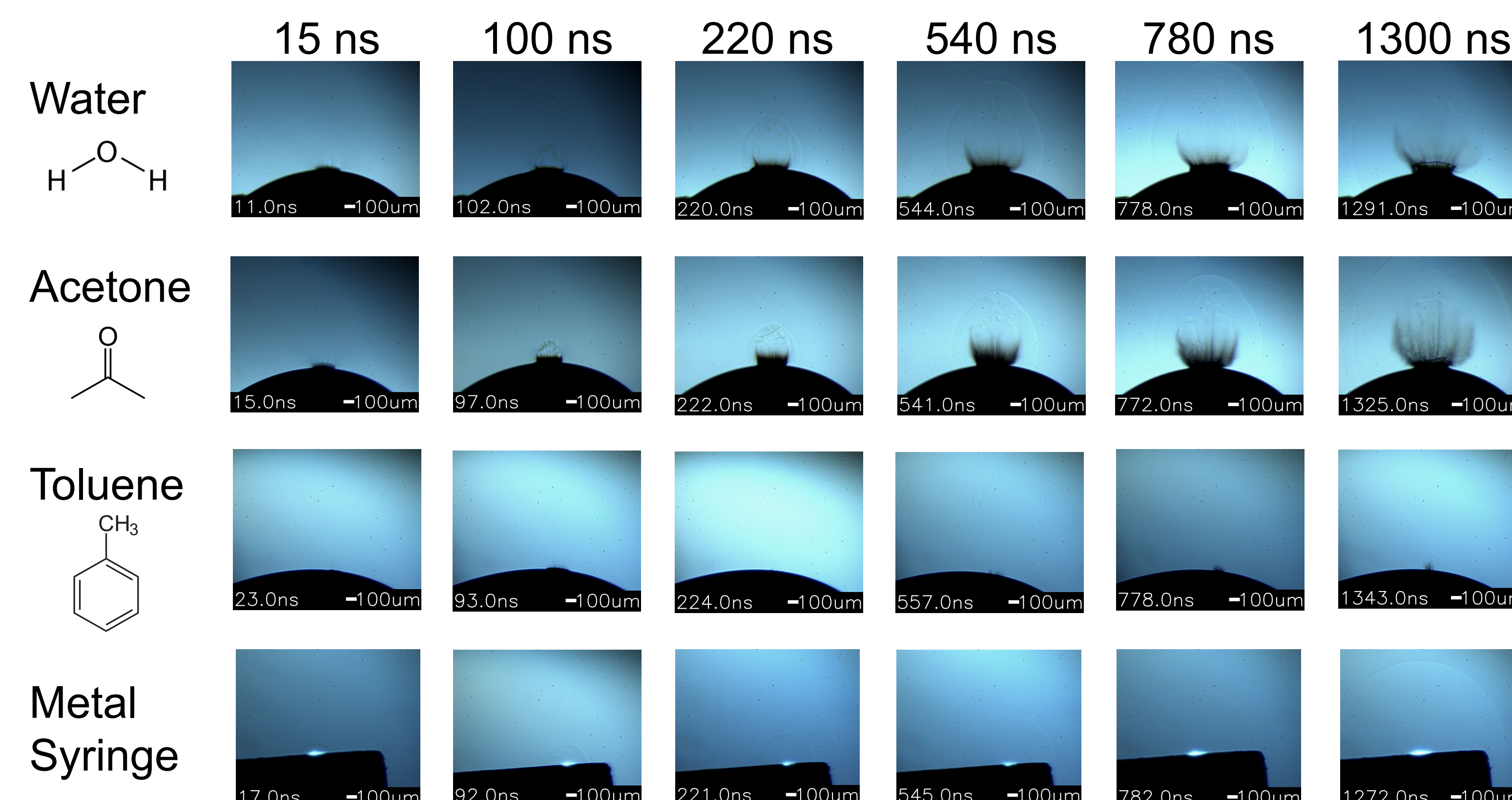


Figure: Plume expansion at comparable time points from distilled water, liquid acetone ≥99%, toluene ≥99%, and a metal syringe for high fluence (2.7 J cm⁻²). Scale bars indicate 100μm.

Acetone, which has significantly less hydrogen bonds compared to water, demonstrates plume structures similar to that of water. This is because the IR absorbance spectra of acetone shows an absorbance peak near the PIRL wavelength. Toluene has no peak near the PIRL wavelength.

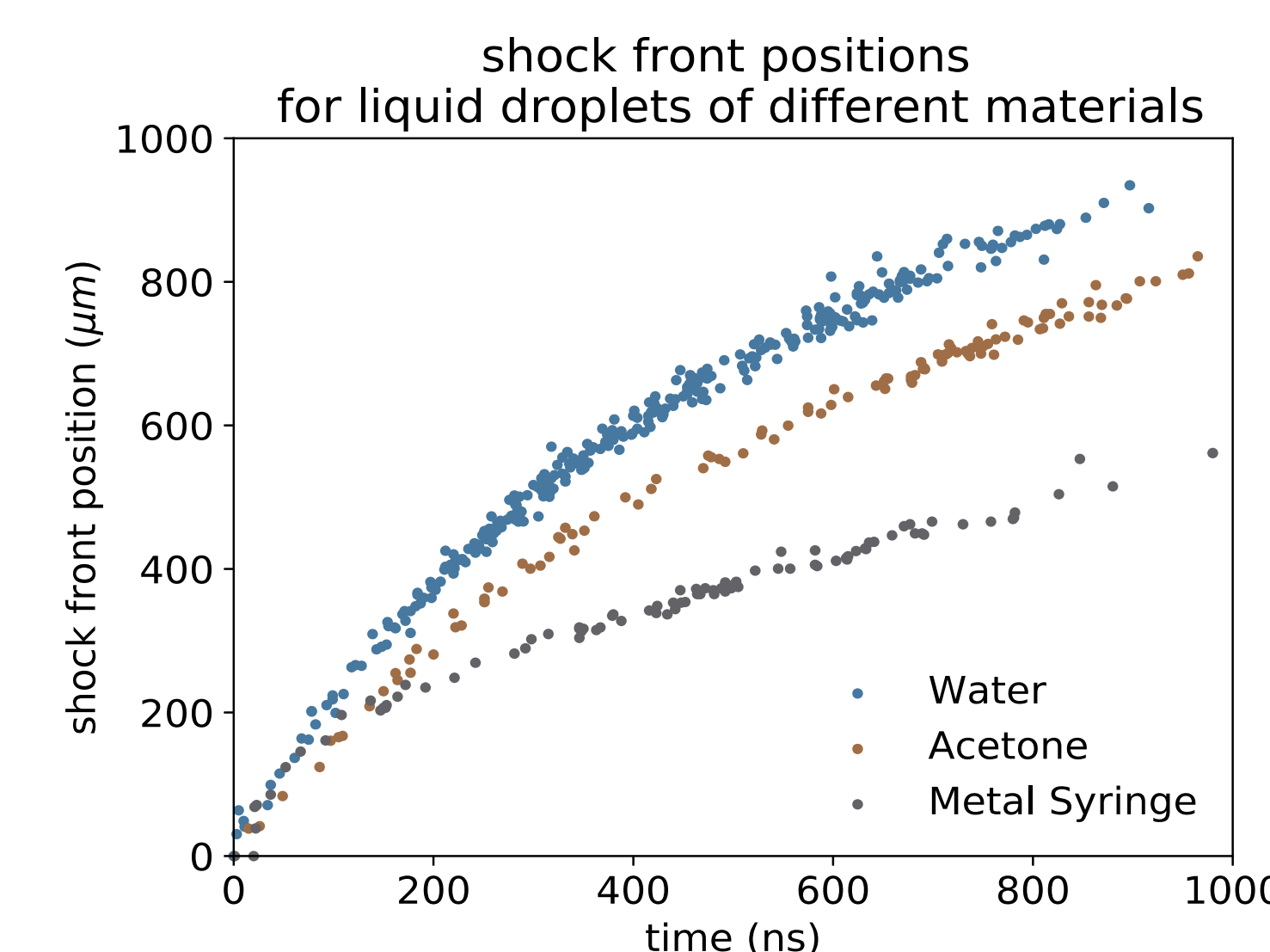


Figure: shock front positions for different materials.

Plume Dynamics of Free-Standing Thin Water Films

For thin water films with thicknesses 200-300nm, shock waves and material ejections can also be observed. By conservation of momentum, if there is a shock wave propagating away from one side of the film, there will be an equal and opposite effect on the other side.



Figure: thin water film

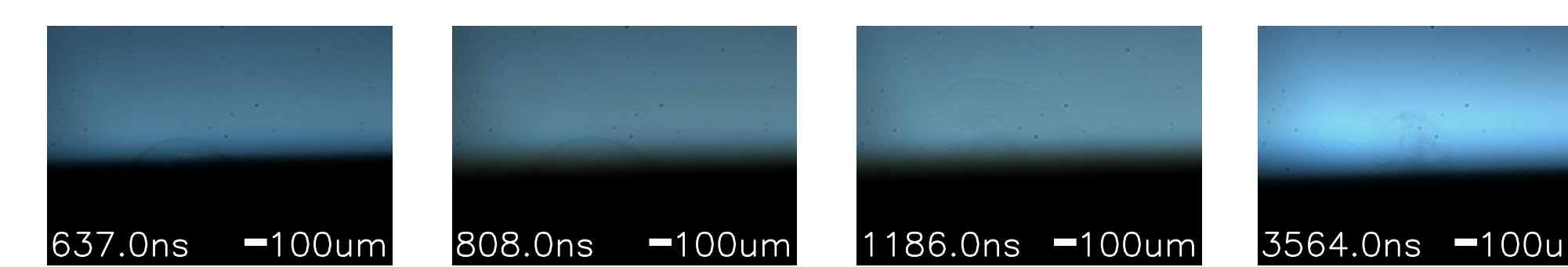
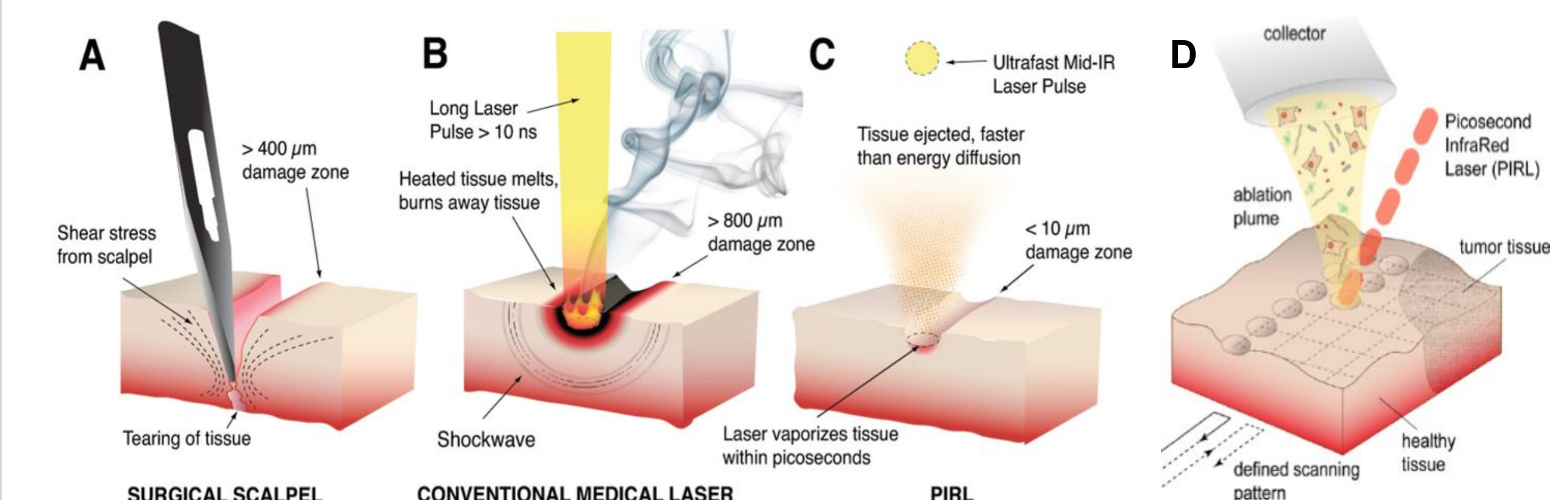


Figure: Plume expansion at various time points from thin free-standing water film for high fluence (2.7 J cm⁻²). Scale bars indicate 100μm.

Applications



- Surgical scalpels apply shear stress on tissue, increasing damage on surrounding tissues.
- A conventional laser is limited by damages from shock waves and thermal damage.
- The PIRL selectively excites the O-H bond using water as a propellant. Wounds created with the PIRL system showed near absence of scar formation^{4,5}.
- Functional biomolecules are ejected from the ablated cells. By collecting the plumes for a mass spectrometer to analyze, a molecular map of the ablated cell can be created.

Conclusions

- Shock waves are present in DIVE processes. Materials with a higher water content will have a faster shock wave.
- The thermal and acoustic relaxations are demonstrated to be in the μm and ns regime.
- While the PIRL can selectively excite water molecules, it can also ablate materials that absorb at its wavelength.
- The PIRL is an efficient tool for the ablation of aqueous biological tissue.

References

1. K. Franjic, M. L. Cowan, D. Kraemer, and R. J. D. Miller, *Opt. Express*, vol. 17, no. 25, pp. 22937–22959, Dec. 2009.
2. L. Ren et al., *Nanotechnology*, vol. 26, no. 28, p. 284001, Jul. 2015.
3. A. Krutilin et al., submitted Jul. 2018.
4. S. Amini-Nik et al., *PLoS ONE*, vol. 5, no. 9, p. e13053, Sep. 2010.
5. P. D. S. J. Linke et al., *Ophthalmology*, vol. 111, no. 6, pp. 523–530, Jun. 2014.

