Shadowgraphy of the Plasma's Evolution Around Water Micro-Droplets Irradiated by High-Power Laser Pulses

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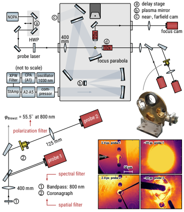
We present the results of a laser-driven plasma evolution experiment at the POLARIS laser system at the Institute for Optics and Quantum Electronics at the Friedrich-Schiller-University Jena and the Helmholtz-Institute Jena [1]. The interaction of a high intensity main laser pulse with water microdroplet targets was investigated with off-harmonic optical probe pulses. In contrast to experiments with thin foils, the spherical symmetry of droplets facilitates a direct imaging of the plasma expansion process using shadowgraphy. By changing the temporal delay of the probe laser with respect to the main laser, the expansion process was probed in a temporal window between -4.7 to +258 ps relative to the arrival of the main laser pulse. The strong emission of light from the laser-induced plasma at the fundamental and second harmonic frequency was suppressed with a bandpass filter, a polarization filter and a spatial filter (coronagraph). A detailed analysis of the shadowgraphic images allowed us to estimate the plasma expansion velocity of the front and rear side of the droplets at early times of the interaction.

Experimental setup and diagnostics



- **POLARIS** at 1030 nm, contrast enhanced with plasma mirror, $\tau \approx 150$ fs (FWHM), $I = 4 \times 10^{19}$ W / cm^2, $a_0 \approx 5.5$, linear polarization
- **Water droplets** with $d \approx 20$ µm, commercial nozzle (Micro Jet Components), synchronized with laser
- **Optical probe system** [2]: single pass NOPA, µJ-level energy, broad bandwidth between 750-950 nm, spectrally filtered after interaction to 800 nm (40 nm FWHM).
- **Imaging setup**: Mitutoyo NIR 10x objective (d), wedged glass plate (Brewster angle) + spatial filter (coronagraph) to suppress the strong plasma emission and scattered light from the main laser pulse, reference setup (probe 1) for comparison
- **Coronagraph**: circular mask of diameter $d = 300$ µm placed in the intermediate image plane of the droplets

Shadowgraphy measurement

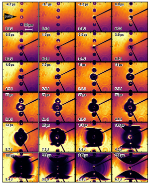


Fig. 1: Shadowgraphic images of water droplets with coronagraph for different pump-probe delays τ (top left). The laser energy E on the target is also shown (bottom left) [1].

Plasma Expansion

- $\tau = 0$: blackening of the neighbouring droplets due to generation of plasma ⇒ $n_e \gg n_c = 1.74 \times 10^{21}$ / cm^3 at 800 nm
- Growing spatial extent of the dark volume (overcritical plasma) for increased delays
- Edge of the dark region corresponds to $n_e \ll n_c$ [3], still, the expansion of the shadow can be measured
- Delays $\tau < 20$ ps: front and rear side grow along the laser axis linearly: velocity $v_{\text{front}} \approx 1.27$ µm / ps and $v_{\text{rear}} \approx 0.77$ µm / ps ⇒ comparable to similar experiments with liquid targets [4, 5]
- Estimated **ion sound speed**: $c_s = 0.25$ µm / ps (for $n_e = 153 n_c$)

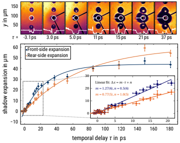


Fig. 2: Expansion of the front (blue) and rear (orange) of the plasma parallel to the laser propagation axis as a function of the delay τ [1].

- after the interaction: decreasing electron temperature, change of expansion geometry to spherical expansion ⇒ smaller expansion velocity for larger times
- Ponderomotive scaling for hot electrons ($k_B T_e \approx 2.4$ MeV) leads to an ion sound speed of $c_s \approx 15$ µm/ ps (protons) ⇒ disagreement of measured values may indicate a different intensity scaling or that the hot electron plasma model cannot be applied

Summary

- Implementation of a pump-probe setup in a water-based microdroplet experiment to study the temporal evolution of the plasma using shadowgraphy
- Successful suppression of the plasma emission and main laser light scattering by using an off-harmonic spectral filter, a polarization filter and coronagraph
- Measurement of the evolution of the plasma expansion up to delays of +258 ps,
- Linear expansion in the first 20 ps with an expansion velocity $v_{\text{front}} = 1.27$ µm / ps (plasma front) and different behaviour on the rear side
- Estimated ion sound speed $c_s = 0.25$ µm / ps

Acknowledgements

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References:
[1] M. Beyer, Development of Laser Sources and Diagnostics for Probing Relativistic Laser-Matter Interaction, Master thesis, 2022
[2] I. Tamer et al., Few-cycle fs-pumped NOPA with passive ultrabroadband spectral shaping, 2020
[3] M. Nolte, Characterization of liquid micro-droplets for laser-driven proton acceleration, Master thesis, 2023
[4] G. Becker et al., Characterization of laser-driven proton acceleration from water microdroplets, 2019
[5] C. Bernert et al., Off-harmonic optical probing of high intensity laser plasma expansion dynamics in solid density hydrogen jets, Scientific reports, 2022

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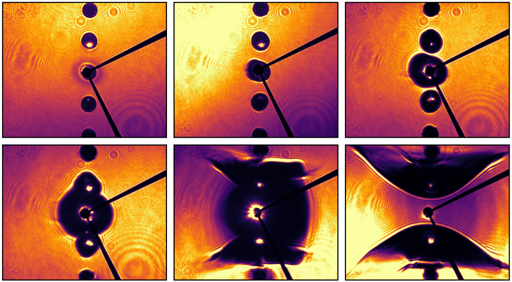


September 22nd, 2023

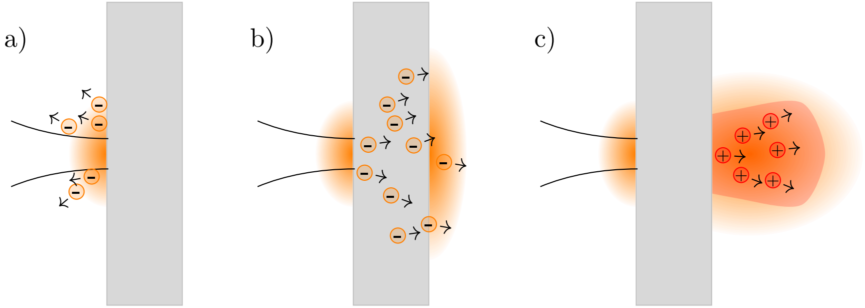


Fig.: Working principle of TNSA with foil targets.

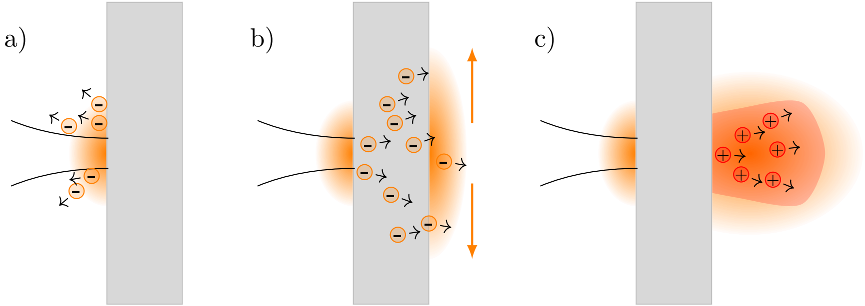


Fig.: Working principle of TNSA with foil targets.

- Electrons can leave the interaction zone along the foil's rear side.

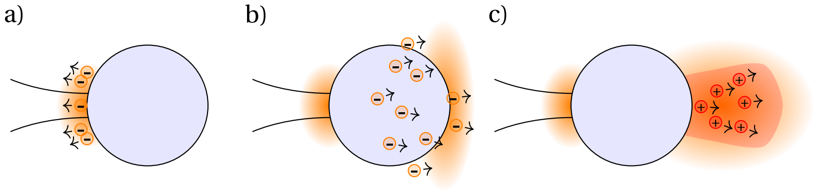


Fig.: Working principle of TNSA with droplet targets.

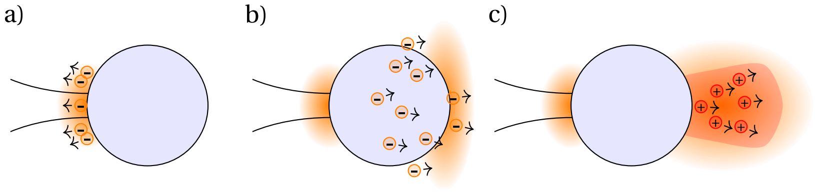
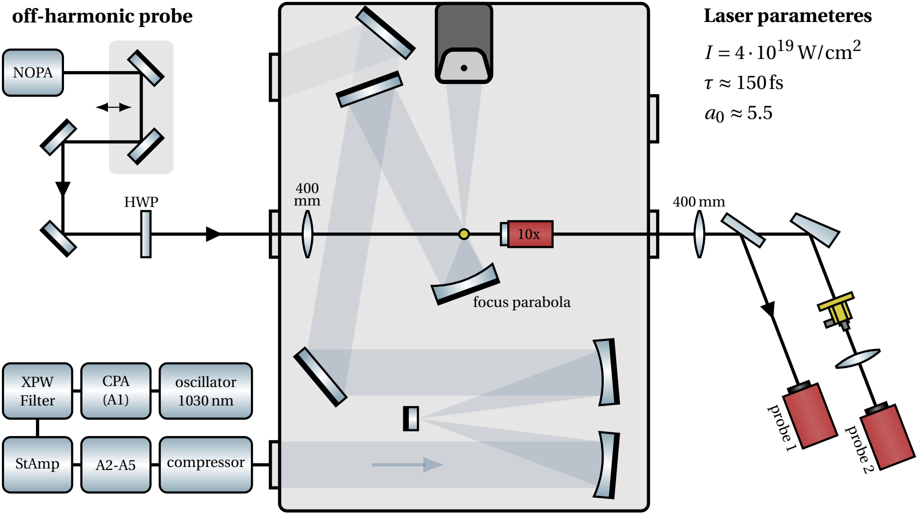


Fig.: Working principle of TNSA with droplet targets.

- limited spatial extension
- cheap and high repetition rate

Experimental setup



Laser parameteres

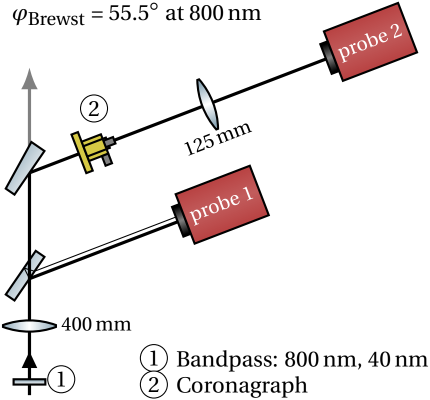
$I = 4 \cdot 10^{19}\,\mathrm{W/cm^2}$

$\tau \approx 150\,\mathrm{fs}$

$a_0 \approx 5.5$

Diagnostics setup

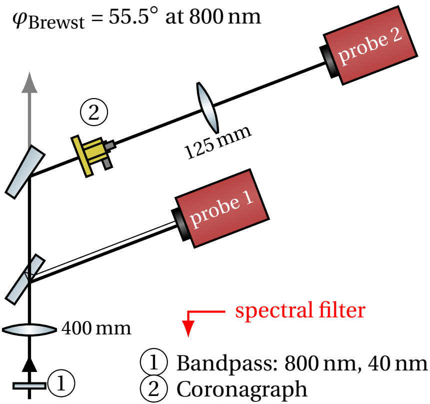
$\varphi_{\text{Brewst}} = 55.5^{\circ}$ at 800 nm

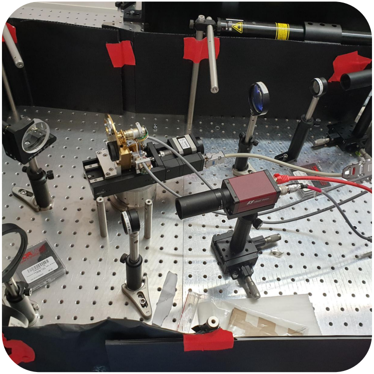


① Bandpass: 800 nm, 40 nm (FWHM)
② Coronagraph

Diagnostics setup

polarization filter



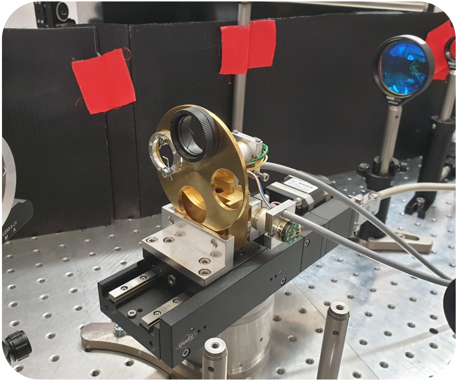


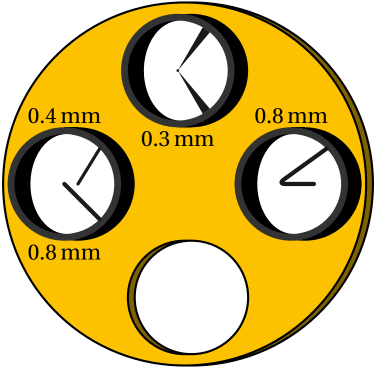
spectral filter

1. Bandpass: 800 nm, 40 nm (FWHM)
2. Coronagraph

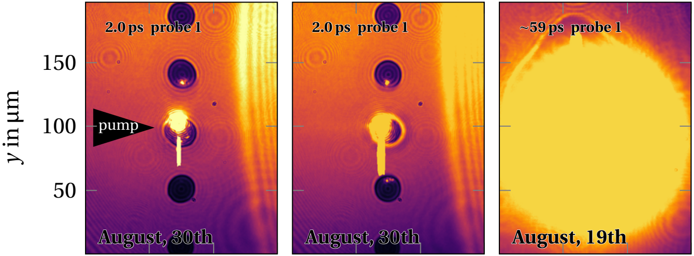
spatial filter

Spatial filter - Coronagraph

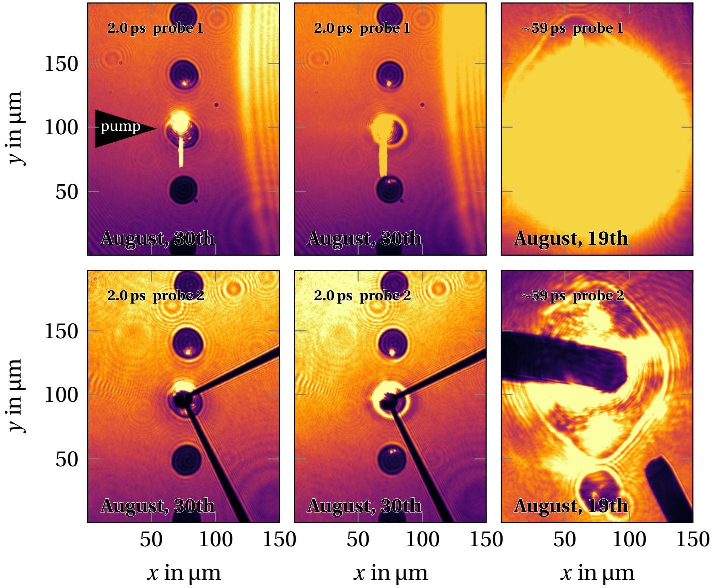




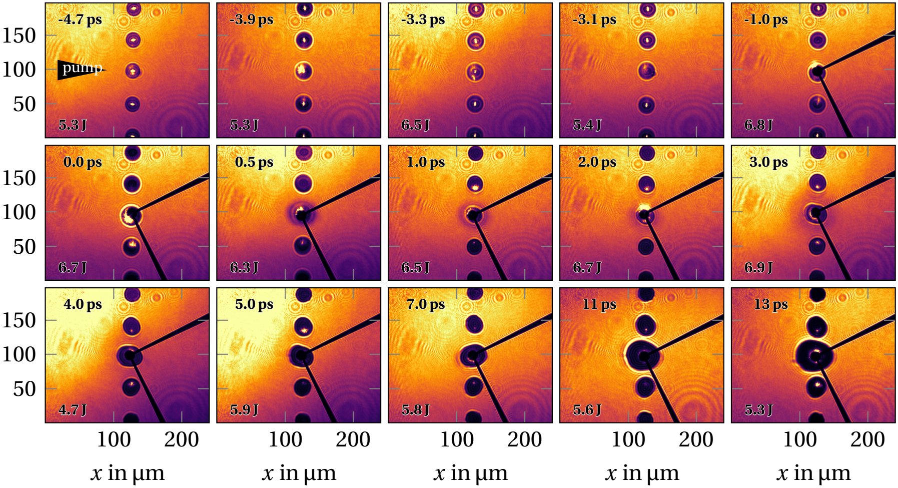
Coronagraph - Experimental results



Coronagraph - Experimental results



Shadowgraphy of the plasma evolution



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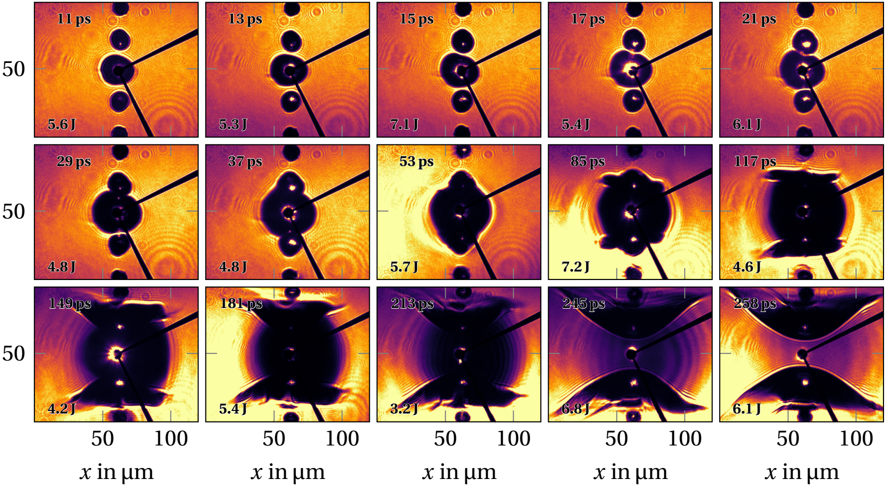
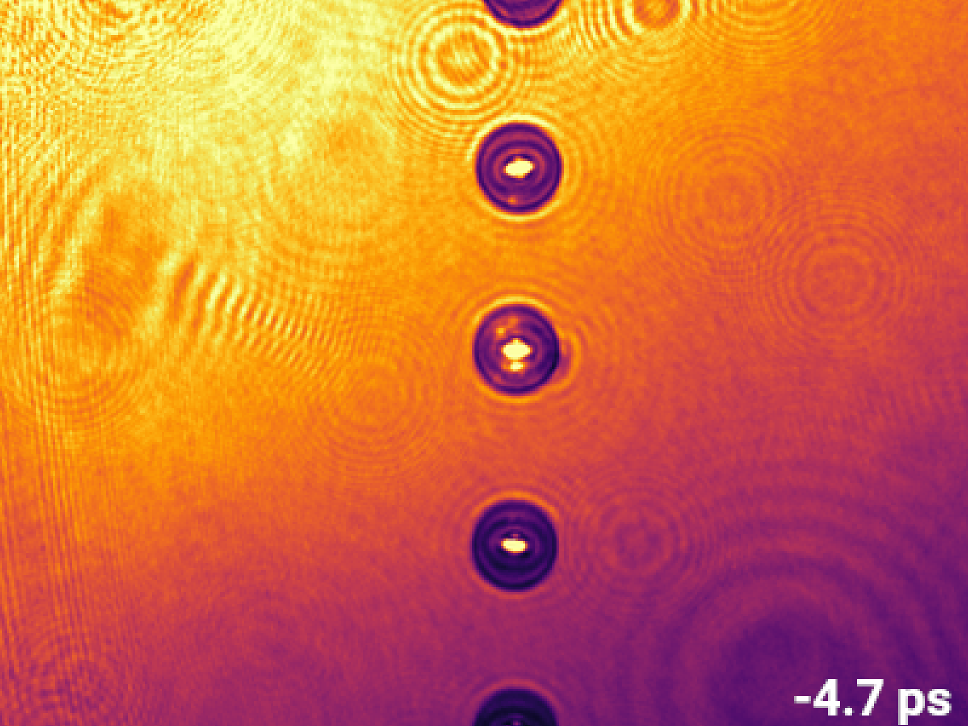
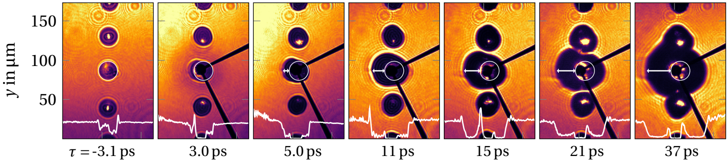
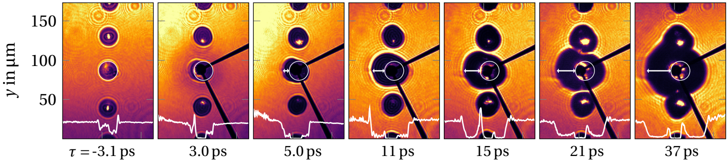
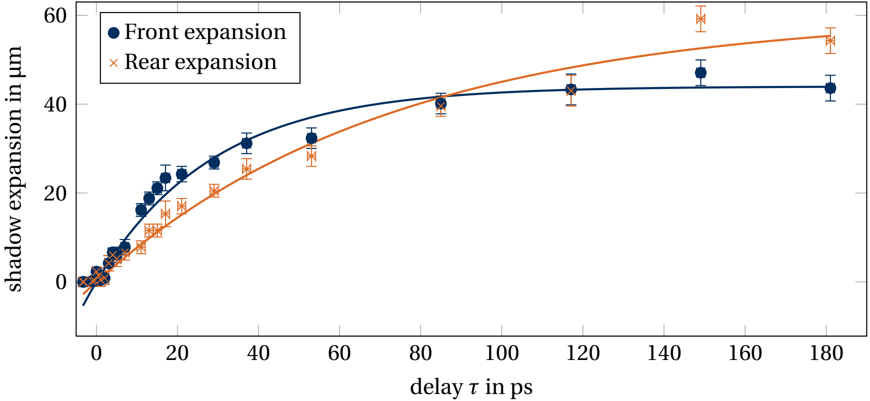



-4.7 ps

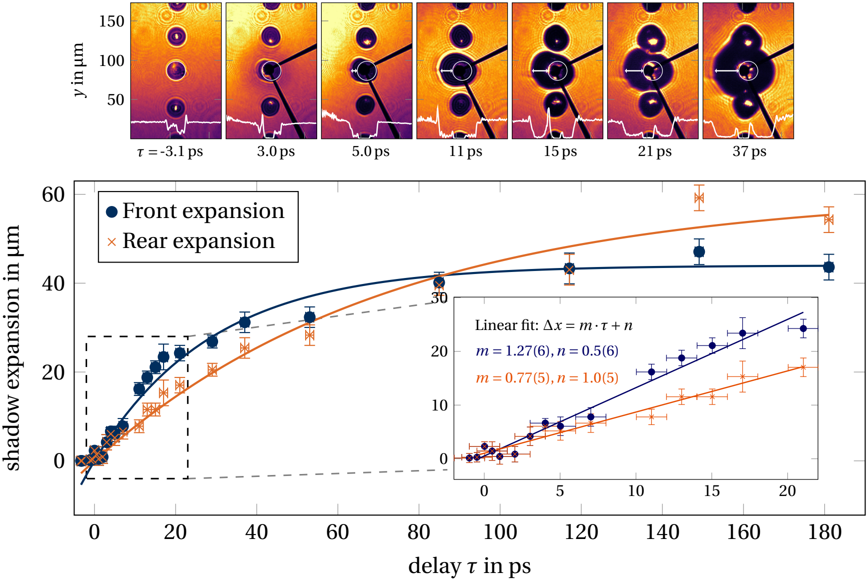

150
100
50
y in µm
τ = -3.1 ps
3.0 ps
5.0 ps
11 ps
15 ps
21 ps
37 ps

Estimation of plasma expansion velocity





Estimation of plasma expansion velocity



Estimation of plasma expansion velocity

$$\tau = 3\text{–}20\,\text{ps} \quad v_{\text{front}} = (1.27 \pm 0.06)\,\mu\text{m/ps}, \quad v_{\text{rear}} = (0.77 \pm 0.05)\,\mu\text{m/ps}$$

$$\tau = 80\text{–}190\,\text{ps} \quad v_{\text{front}} = (0.09 \pm 0.03)\,\mu\text{m/ps}, \quad v_{\text{rear}} = (0.22 \pm 0.05)\,\mu\text{m/ps}.$$

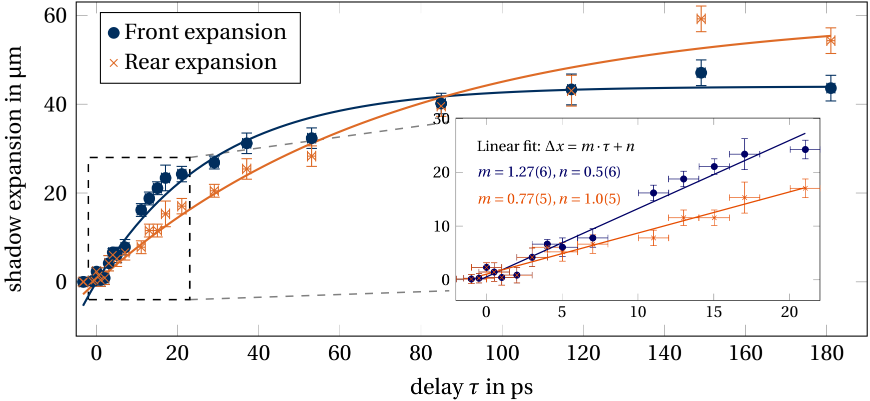


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Table: Comparison of shadowgraphy plasma expansion experiments with targets for different peak intensities.

experiment	target	intensity	λ	v_{front}
Becker et al.[1]	H_2O droplets	10^{16} W/cm^2	800 nm	0.38 µm/ps
Beyer et al.	H_2O droplets	$4 \cdot 10^{19}$ W/cm^2	1030 nm	1.3 µm/ps
Bernert et al.[2]	hydrogen jet	$5 \cdot 10^{21}$ W/cm^2	800 nm	23 µm/ps

[1] "Becker, G.A., Schwab, M.B., Lötzsch, R. et al. Sci Rep 9, 17169 (2019)"
[2] "Bernert, C., Assenbaum, S., Brack, FE. et al. Sci Rep 12, 7287 (2022)"

Summary and Outlook

Summary

- water-based microdroplet experiment to study the temporal evolution of the plasma up to +258 ps using shadowgraphy
- Successful suppression of the plasma emission
- Estimation of the expansion velocity + ion sound speed

Outlook

- Investigation of different target materials e. g. ethylene glycol
- build a “one-shot” setup using chirped pulse probing
- experiment with a higher laser energy

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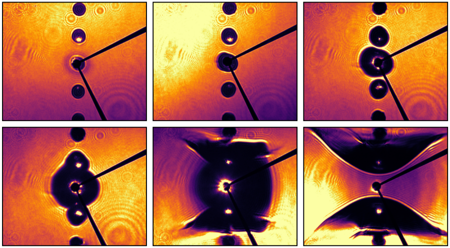

Thank you for your attention.