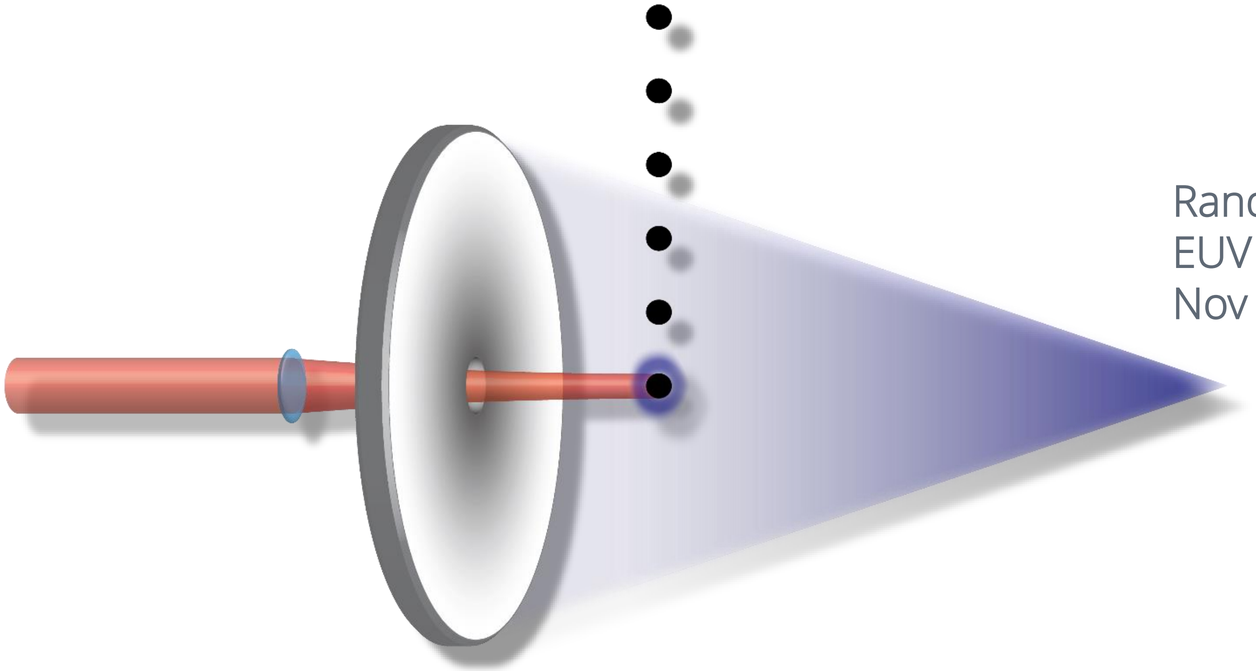
The transition from *short to long* timescale pre-pulses

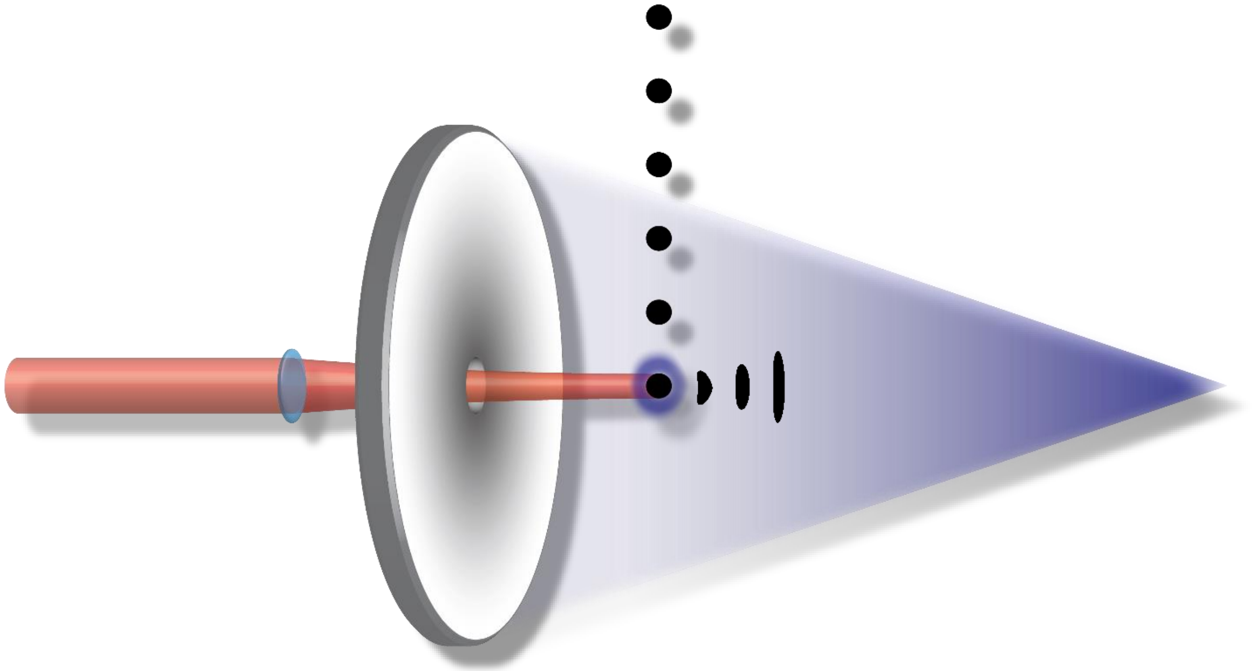
Laser-pulse impact on tin microdroplets.



Randy Meijer
EUV Litho Source Workshop
Nov 4 2019

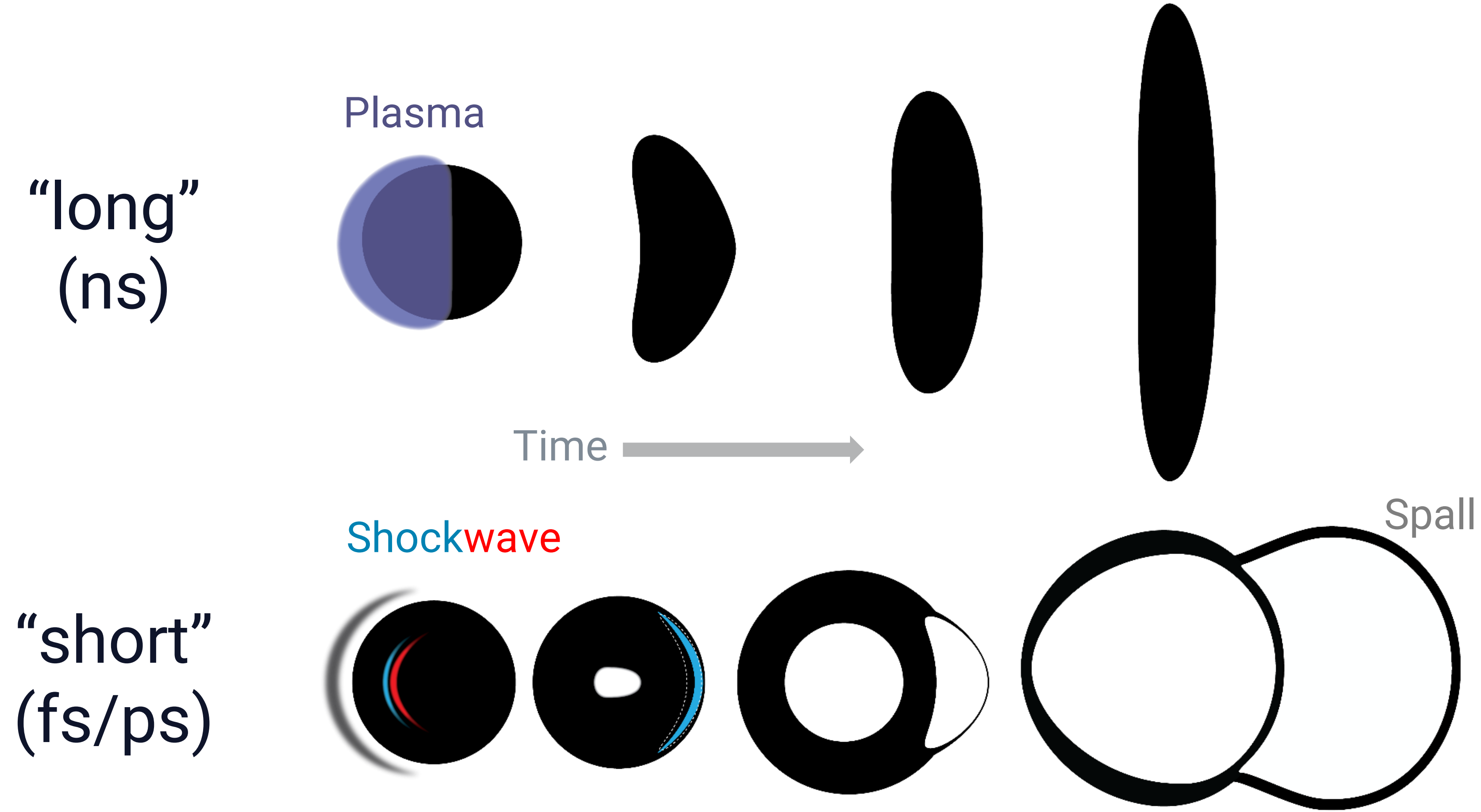
The transition from *short to long* timescale pre-pulses

Laser-pulse impact on tin microdroplets.



“long”
(ns)

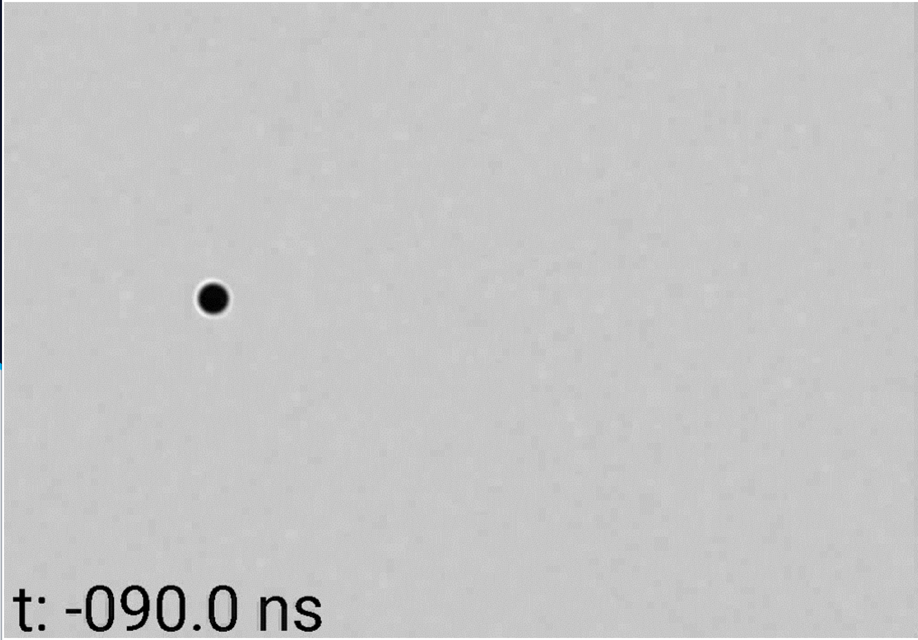
Kurilovich, D. et al. Plasma Propulsion of a Metallic Microdroplet and its Deformation upon Laser Impact. Phys. Rev. Appl. 6, 1–8 (2016).



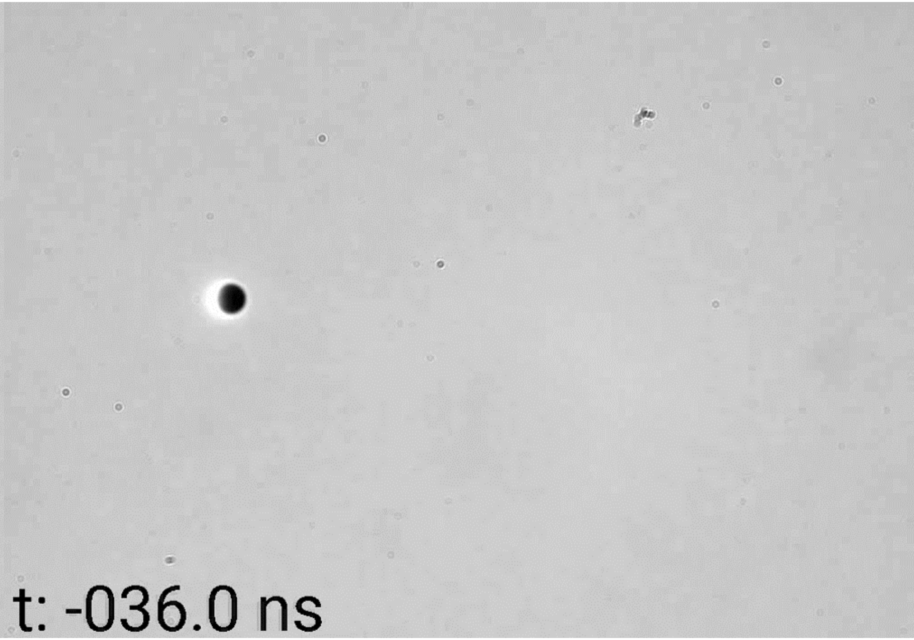
Kurilovich, D. et al. Expansion Dynamics After Laser-Induced Cavitation in Liquid Tin Microdroplets. Phys. Rev. Appl. 10, 1–7 (2018).

What is short, what is long, and what is in between??

‘Short’

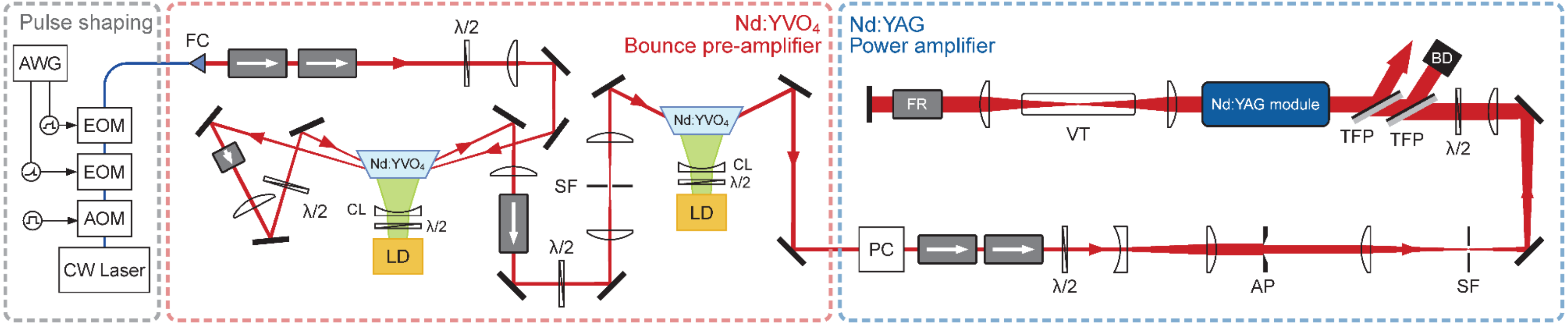


‘Long’



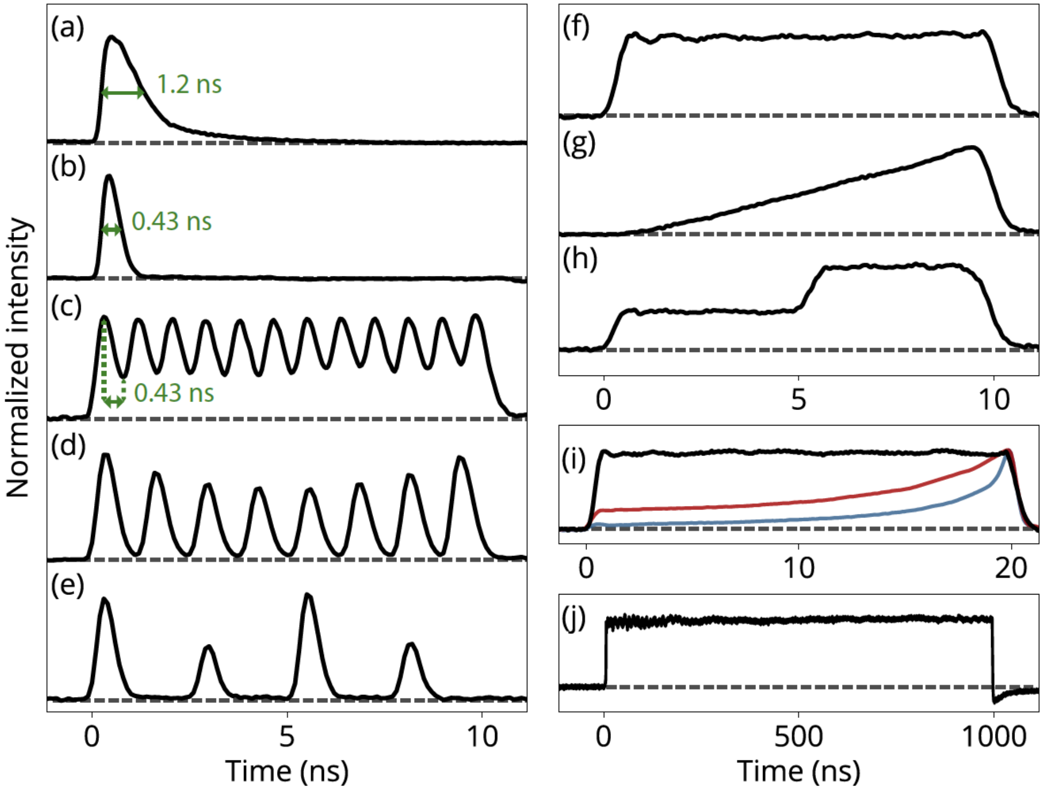
Interlude: Flexible pulse laser @ ARCNL

λ = 1064 nm, (Nd:YAG)



Meijer, R. A., Stodolna, A. S. & Eikema, K. S. E. High-energy Nd : YAG laser system with arbitrary sub-nanosecond pulse shaping capability. *Opt. Lett.* **42**, 2758–2761 (2017).

Interlude: Flexible pulse laser @ ARCNL



λ = 1064 nm, (Nd:YAG)

- CW seeded
- Pulse duration

  0.43 ns → 1.1 us
- Energy (100 Hz)

  300-500 mJ
- Multiple pulses, 1 laser
- PP, MP

Meijer, R. A., Stodolna, A. S. & Eikema, K. S. E. High-energy Nd : YAG laser system with arbitrary sub-nanosecond pulse shaping capability. *Opt. Lett.* **42**, 2758–2761 (2017).

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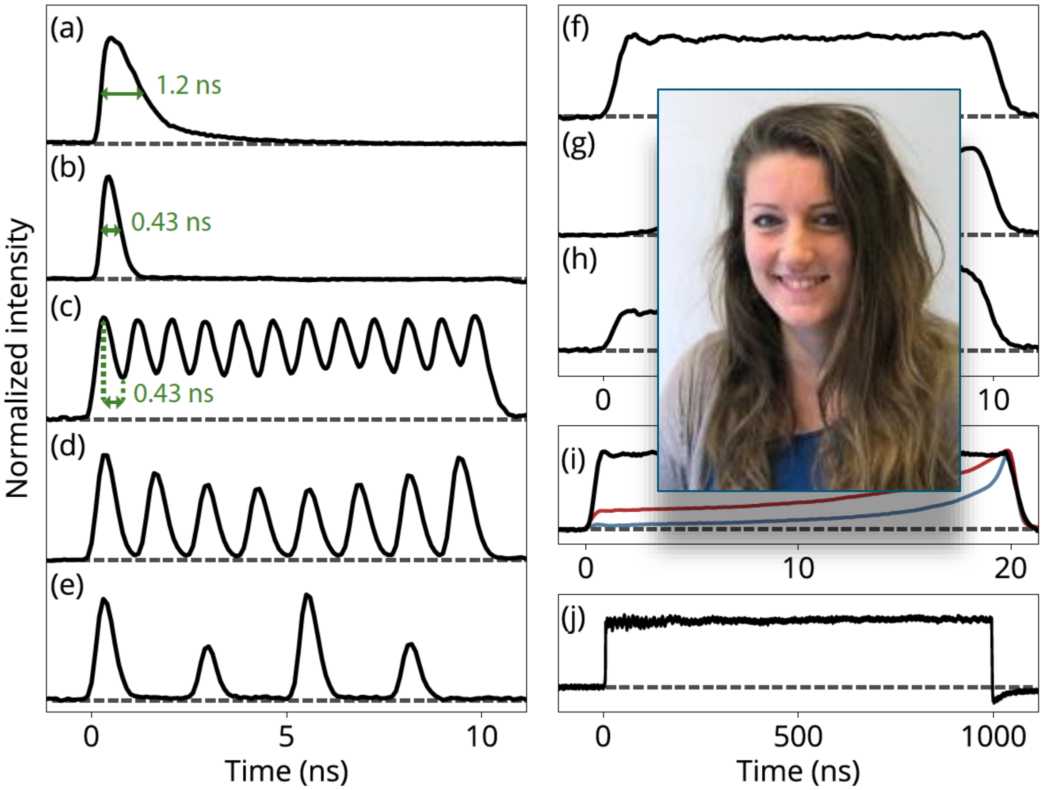


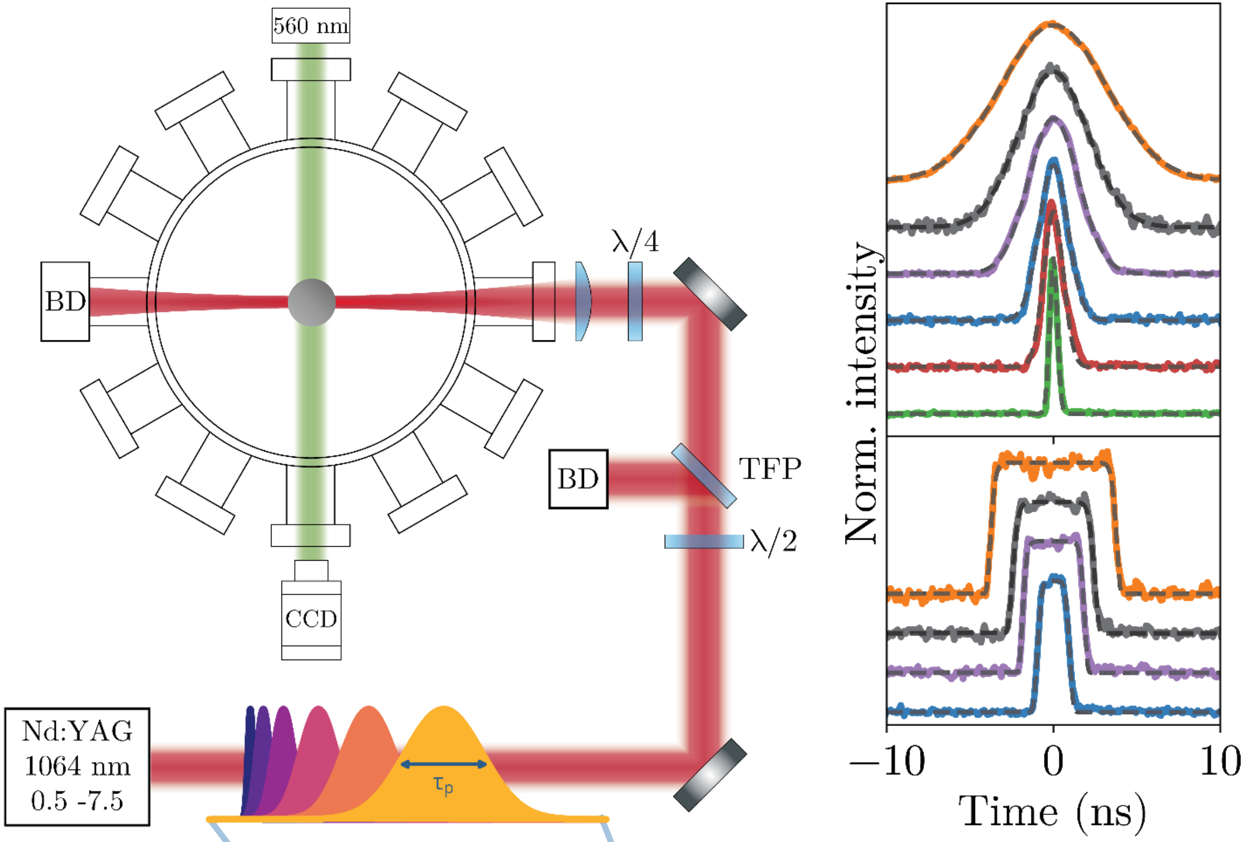
λ = 1064 nm, (Nd:YAG)

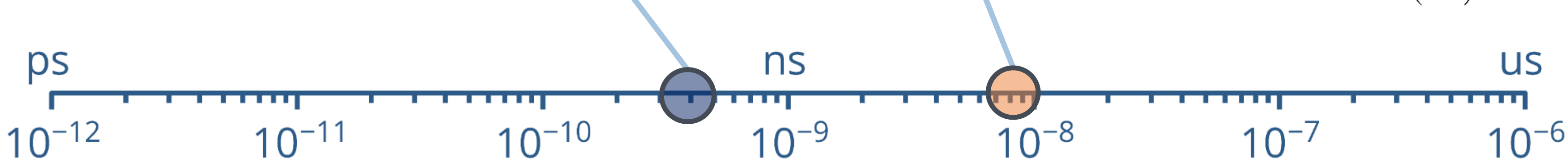
- CW seeded
- Pulse duration
  0.43 ns → 1.1 us
- Energy (100 Hz)
  300-500 mJ
- Multiple pulses, 1 laser
- PP, MP
- Realignment and improvements, see poster S74

Meijer, R. A., Stodolna, A. S. & Eikema, K. S. E. High-energy Nd : YAG laser system with arbitrary sub-nanosecond pulse shaping capability. *Opt. Lett.* **42**, 2758–2761 (2017).

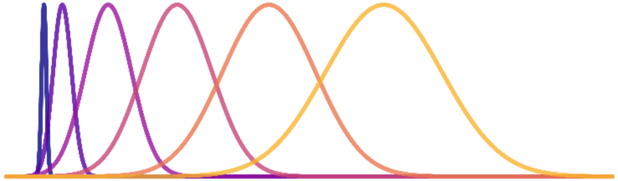
Experiment

- Pulse durations
  0.5 ns – 7.5 ns FWHM
- Droplet size = 45 µm
- Gaussian focus
  45 µm FWHM
- Shadowgraphy
  Spatial res. = 7 µm
  Temporal res. = 5 ns

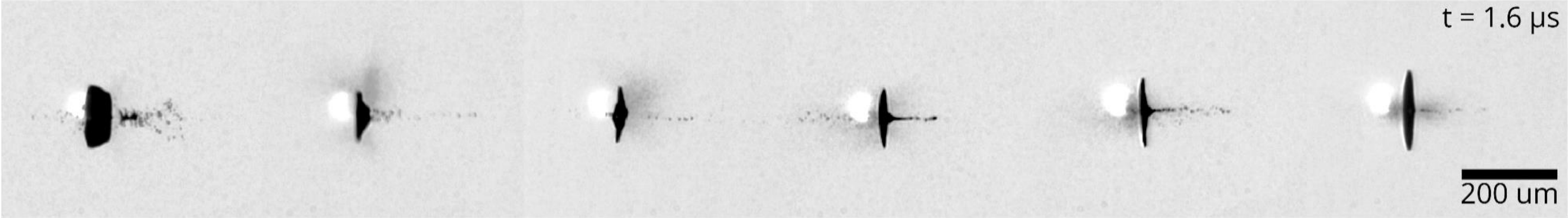




Deformation transition



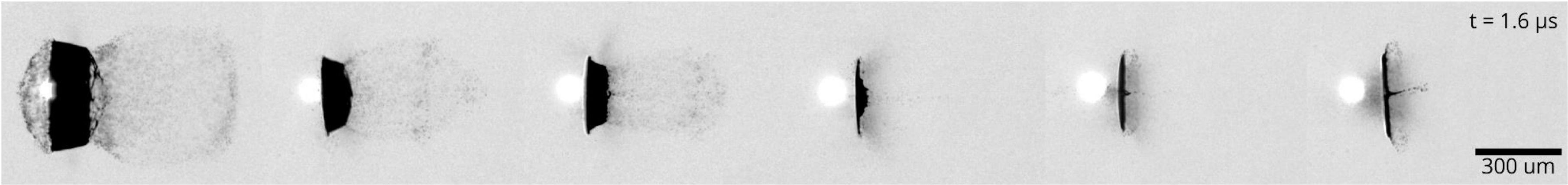
E_{od} = 0.4 mJ



0.5 ns | 1.3 ns | 2.0 ns | 3.5 ns | 5.0 ns | 7.5 ns

E_{od} = 2.2 mJ

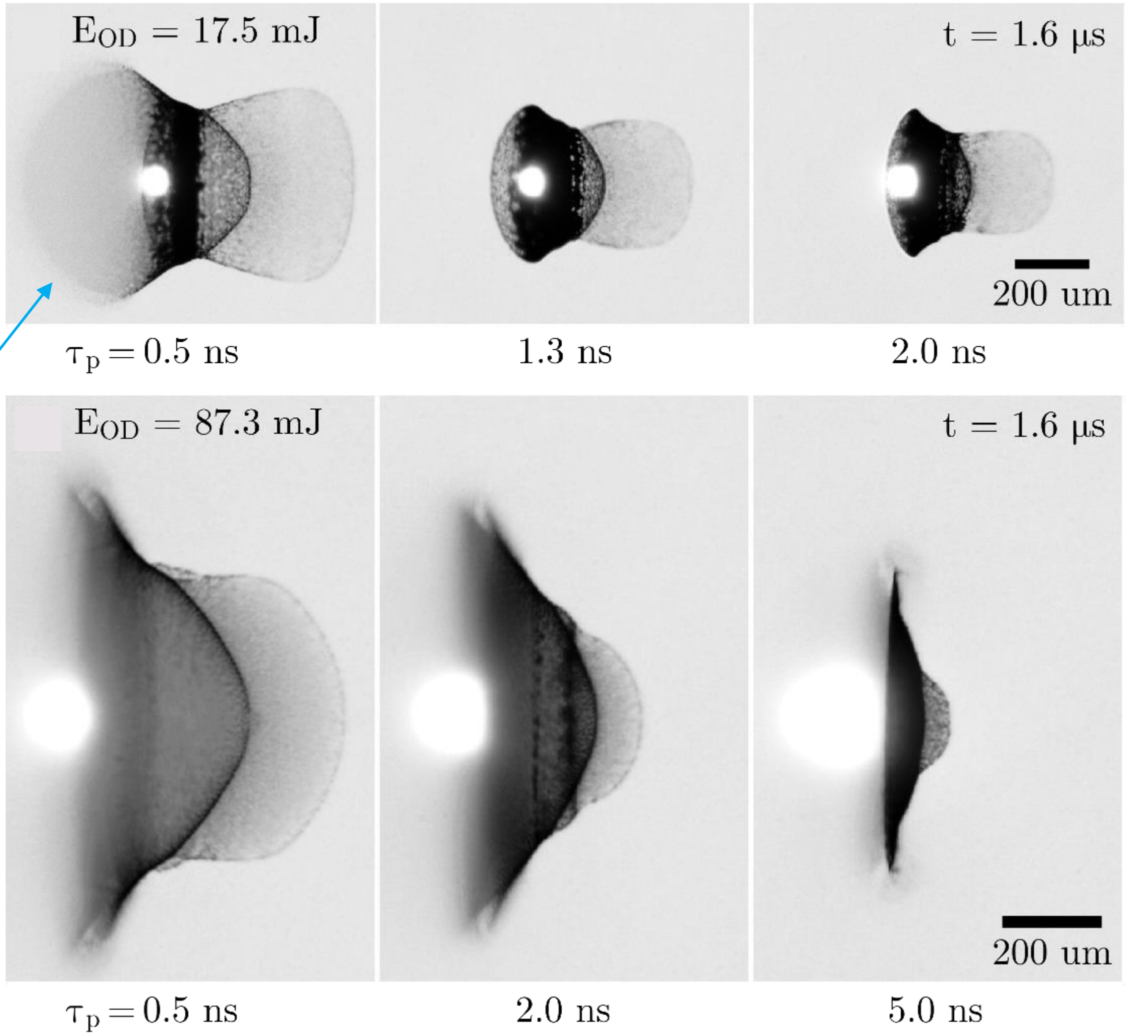
Pulse duration →



0.5 ns | 1.3 ns | 2.0 ns | 3.5 ns | 5.0 ns | 7.5 ns

High energy

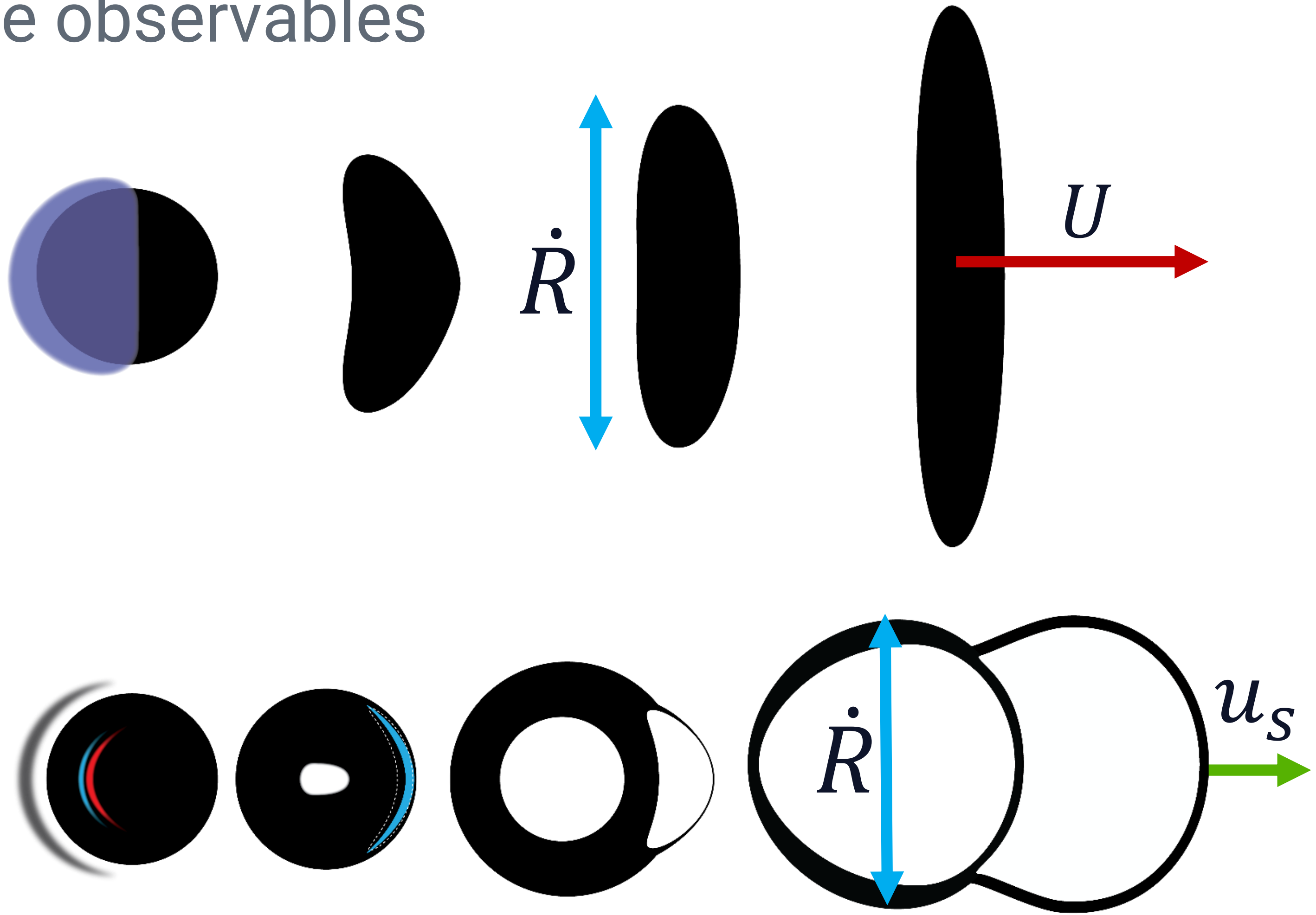
- Same trend observable
- New observed cloud towards laser (Triple dome structure)
- Strong fragmentation



Quantifiable observables

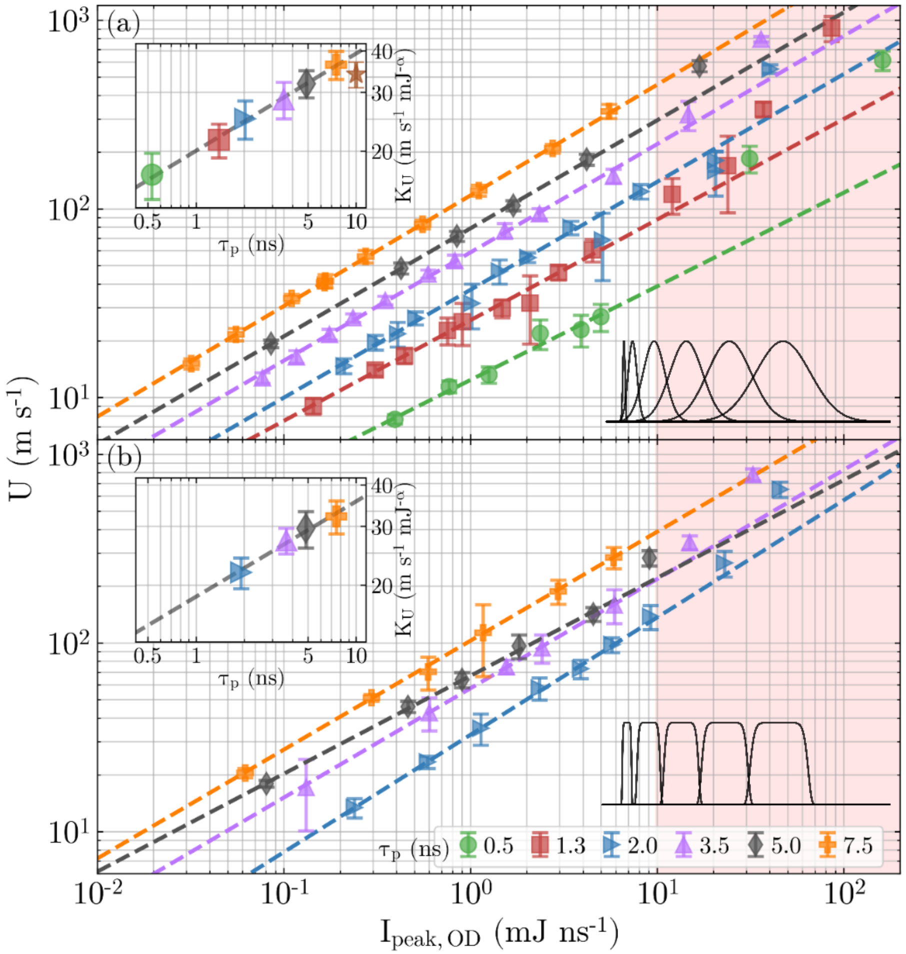
“long”
(ns)

“short”
(ps/fs)

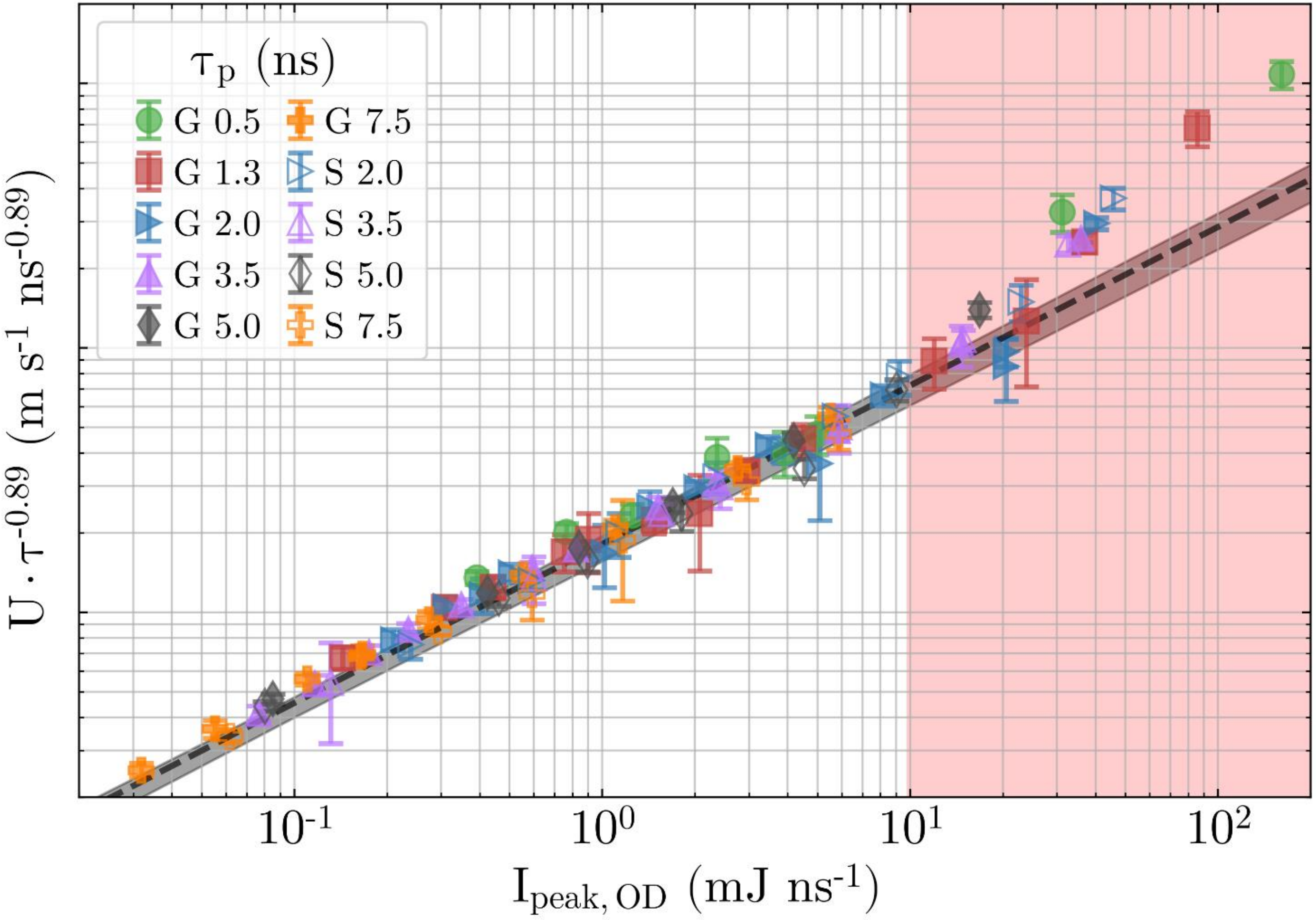


Propulsion

- Agreement with previous found scaling*
- New scaling with pulse duration obtained
- $U \propto \tau_p^{0.3}$



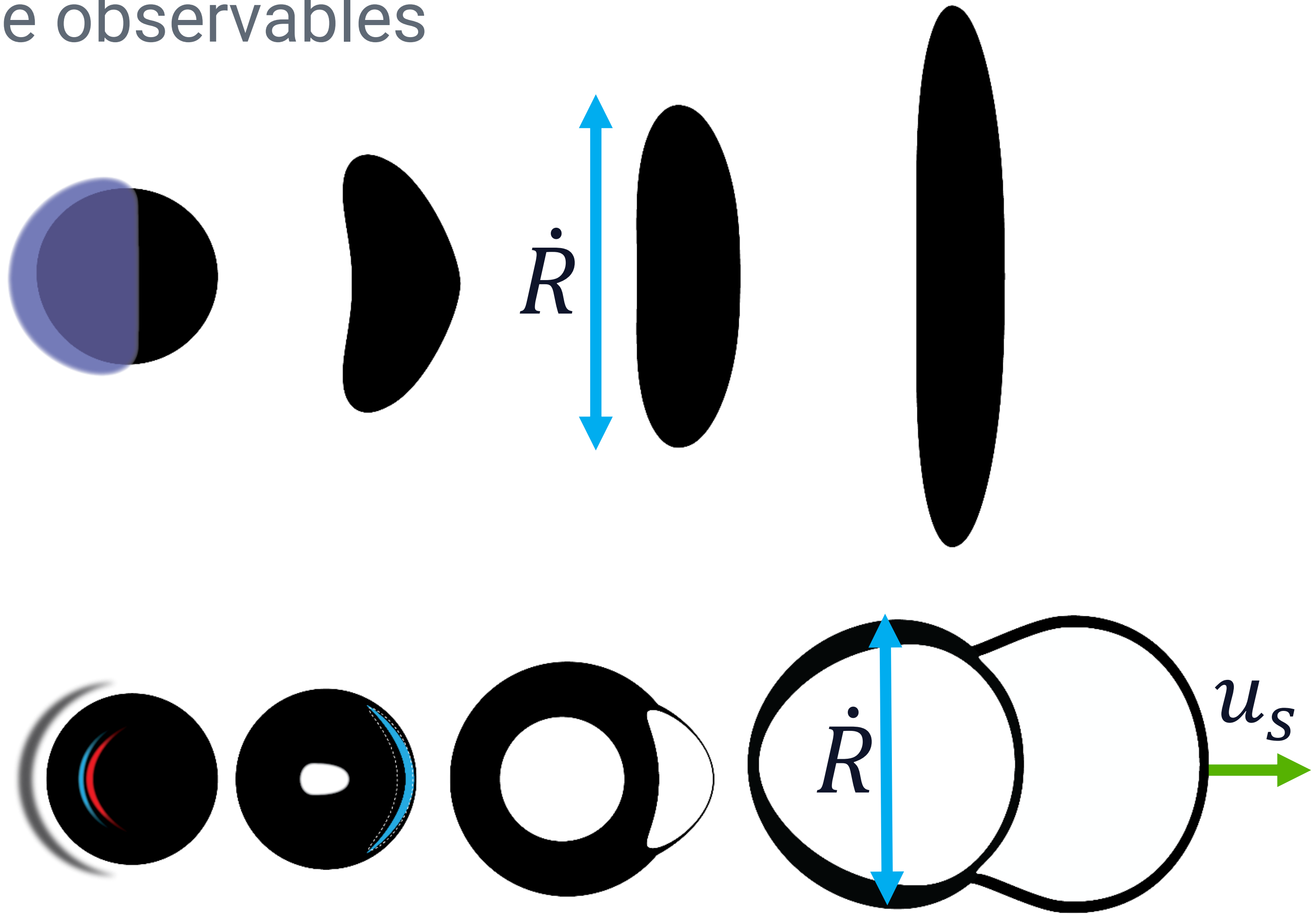
*Kurilovich, D. et al. Power-law scaling of plasma pressure on laser-ablated tin microdroplets. Phys. Plasmas 25, (2018).


τp (ns)
G 0.5
G 7.5
G 1.3
S 2.0
G 2.0
S 3.5
G 3.5
S 5.0
G 5.0
S 7.5
U · τ^-0.89 (m s^-1 ns^-0.89)
10^-1
10^0
10^1
10^2
I peak, OD (mJ ns^-1)

Quantifiable observables

"long"
(ns)

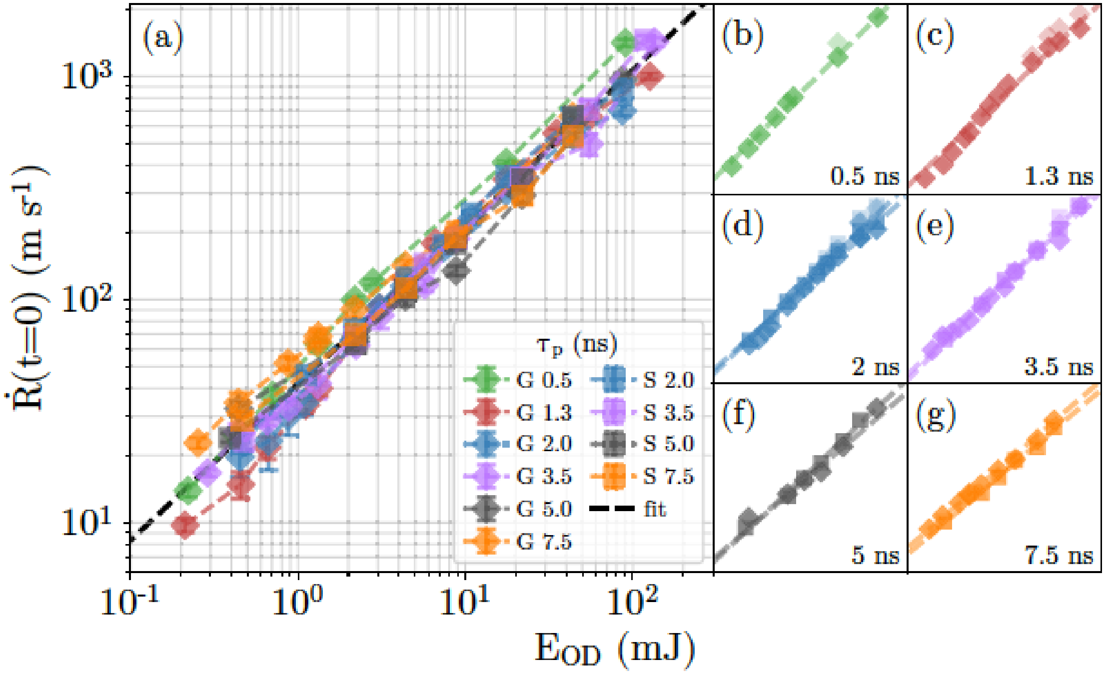
"short"
(ps/fs)



Radial expansion

0.5 ns : 0.75 –> 7.5 ns: 0.65
(Sheet expansion prediction 0.6)

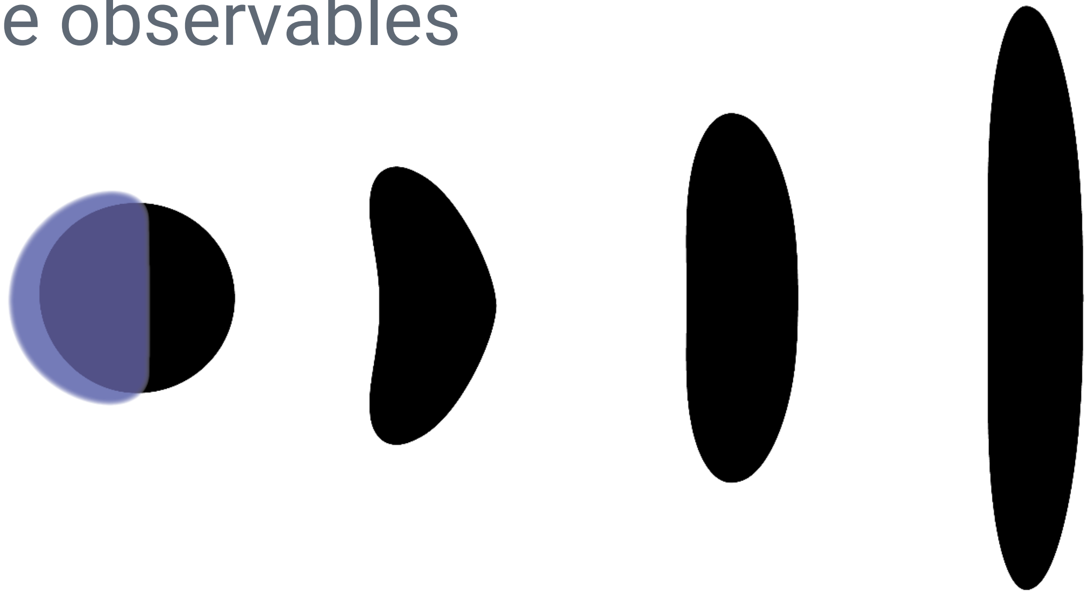
- Energy on droplet dominant factor
- Minor differences between 'short' & 'long'



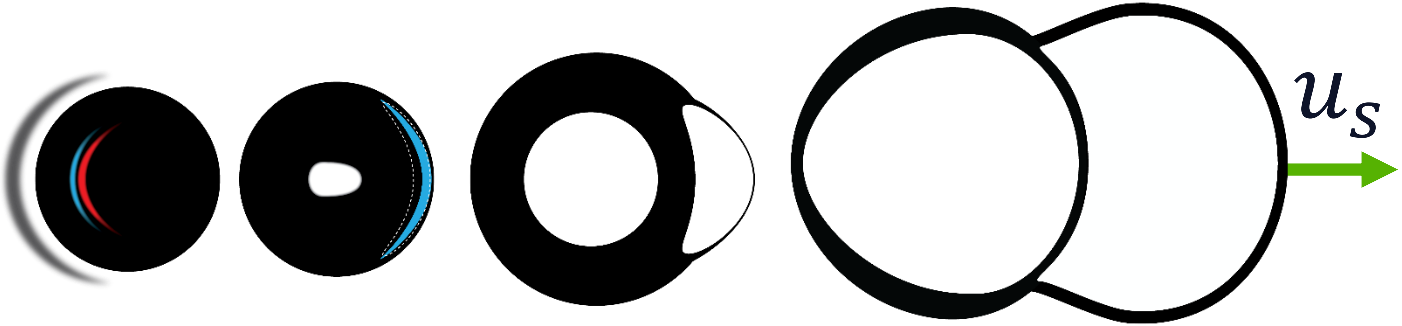
1. Kurilovich, D. *et al.* Expansion Dynamics After Laser-Induced Cavitation in Liquid Tin Microdroplets. *Phys. Rev. Appl.* **10**, 1–7 (2018).
2. Kurilovich, D. *et al.* Plasma Propulsion of a Metallic Microdroplet and its Deformation upon Laser Impact. *Phys. Rev. Appl.* **6**, 1–8 (2016).
3. Klein, A. L. *et al.* Drop fragmentation by laser-pulse impact. (2019).

Quantifiable observables

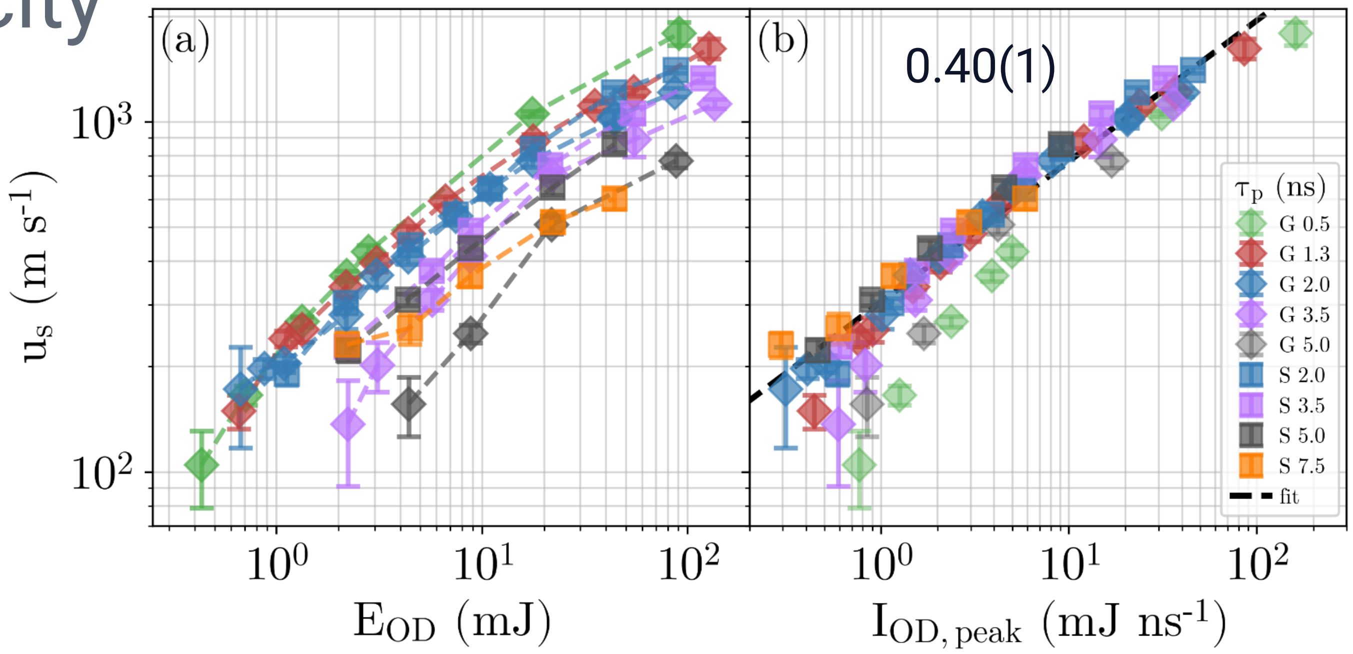
“long”
(ns)



“short”
(ps/fs)



Spall velocity



- Peak intensity relevant parameter
- Collapse of all square pulse shapes (No effect of duration)
- Characteristic timescale

Conclusions

By studying droplet deformation as function of pulse duration we find:

- Deformation types coexist and transition ‘smoothly’.
- Scaling of propulsion with pulse duration.
- Remarkably little sensitivity of expansion velocities.
- Spall velocities promising tool to understand shockwaves.

On our way to answering: What is ‘short’, what is ‘long’.

Acknowledgements

Dmitry Kurilovich

Oscar Versolato

Kjeld Eikema

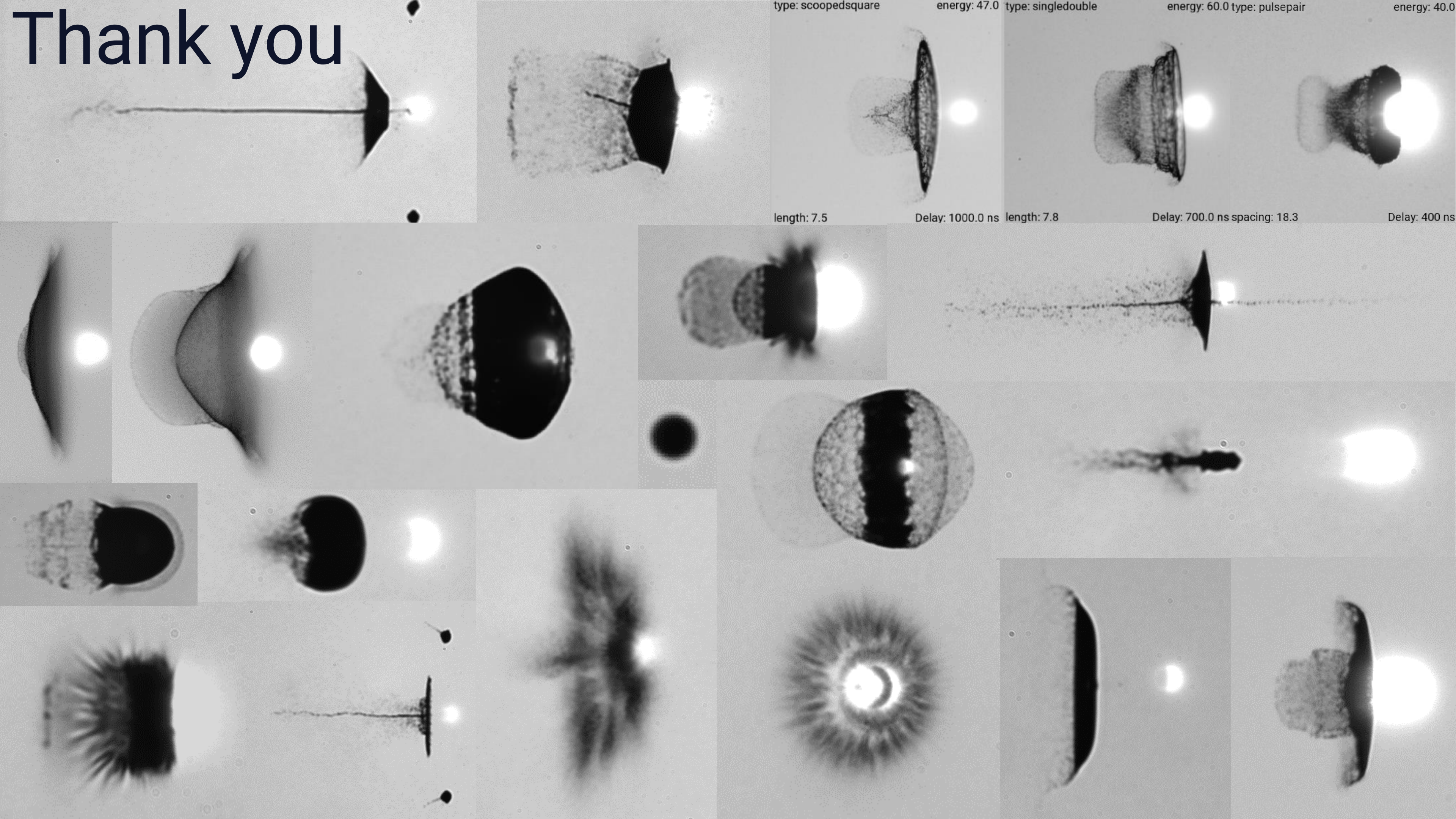
Stefan Witte

Groups :

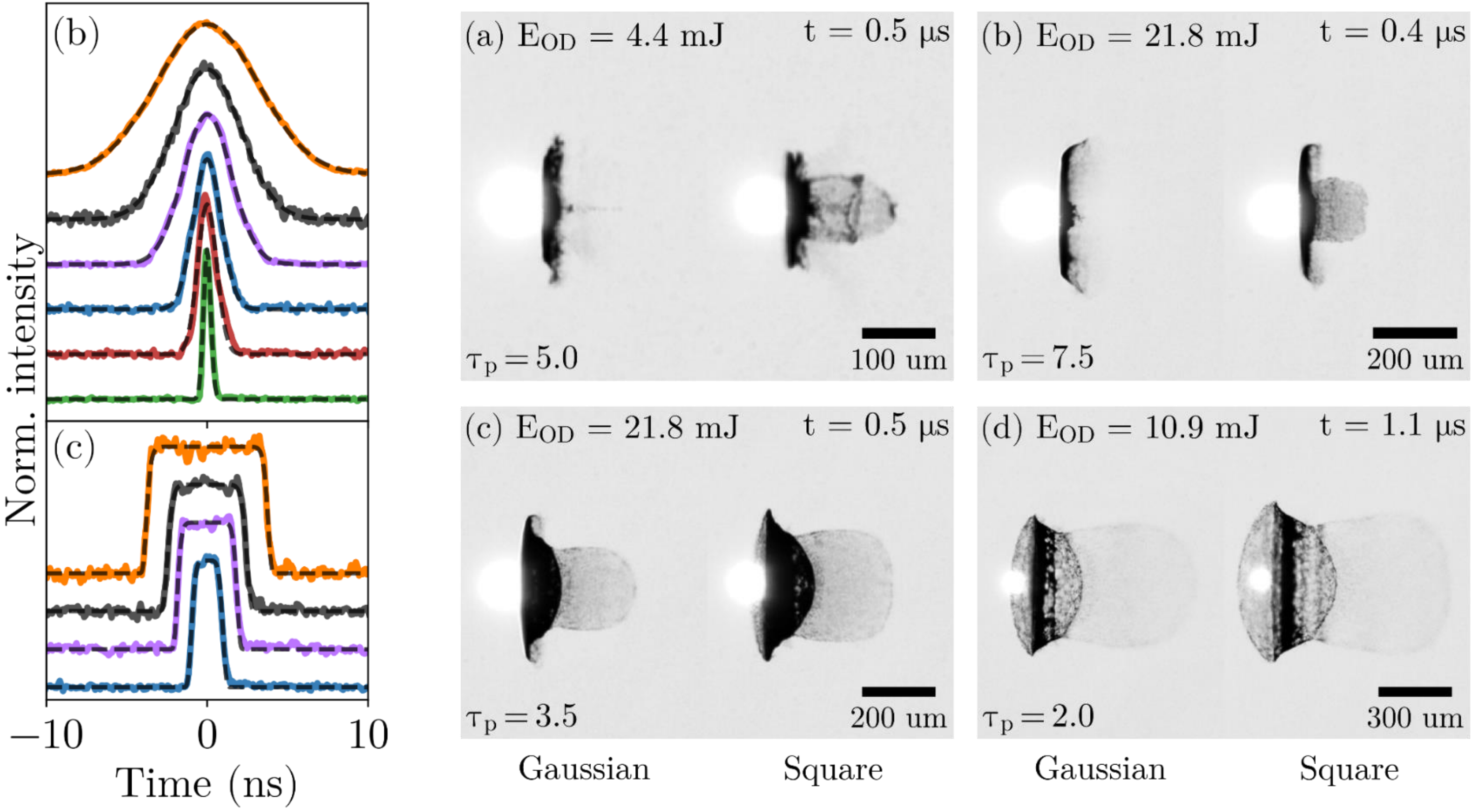
- EUV Generation & Imaging
- EUV Plasma Processes

ARCNL ASML VU UNIVERSITY AMSTERDAM UNIVERSITEIT VAN AMSTERDAM NWO

Thank you


type: scoopedsquare
energy: 47.0
length: 7.5
Delay: 1000.0 ns
type: singledouble
energy: 60.0
length: 7.8
Delay: 700.0 ns
type: pulsepair
energy: 40.0
spacing: 18.3
Delay: 400 ns

Gaussian vs. Square pulse shape



Square pulse shows stronger shockwave induced deformation and less plasma push.