International High Power Laser Ablation and Beamed Energy Propulsion Conference

Santa Fe, New Mexico, USA, April 21 – 25

Overview of Laser Ablation Micropropulsion Research Activities at DLR Stuttgart

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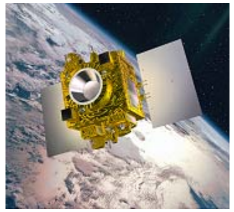
Presentation Outline

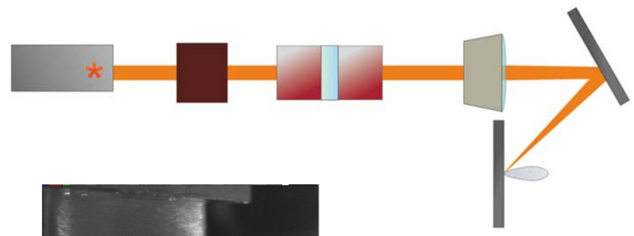
Motivation

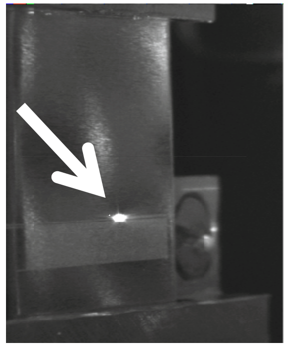
Laser-ablative MICROLAS thruster
- Thruster concept
- Research strategy

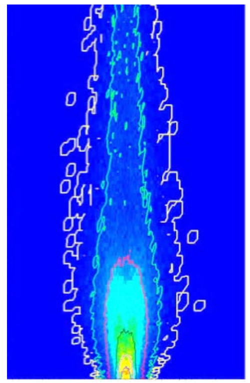
Results and discussion
- Momentum coupling in the µN range
- Plume diagnostics
- Propellant surface analysis

Conclusions and Outlook









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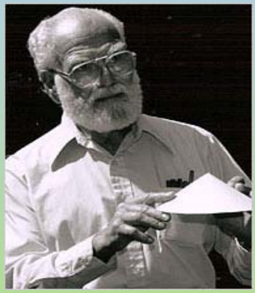
Motivation

4P-principle



Photons

Propellant

Payload

Period

Sources of motion in a microthruster …

Photons: Stimulated emission, reflection, and refraction
No moving elements, e.g. turnable mirrors…

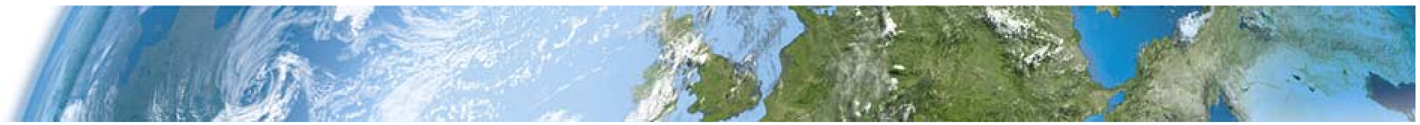
Propellant: Laser ablation
No transport components, e.g. discs, conveyor belts …

Payload: Recoil of the ablation jet
No moving parts, e.g. valves

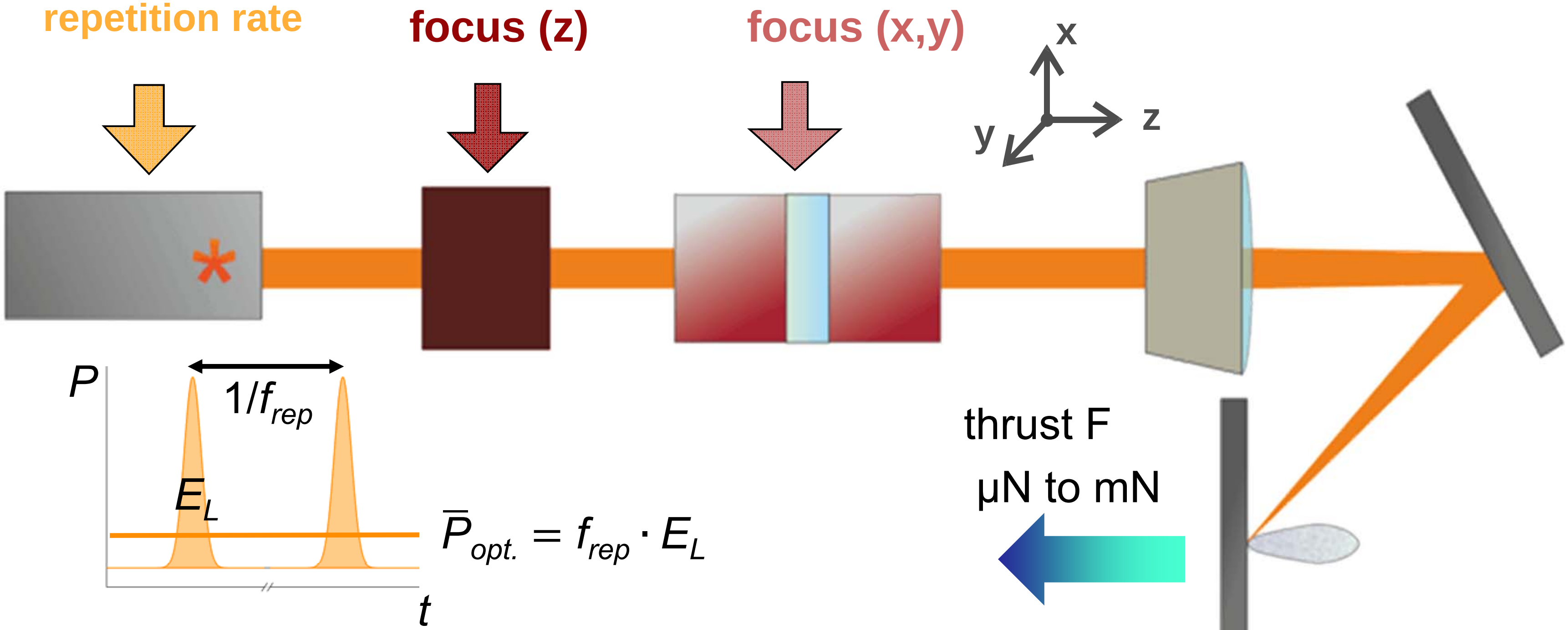
Period: Nothing else moves
→ Very low thrust level (*0.1 µN resolution*)

... required for **scientific space missions**

- compensation of small disturbing forces
- satellite formation flight



MICROLAS Thruster Concept

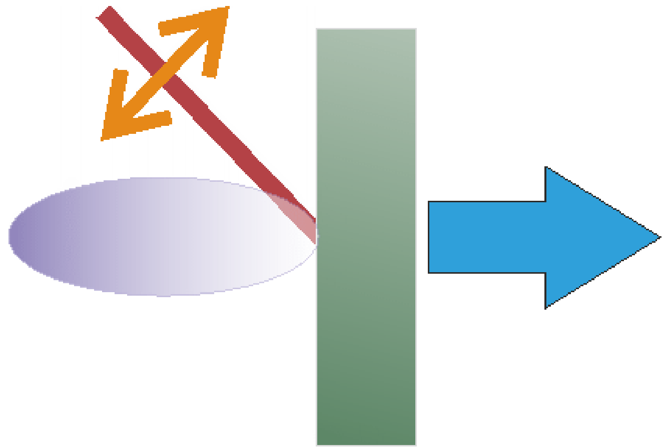


$$\overline{P}_{opt.} = f_{rep} \cdot E_L$$

$$I_{sp} = \frac{v_{jet}}{g}$$

$$c_m = \frac{F}{\overline{P}} = \frac{\Delta p}{E_L}$$

Overall Research Strategy



parameters		figures of merit		experiment / theory
ablation scheme	optimize	imparted impulse	←	thrust measurement VLL
target material		ablated mass	←	surface diagnostics VLL / IMD
		surface quality	←	
laser parameters		plume characteristics	←	plasma diagnostics DSMC-PiC

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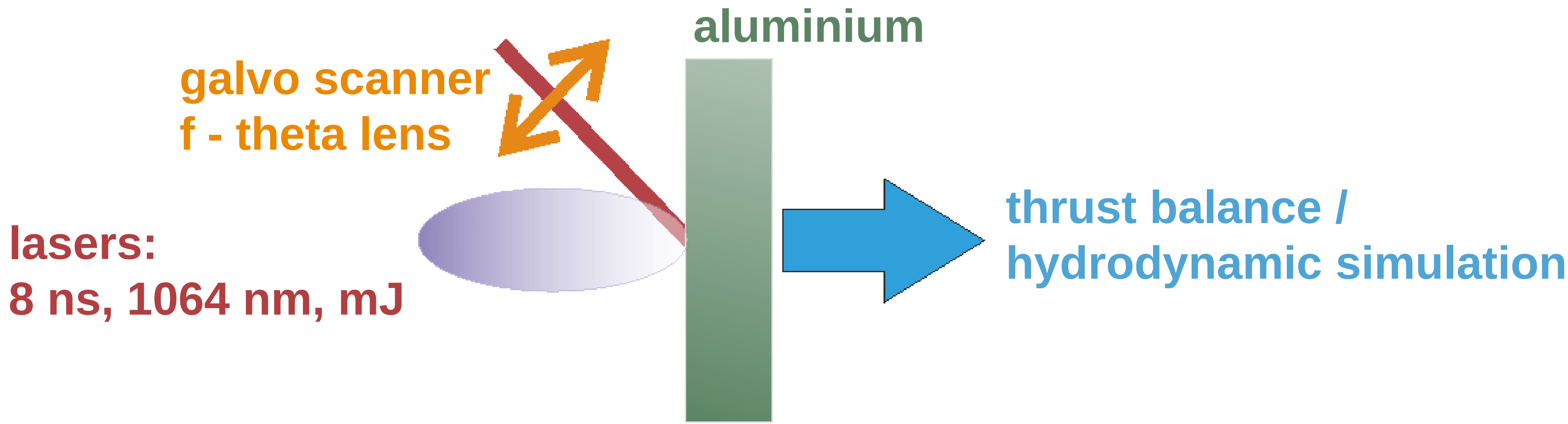
Thrust analysis



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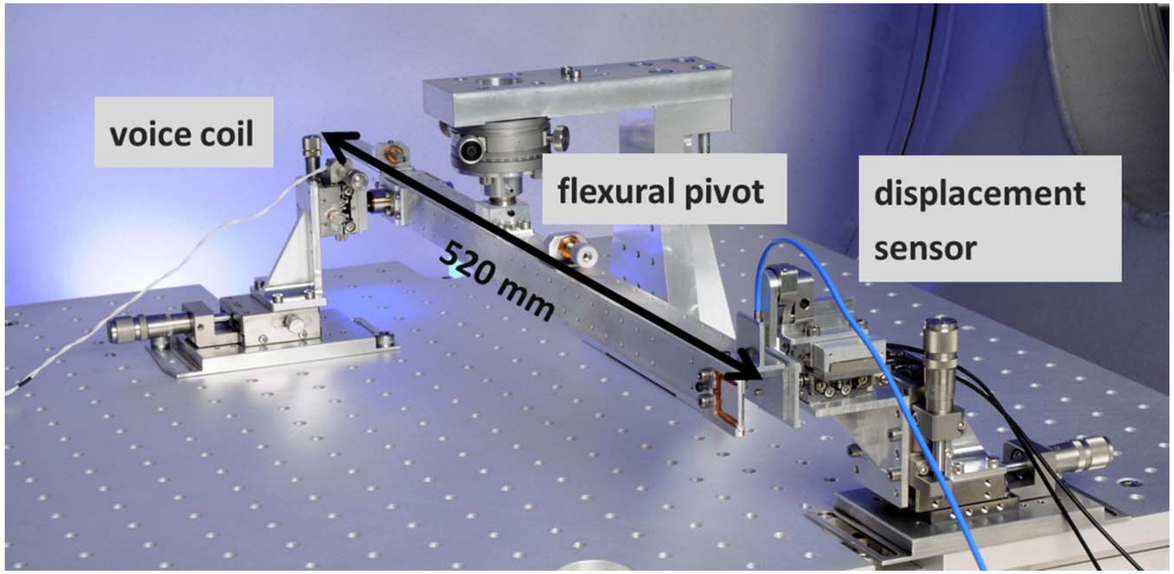
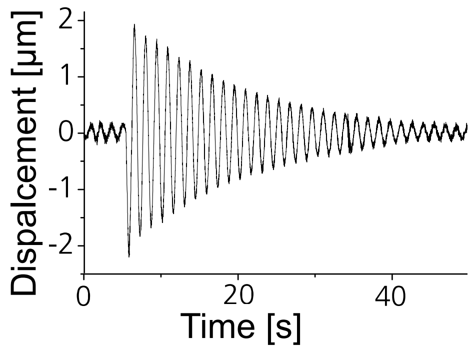
Thrust measurement

- torsional pendulum with flexural pivots
- open or closed-loop operation
- beam steering for impulse from single shot ablation
- calibration: voice coil
- for more details: „Laser Propulsion Research Facilities at DLR Stuttgart”

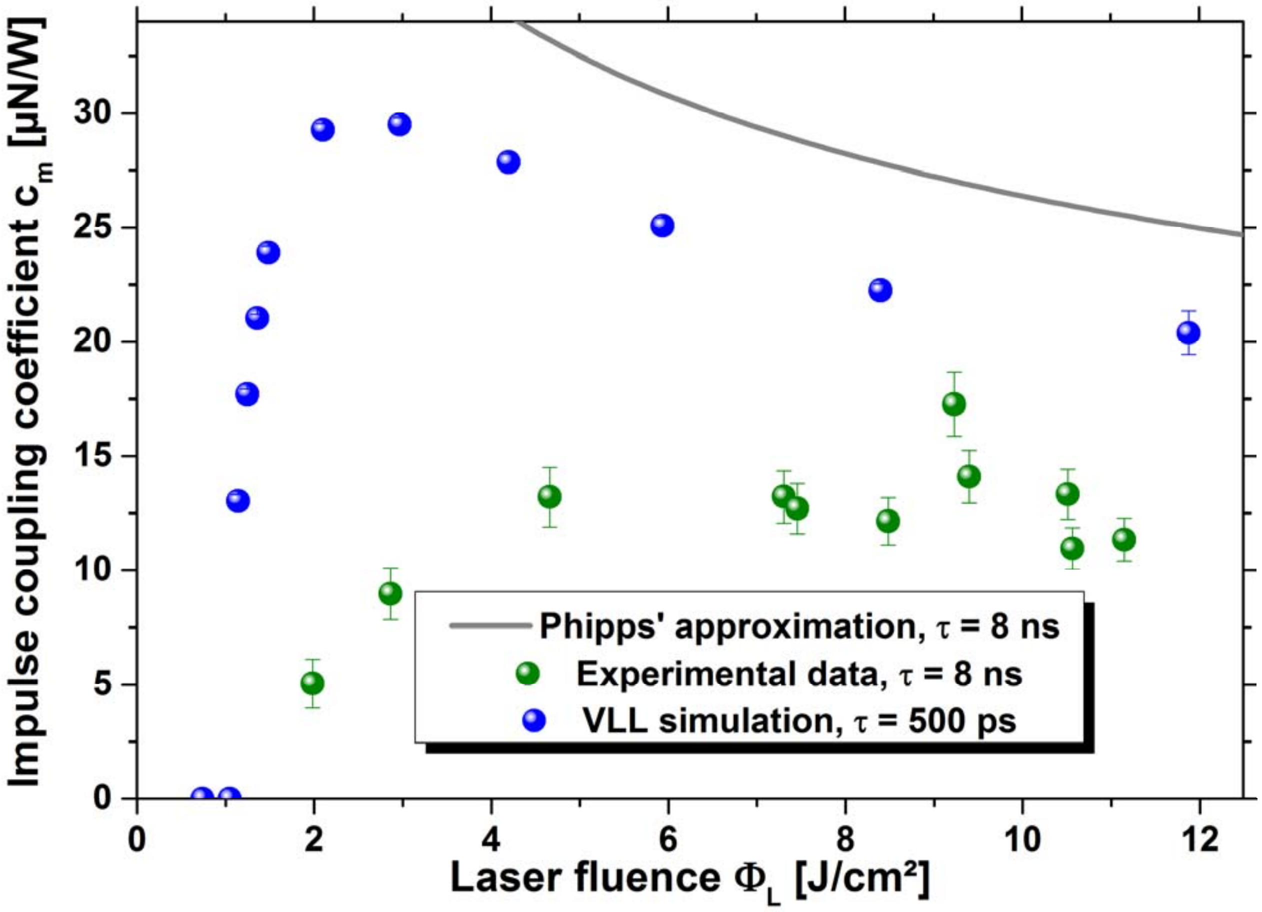




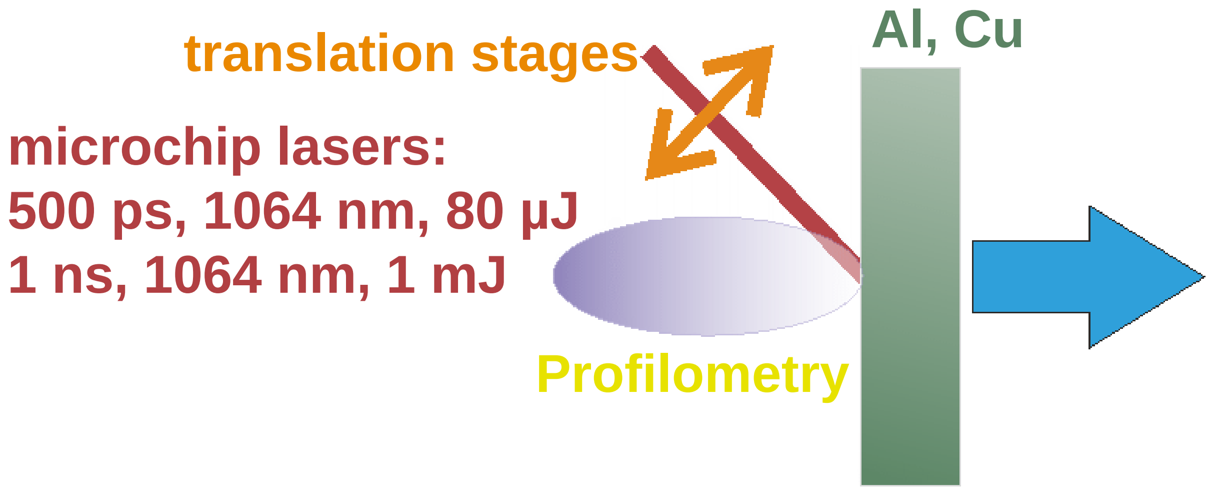
Thrust generation – Experiment vs. Simulation

Experiment
- Torsional balance
- Repetitive scan
- Al target
- 8 ns pulse length

Simulation
- Phipps' approximation
- ns, µs range
- Plasma regime
- VLL – Virtual Laser Lab http://vll.ihed.ras.ru
- fs, ps range
- TTM
- Poster: "Open Access Tools for the Simulation of Ultrashort-Pulse Laser Ablation"



Plume analysis



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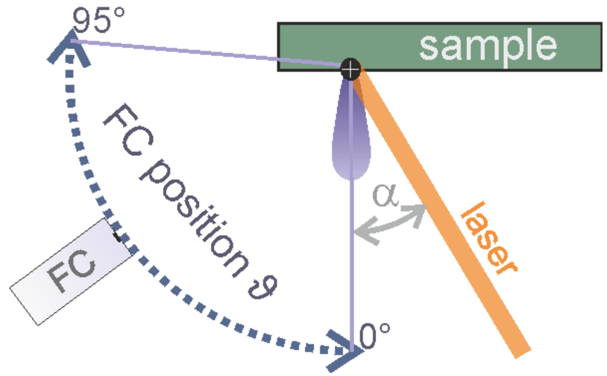
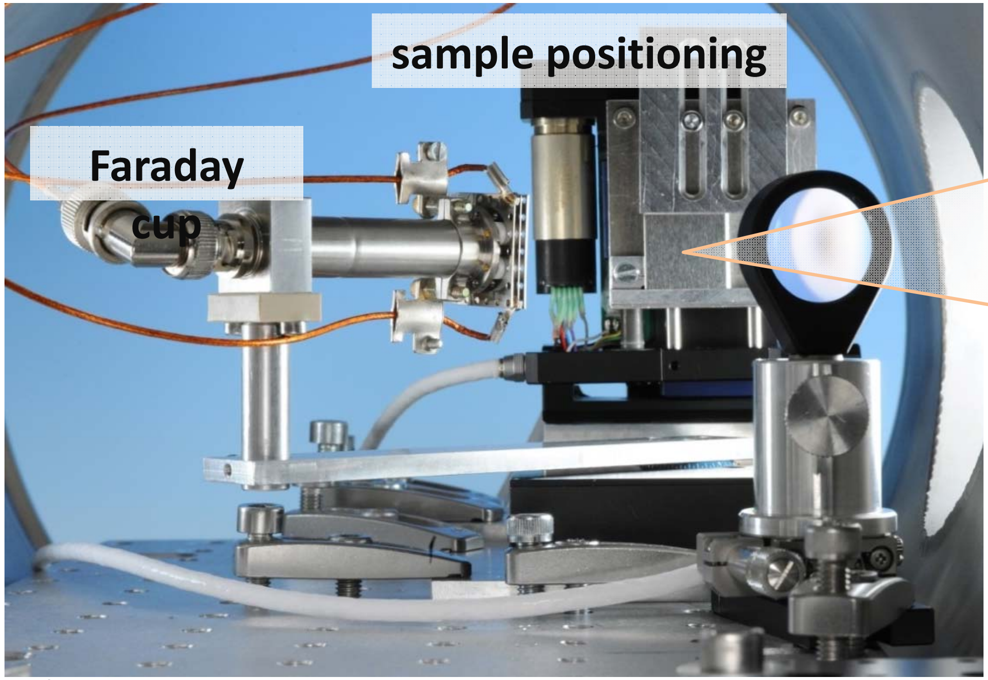
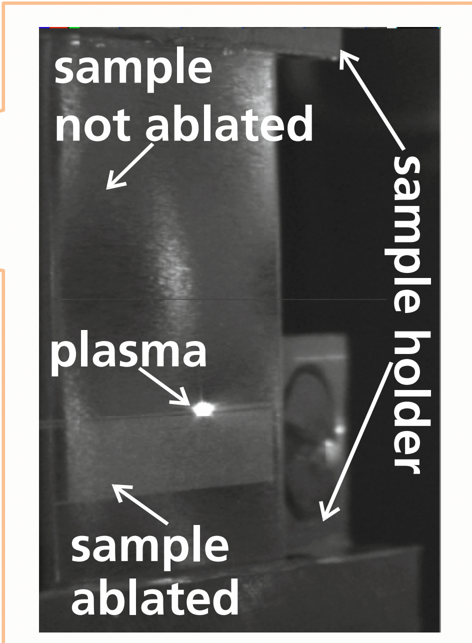
Ablation Jet - Plasma Diagnostics

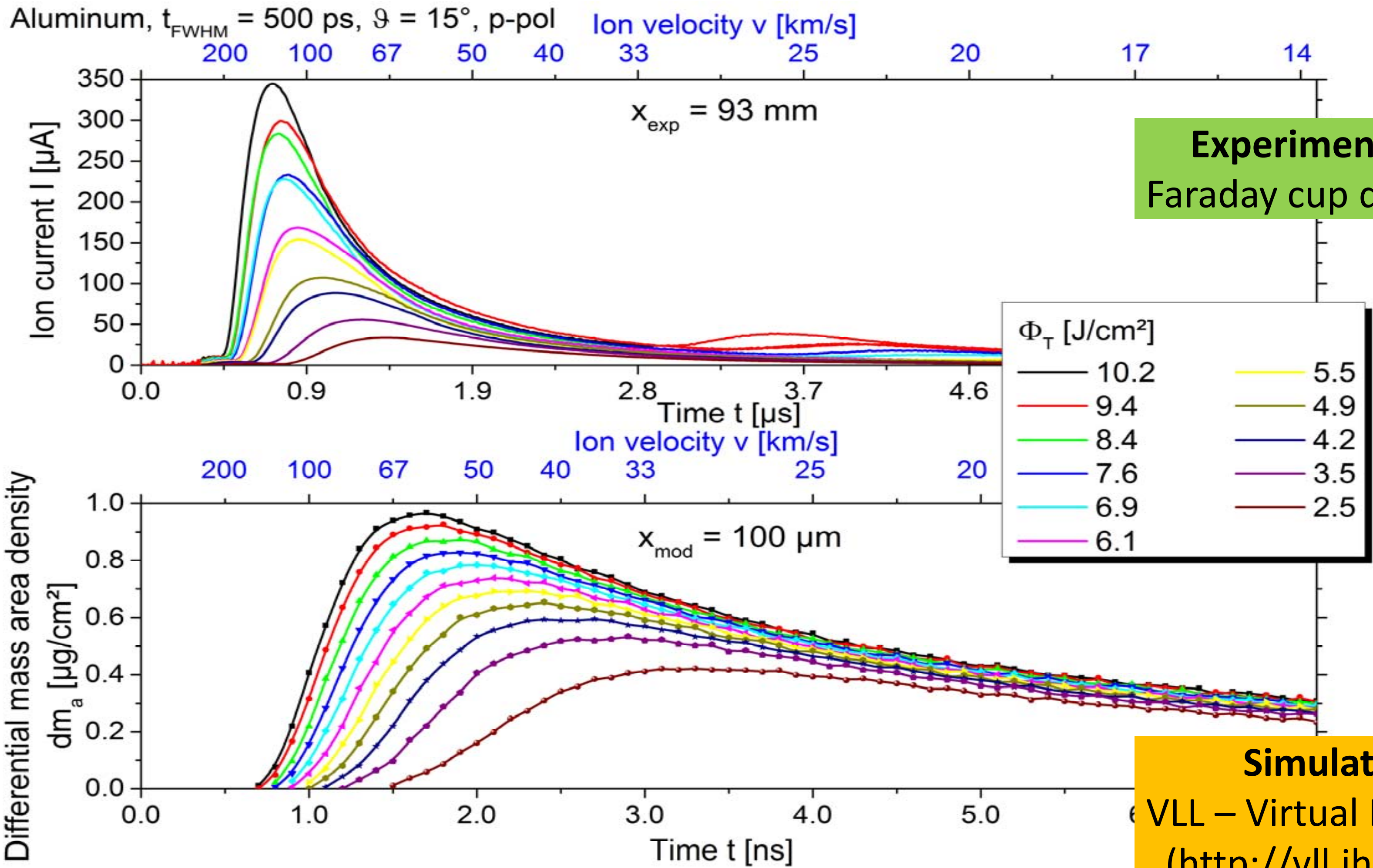


- vacuum chamber (0.6 m x 0.25 m ∅)
  pressure 10^{-6} - 10^{-7} mbar
- microchip lasers: 1 mJ @ 1 ns and
  80 µJ @ 500 ps , 1064 nm
- Faraday cup on rotational stage





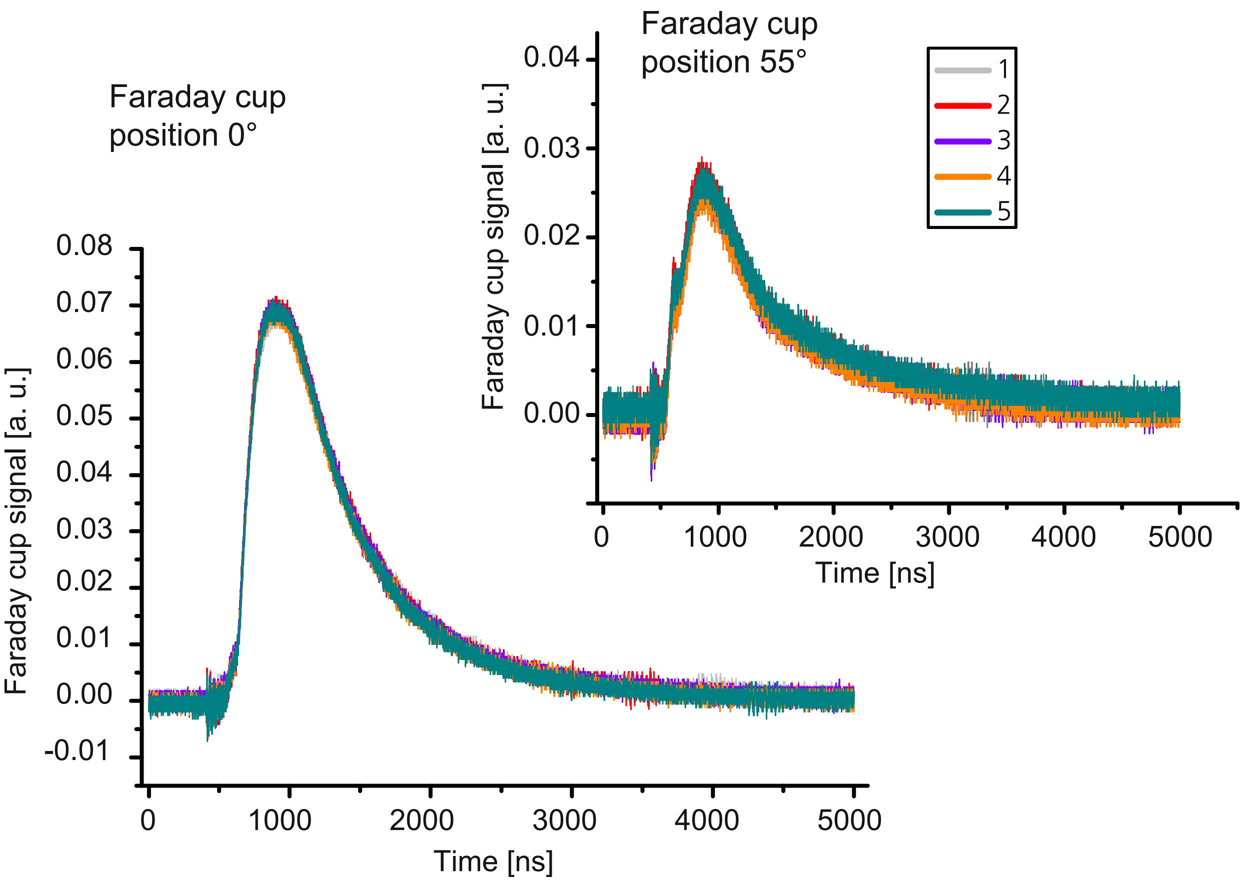
Plume analysis – Velocity distribution

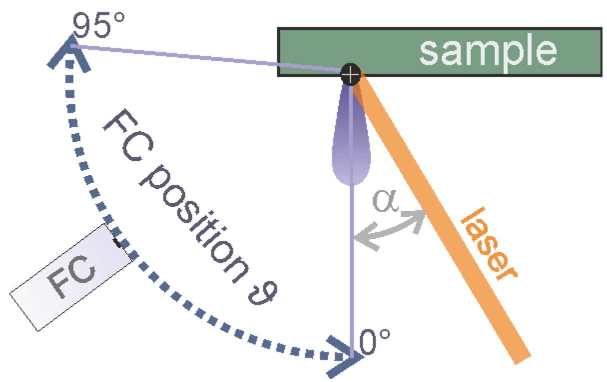


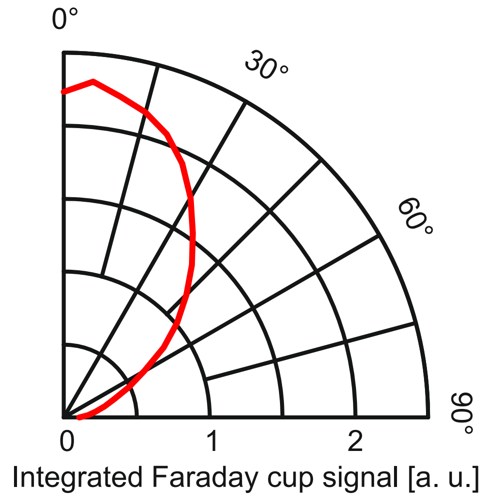
Experiment
Faraday cup data

Simulation
VLL – Virtual Laser Lab
(http://vll.ihed.ras.ru)

Plume analysis – Angular distribution





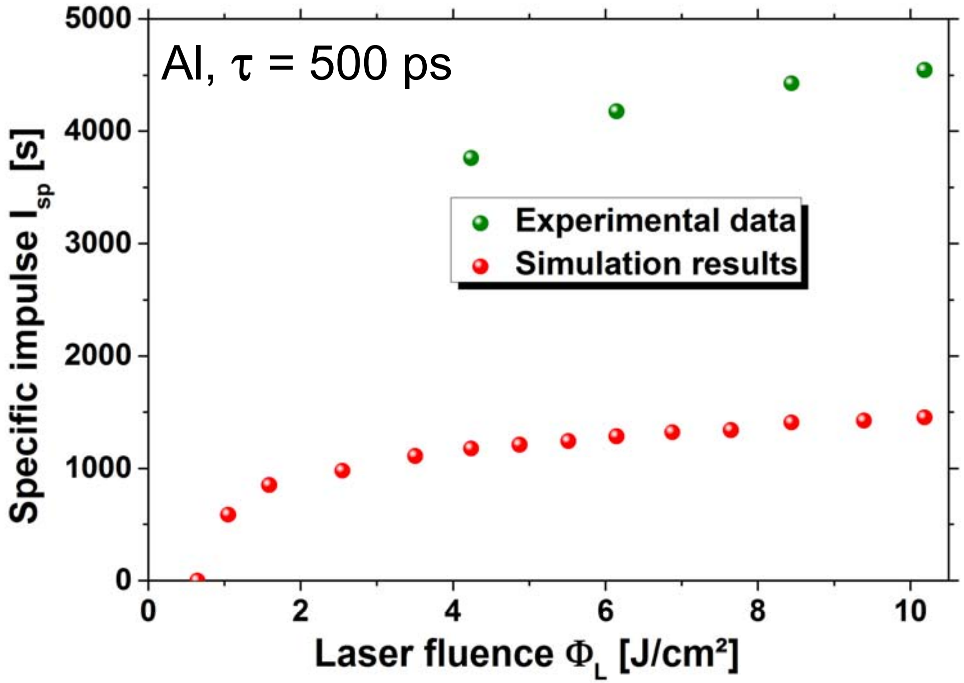


Specific Impulse – Theory and Experiment

$$I_{sp} \approx \frac{1}{g} \sum_{\alpha} \frac{A_\alpha}{A_0} \frac{\cos\alpha \sum_t I_\alpha(t) \cdot v_\alpha(t) \cdot \Delta t}{\sum_t I_\alpha(t) \cdot \Delta t}$$

Experiment

- Faraday cup data
- 93 mm to target
- 2D Angular scan
- 3D weighted average:
    - normal component $\cos\alpha$
    - signal strength $I_\alpha(t)$
    - reference area A_α



Simulation

- VLL – Virtual Laser Lab
  (http://vll.ihed.ras.ru)
- approx. 500 µm extension
- 1D Simulation

$$I_{sp} \approx \frac{1}{g} \lim_{t\to\infty} \frac{1}{\mu_a(t)} \sum_j \left[\varrho_j \left(x_{r,j} - x_{l,j}\right)\right]$$

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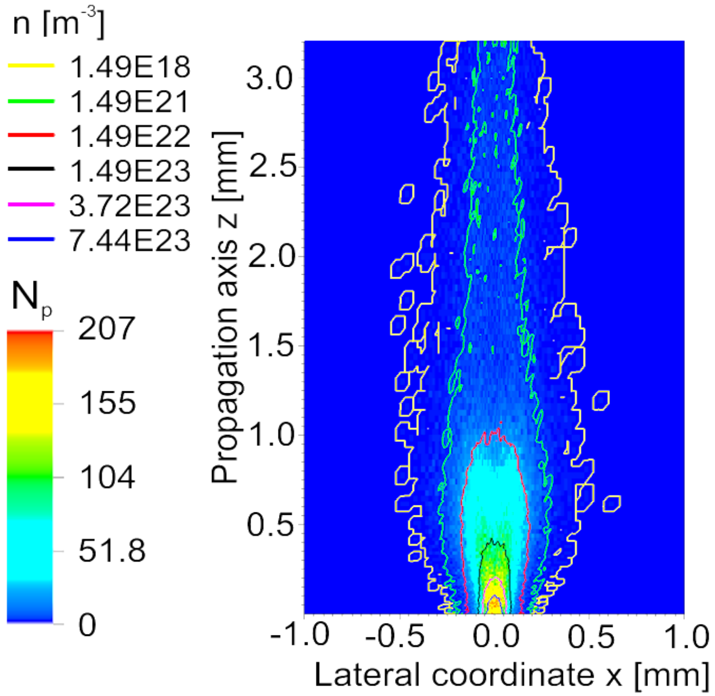
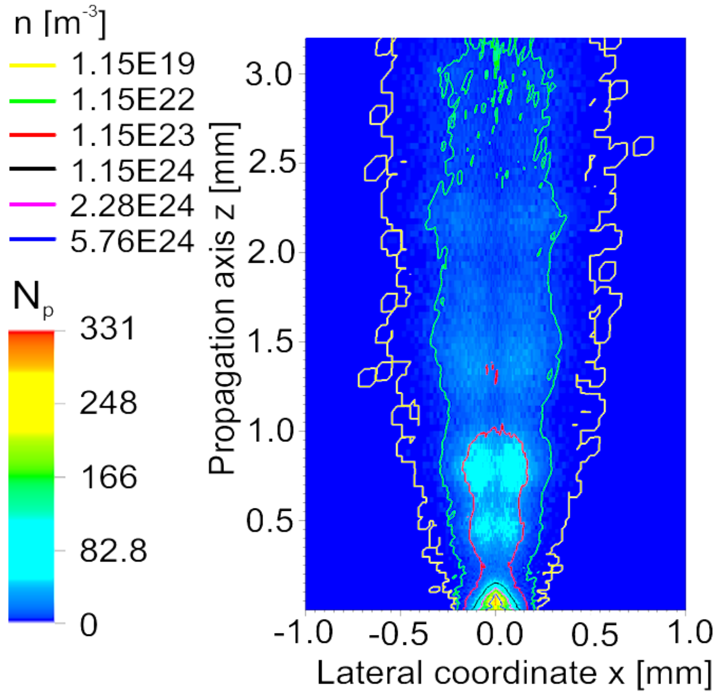
3D Plume Simulation (DSMC)

- PicLas – PIC-DSMC simulation code, University of Stuttgart
- DSMC: Static initial state (VLL results) → Time-dependent source
- PIC: → Ionization → Recombination



Top hat spot



Gaussian spot

***n*: Particle density**

N_p: Simulation particle density

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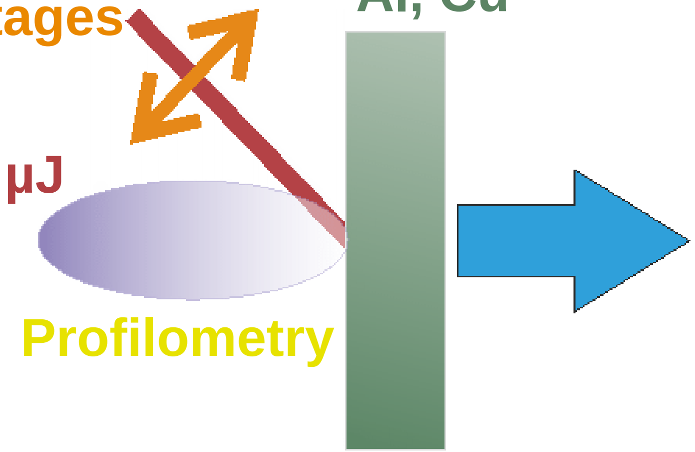
Target analysis



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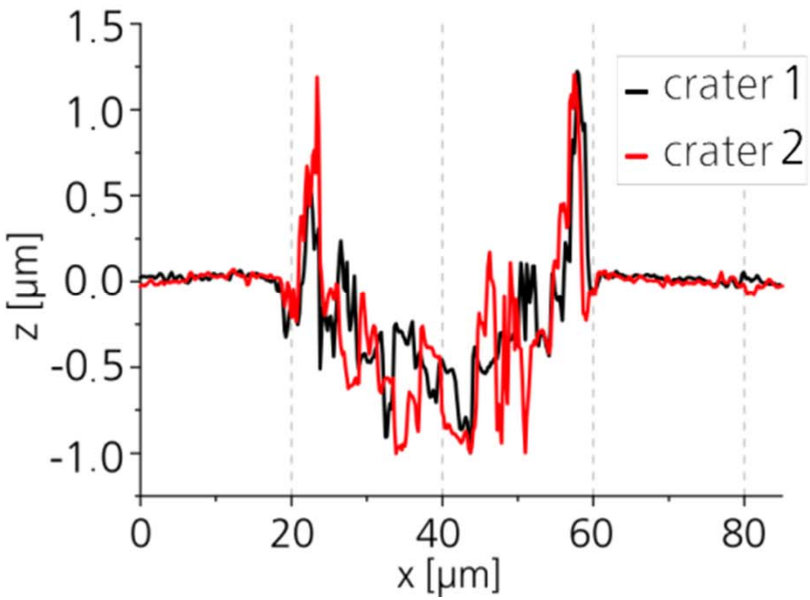
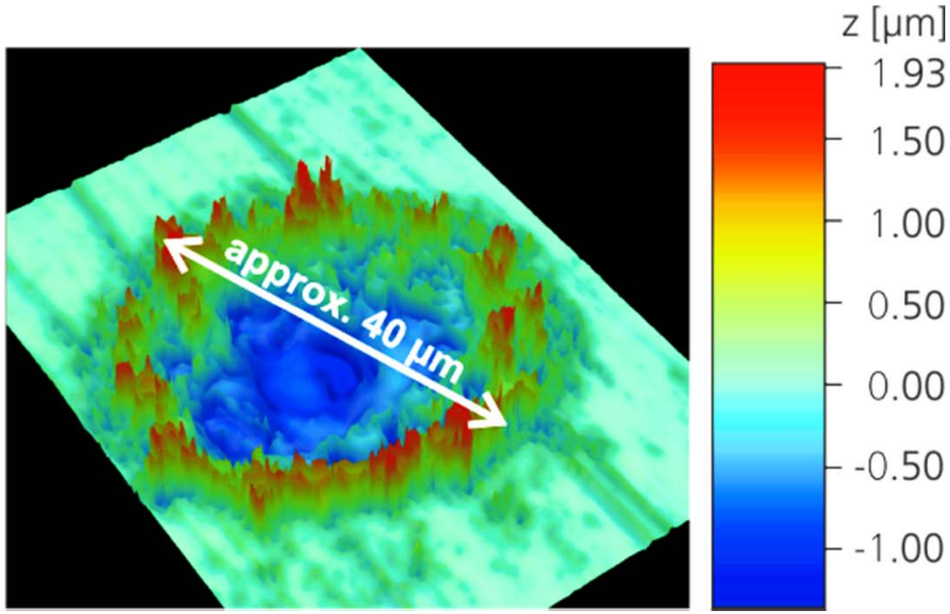
Target surface analysis

Profilometry

- commercial white light interferometer: Veeco NT9100
- surface roughness, crater geometry
  → ablated mass, beam-steering testing





ablated mass approx. 1 ng @ 500 ps , 71.7 µJ

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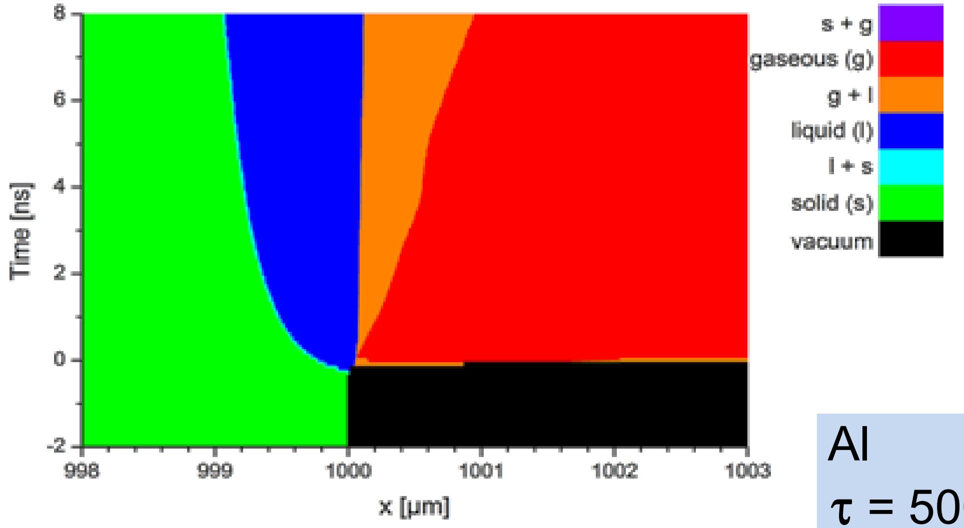
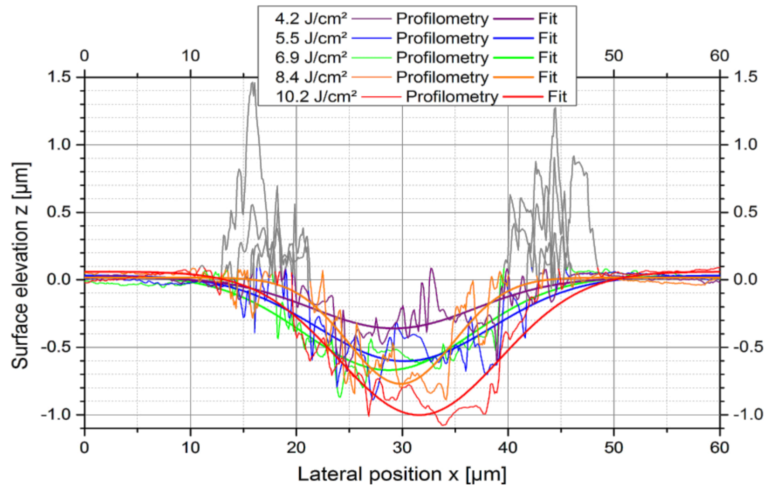
Crater depth – Hydrodynamic Simulation





Al
τ = 500 ps
ϑ = 15°

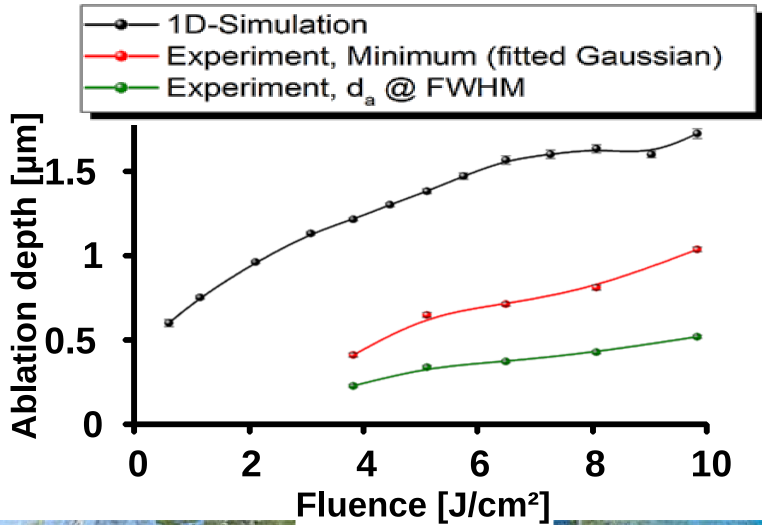
Solid / liquid transition

Upper estimation of ablation depth

- liquid plume components
- lateral expulsion → crater rim
- solidification

VLL 1D simulation (Top hat, http://vll.ihed.ras.ru)

vs. 3D experiment (Gaussian)



Summary

"Inertia free" thruster concept under development

- extremely low thrust noise
- 3D electro-optical beam-steering
- Δp: 1 … 100 nNs
- E_L, $\varnothing_{spot}$, Φ fixed $\rightarrow$ Thrust control by f_{rep}

Thrust

- measurements (precise thrust balance)
- modelling (VLL & IMD)

Plume

- plasma diagnostics (angular velocity distribution)
- modelling (VLL & DSMC-PIC)

Target

- surface analysis
- crater modelling (VLL & IMD)

Outlook

Laser

- 3D electro-optical beam-steering → EO-variable focus length
- picosecond pulse lasers advantageous

Thrust

- measurements (precise thrust balance)
- modelling (VLL)

Plume

- oblique laser incidence
- symmetric double spot operation

Target

- crater overlap
- 3D simulations needed (Hydrodynamic / DEM)

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Questions?