Laser-Ion-Acceleration using Water Droplets and Optical Probing

seit 1558

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A proton acceleration experiment was performed at the JETI 40 laser in the Institute for Optics and Quantum Electronics at the University Jena. As targets, water-based micro-droplets were irradiated with the driver laser and simultaneously observed using an optical probe system. To minimize strong noise from plasma emission, the main pulse was frequency doubled to 400 nm while the broadband optical probe was filtered around 710 nm.

This allowed us to study the influence of the laser's focus position on the target's surface with and without using an added prepulse. The maximum proton energy in the laser's forward direction was measured using a Thomson-Parabola and was also correlated to the varying preplasmas generated by the prepulse.

The proton beam profile was observed with an online measurement system consisting of a plastic scintillator and a gateable CCD camera. Complementary measurements covering a larger solid angle were performed with CR-39 nuclear track detectors.

Motivation

- Achieve more experimental insights into and control over the experiment with an optical probe system
  - ➢ Main pulse @ 2ω and probe with broad spectrum in order to find spectral window with reduced plasma emission
- Very high temporal intensity contrast achieved with Second Harmonic Generation
  - ➢ Investigation of the influence of an intentionally added prepulse possible
- Further investigation of laser-driven proton acceleration with water droplets
  - ➢ High-repetition rate target (~1 MHz) and cheap price makes water droplets interesting for applications

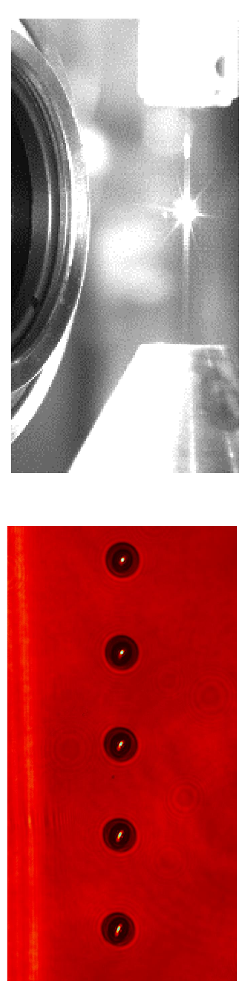
Experimental setup and main diagnostics

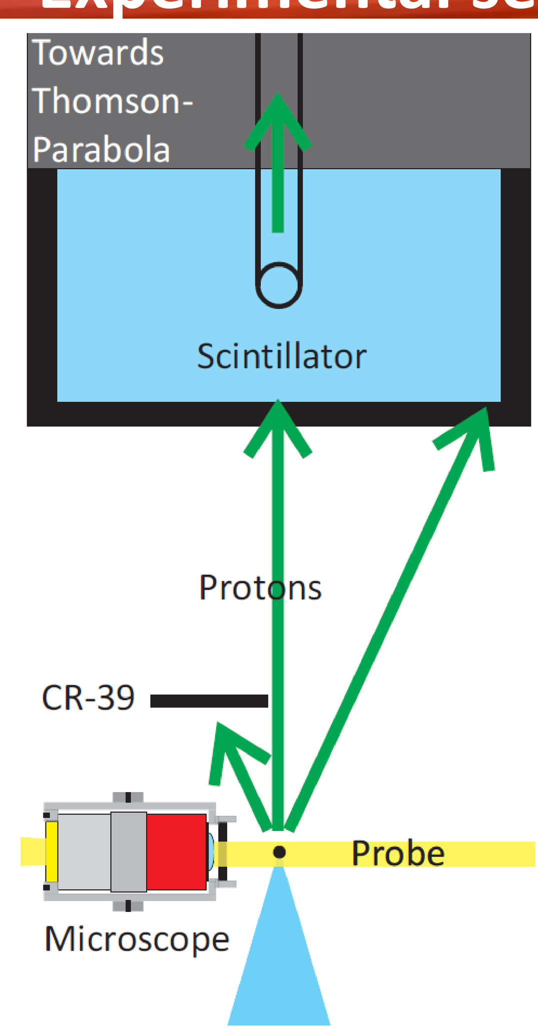
Laser :

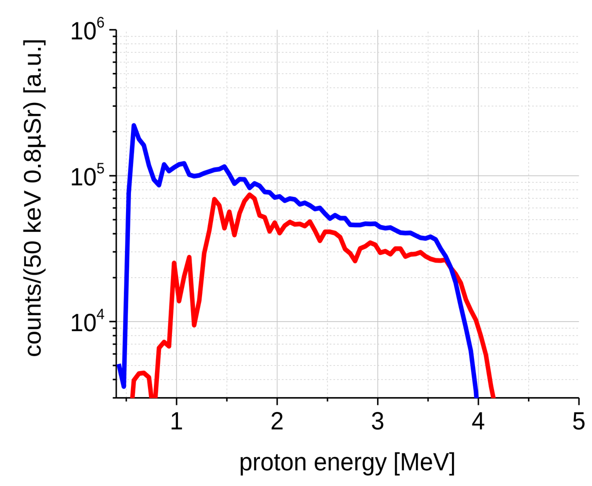
- **JETI 40** @ 400 nm, $E = 100$ mJ
  - ➢ Linear (horizontal) polarization
  - ➢ $\tau_{\mathrm{FWHM}} \approx 35$ fs
  - ➢ Focus diameter $d_{\mathrm{FWHM}} \approx 1\ \mu m$
  - ➢ $I_{\mathrm{FWHM}} \approx 7 \cdot 10^{19}\ \mathrm{W/cm^2}$ $\hat{=}\ a_0 \approx 3$
- **Prepulse** @ 400 nm
  - ➢ $E_{\mathrm{pre}} \approx 1$ mJ , $d_{\mathrm{pre}} \approx 7\ \mu m$
  - ➢ $\tau_{\mathrm{pre}} \approx 35$ fs
  - ➢ $I_{\mathrm{pre}} \approx 1 \cdot 10^{16}\ \mathrm{W/cm^2}$

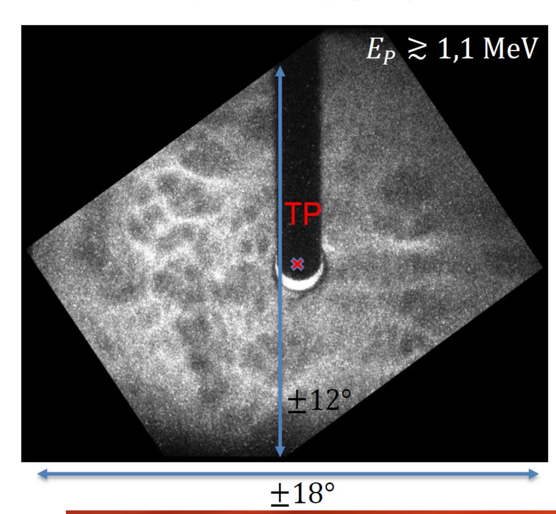
Target/Nozzle:

- **Microjet components** with piezo driver [1]
  - ➢ Droplets with $d \approx 20$ µm and $f \approx 1{,}4$ MHz synchronized with laser





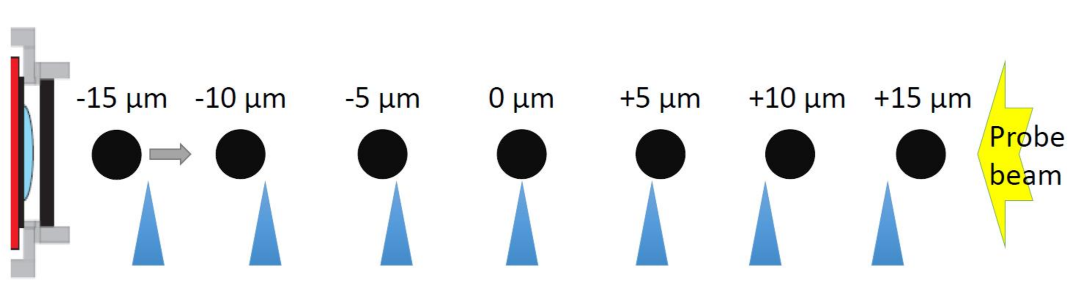




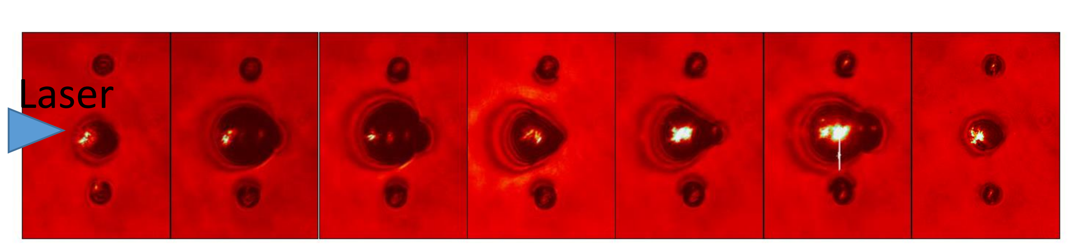
Diagnostics:

- ***Thomson Parabola spectrometer*** under laser's forward direction with MCP detector for measuring the proton spectrum
- ***Plastic Scintillator with gateable CCD*** for measuring the proton beam profile at 29 cm distance
  - ➢ Works as Time-of-flight spectrometer
  - ➢ Covered with 15 µm thick aluminum foil, which shields from heavy ions, slow electrons, laser light reflections and protons with $E_{\mathrm{kin}} < 1.1$ MeV
- (Few-cycle) ***optical probe*** [2] spectrally filtered to 710 ± 20 nm
  - ➢ Reduces noise due to plasma emission

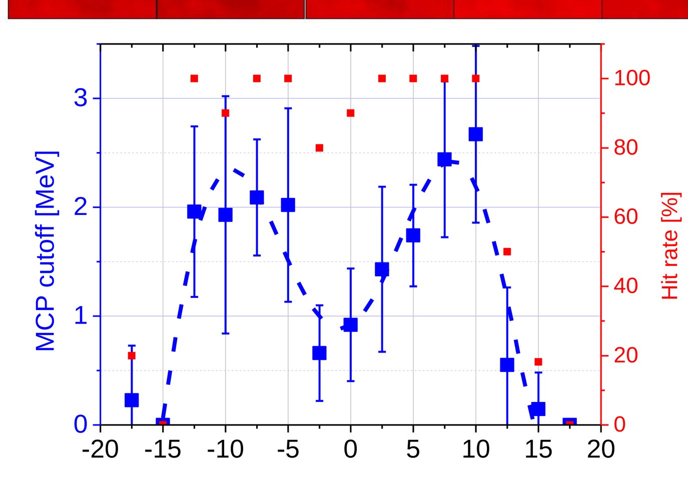
Influence of target position and pre-pulse



- Droplet movement along the laser's polarization axis

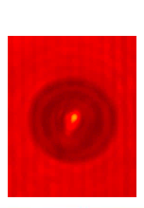


- Shadowgraphy pictures taken 150 ps after main pulse has hit the droplet (**without prepulse**)



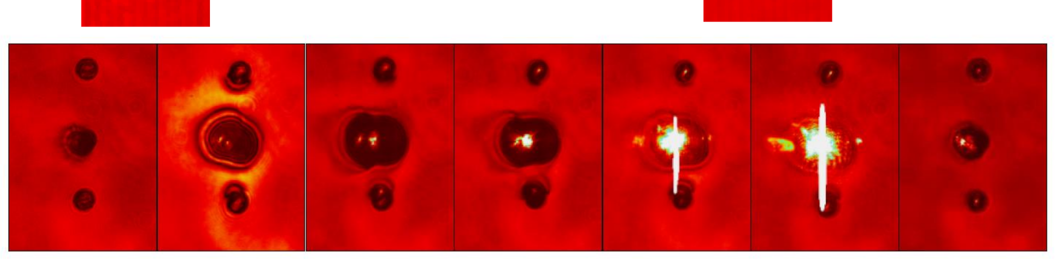
- When droplets were illuminated on the sides
  - ➢ Larger plasma expansion
  - ➢ Higher maximum proton energies
- Here the laser's electric field points into droplet
- Steep plasma density gradient
  - ➢ The dominant electron heating mechanism is most likely Brunel heating

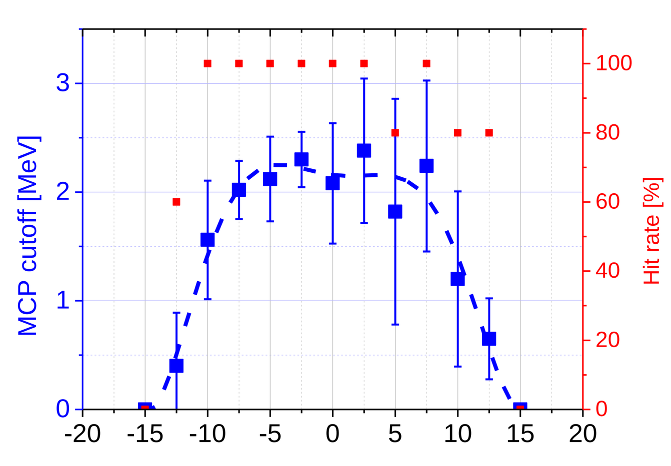
- Influence of a **prepulse** arriving **5 ps** before the main pulse



➢ Droplet before prepulse arrival

➢ Droplet expansion at time of main pulse arrival

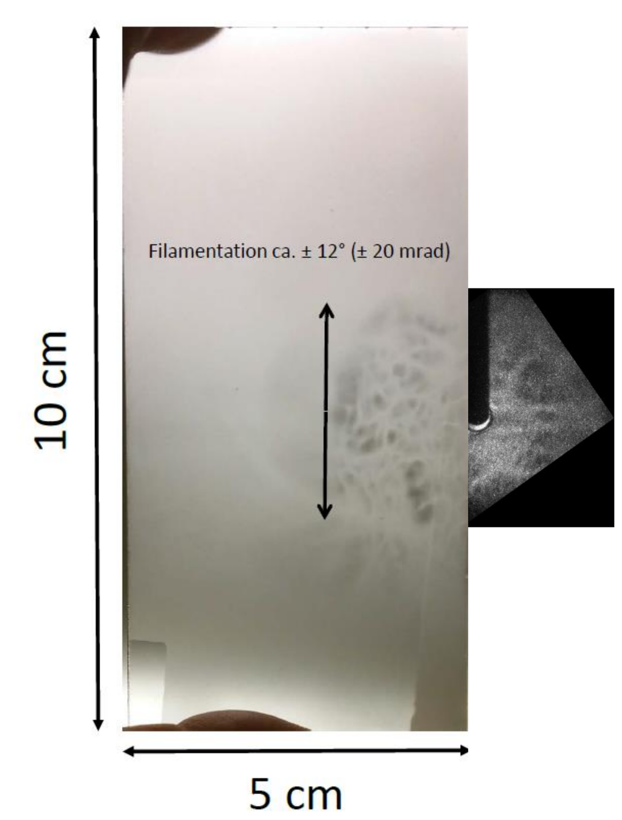




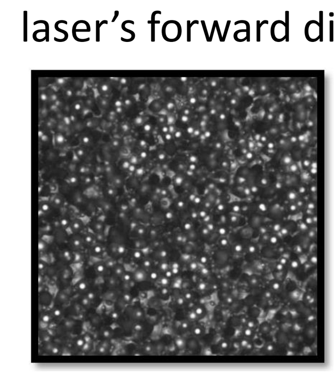
- Expansion behavior is similar for different positions
- No dip in maximum proton energies
  - ➢ Preplasma enhances laser absorption for small incidence angles

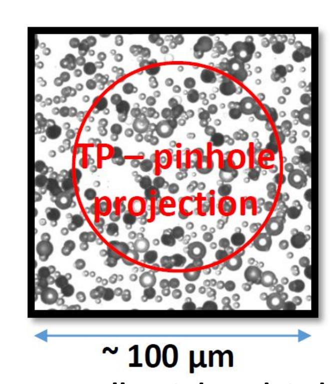
Proton beam profile

- Proton beam profile measured at 7,2 cm distance to target
- CR-39 nuclear track detector shielded with 15 µm thick aluminum foil

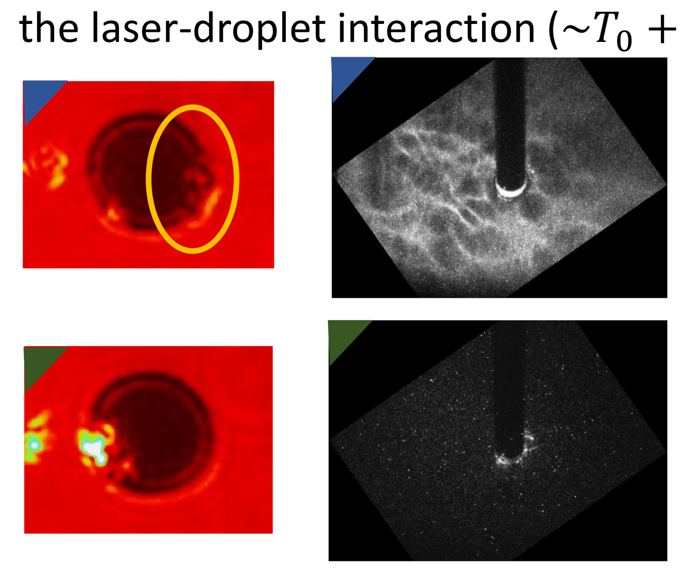


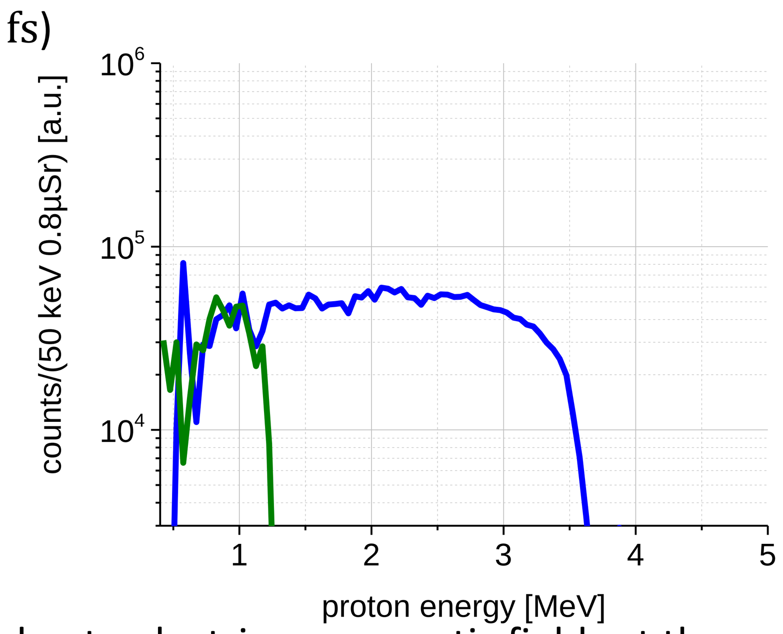
- Proton beam is filamented in a region around the laser's forward direction





- This region consists of "filaments" with a high particle density (left image above) and regions significantly lower particle density (right image above).
  - ➢ Spatial dependence of beam strongly influences the measured proton spectrum due to the Thomson Parabola's small acceptance angle
- Density modulations at target rear surface are visible on images taken at the time of the laser-droplet interaction ($\sim T_0 + 100$ fs)





- Origin of these modulations are probably due to electric or magnetic fields at the droplet's rear side which are connected to the Weibel-Instability [3]

Acknowledgements

Special thanks go to B. Beleites, and F. Ronneberger for running the JETI 40 laser system; and to E. Eckner and J. Bierbach for providing the prepulse mirror setup. This study was supported by DFG (Grants No. TR18 A5, and No. KA 2869/2-1), BMBF (Contracts No. 05K10SJ2 and No. 03ZIK052), and European Regional Development Fund (EFRE).

Summary

- The position of the laser's focus on the droplet surface parallel to the polarization axis of the driver has a strong influence on the protons' kinetic energy and the droplet's hydrodynamic expansion
- This sensitivity on the laser's focus position is reduced by introducing a prepulse
- The detected transverse proton beam profile is strongly modulated
- A correlation between the strongly modulated proton beam profile and the droplet's rear surface at the time of the laser droplet interaction was observed

References

[1] S. Ter-Avetisyan et al., PRL 93, 155006 (2004), Schnürer et al., LPB 23, 337 (2005), …
[2] M. B. Schwab et al., APL 103, 191118 (2013).
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