Laser-Assisted Discharge Ignition for Plasma Waveguides

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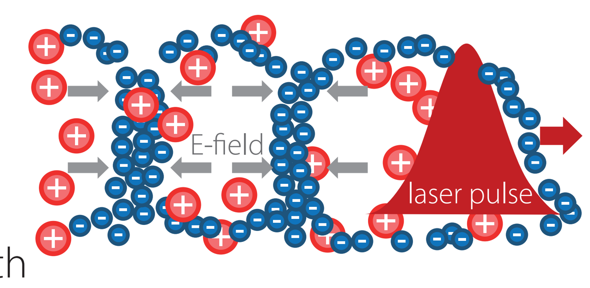
We present the results of a stability analysis of a high voltage discharge in a hydrogen filled capillary. In the experiment, the influence of preionizing the gas target with a femtosecond laser pulse on the discharge and the guiding properties of the plasma waveguide has been investigated.

Motivation

- Laser-Wakefield Acceleration (LWFA): longitudinal electric fields ≥ 100 GV/m
  - ⟶ GeV-energies on a centimeter-scale [1]
- Efficient use of huge longitudinal fields of the plasma wave
  - ⟶ Plasma wave has to sustain itself over whole acceleration length
  - ⟶ Laser intensity has to be sufficiently high throughout whole length
    - ⟶ Can be achieved by guiding the laser pulse in a preformed plasma channel



Theory

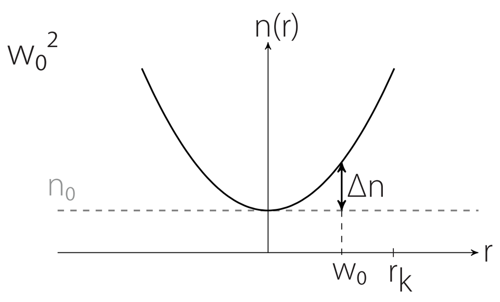
- plasma channel with parabolic density profile $n(r) = n_0 + \Delta n \cdot r^2 / w_0^2$
  - ⟶ Suited to guide a Gaussian laser beam

Guiding conditions [2]:

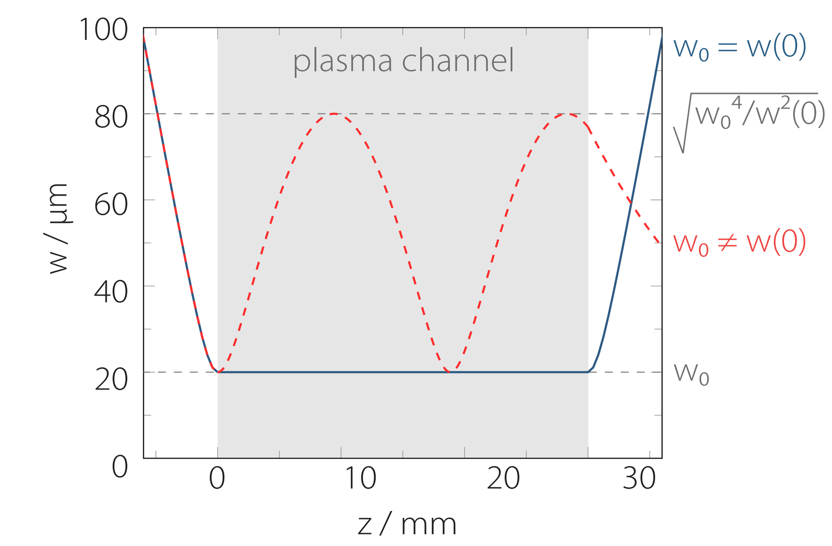
$$\Delta n = \Delta n_{crit} = (\pi \cdot r_e \cdot w_0^2)^{-1}$$

r_e ... classical electron radius

$$w(0) = w_0$$



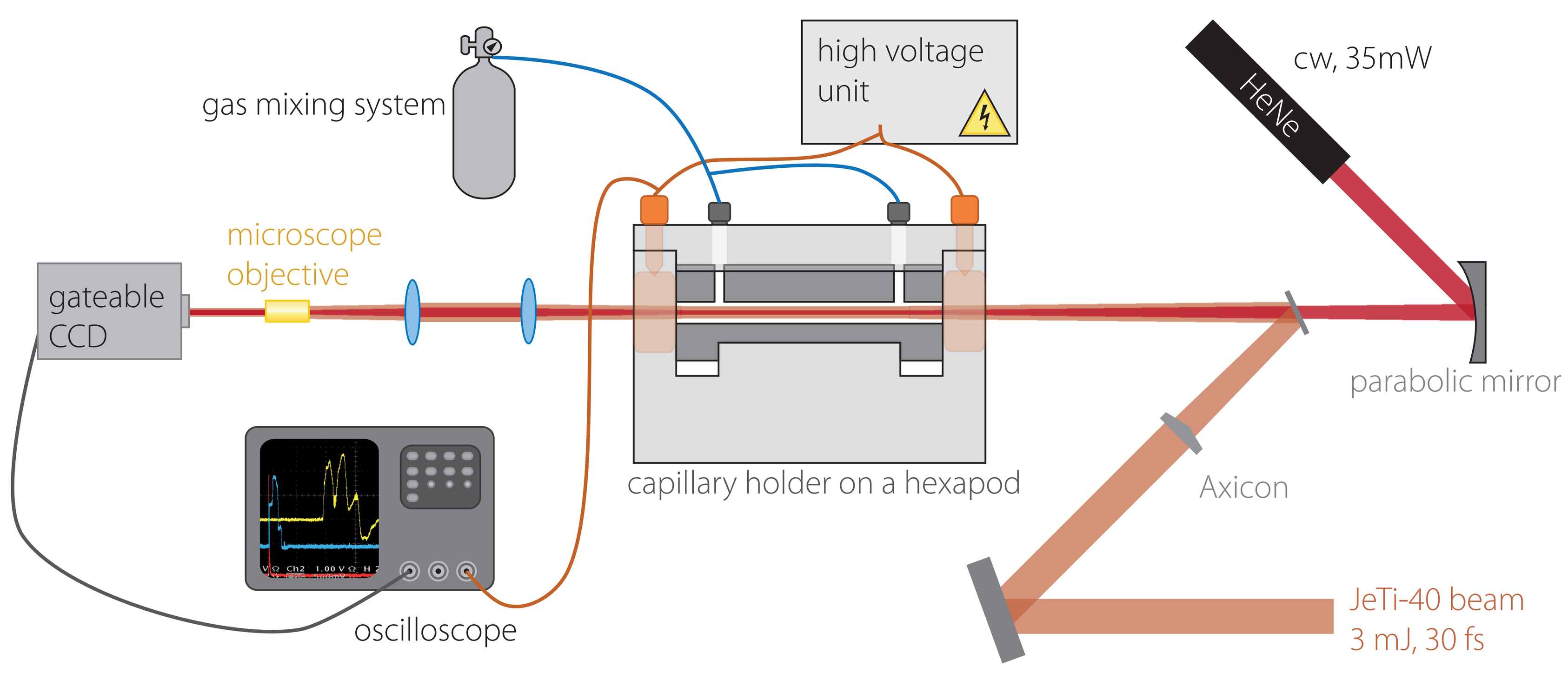
parabolic electron density profile for guiding a gaussian laser beam
n_0 ... background density, Δn ... channel depth, w_0 ... matched spot size

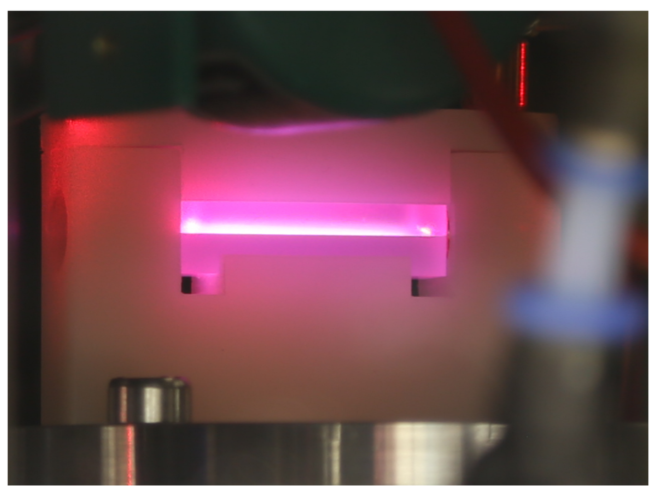


- $\Delta n = \Delta n_{crit}$ und $w(0) = w_0$
  - ⟶ Beam is guided with constant waist
- $\Delta n = \Delta n_{crit}$ und $w(0) \neq w_0$
  - ⟶ Beam waist oscillates in plasma channel

Experiment

- Sapphire capillary, L = 33 mm, Ø 500 µm
- JeTi-40 pulse: preionization (τ = 30 fs, E = 3 mJ, $2 \cdot w_0$ = 54 µm)
- HeNe-Laser: guiding analysis
- Gateable CCD: exposure time in ns-regime
- Oscilloscope: temporal sequence of JeTi-40 signal, gCCD trigger and HV discharge
- HV unit: voltage range 4 kV... 14 kV

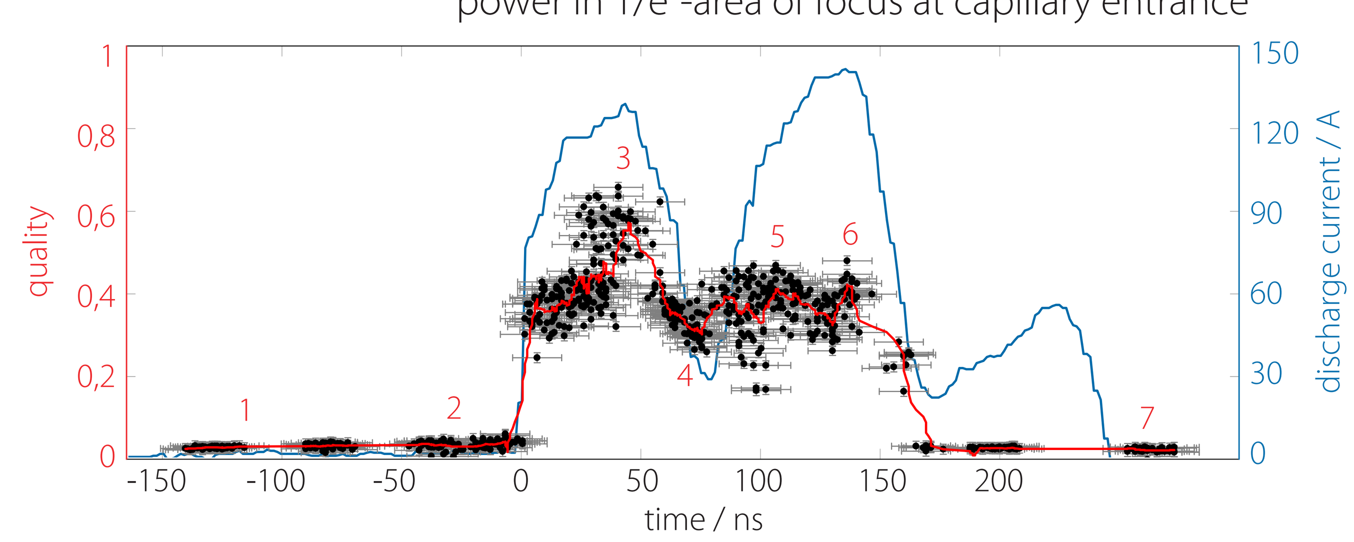


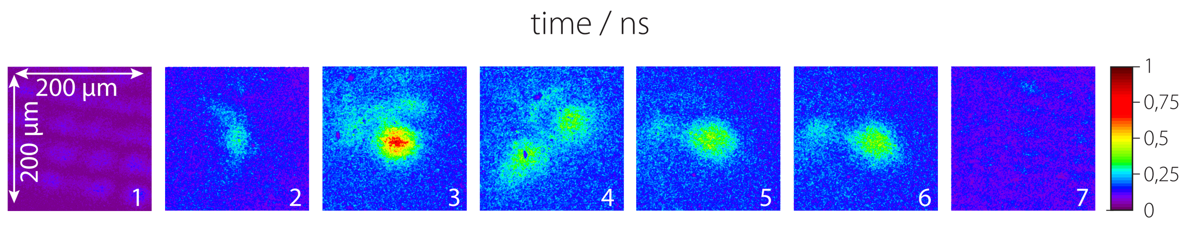


Successful ignition of the hydrogen gas inside the capillary.

Guiding Analysis

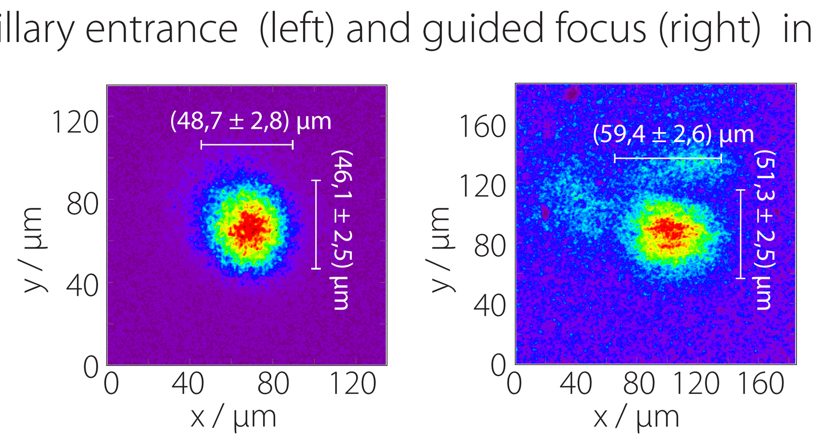
- Investigation of the guiding behavior of the plasma channel inside the capillary caused by the HV-discharge-ignition with and without preionization.
- The image shows the quality of the guided focus and the behavior of the discharge current as a function of time.
- The quality, q, is defined as: $q = \frac{\text{power in } 1/e^2\text{-area of focus at capillary exit}}{\text{power in } 1/e^2\text{-area of focus at capillary entrance}}$





- Quality follows discharge current
- Optimal guiding ~ 40 ns after ignition
- Reached quality values up to 65%

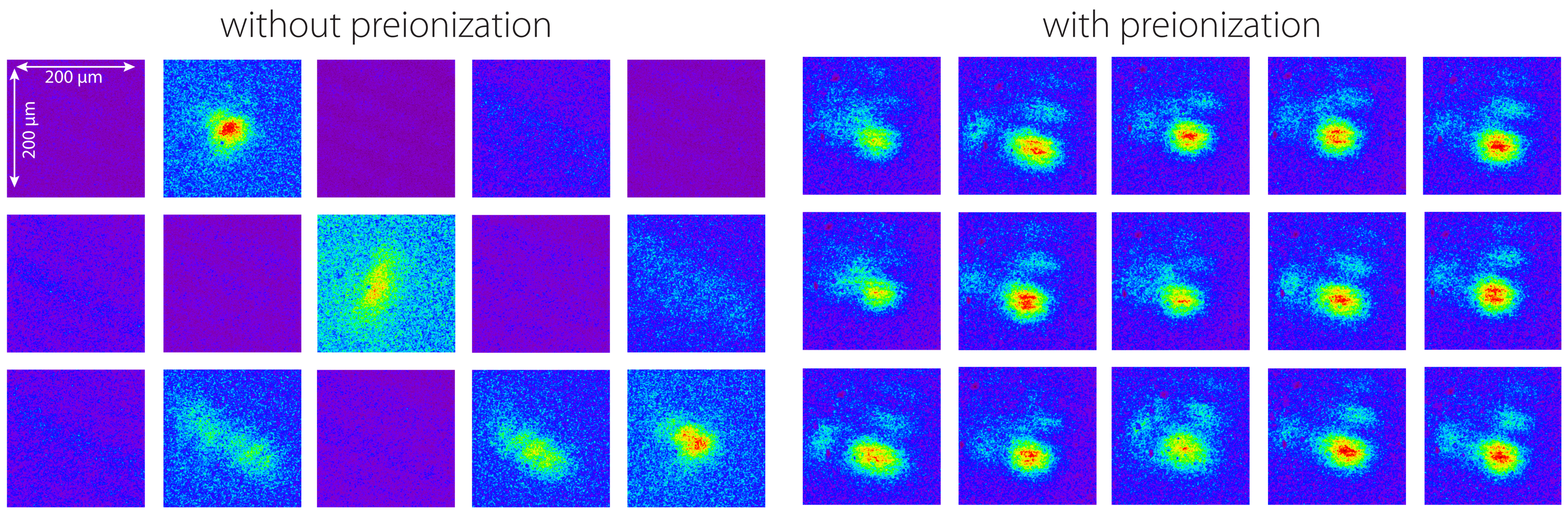
Comparison: focus at capillary entrance (left) and guided focus (right) in region of highest quality.



	$1/e^2$ - width capillary exit	$1/e^2$ - width capillary entrance	% entrance focus
x-direction	(67,7 ± 3,4) µm	(48,7 ± 2,8) µm	140
y-direction	(54,5 ± 2,8) µm	(46,1 ± 2,5) µm	118

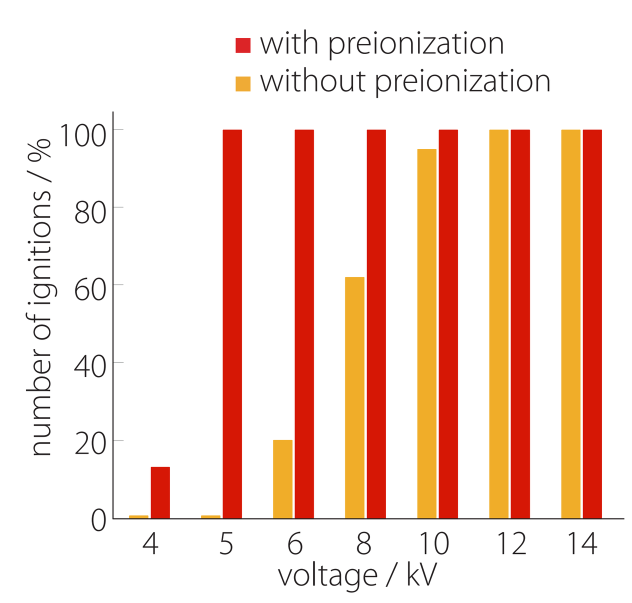
Guided focus in region of highest quality for 15 consecutive shots.

without preionization / with preionization



Stability Analysis

Investigation of the stability of the high-voltage discharge with and without preionization with intensive femtosecond laser pulses

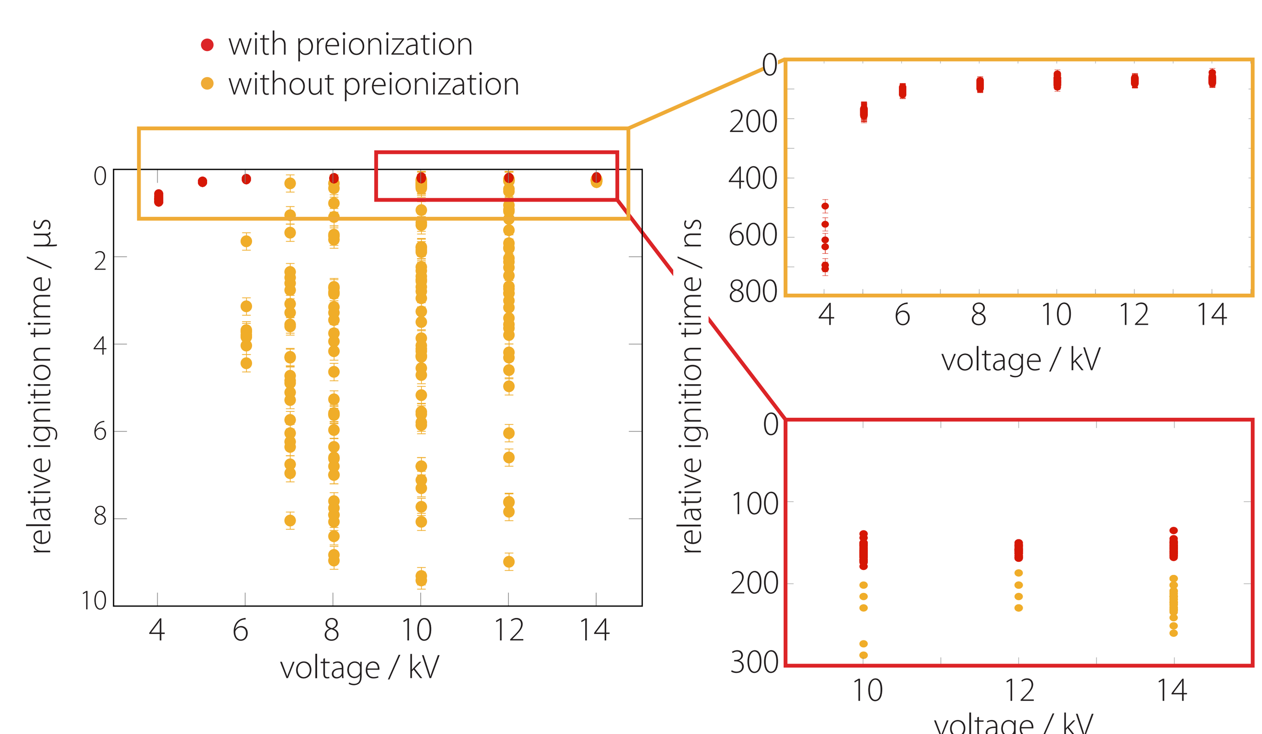


Number of HV-ignitions (in %) for different high voltages

With preionization:

- Reduction of the breakdown voltage from 6 kV to 4 kV
- Reduction of the voltage for stable ignition from 12 kV to 5 kV

Behavior of the relative ignition time for different voltages for a fixed delay between ionization pulse and HV-Trigger.



relative ignition time: delay between ionizing laser pulse and beginnig of the HV-discharge

With preionization

- Reduction of jitter from some µs to ~ 22 ns
- HV-ignition occurs 20 ns earlier as without preionization

Without preionization

- Stable ignition (Jitter ~ 30ns) only for 14 kV

Outlook

- Optimization of HV-unit and thus jitter reduction to ~1 ns
- Usage of the capillary at the JeTi-200 laser system at the Helmholtz Institute Jena
  - ⟶ laser beam will be split and used for preionization as well as electron acceleration
- Useage of a few-cycle probe beam [3] for imaging the plasma wave inside the capillary
  - ⟶ enabling direct insight into electron acceleration [4]

[1] W. P. Leemans et al., Nat. Phys. 2, 2006
[2] E. Esarey und A. Ting, PRL 65, 1961 (1990)
[3] M. B. Schwab et al., APL 103, 2013
[4] A. Sävert et al., PRL 115, 2015

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