Beam driven wakefield characteristics probed by femtosecond-scale shadowgraphy

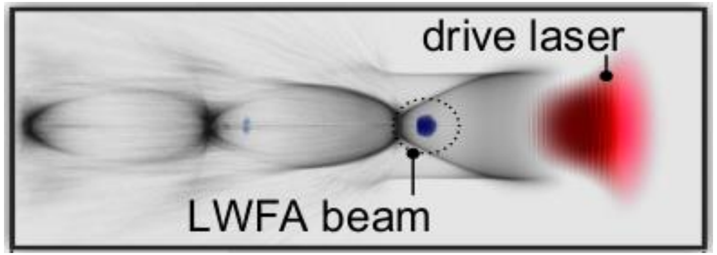
Susanne Schöbel[1,2], Richard Pausch[1], Yen-Yu Chang[1], Sébastien Corde[3], Jurjen Couperus Cabadağ[1], Alexander Debus[1], Hao Ding[4], Andreas Döpp[4], Moritz Förster[4], Max Gilljohann[3,4], Florian Haberstroh[4], Thomas Heinemann[5,6], Bernhard Hidding[6], Stefan Karsch[4], Alexander Köhler[1], Olena Kononenko[3], Alastair Nutter[6], Klaus Steiniger[1], Patrick Ufer[1,2], Alberto Martinez de la Ossa[5], Ulrich Schramm[1,2], and Arie Irman[1]

[1]Helmholtz-Zentrum Dresden-Rossendorf, Germany
[2]Technische Universität Dresden, Germany
[3]LOA, ENSTA ParisTech, CNRS, Ecole Polytechnique, Université Paris-Saclay, France
[4]Ludwig-Maximilians-Universität München, Germany
[5]Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[6]University of Strathclyde, Glasgow, UK

Hybrid Collaboration partners:

Plasma based electron acceleration

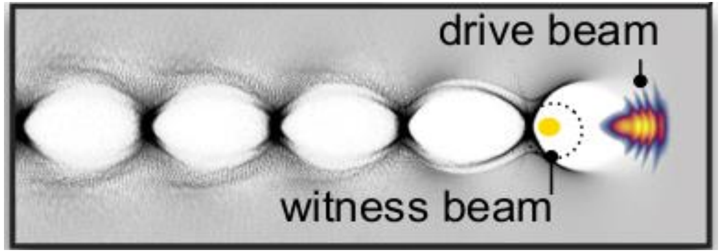
Laser Wakefield Acceleration (LWFA)



T. Kurz - Realization of a compact plasma accelerator for high quality electron beams – Phd Thesis

- Laser lab size
- **Lower phase velocity** due to the refractive index of the plasma
  - **Lower** trapping **threshold**
  - **Dephasing**
- Higher field strengths + **oscillating** field
  - **Hot** background **plasma**
  - more **fluctuations**
- intrinsically short bunches (few fs)
  → **high (>10kA) peak current**

Plasma Wakefield Acceleration (PWFA)



T. Kurz - Realization of a compact plasma accelerator for high quality electron beams – Phd Thesis

- Requires relativistic electron driver (e.g. LINAC)
- Electron driver propagate with approx. the **speed of light**
  - **Higher** trapping **threshold**
  - **No-dephasing**
- Lower field strength + **constant** field
  - **Cold** background **plasma**
  - **more stable** wakefield
  - ➢ **Acceleration of high brightness witness beams**

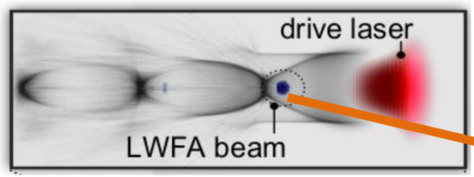
Hybrid LWFA-PWFA staging

Complementary features of LWFA and PWFA: Combination of both schemes by **driving PWFA** with **LWFA beam** with the **potential** to reach**:**

- **Higher brightness**
- **Enhanced stability**
- **Higher energy**

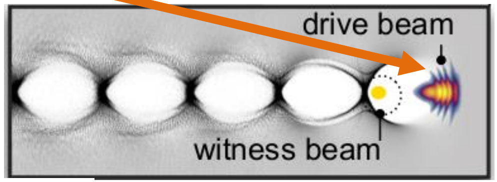
→ Talk by Stefan Karsch (Thursday, 10:15)
→ Poster by Patrick Ufer
→ Poster by Moritz Förster

Laser Wakefield Acceleration (LWFA)



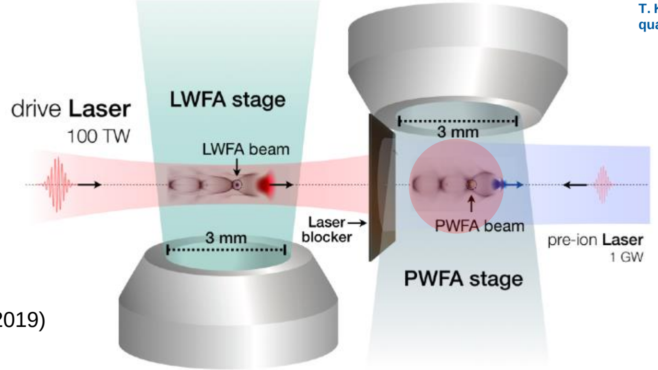
T. Kurz - Realization of a compact plasma accelerator for high quality electron beams – PhD Thesis

Plasma Wakefield Acceleration (PWFA)



T. Kurz - Realization of a compact plasma accelerator for high quality electron beams – PhD Thesis

Hybrid (LPWFA)



PWFA at the order of **~10^{18}cm^{-3}** density:
→ optical probing possible

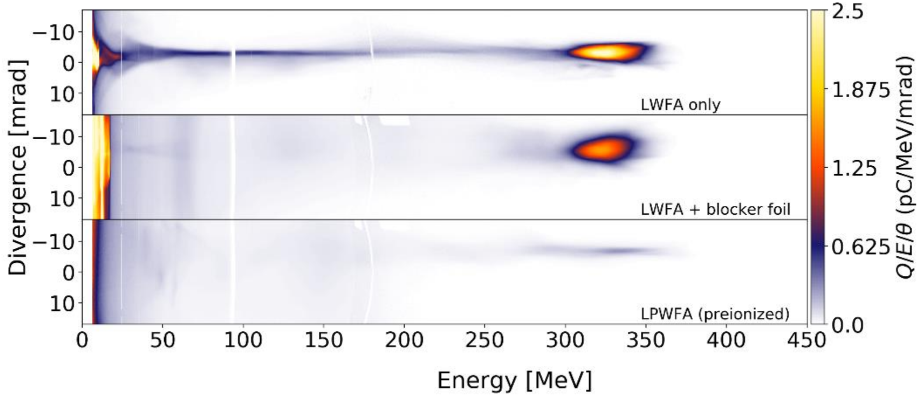
B. Hidding et al., PRL 104, 195002 (2010)
A. Martinez de la Ossa et al., Phil. Trans. R. Soc. A 377: 20180175 (2019)
B. Hidding, et al., Appl. Sci. 2019, 9, 2626 (2019)
T. Kurz et al., Nat Commun 12, 2895 (2021)
J. Couperus Cadabag et al. Physical Review Research 3, L042005 (2021)

LPWFA setup @ HZDR

DRACO Laser
100 TW line

- 2.3J on target
- 30fs duration
- focused by F/20 off-axis parabola

- two similiar nozzles (3mm diameter) used as LWFA and PWFA stage
- Blocker foil (Kapton) avoids LWFA driver laser to propagate into PWFA stage
- Pre-ionization laser for PWFA stage from the back
- **10-fs** duration **optical probing** perpendicular to wakefield evolution axis

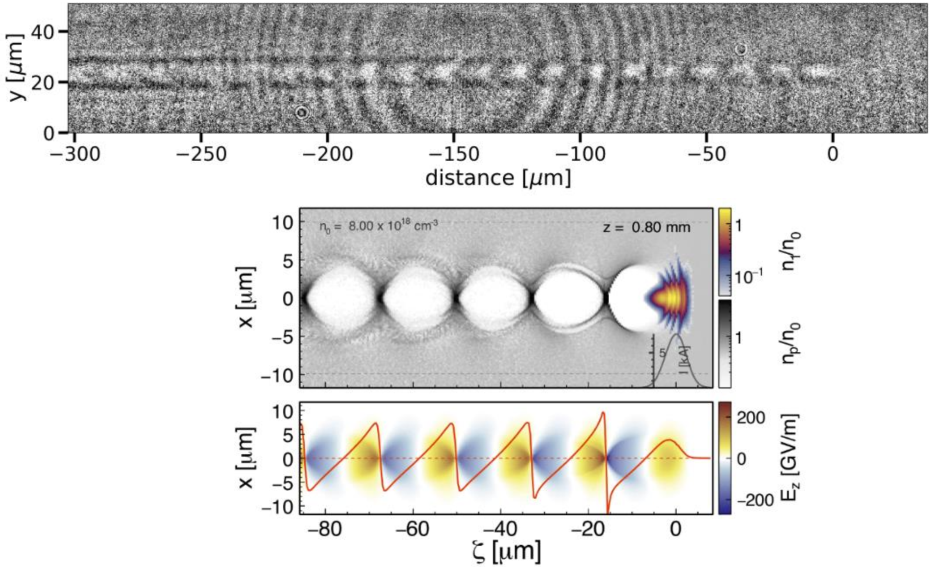


LWFA Electron beam parameters	
Peak energy:	328 ± 29 MeV
Energy spread:	44 ± 18 MeV
FWHM bunch charge:	318 ± 71 pC
Divergence (rms):	1.81 ± 0.17 mrad
FWHM duration:	14.8 ± 1.6 fs

G. Raj et al. Physical Review Research **2**, 023123 (2020)

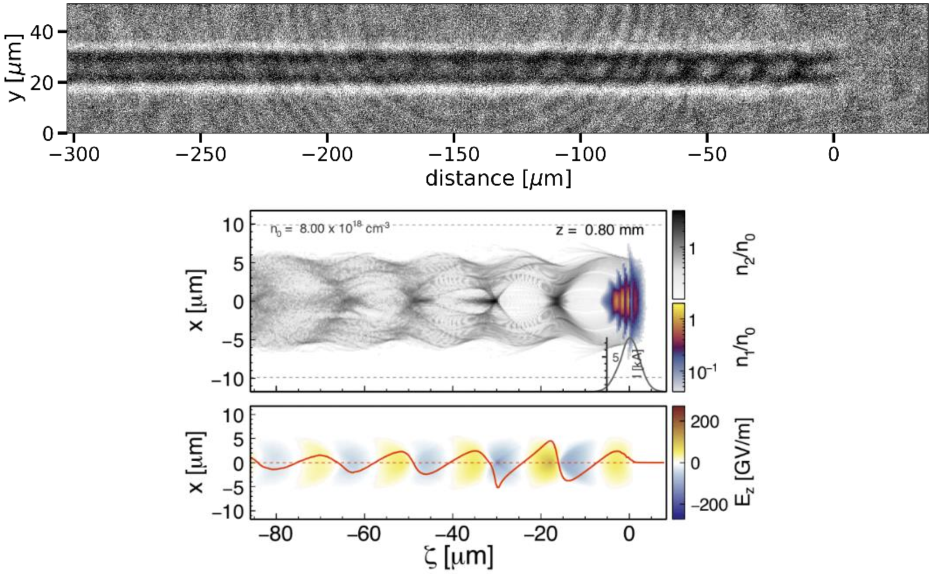
Plasma wave structures in two regimes

Pre-ionized



- additional **laser for pre-ionization** prior to drive beam arrival → **large plasma volume** surrounding the wakefield
- Multiple **stable cavities**, just slowly dampening

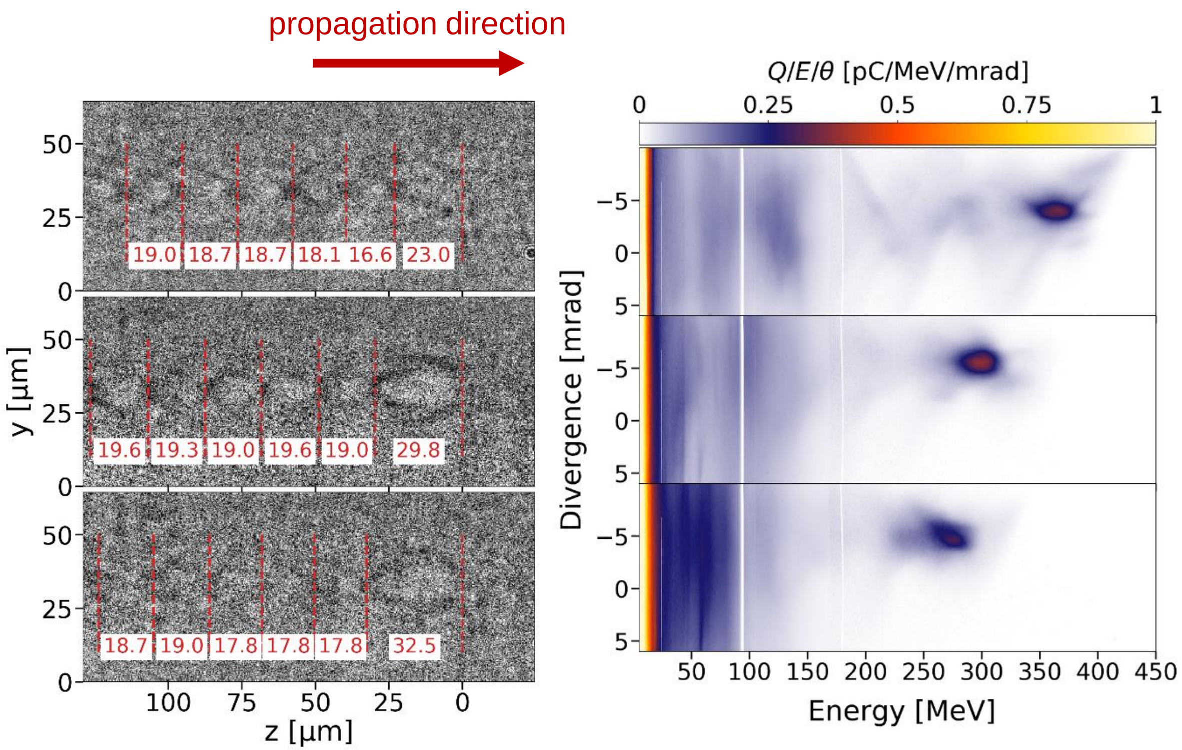
Self-ionized



- driver beam enters neutral gas, ionization due to the drivers **space charge field → narrow plasma channel** ~ same size as cavity
- **Quick dampening** and **smearing** out of the cavity structures

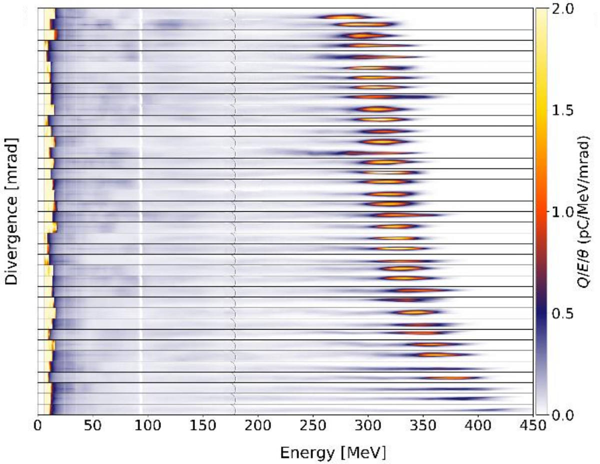
Cavity size vs. driver charge

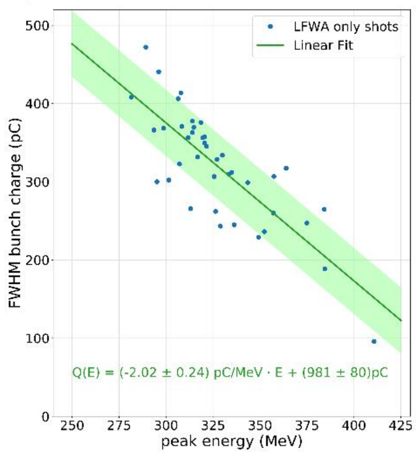
- different shots for PWFA plasma density of $n_p = 3 \cdot 10^{18}$ cm^{-3}
- Size of the **first cavity** is **elongated**
- **trailing** are close to the **linear plasma wavelength** of $\lambda_p = 19.3$µm
- Corresponding spectrometer data: **less energy** of driver leads to **more elongation**

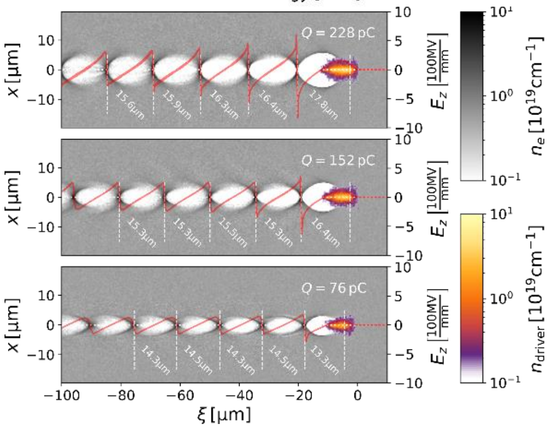


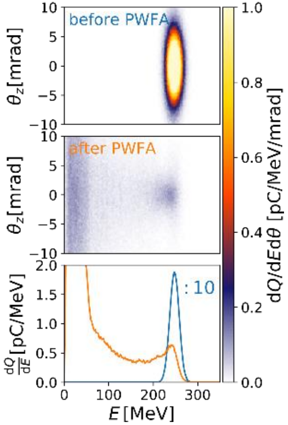
Cavity size vs. driver charge

- LWFA **driver charge and energy** connected via **beam loading**: **less energy→ higher charge**
- **3D PIConGPU** Simulation: energy constant, different driver bunch charge: **elongation depends** on the **charge**
- **deceleration** of the driver: charge is hard to reconstruct from remaining bunch
- **Energy peak position is preserved** (see simulation) → via **beam loading** allows **estimation** of **charge** possible





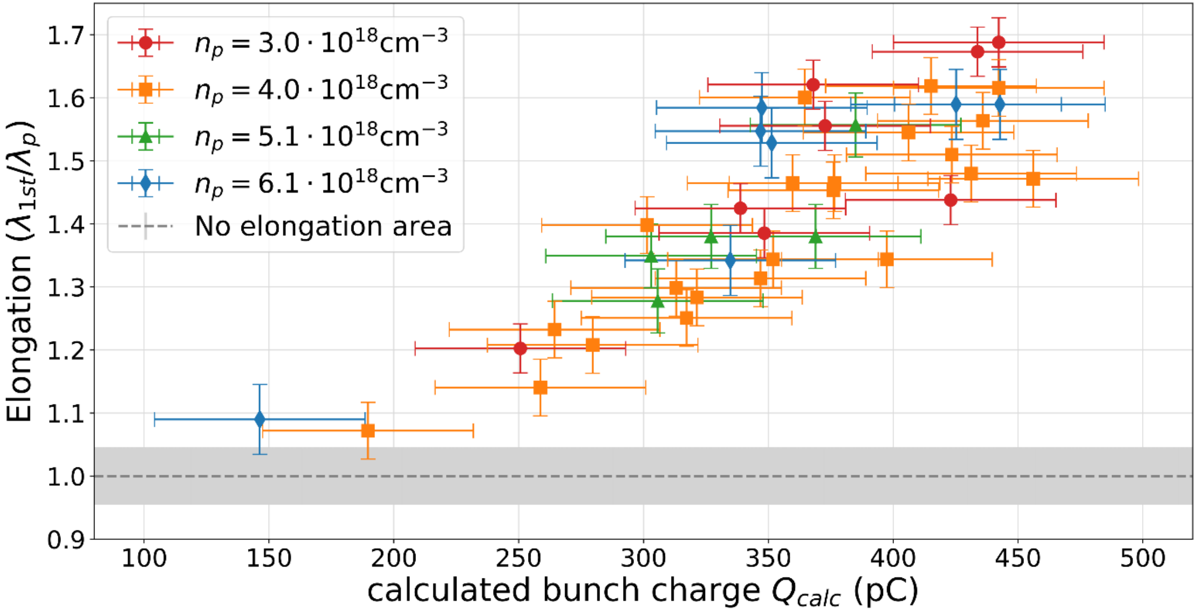




Poster by Richard Pausch

J. Couperus et al., Nature Communication **8**, Article number: 487 (2017)
J. Götzfried et al. Phys. Rev. X **10**, 041015 (2020)
M. Kirchen et al. Phys. Rev. Lett. **126**, 174801 (2021)

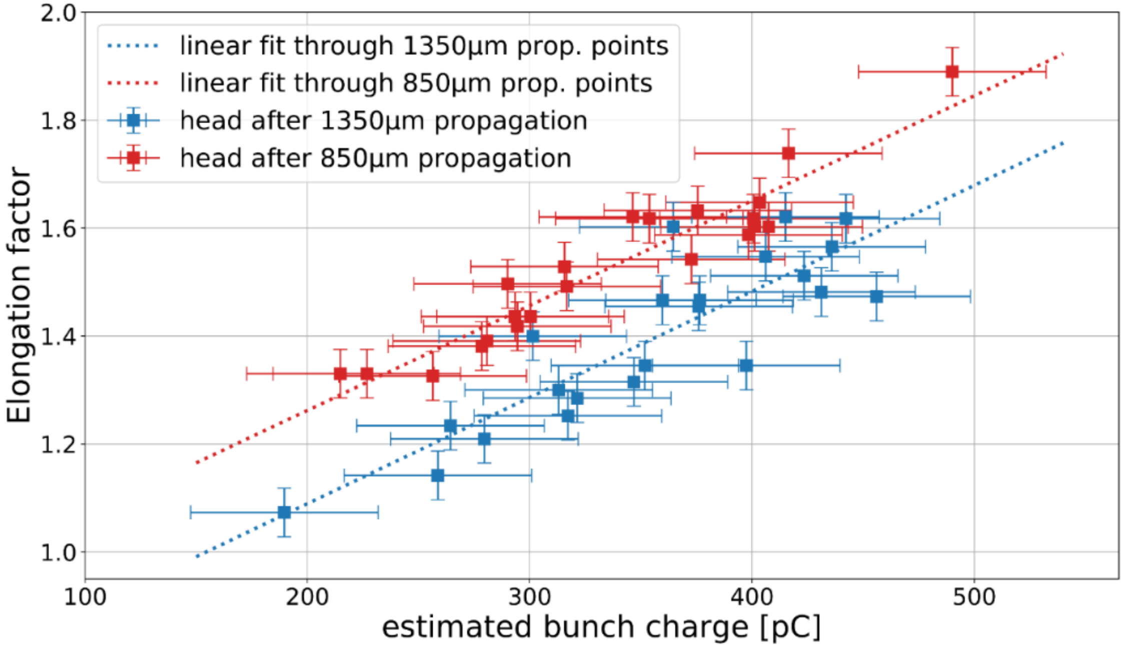
Cavity size vs. driver charge



- **Elongation** of first cavity **depends on bunch charge**
- Cavities at different densities show: **charge is dominant** for the elongation (compared to e.g. bunch duration)

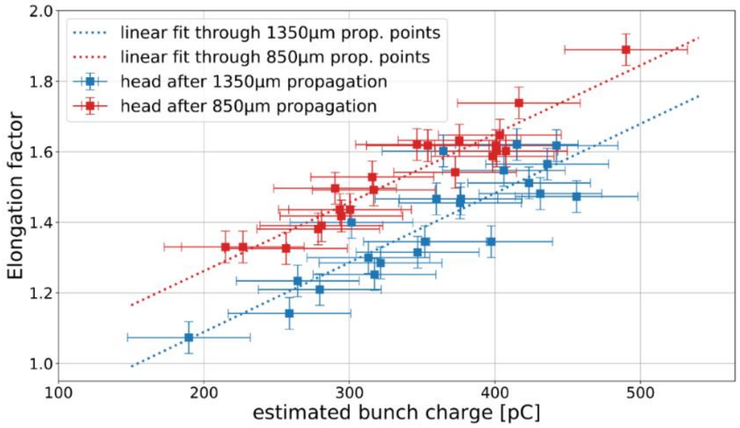
Cavity size vs. driver charge and propagation distance

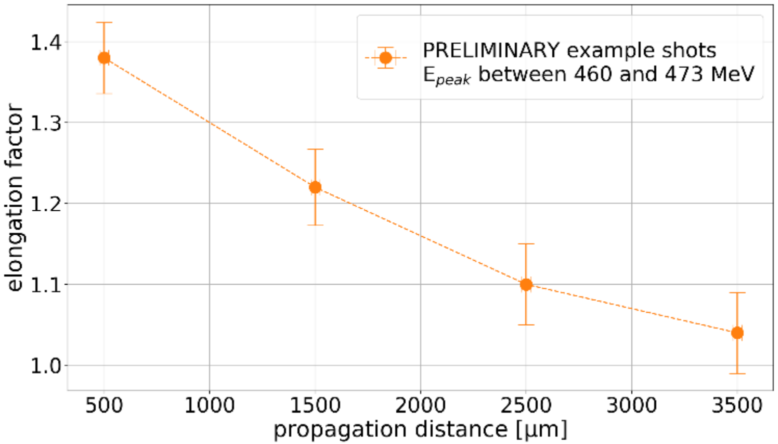
- probing further **downstream: less elongation**
- **remaining charge** at probing position defines **cavity size**



Cavity size vs. driver charge and propagation distance

- probing further **downstream: less elongation**
- **remaining charge** at probing position defines **cavity size**

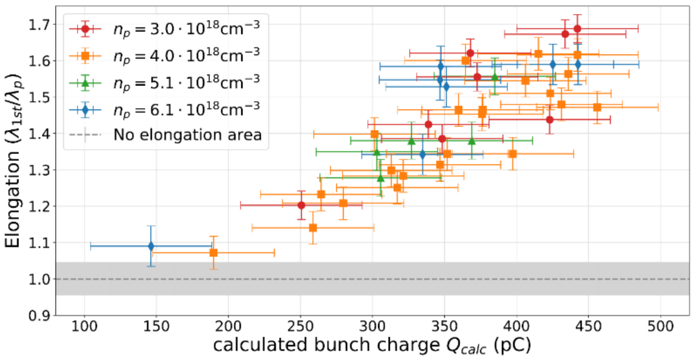




- ➢ Probe measurements could be used to measure the driver **depletion** along the jet

Summary and Outlook

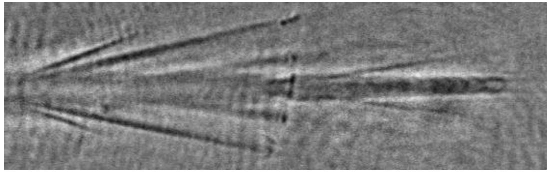
- **Length** of the **first cavity** correlates to **charge/peak current** of the driver beam
- Confirmed by **3D PIConGPU Simulation**
- **Driver bunch depletion** (charge loss during propagation through the plasma) can be studied using this method
- **Optical probing** gives an **inside view** into PWFA, more things to explore e.g.:
  - Breakups
  - plasma wave through shock
  - first cavity shape

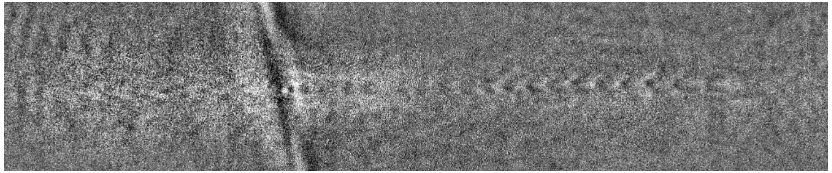


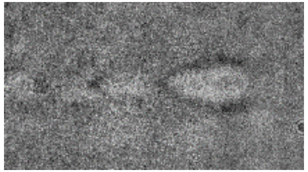
More information:

→ *New J. Phys.* **24** (2022) 083034

→ Poster Susanne Schöbel (Nr.)







Thank you for your attention!