Overview of the hybrid LWFA-driven PWFA

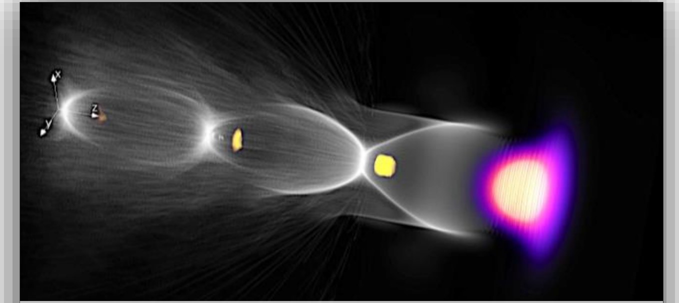
Susanne Schöbel[1]

Finn-Ole Carstens[1,2], Yen-Yu Chang[1], Sébastien Corde[3], Alexander Debus[1], Andreas Döpp[4], Moritz Förster[4], Max Gilljohann[3], Florian Haberstroh[4], Fahim Habib[5], Thomas Heinemann[5,6], Franziska Marie Herrmann[1,2], Bernhard Hidding[5,6], Arie Irman[1], Stefan Karsch[4], Lena Kononenko[5], Maxwell LaBerge[1], Alberto Martinez de la Ossa[7], Alastair Nutter[3], Richard Pausch[1], Felipe Peña[4], Ulrich Schramm[1,2], Jessica Tiebel[1,2] and Patrick Ufer[1,2]

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

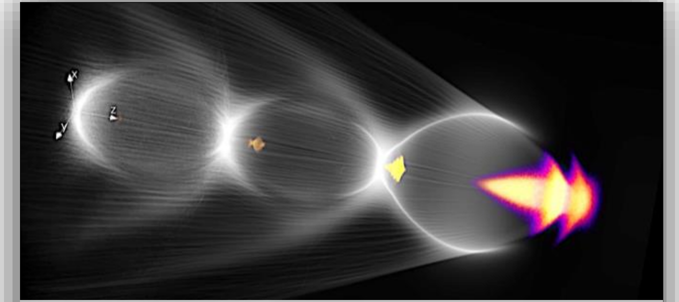
Hybrid Collaboration partners:

General concept of Hybrid LWFA-PWFA staging



Laser-driven plasma wakefield accelerator (LWFA)

- Driven by a **high-intensity laser pulse**
- **Dephasing limits** the acceleration length
- Widely accessible at high-power laser facilities
- **Operation at high (~10^{17}-10^{19} cm^{-3}) densities: compact** generation of **µm sized, ultrashort** (~10s of fs) and **high peak current (>10 kA)** electron beams

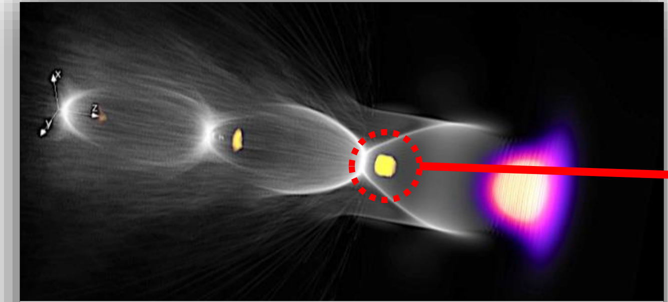


Beam-driven plasma wakefield accelerator (PWFA)

- Driven by a **relativistic charged particle bunch**
- **Dephasing free** acceleration
- **Less background** due to higher driver velocity
- **Cold injection schemes** (e.g. plasma photocathode) are applicable

→ Potentially **better suited** for **high quality** (brightness) **beam** generation

General concept of Hybrid LWFA-PWFA staging



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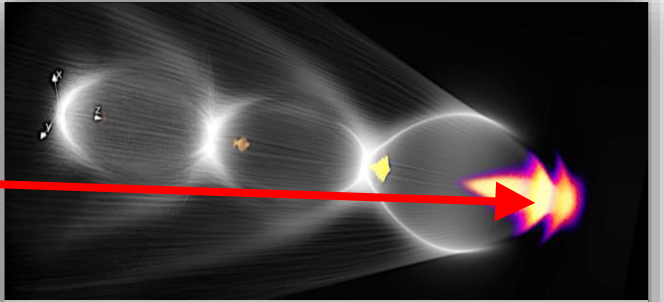

Beam-driven plasma wakefield accelerator (PWFA)

- Driven by a
- **Dephasing**
- Widely acce facilities
- **Operation densities: sized, ultra current (>1**

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high quality

(brightness) **beam** generation

<u>Idea of Hybrid:</u>

use **LWFA generated beam** as **driver** for a subsequent **PWFA,** exploiting individual benefits of both schemes

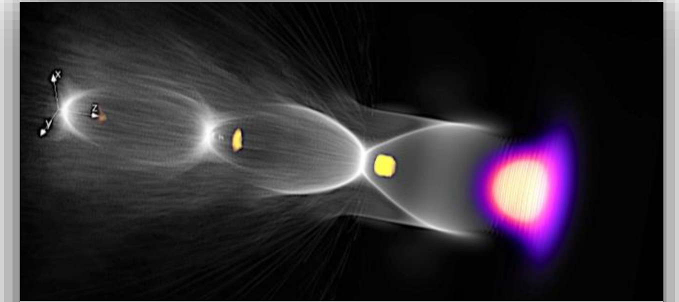
to

→ generate **high-brightness** beams on a university laboratory-scale

→ potential energy and stability booster

Hidding, B. et al: **PRL 104**, 195002 (2010)

General concept of Hybrid LWFA-PWFA staging



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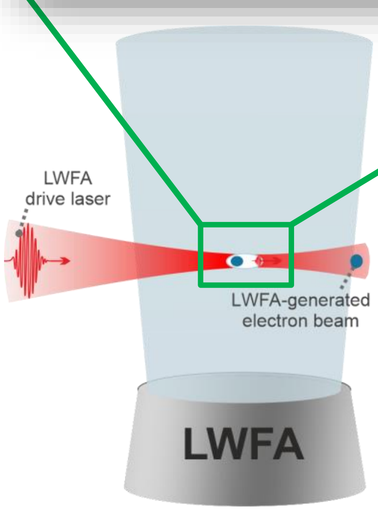
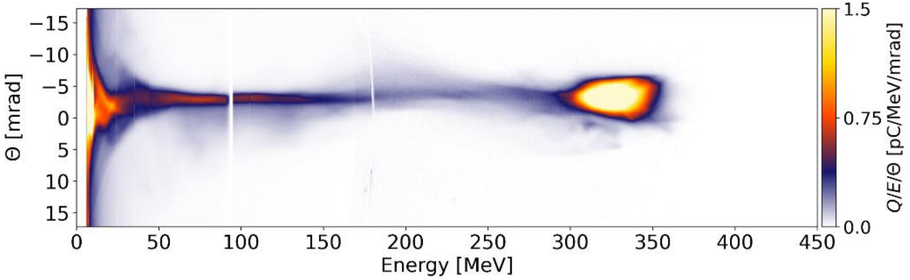
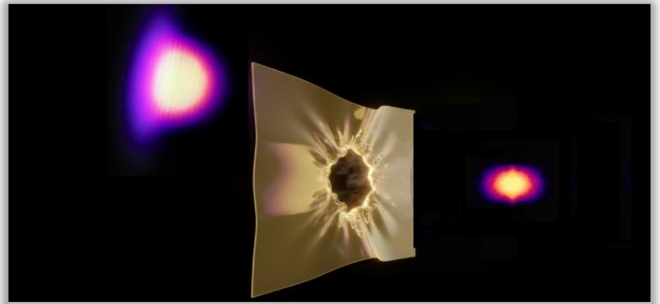




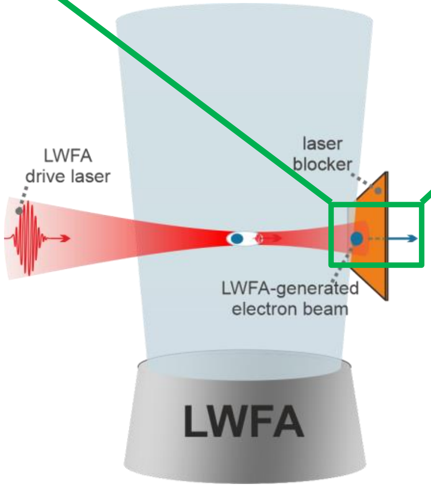
Typical LWFA Electron beam parameters @ HZDR, self-truncated ionization injection	
Peak energy:	200 – 500 MeV
Energy spread:	25 – 70 MeV
FWHM bunch charge:	100 – 350 pC
Divergence (rms):	1.7 – 3 mrad
FWHM duration:	14.8 ± 1.6 fs
Peak current:	up to 50 kA

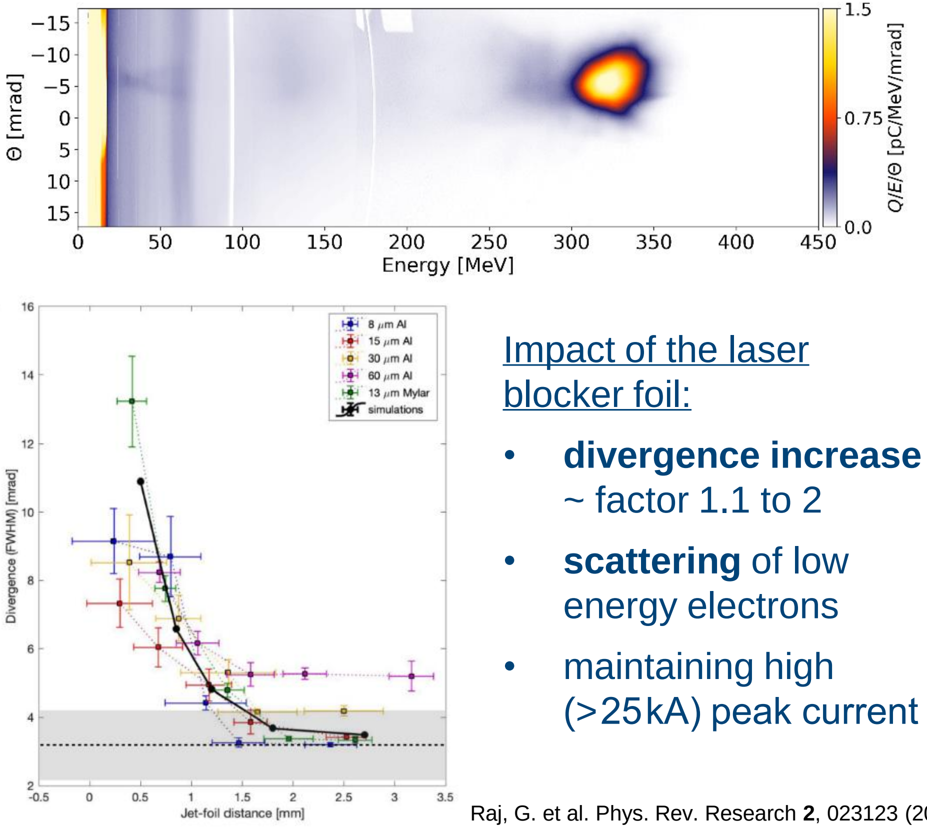
J. P. Couperus et al., *Nat. Commun.* 8 (2017), p. 487
A. Irman et al., *PPCF* 60, 044015 (2018)

General concept of Hybrid LWFA-PWFA staging



Interaction with laser blocker foil





Impact of the laser blocker foil:

- **divergence increase** ~ factor 1.1 to 2
- **scattering** of low energy electrons
- maintaining high (>25 kA) peak current

Raj, G. et al. Phys. Rev. Research **2**, 023123 (2020)

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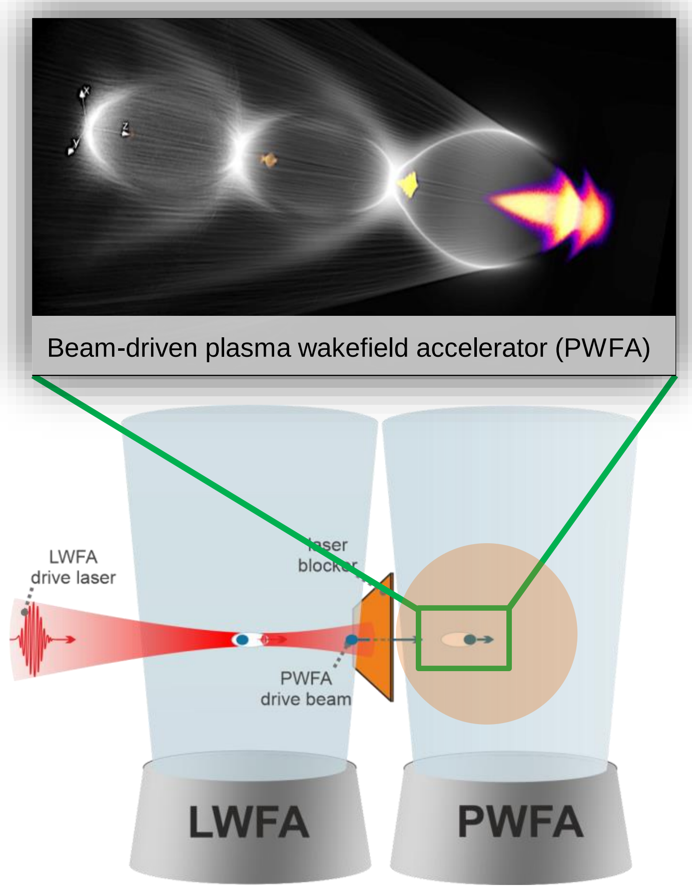

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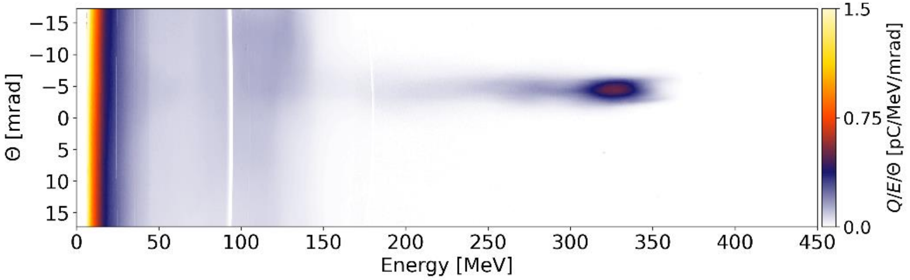
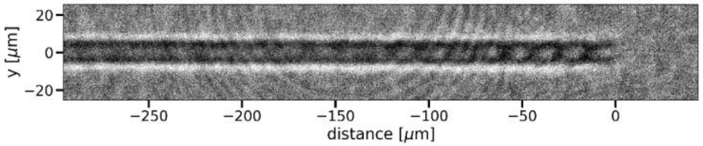
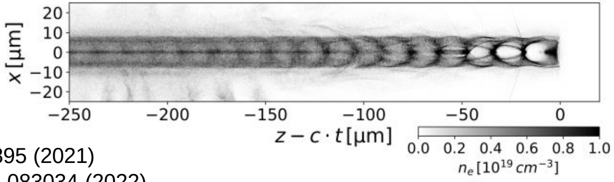


- **deceleration** of driver electrons (charge loss)
- divergence decrease due to **focusing**

Few-cycle shadowgraphy:



Plasma density distribution from simulation:



Kurz, T. et al. **Nat Commun 12**, 2895 (2021)
Schöbel, S. et al. **New J. Phys. 24** 083034 (2022)

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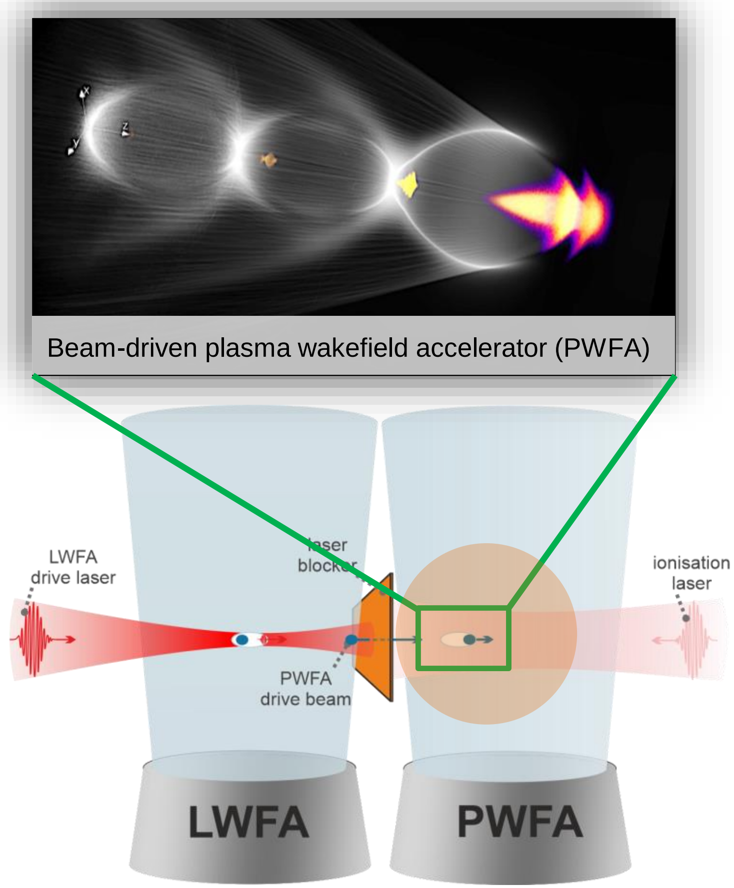
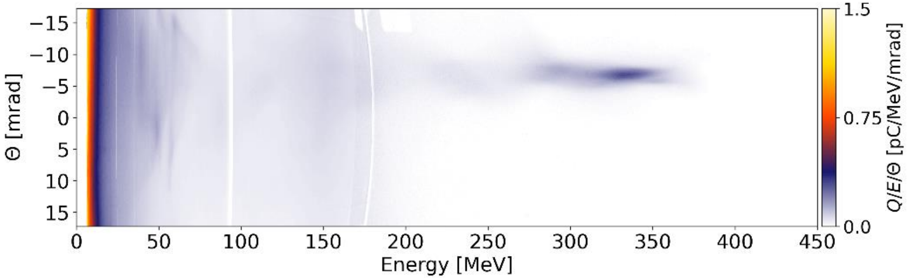
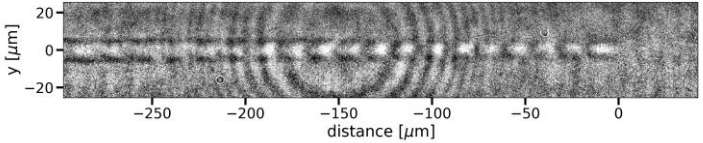




- **stronger deceleration** of driver electrons (more charge loss)
- divergence decrease due to **focusing**

Few-cycle shadowgraphy:



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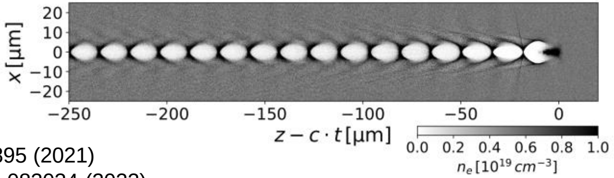
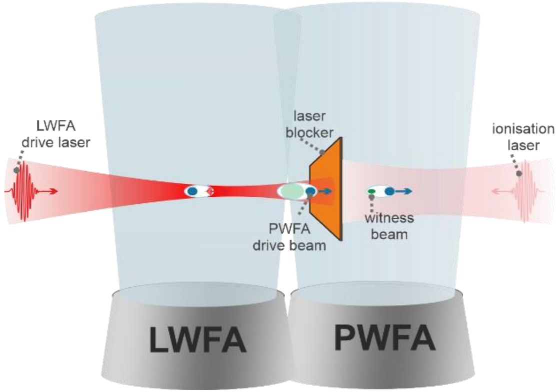


Kurz, T. et al. **Nat Commun 12**, 2895 (2021)
Schöbel, S. et al. **New J. Phys. 24** 083034 (2022)

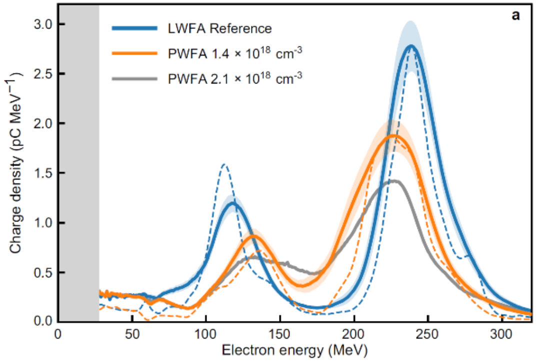
Proof of principle: LWFA-generated beams can drive PWFA

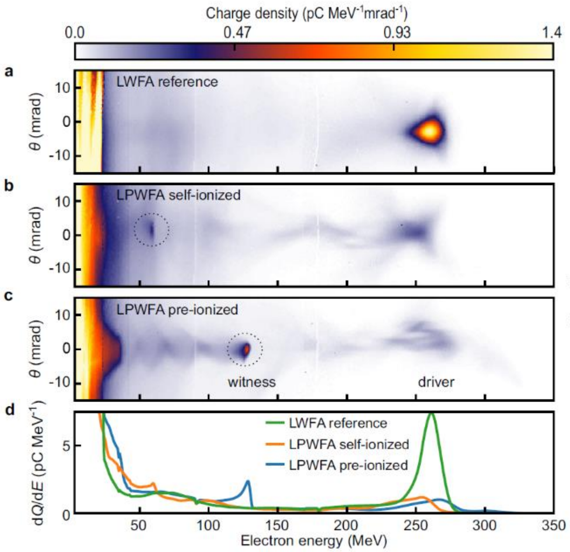
First steps @ HZDR and LMU:

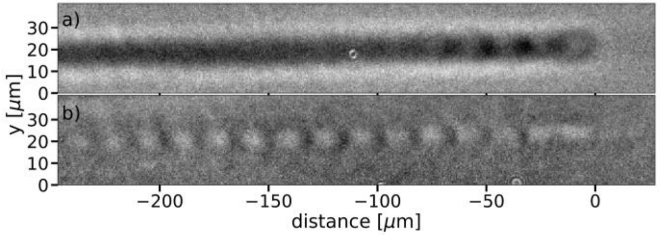
- **Witness beam acceleration in driver-witness pair** from LWFA: driver decelerates, witness accelerates
- Observation of **beam driven plasma waves** (using Laser beam blocker) in pre- and sel-ionized regime
- **Different acceleration gradients** in **pre- vs. self-ionized** regime



Kurz, T. et al. Nat Commun 12, 2895 (2021)
Gilljohann, M. et al. PRX 9, 011046 (2019)
Schöbel, S. et al. New J. Phys. 24 083034 (2022)



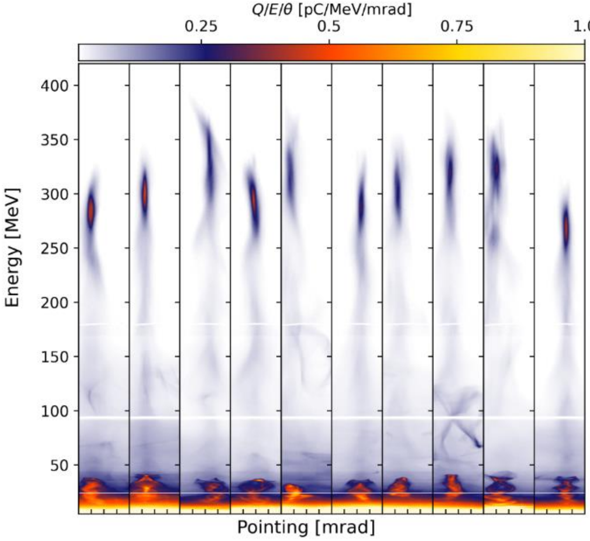




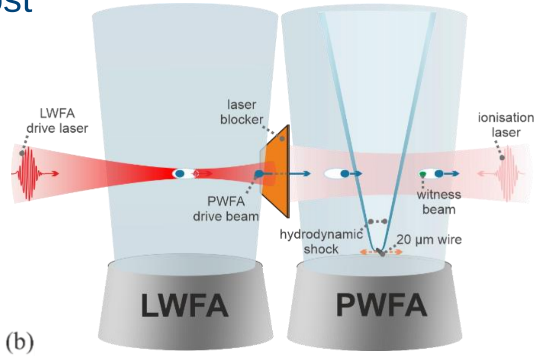
Internal injection via injection at a density downramp

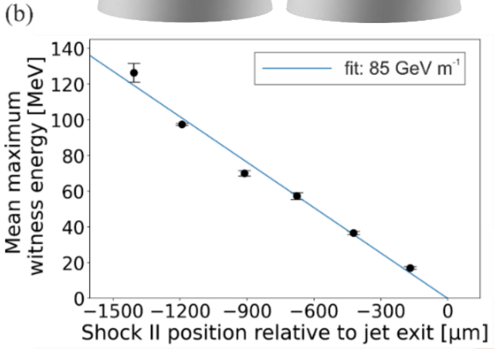
Controllable injection at a density downramp

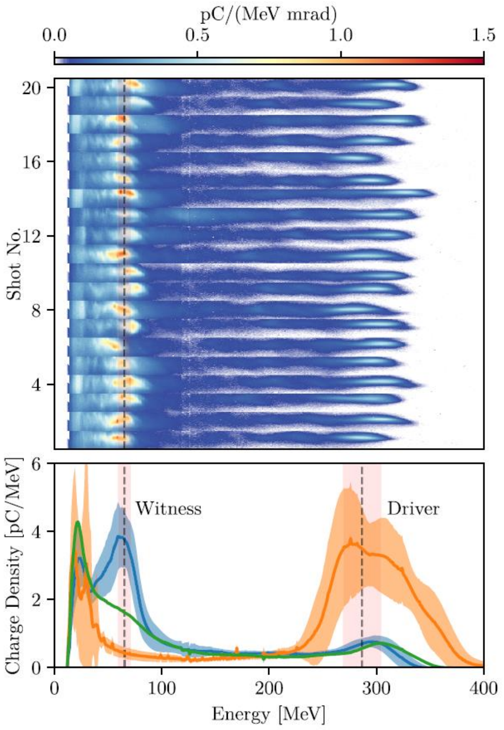
- **reliable injection** from **hydrodynamic** or **optically** generated **shock**
- **Stability booster** (energy) for optically generated shock
- But: witness energy and quality most likely not better than driver



hydrodynamic shock:
Couperus Cabadağ, J. P. et al. **Phys. Rev. Research** 3 (2021)







Optically generated shock:
Foerster, M. et al. **PRX 12**, 041016 (2022)

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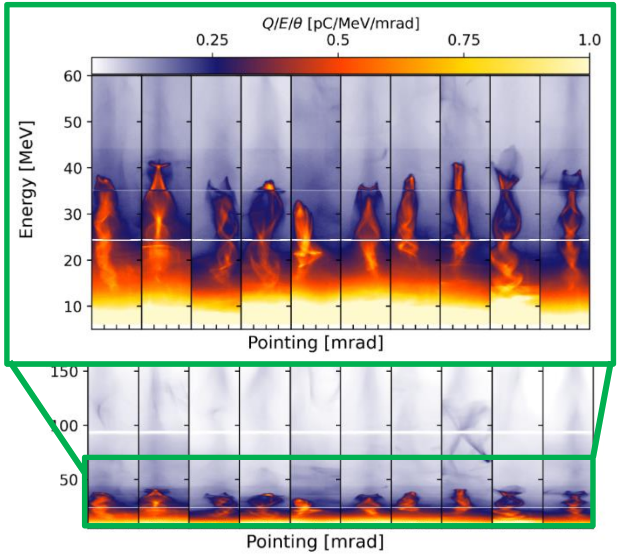

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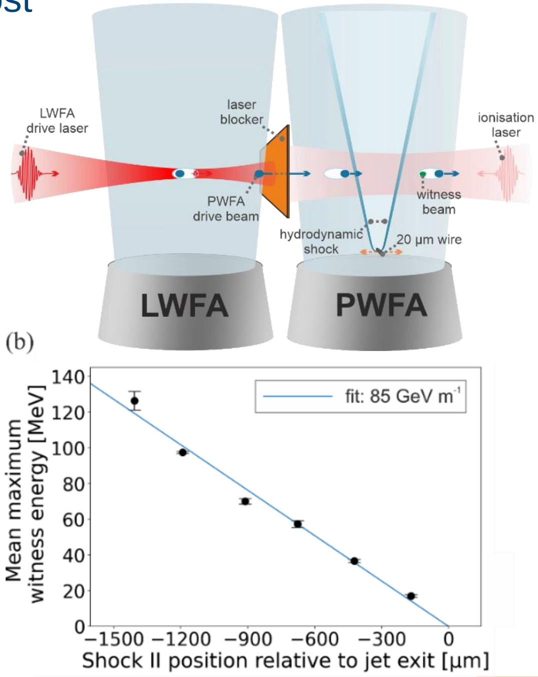

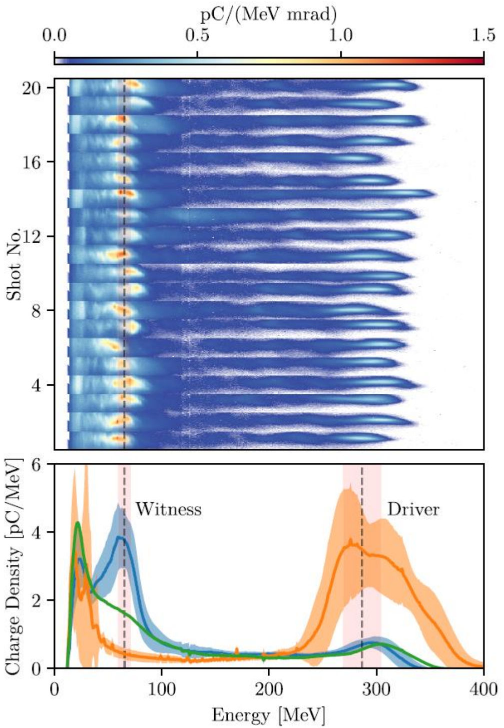

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- **Stability booste**
- But: witness ene
  likely not better t

✓ LWFA generated beams can drive plasma waves

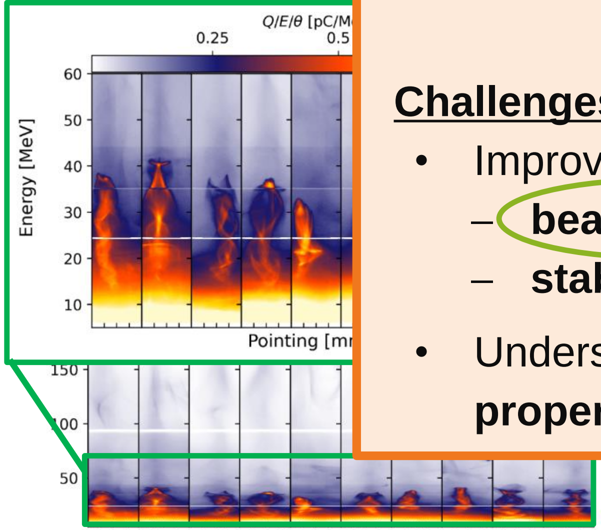
✓ **Acceleration** of witness bunches

✓ Controlled **internal injection**

Challenges & next steps:

- Improvement of
  - **beam quality**
  - **stability** and reliability
- Understanding of **impact** of the **driver beam properties**

Plasma photocathode
(Trojan Horse)



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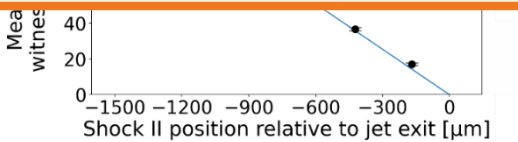
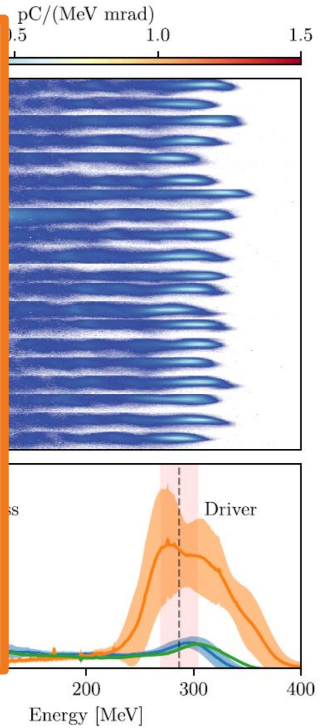




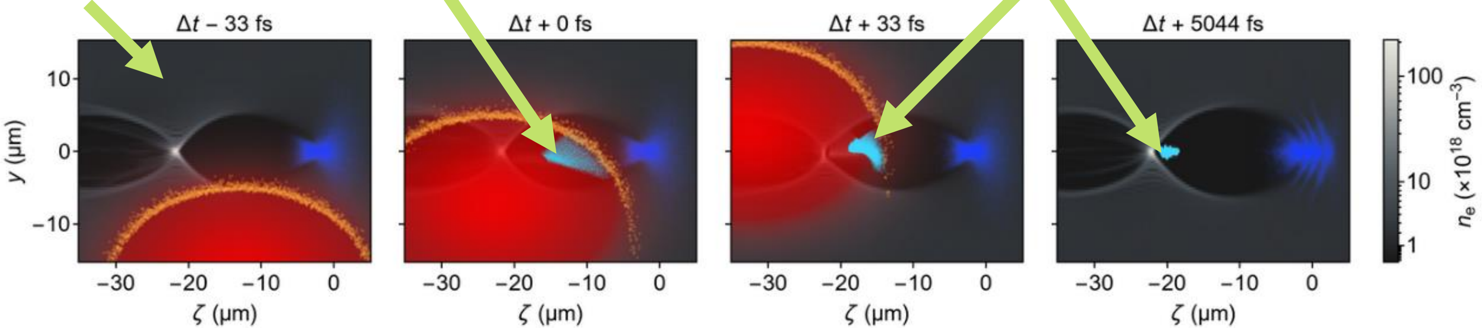
Optically generated shock:
Foerster, M. et al. **PRX 12**, 041016 (2022)

Injection via plasma photocathode – potential quality booster?

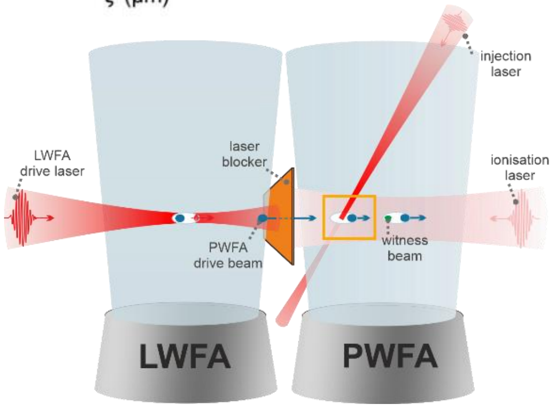
plasma electrons from hydrogen + first level helium

Injector laser releases second level helium electrons

trapping and acceleration of this electrons



- **Not feasible in** LWFA
- **First demonstration at FACET**:
  Deng et al. Nature Physics 15, 1156–1160 (2019)
- **LPWFA** enables plasma photocathode in **high (~10^{18} cm^{-3}) plasma densities**
- simulations: potential for **high brightness** witness bunches

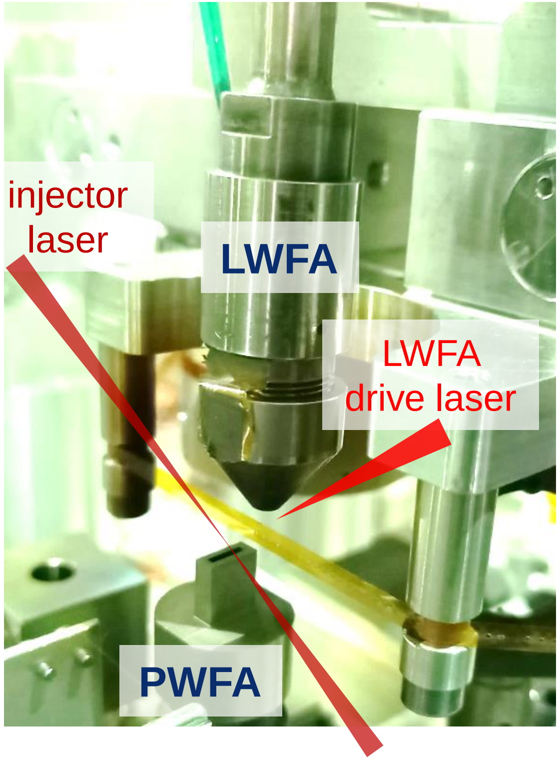


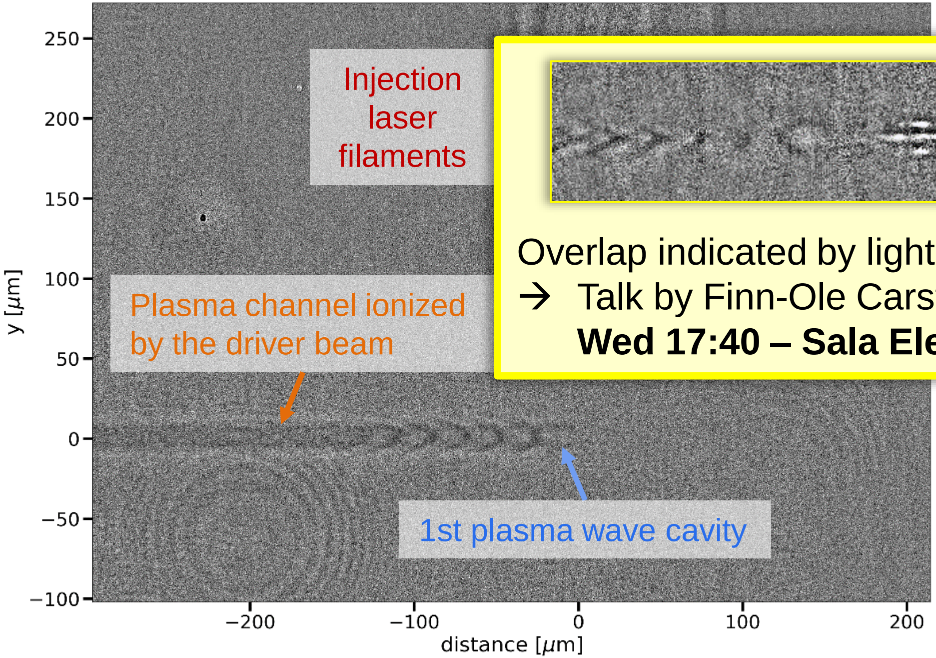
B. Hidding et al., *Phys. Rev. Lett.* 108.3 (Jan. 2012), p. 35001

Experimental realization of Trojan Horse injection @ HZDR

Challenge:

spatial and temporal overlap of **injection laser** (⌀ 16µm) and **1st cavity** (here: 25-30µm length)



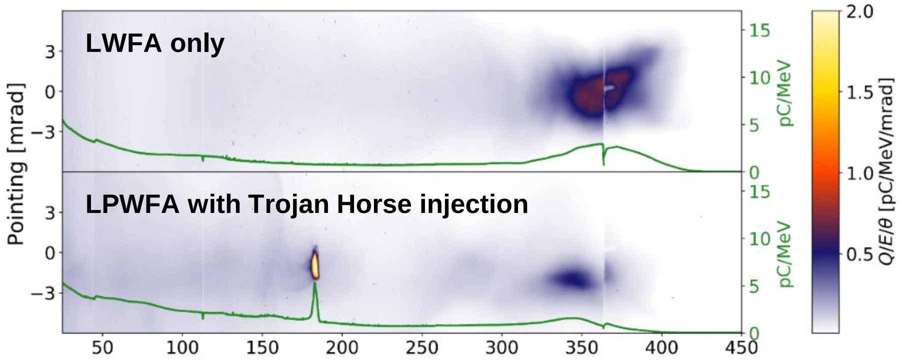


Overlap indicated by light signal
→ Talk by Finn-Ole Carstens, **Wed 17:40 – Sala Elena**

Successful demonstration of plasma photocathode

<u>Example witness beam parameters:</u>

mean energy: 183 MeV	charge (FWHM): 8.7 pC
energy spread: 2.7 MeV (1.5%)	divergence (rms): 0.59 mrad

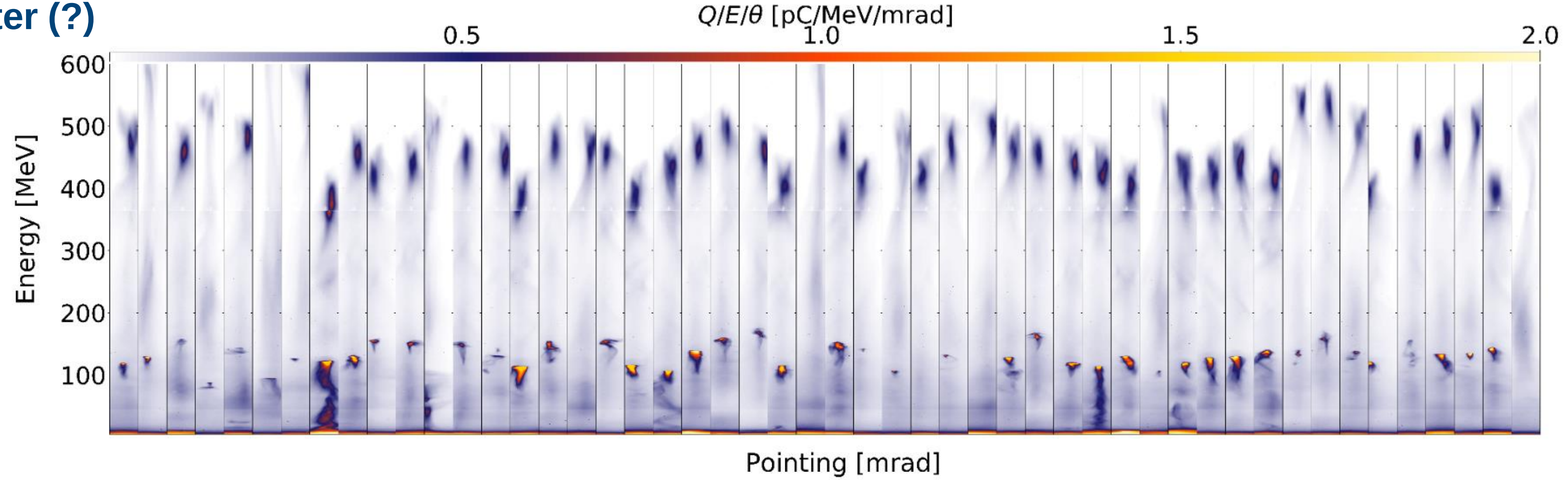


→ **Spectral charge density** of the **witness beam** can **exceed** the **LWFA** reference

→ **Quality booster (?)**

→ Successful **injection** in up to **92%** of the shots

→ Strong **jitter** of witness **energy** and **charge**



P. Ufer et al., in review

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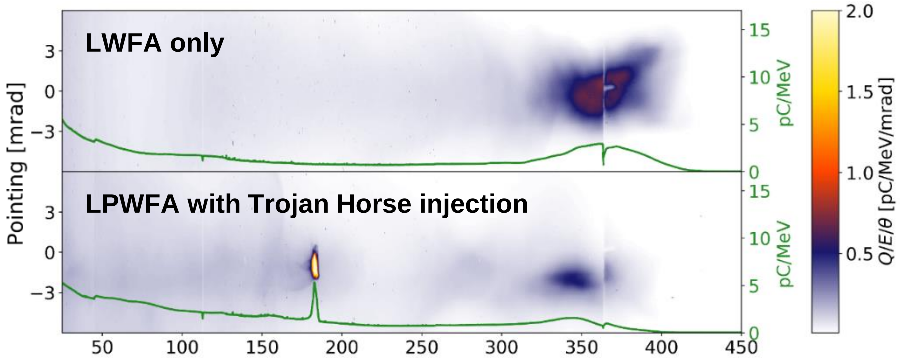

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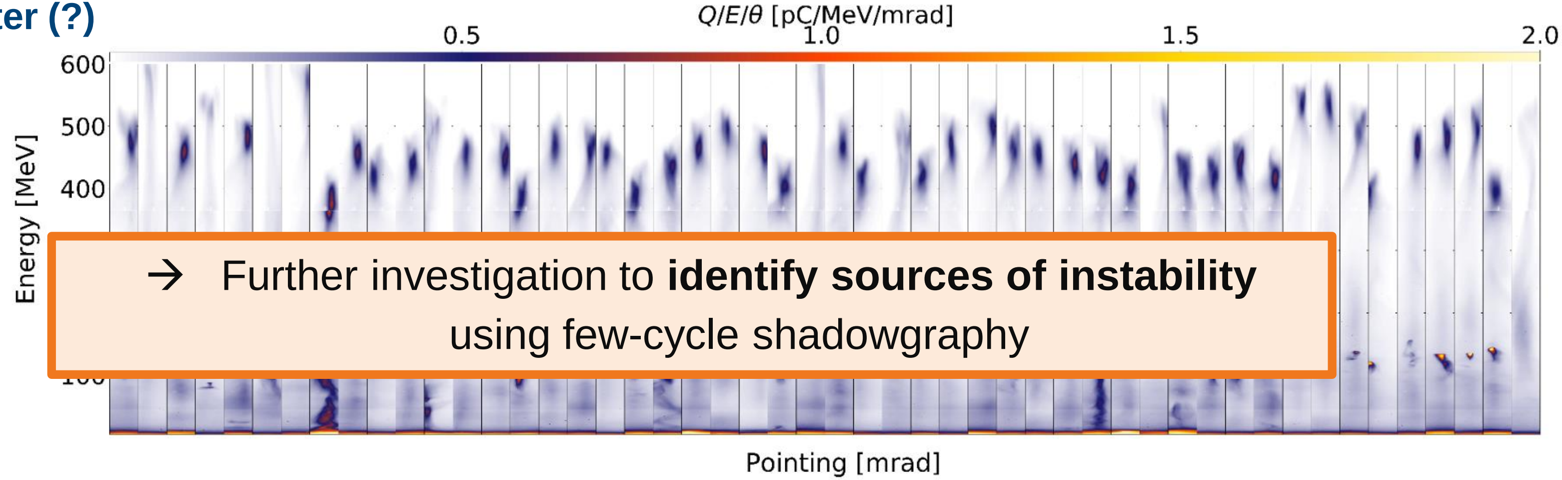


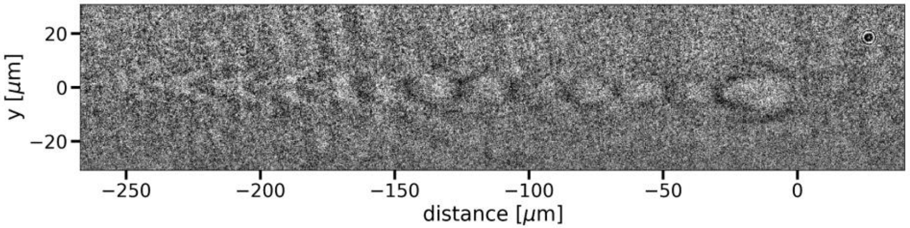
→ Further investigation to **identify sources of instability** using few-cycle shadowgraphy

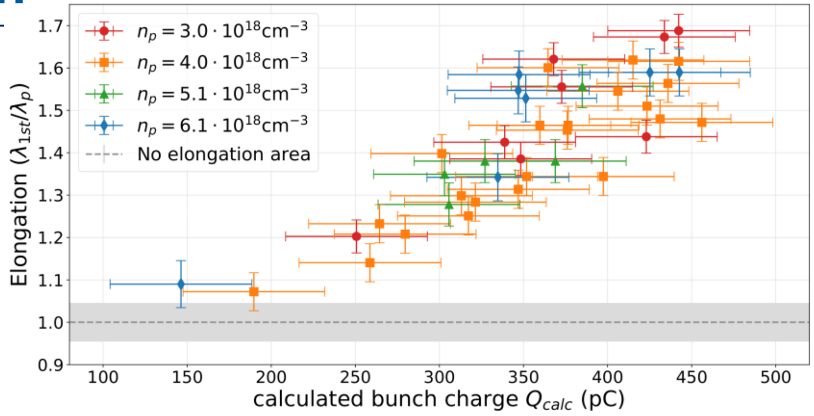
P. Ufer et al., in review

Correlation of charge and cavity length

→ **1st cavity** is **longer** and **wider**

→ **Elongation** (relative to λ_p) increases with amount of driving charge

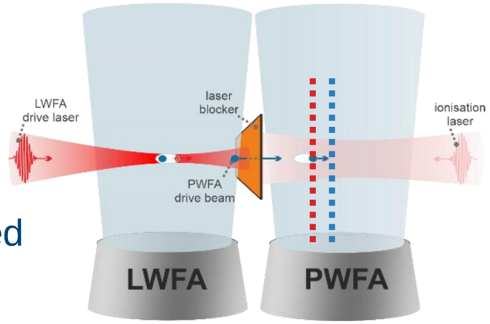


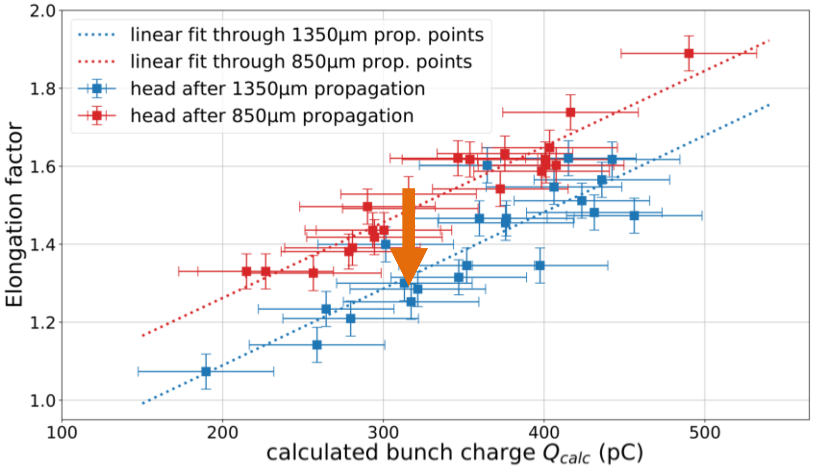


→ **Elongation decreases** for **downstream** probing position

→ **Charge loss (depletion)** already in the front part of PWFA stage (STII generated bunches)

→ **Shrinking cavity**

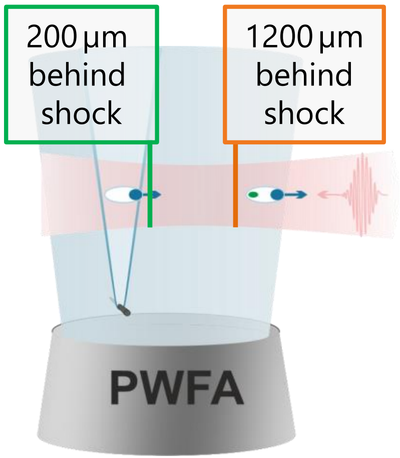


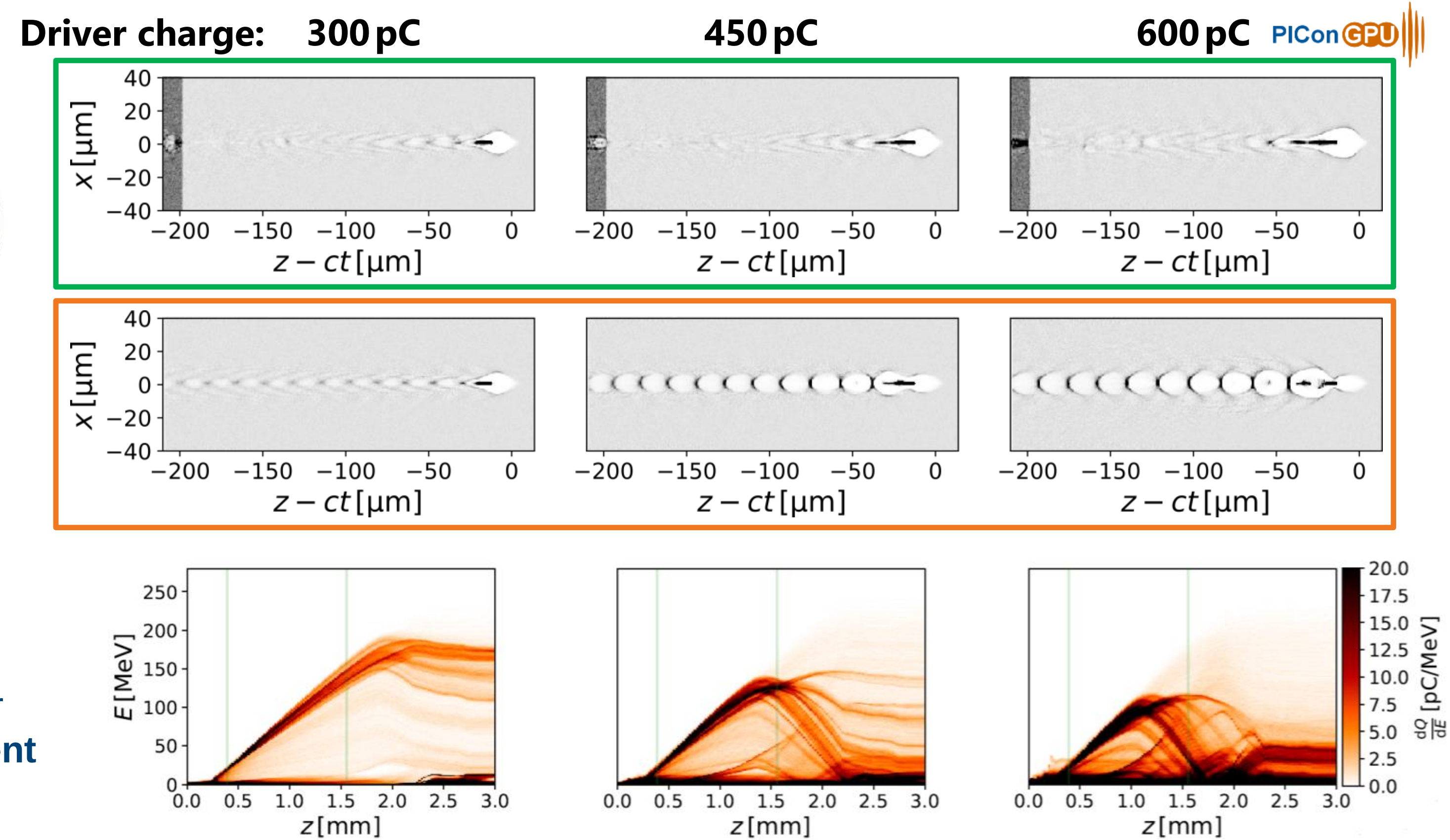


Schöbel, S. et al. **New J. Phys. 24** 083034 (2022)

PhD Thesis Susanne Schöbel, https://nbn-resolving.org/urn:nbn:de:bsz:14-qucosa2-985927

Shrinking cavity limits the acceleration length





→ Shrinking **limits witness energy**

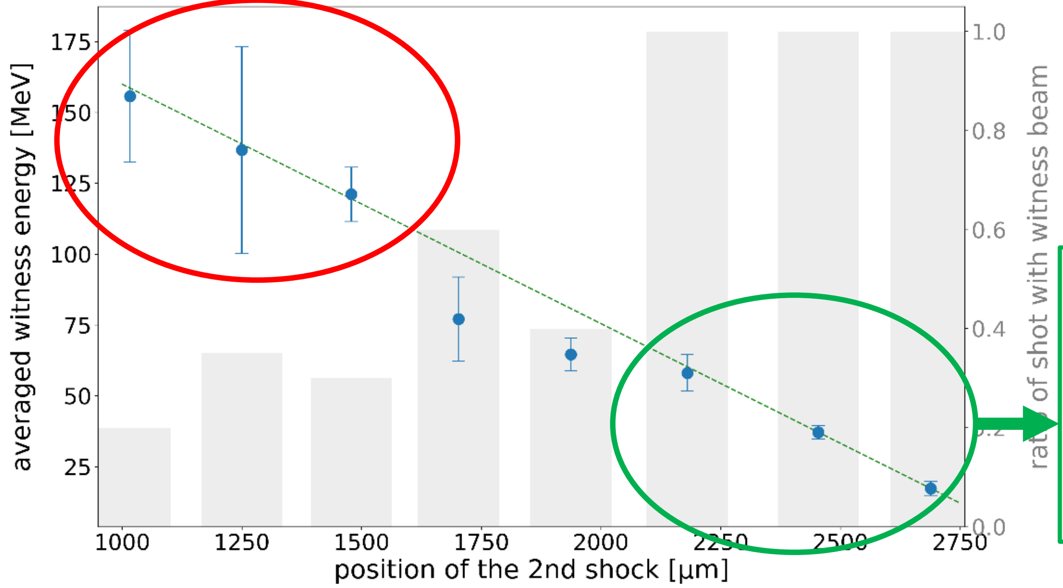
→ **Less** shrinking for **lower peak current** driver

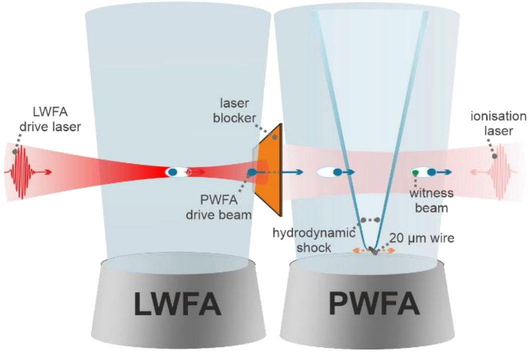
PhD Thesis Susanne Schöbel, https://nbn-resolving.org/urn:nbn:de:bsz:14-qucosa2-985927

Driver charge dependent witness energy limitation

- Reduced number of observed witness beams
- **Increased shot-to-shot fluctuations**

→ **Less stable performance** due to charge jitter





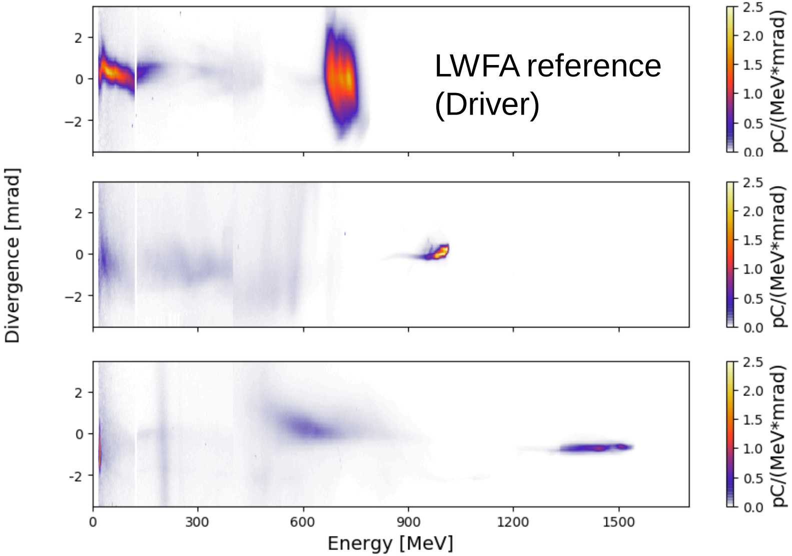
- Small shot-to-shot fluctuation
- Strong accelerating fields although driver depletes already

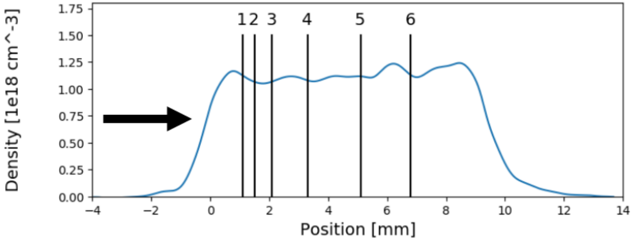
PhD Thesis Susanne Schöbel, https://nbn-resolving.org/urn:nbn:de:bsz:14-qucosa2-985927

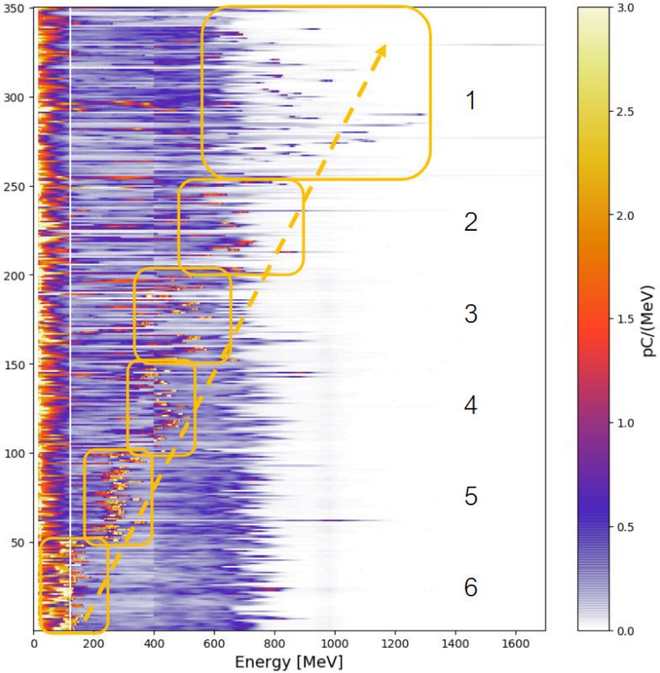
First realization of energy booster

Recent experiments: acceleration of **witness bunch** to **energy exceeding** the **initial driver energy**

→ Demonstration of **energy booster**

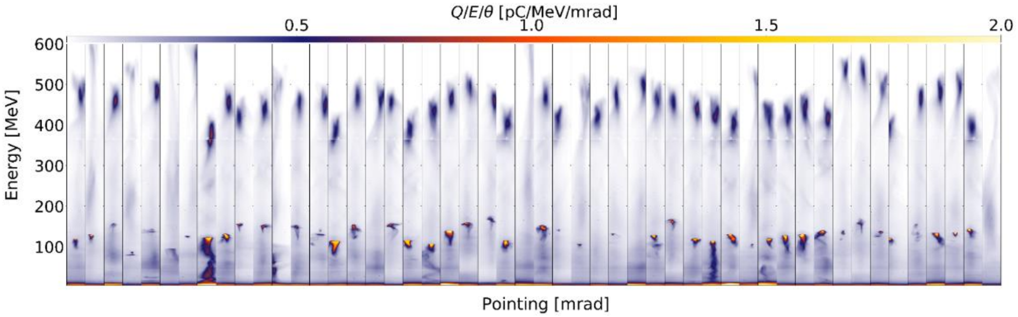


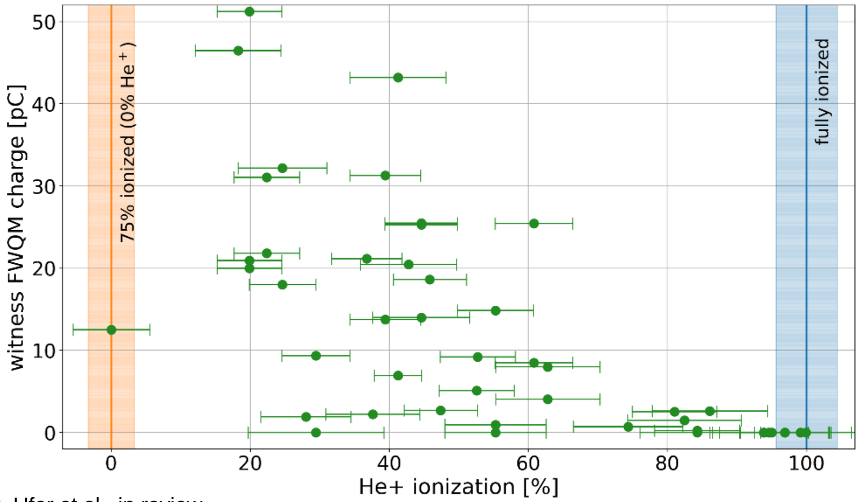


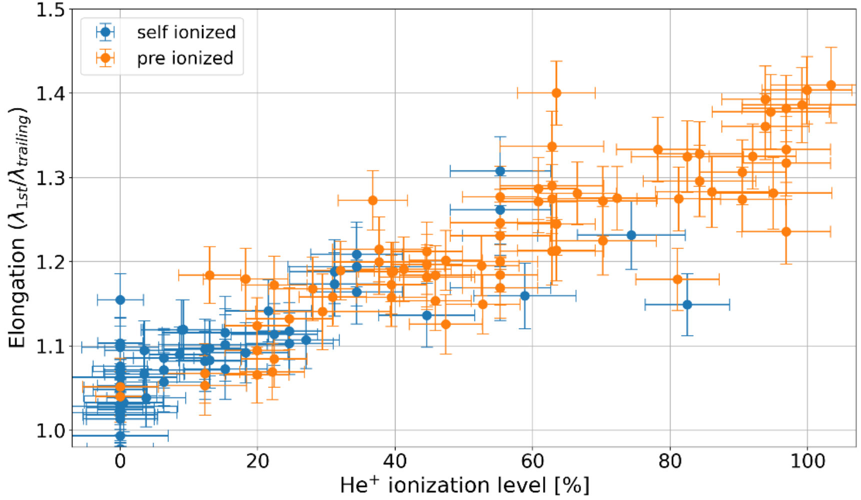


Sources of instabilities in the plasma photocathode

- **Partial ionization of 2nd level of Helium** (wavelength jitters)
- **Witness charge limitation** due to absence of available electrons
- **Ionization caused by the driver**







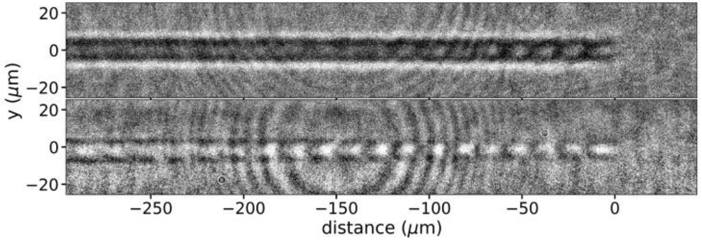
P. Ufer et al., in review

PhD Thesis Susanne Schöbel, https://nbn-resolving.org/urn:nbn:de:bsz:14-qucosa2-985927

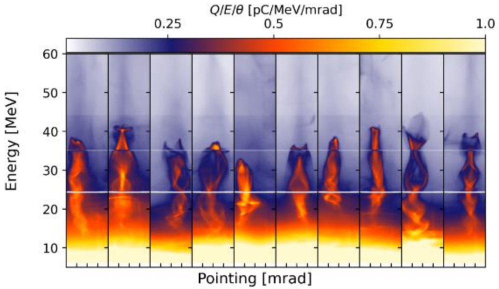
Summary and Outlook

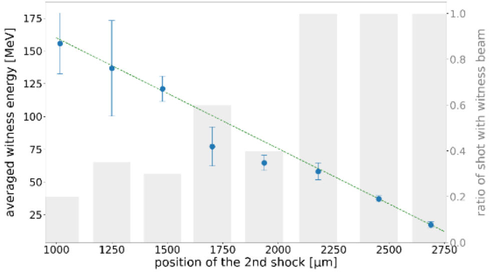
LPWFA enables **PWFA studies** in a plasma density of **~10^{17}-10^{19} cm^{-3}** in **blowout regime**

→ LWFA generated beams can **drive plasma waves**



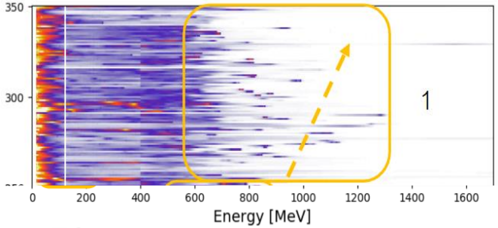
→ **Acceleration of witness bunches**, e.g. injection at a density downramp



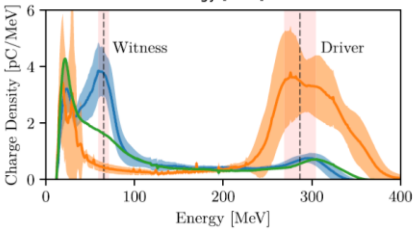


First steps towards booster of:

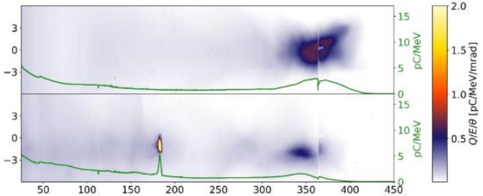
Energy



Stability



Beam quality



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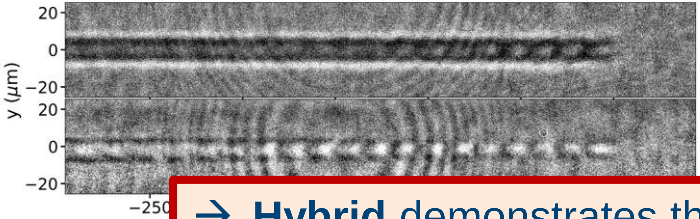
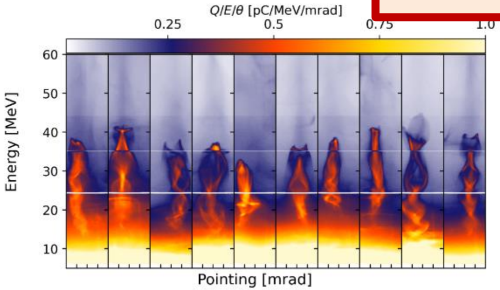
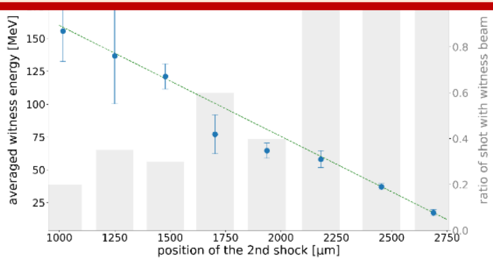


→ **Acceleration o**… injection at a de…





First steps towards booster of:

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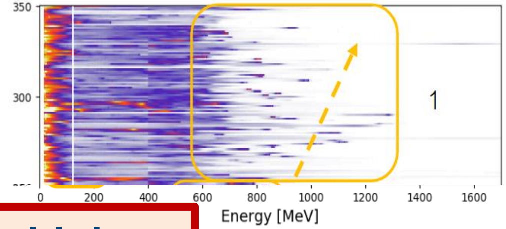
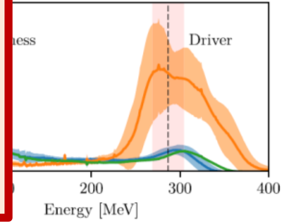
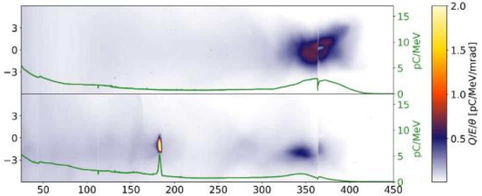




Beam quality



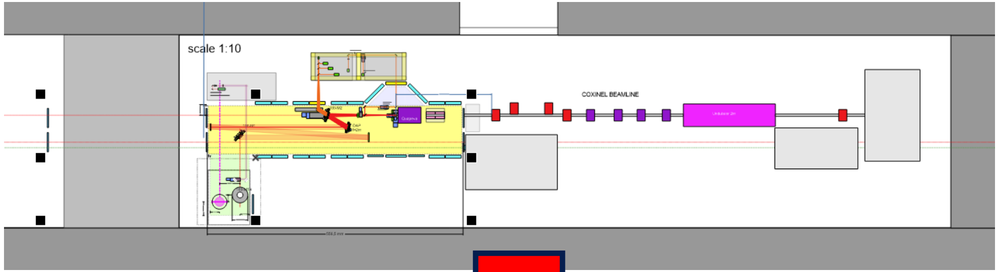
→ **Hybrid** demonstrates the **potential** for **stable high quality beam generation**

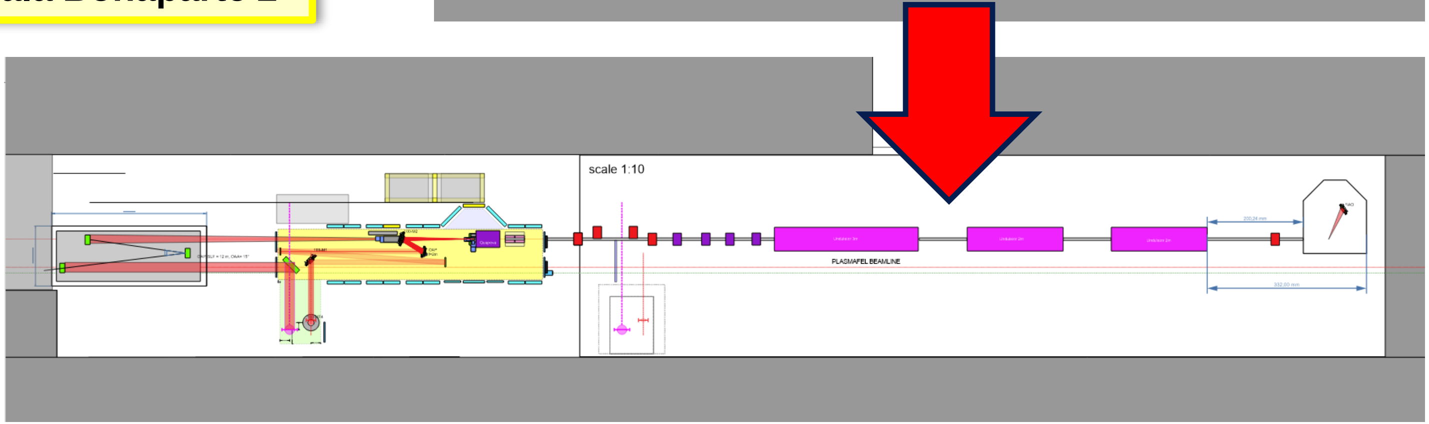
→ Potential use for **hard X-ray FEL applications, as considered by ELI- EuPRAXIA pillar**

Outlook: upgrade of the COXINEL-FEL beamline @ HZDR

- → High brightness **beams from hybrid LPWFA** potentially tested **as FEL drivers** in the upgraded COXINEL beamline
- → Upgrade is planned for 2026 – 2029

→ Talk by Arie Irman,
Wed 17:20 – Sala Bonaparte 2





Thank you for your attention!

Hybrid Collaboration partners: