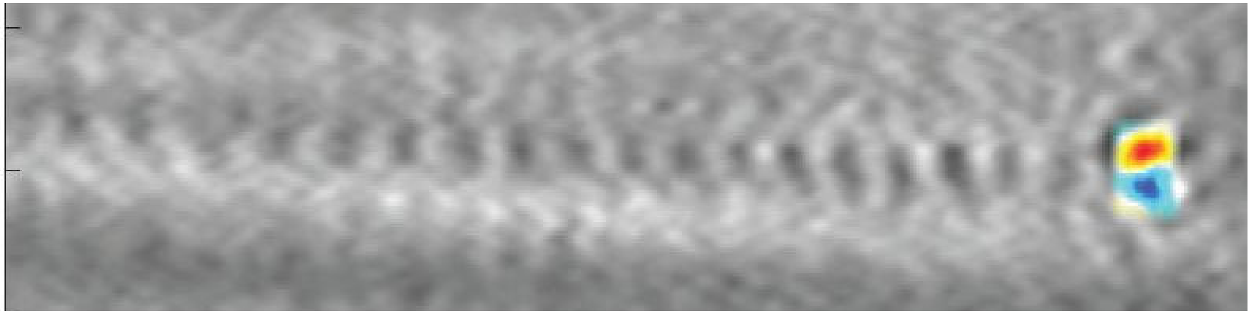
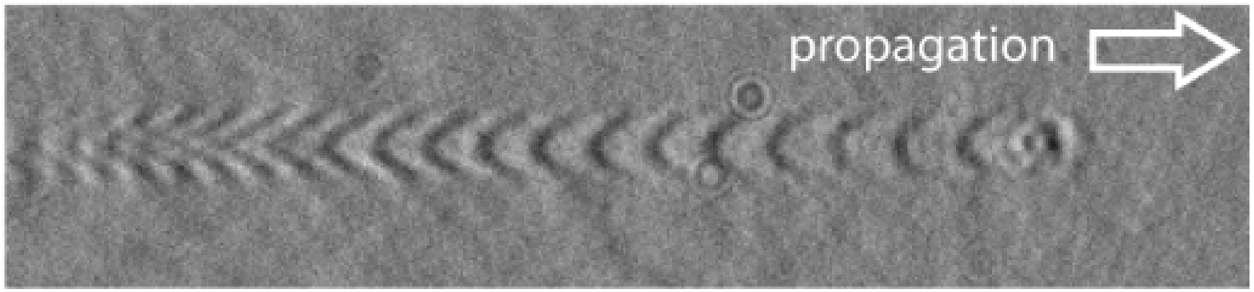
Diagnostics for Laser-Wakefield Accelerators





Malte C. Kaluza

Institute of Optics and Quantum Electronics, FSU Jena, Germany

Helmholtz-Institute Jena

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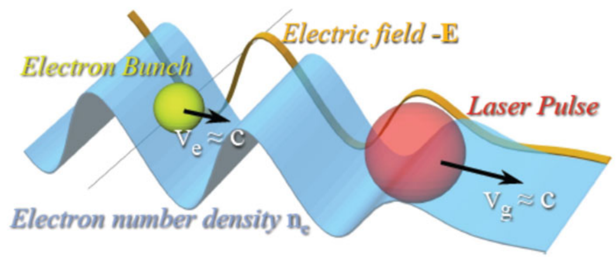

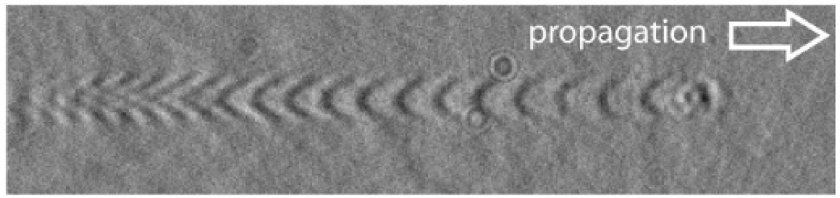

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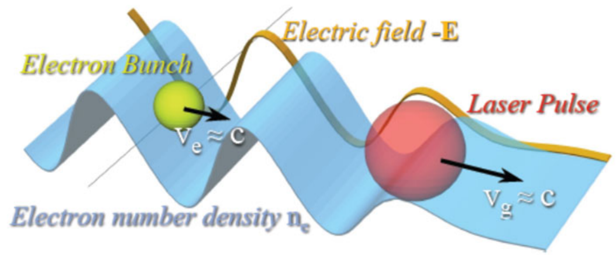
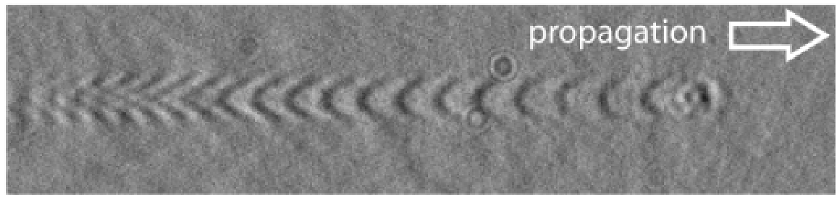
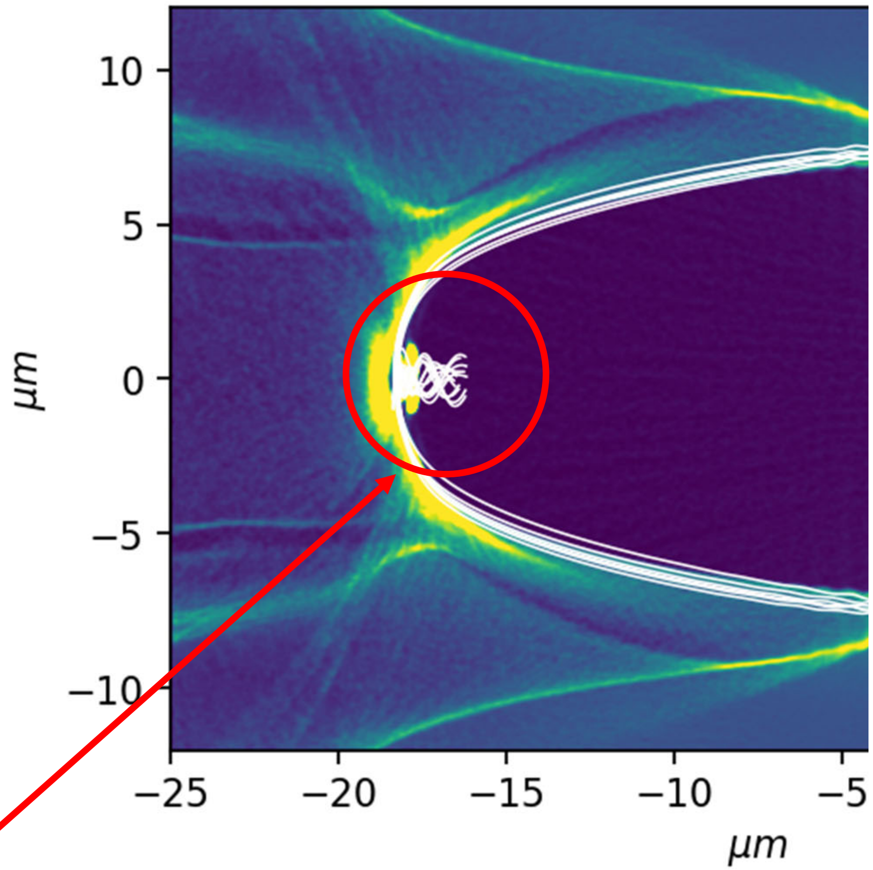
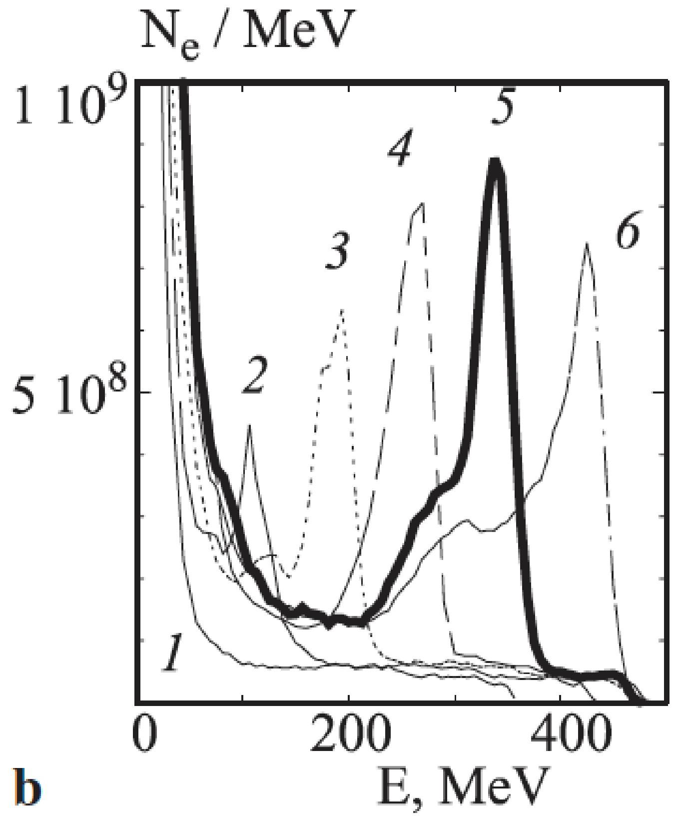




Laser Wakefield Acceleration of Electrons: Principle

- Acceleration of electrons in a (laser-driven) plasma wave



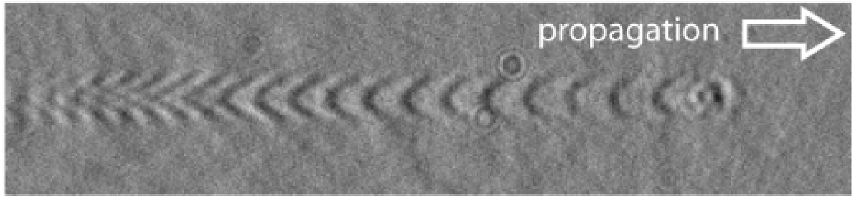


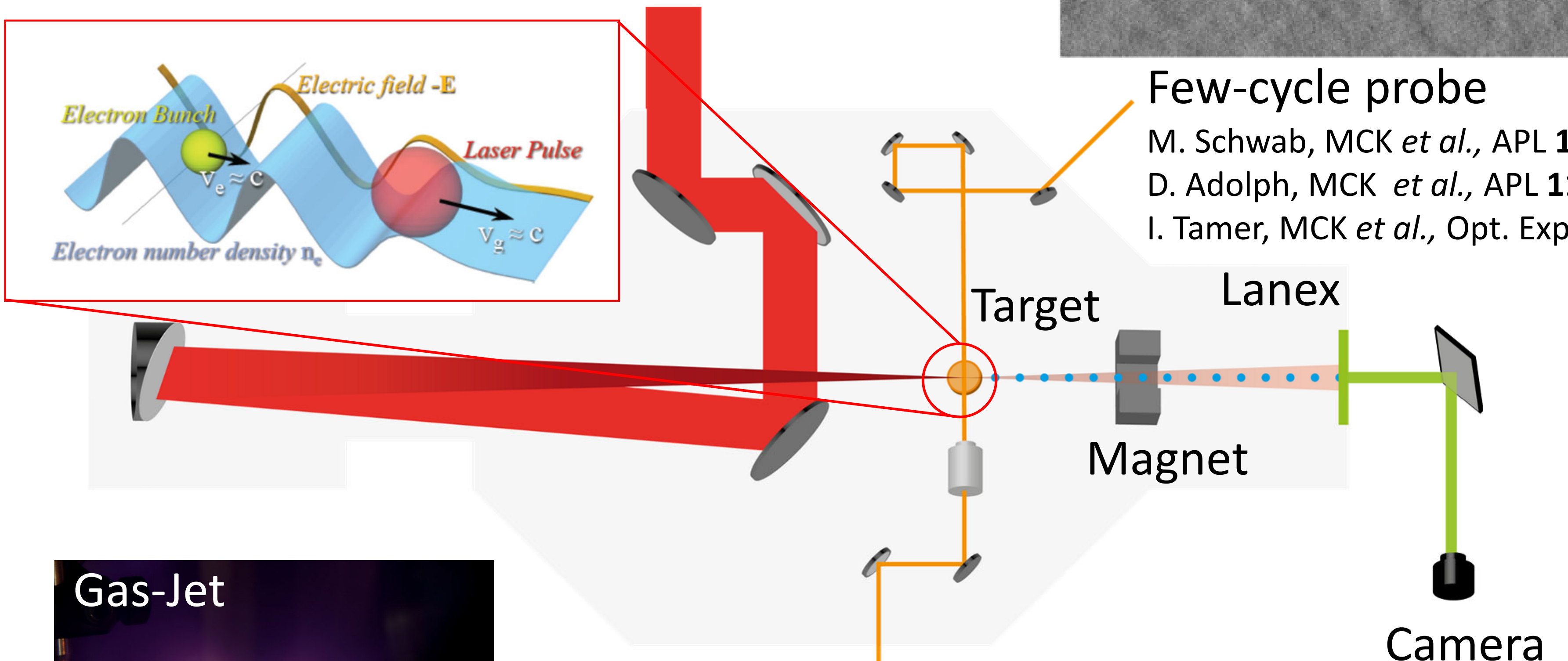
A. Pukhov et al., APB 74, 355 (2002)

- Injection of background electrons into accelerating phase of the plasma wave

Laser Wakefield Acceleration of Electrons @ JETI: Setup

Setup of a LWFA experiment @ JETI:

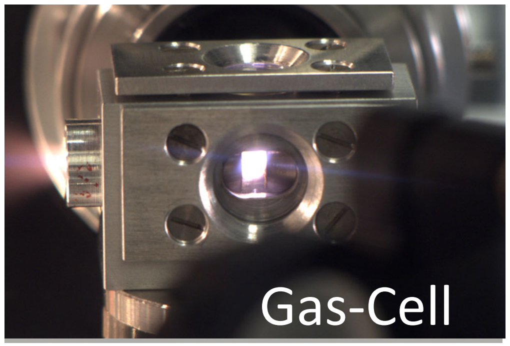


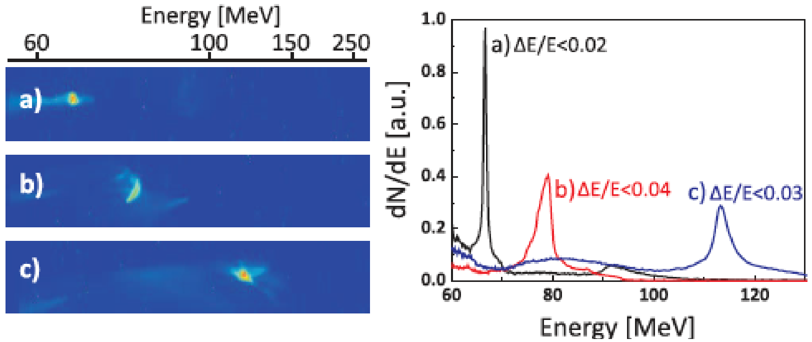


Few-cycle probe

M. Schwab, MCK *et al.*, APL **103**, 191118 (2013)
D. Adolph, MCK *et al.*, APL **110**, 081105 (2017)
I. Tamer, MCK *et al.*, Opt. Expr. **28**, 19034 (2020)

B. Landgraf, MCK *et al.*, RSI **82**, 083106 (2011)
A. Adelmann, MCK *et al.*, Appl. Sci. **8**, 443 (2018)





M. Schnell, MCK *et al.*, PRL **108**, 075001 (2012)
S. Kuschel, MCK *et al.*, PRL **121**, 154801 (2018)

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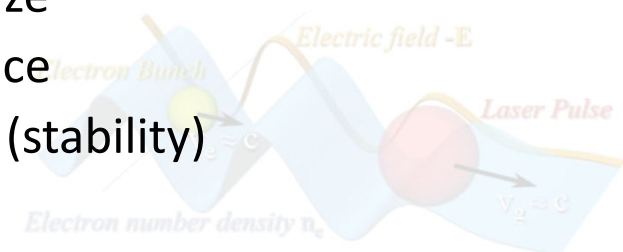
- energy spectrum:
  - energy of (mono-energetic?) peak
  - background?
- charge
- pulse duration
- source size
- divergence
- pointing (stability)
- ...



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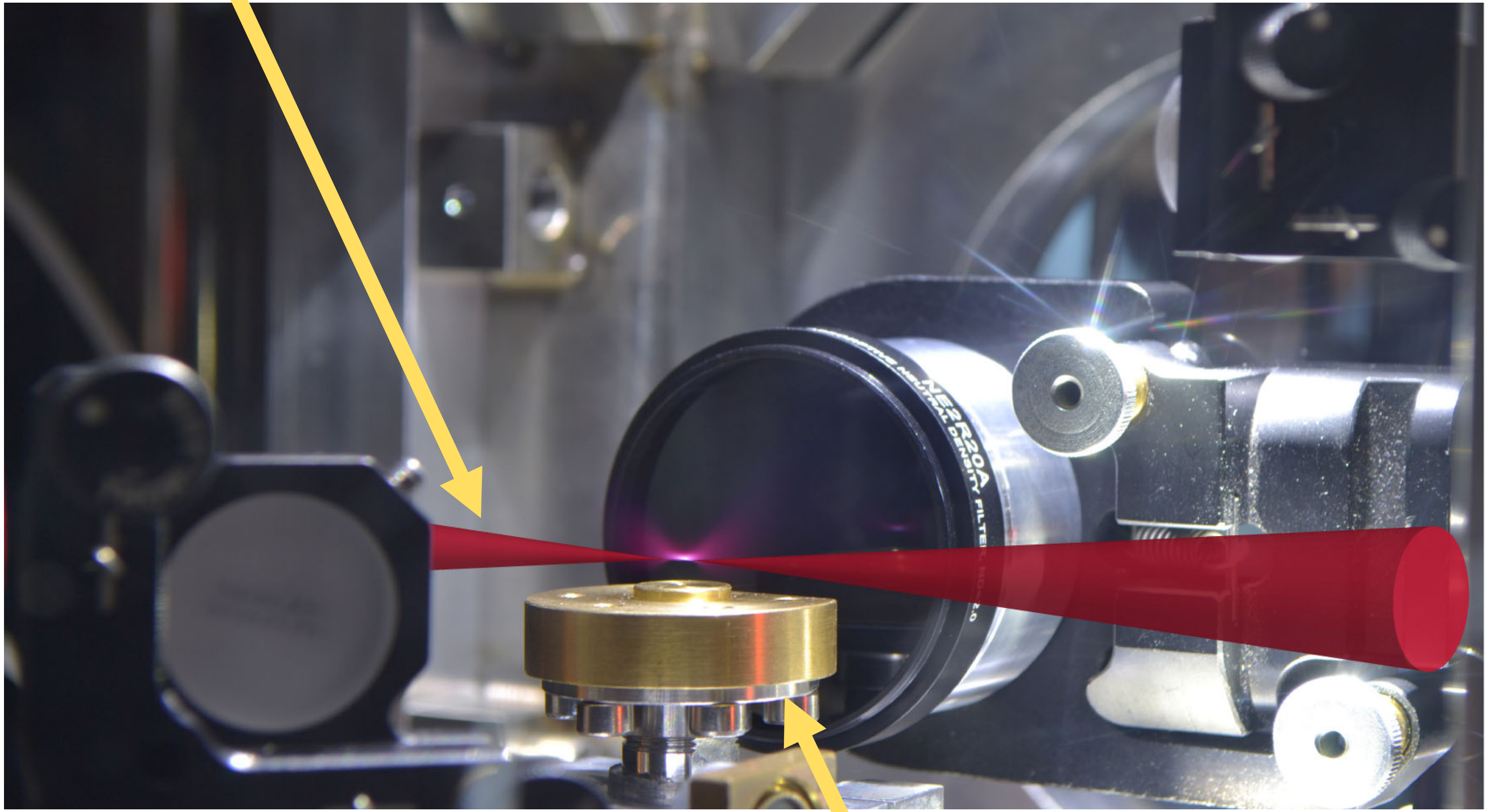
transverse optical probing

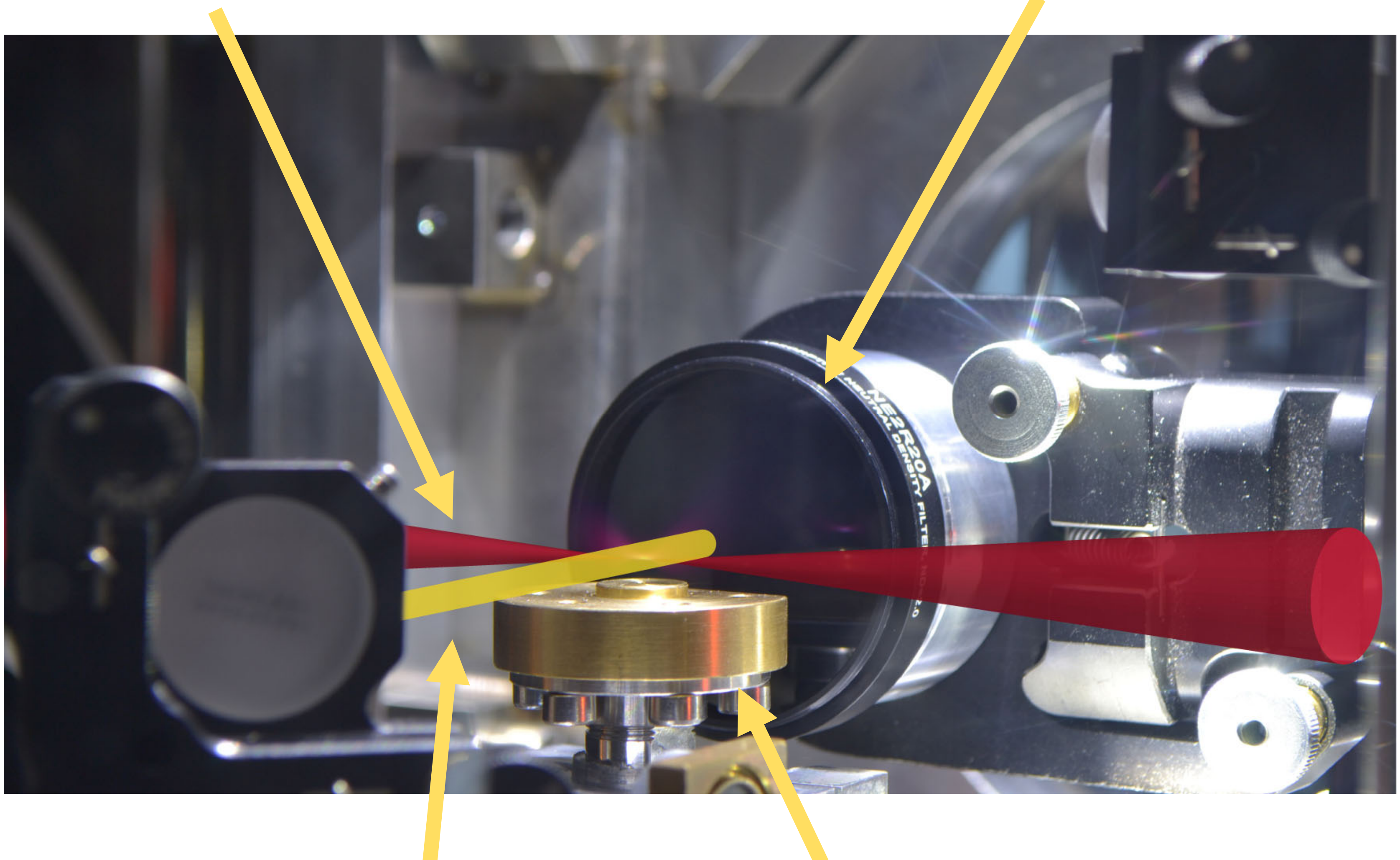
main pulse



electrons
X-rays,…

gas-jet

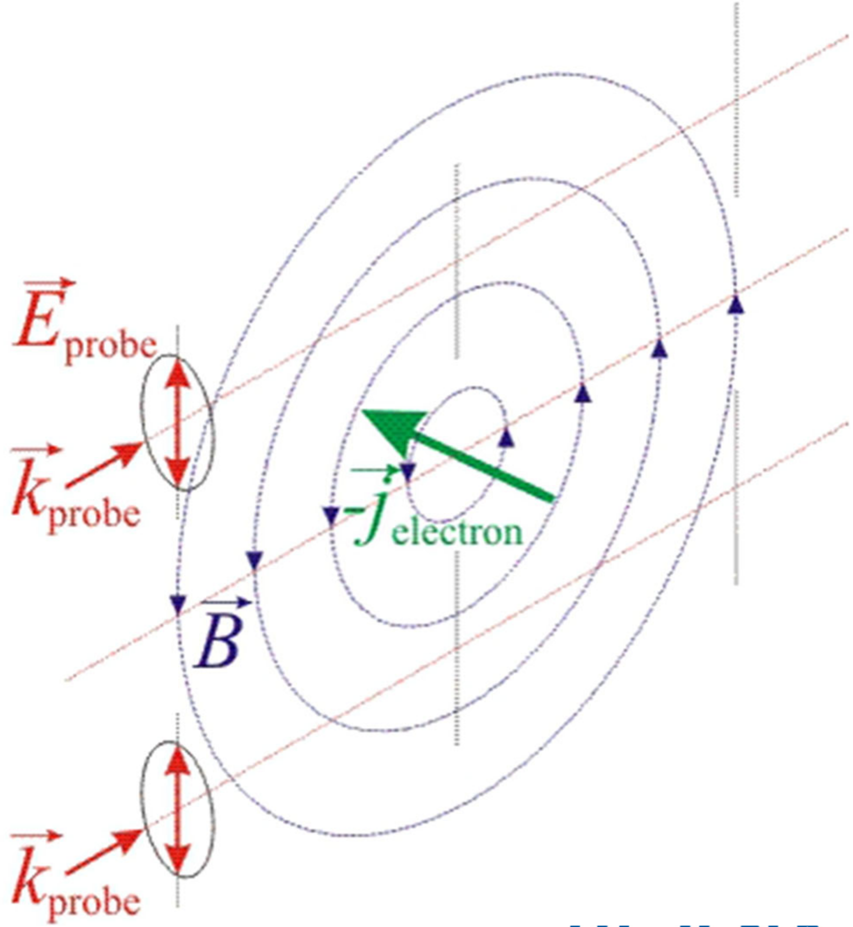
transverse optical probing



- Transverse probing of B-fields in under dense plasma with linearly polarized probe pulse:
  when $\vec{k}_{\mathrm{probe}} \parallel \vec{B} \Rightarrow$ different η for circularly polarized probe-components ("Faraday-effect")

$\Rightarrow$ Rotation of probe polarization:

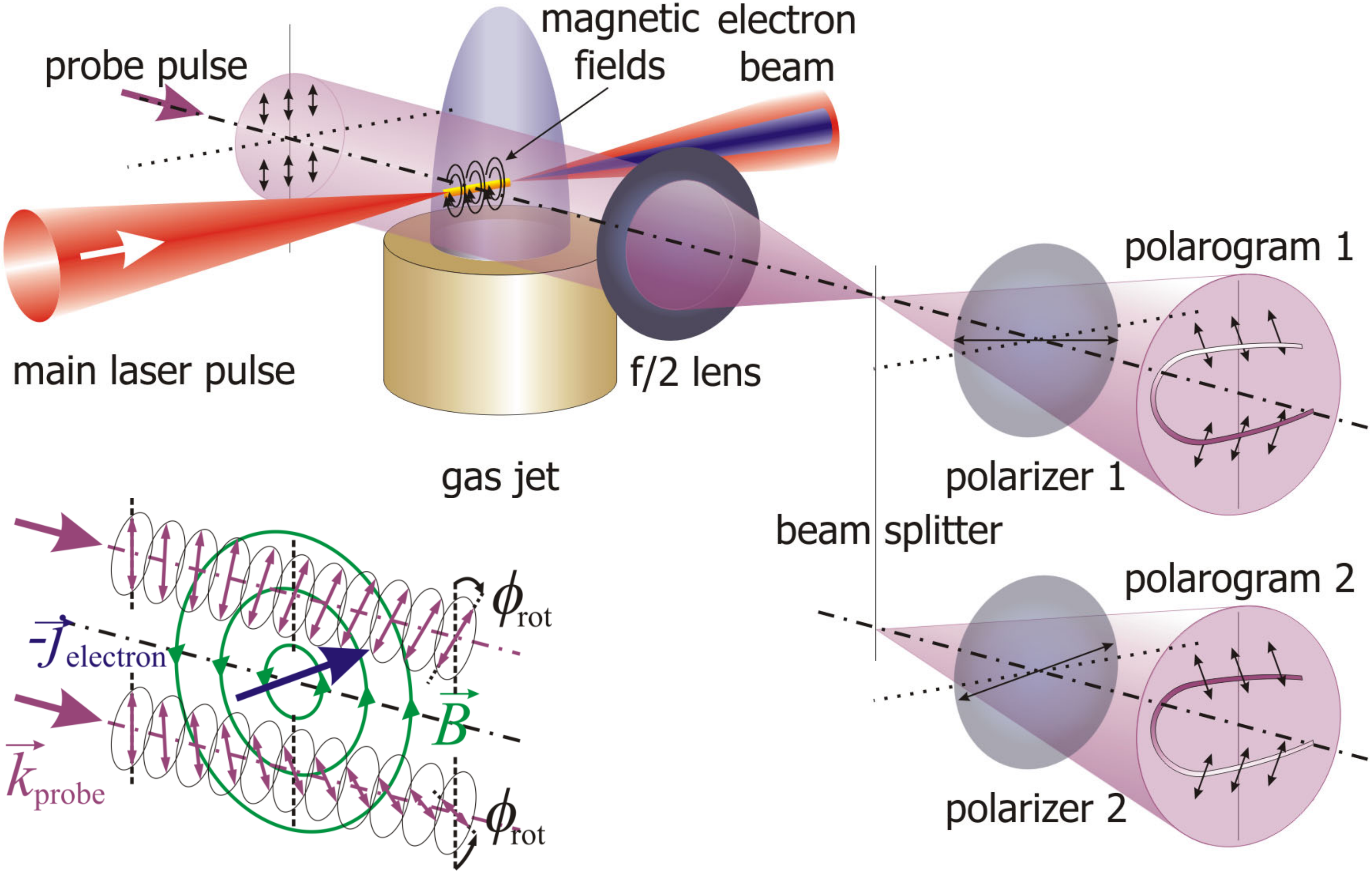
$$\phi_{\mathrm{rot}} = \frac{e}{2m_{\mathrm{e}}c}\int \frac{n_{\mathrm{e}}(\vec{r})}{n_{\mathrm{cr}}}\vec{B}(\vec{r})\cdot\frac{\vec{k}_{\mathrm{probe}}}{k_{\mathrm{probe}}}\,\mathrm{d}s$$



$\Rightarrow$ measure ϕ_{rot} to deduce B-field distribution!

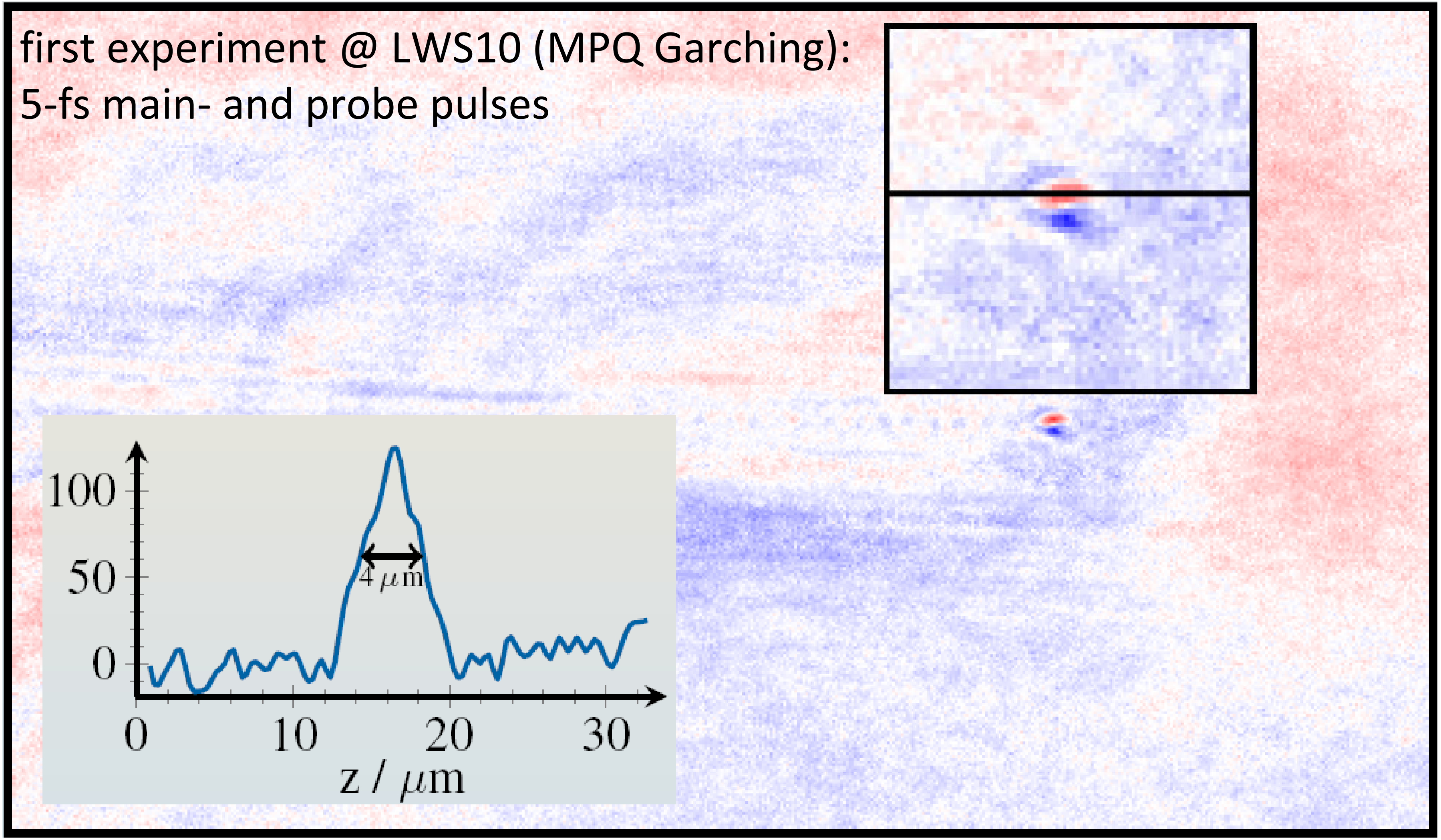
J. A. Stamper et al., PRL (1975)

Laser Wakefield Acceleration of Electrons: Optical probing



MCK *et al.*, PRL **105** 115002 (2010)

Laser Wakefield Acceleration of Electrons: Optical probing



<u>Electron bunch length:</u> Δz = 4 µm

τ_{FWHM}= (6±2) fs, **τ_{RMS}= (2.5±0.9) fs**

A. Buck, MCK *et al.,* Nature Physics **7,** 543 (2011)

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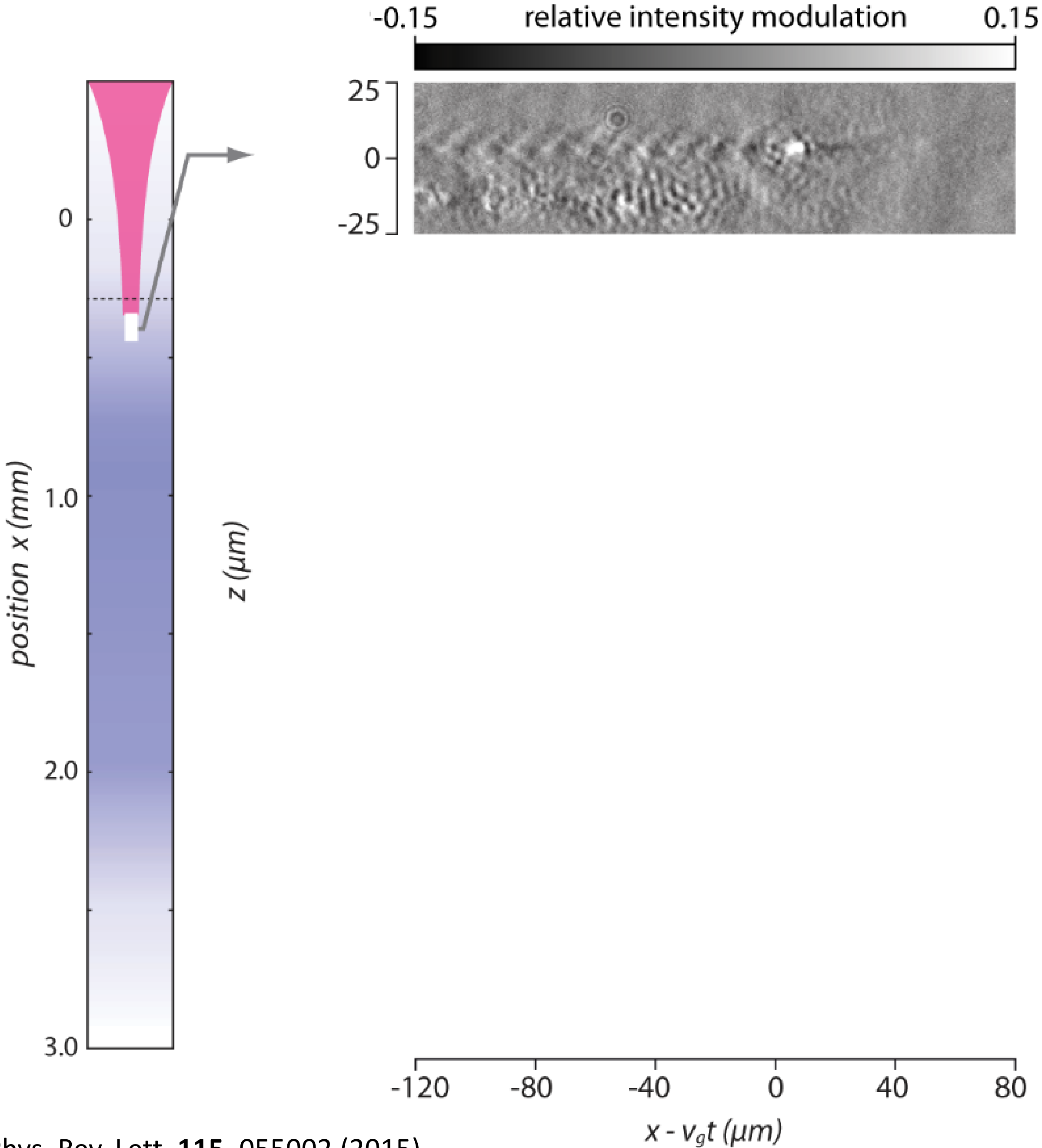
Laser Wakefield Acceleration of Electrons @ JETI: Optical probing



A. Sävert, MCK *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

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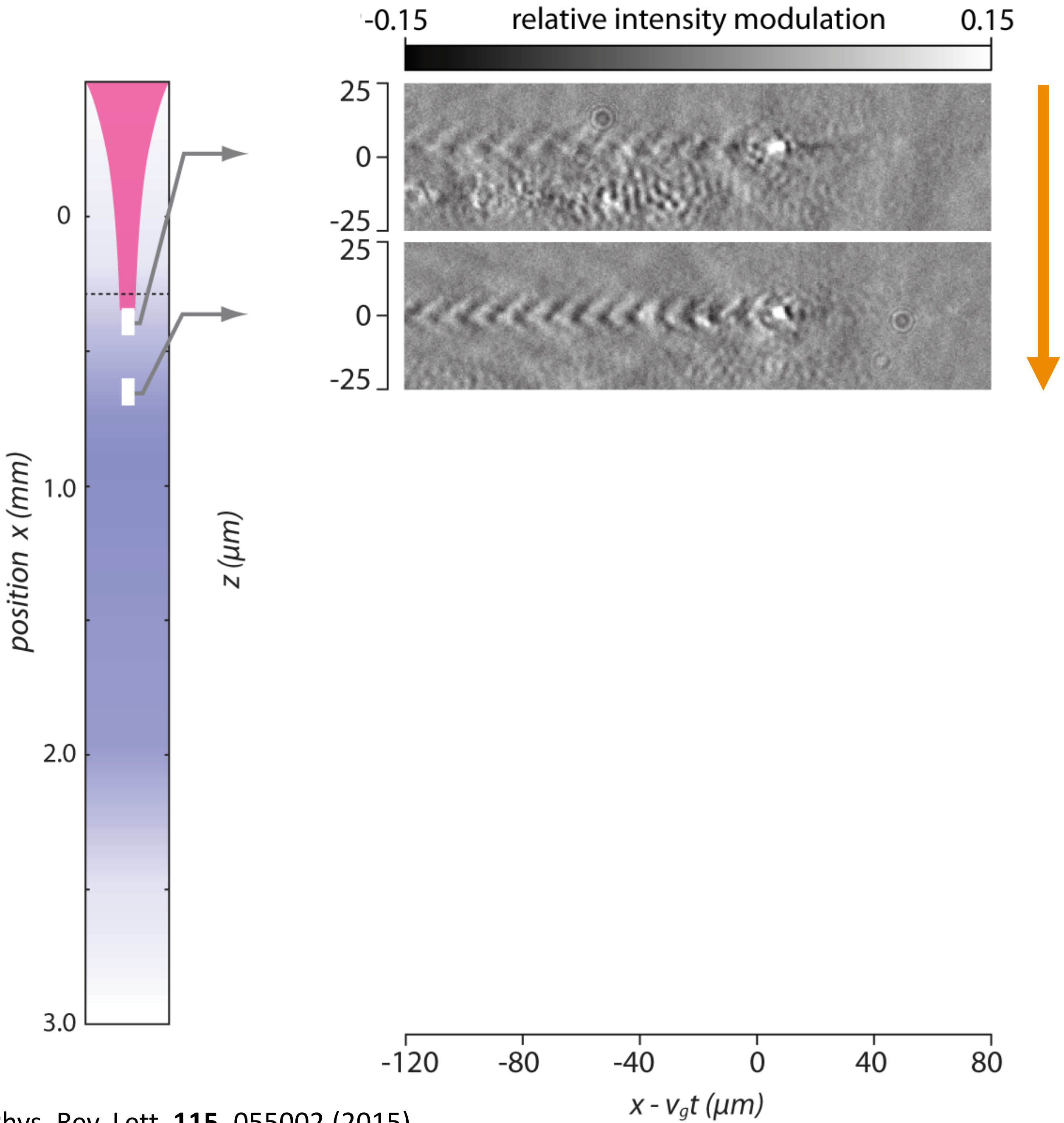

Self focussing

A. Sävert, MCK *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

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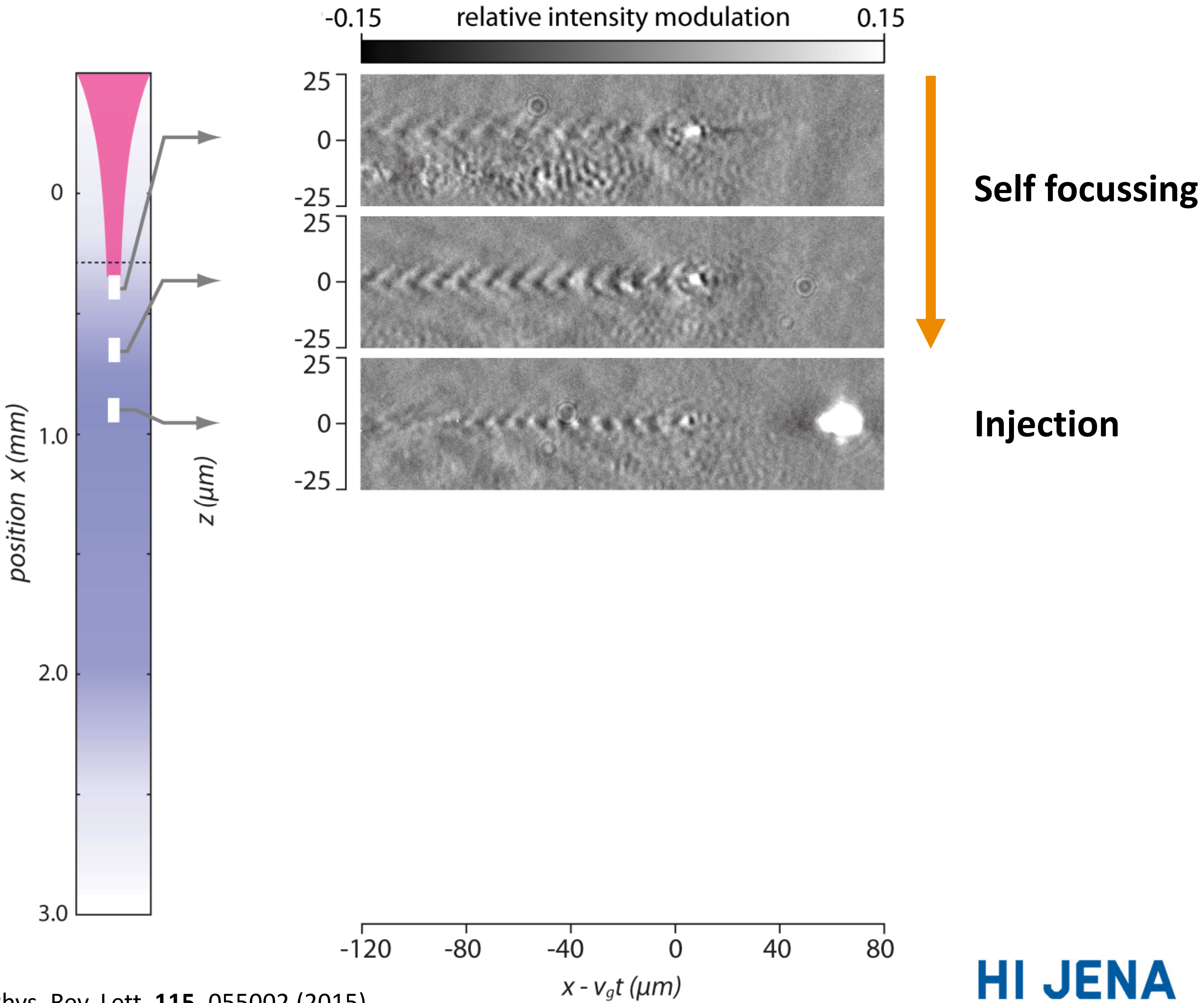

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Laser Wakefield Acceleration of Electrons @ JETI: Optical probing

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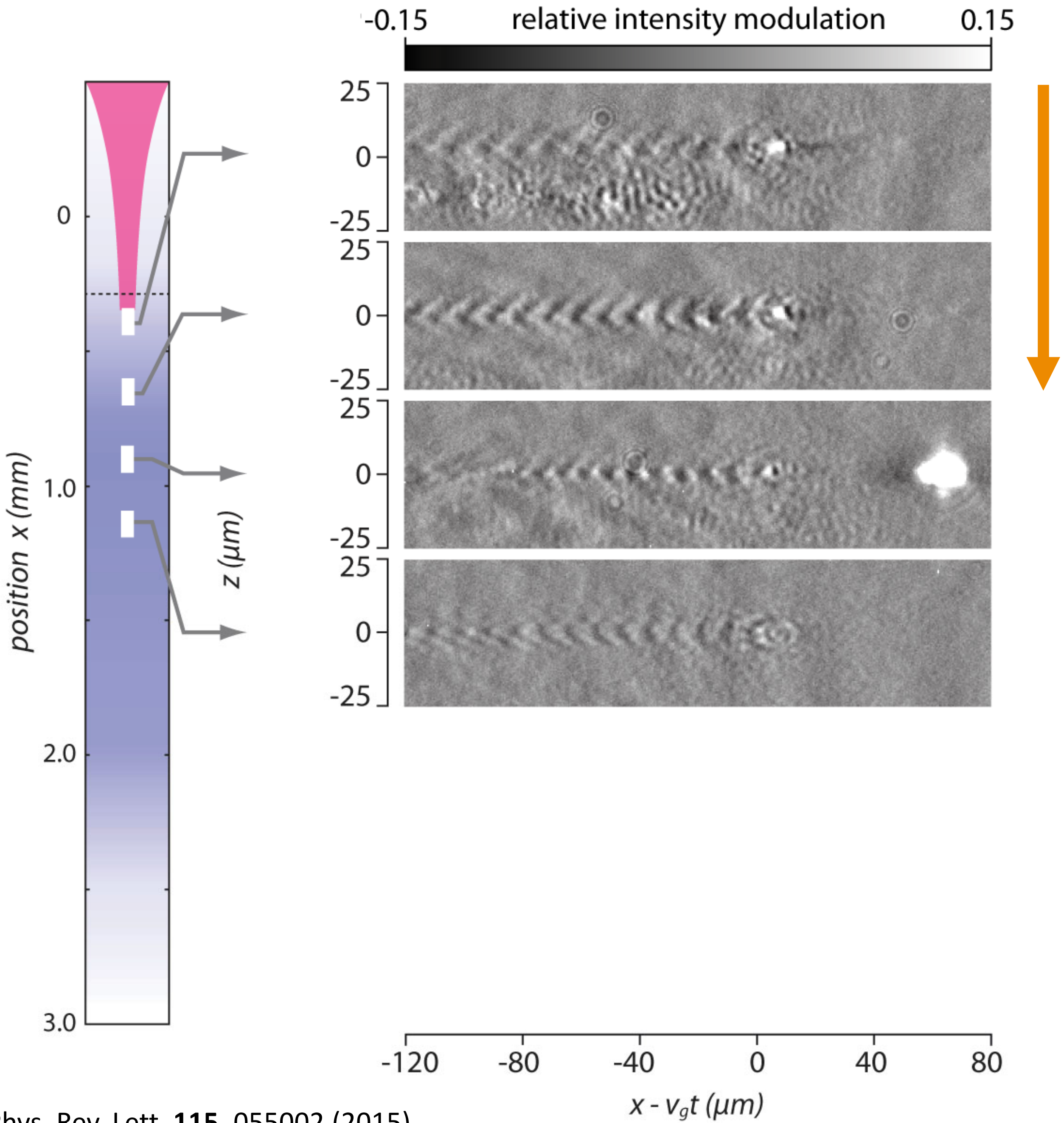

Self focussing

Injection

A. Sävert, MCK *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

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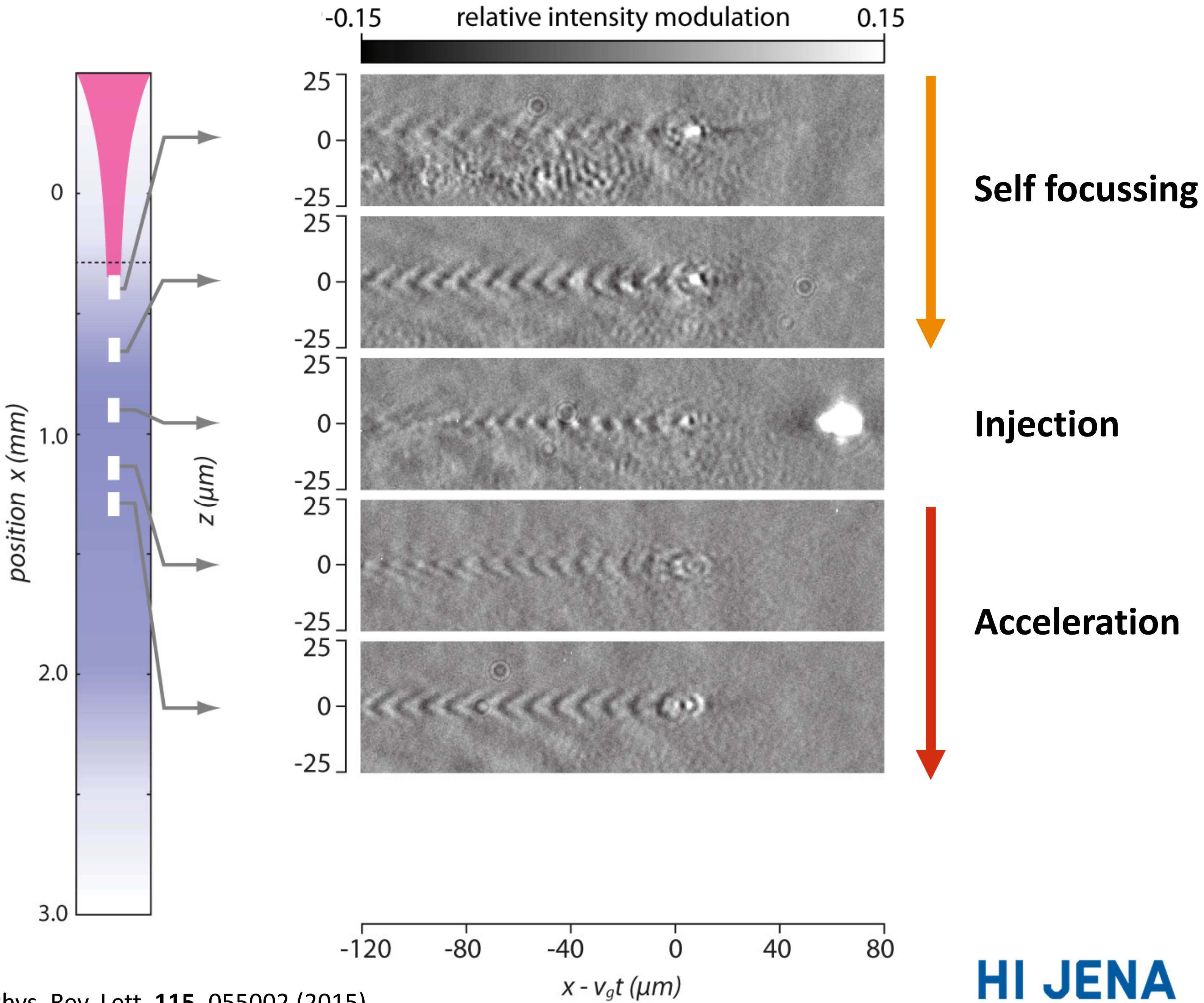
Laser Wakefield Acceleration of Electrons @ JETI: Optical probing



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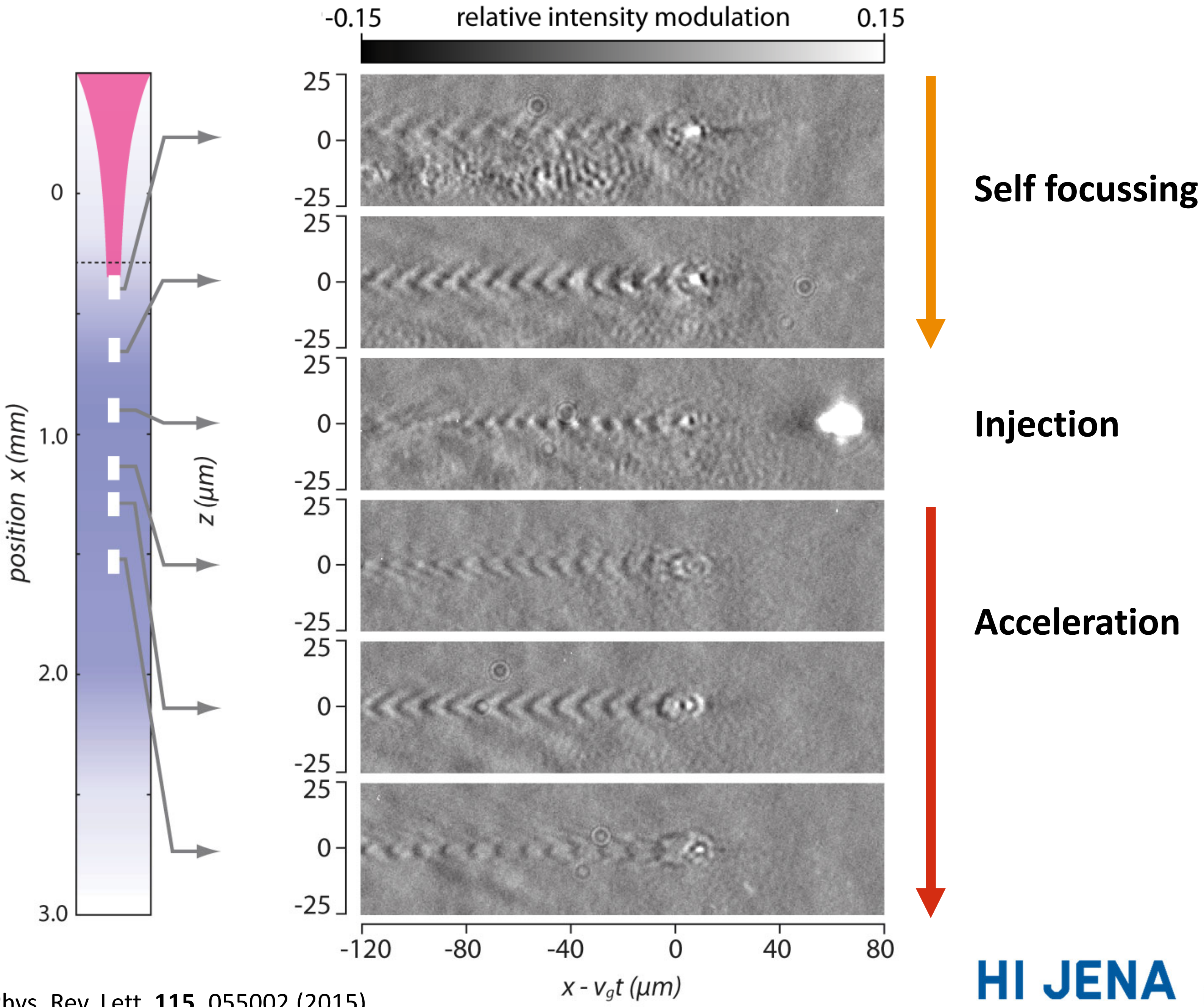

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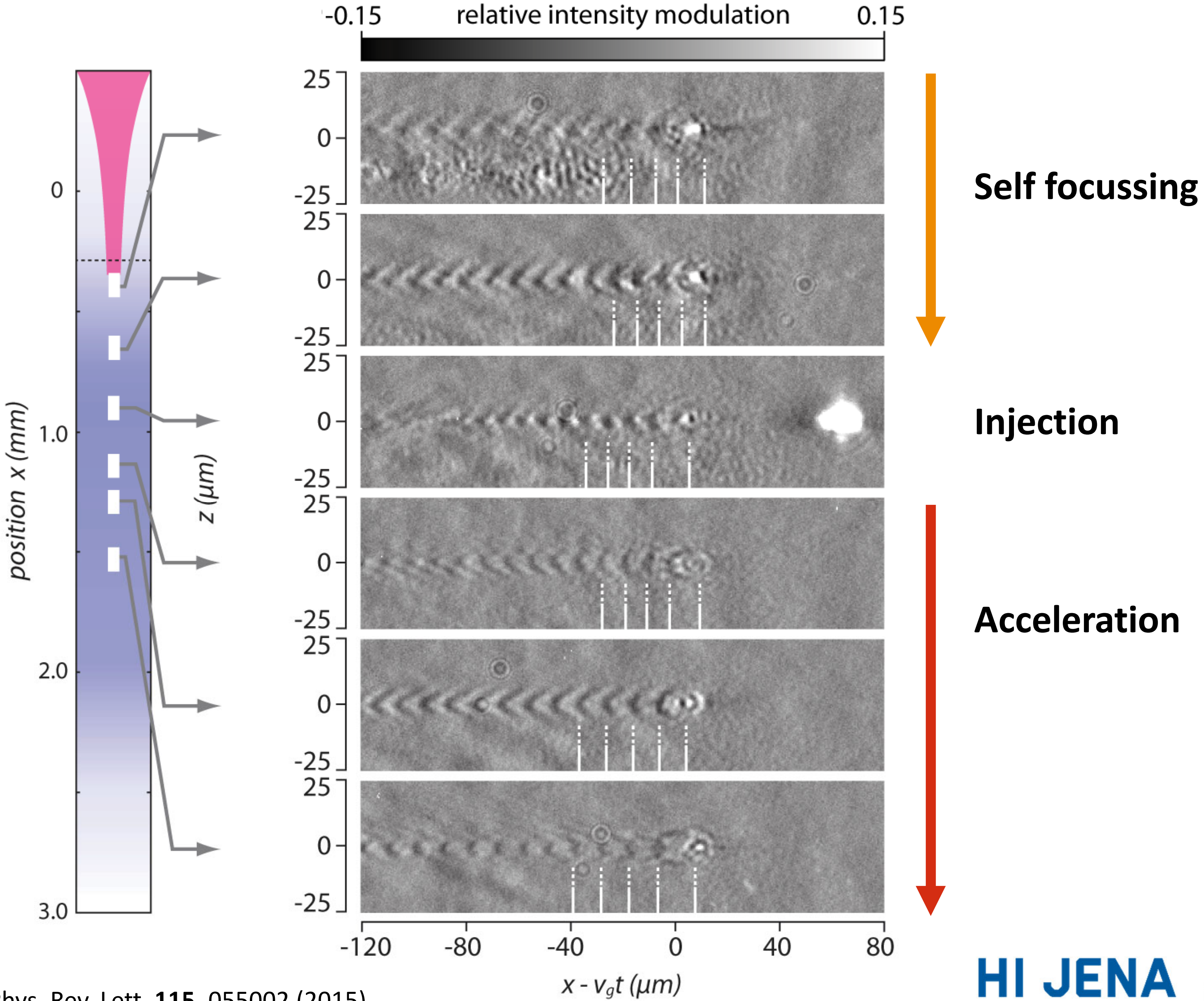

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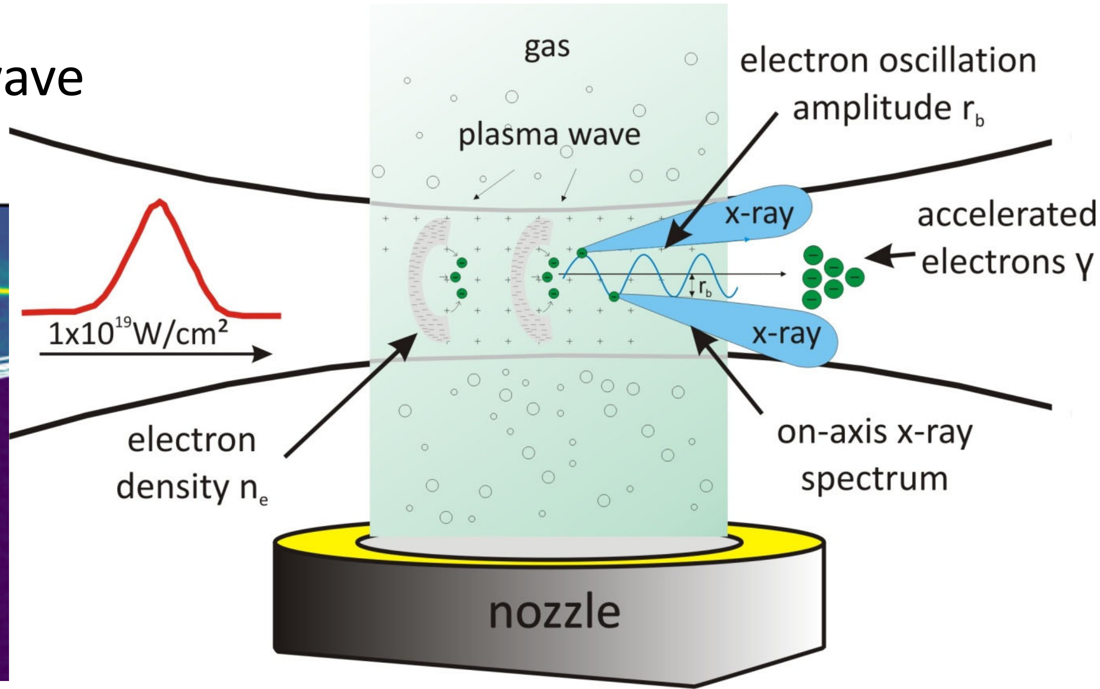
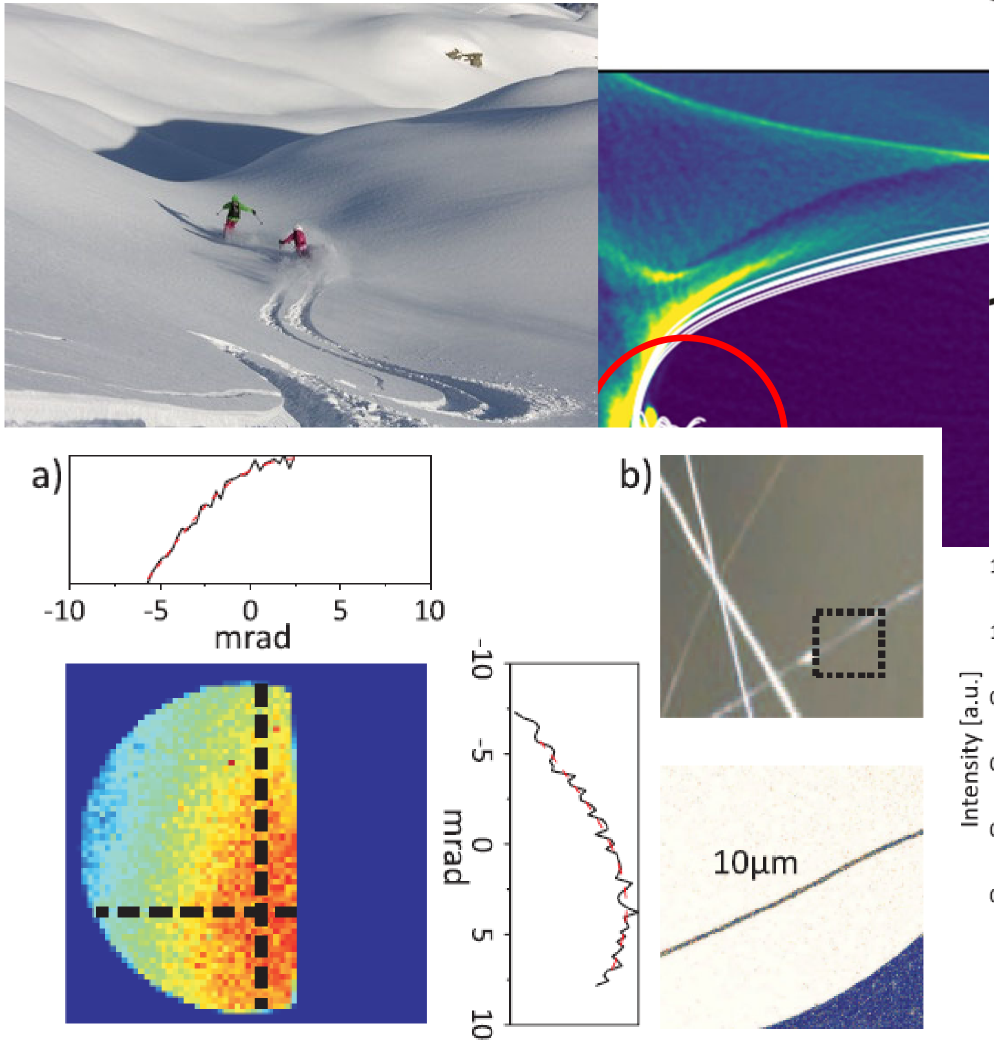
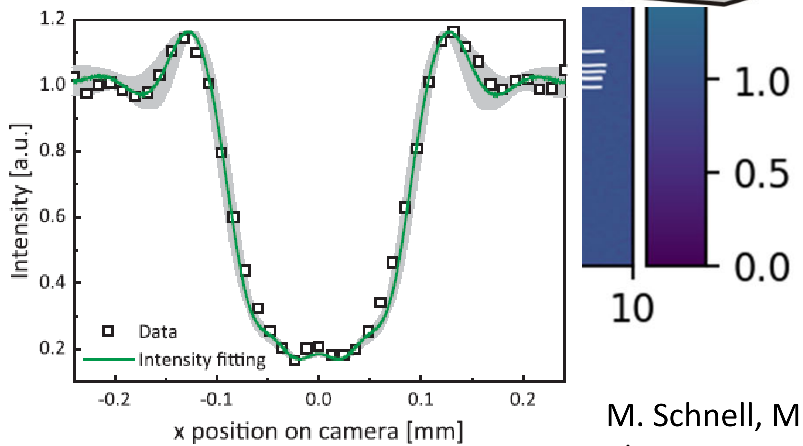
Laser Wakefield Acceleration of Electrons: Betatron Radiation

- Acceleration of electrons in plasma wave







M. Schnell, MCK *et al.*
Phys. Rev. Lett. **108,** 075001 (2012)

- Fresnel-diffraction pattern at wire edges: $r_{\text{x-ray}} = (1.8 \pm 0.3)\ \mu m$
- electron source size: $r_{\text{electron bunch}} = (1.6 \pm 0.3)\ \mu m$

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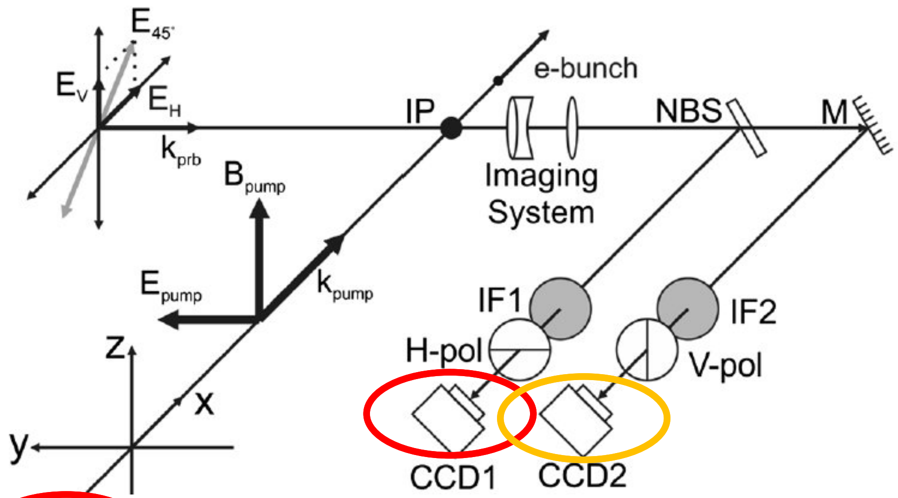
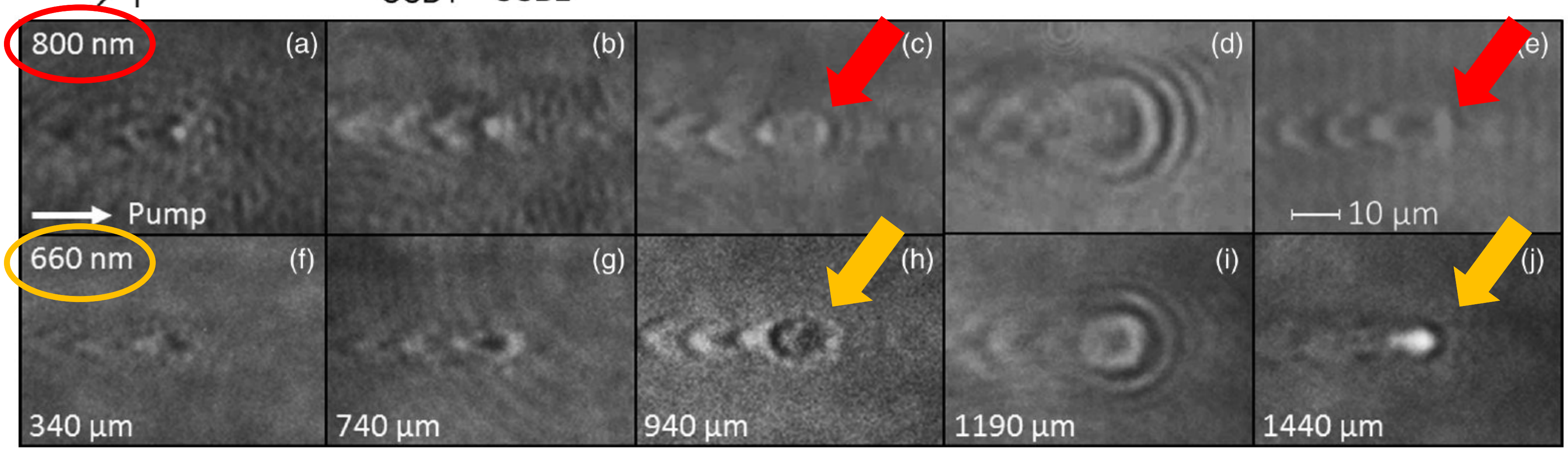
Non-invasive diagnostic of intensity evolution during interaction based on relativistic electron cyclotron resonance





Probe wave length and main-pulse intensity dependent probe-pulse absorption!

Signature of intensity evolution of main pulse during its passage through the plasma!

M. B. Schwab, MCK et al. Phys. Rev. AB **23**, 032801 (2020)

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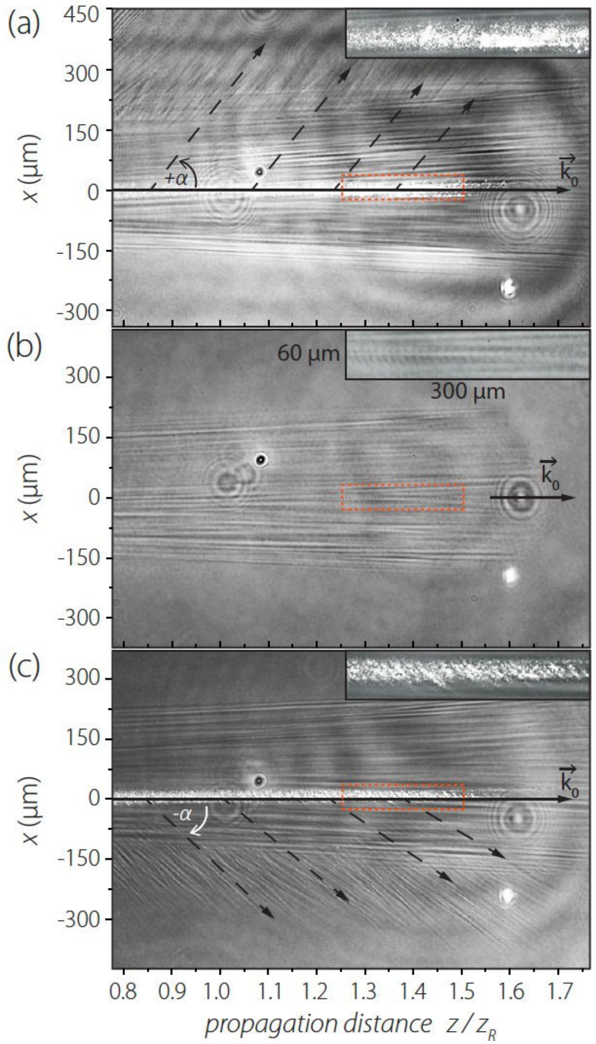
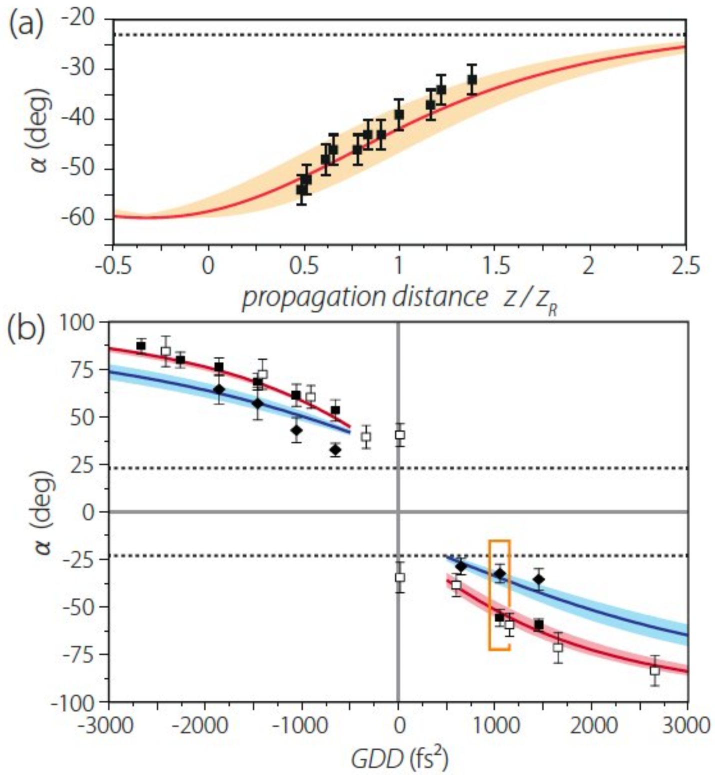
Laser Wakefield Acceleration of Electrons @ JETI: Optical probing

Observation of Stimulated Raman Sidescattering, diagnostic for spatio-temporal couplings of main pulse (PFT) and electron beam steering





C. Zepter, MCK et al. Phys. Rev. Research **5**, L012023 (2023)

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- When electron pulse cannot be measured non-invasively
  - Deduce/estimate e-beam parameters from other parameters (which can be measured non-invasively)
  - Possible, when exact correlations between parameters are known (not yet!)
  - Use machine-learning algorithms + Bayesian optimization models to find such correlations

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Summary and Outlook

- LWFA-based FEL as one of the central goals of EuPRAXIA seems within reach
- essential for its optimization:
  - high-resolution diagnostics for
    - driving laser,
    - plasma/accelerator structure,
    - particle pulses,
  - find correlations between different parameters also using machine-learning methods
- Feedback loops for stabilization of laser and particle pulses.

Thank you for your attention!

Laser Wakefield Acceleration of Electrons @ JETI: Optical probing

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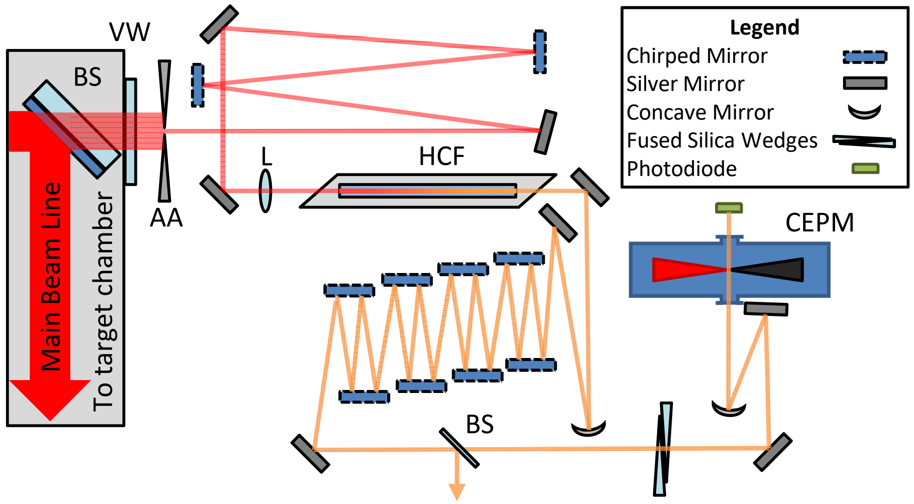
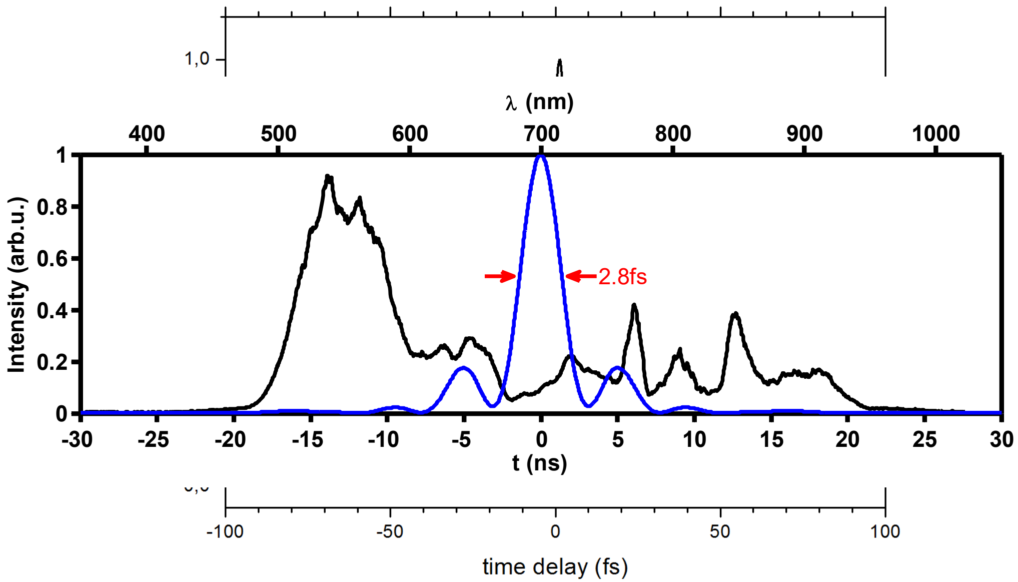
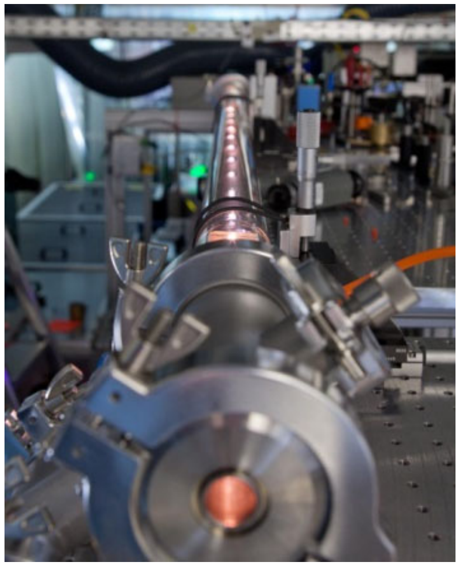
- Generation of few-cycle probe pulses @ JETI via frequency broadening







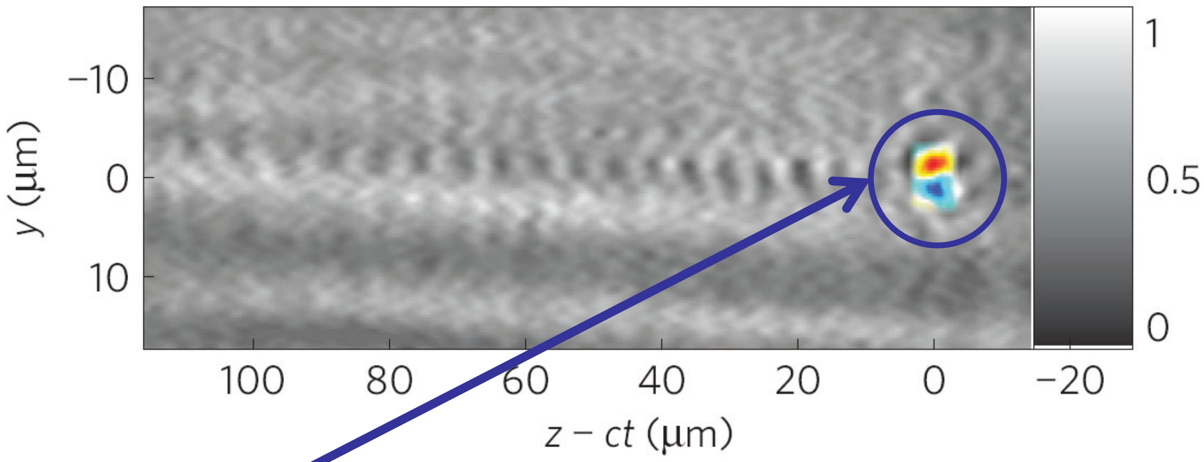
JETI input pulses: 32 fs, ~1 mJ

$\Rightarrow$ (5.9±0.4) fs @ 300 µJ, (2.8±0.4) fs @ 200 µJ

$\Rightarrow$ shadowgraphy, Faraday-rotation, interferometry, … possible

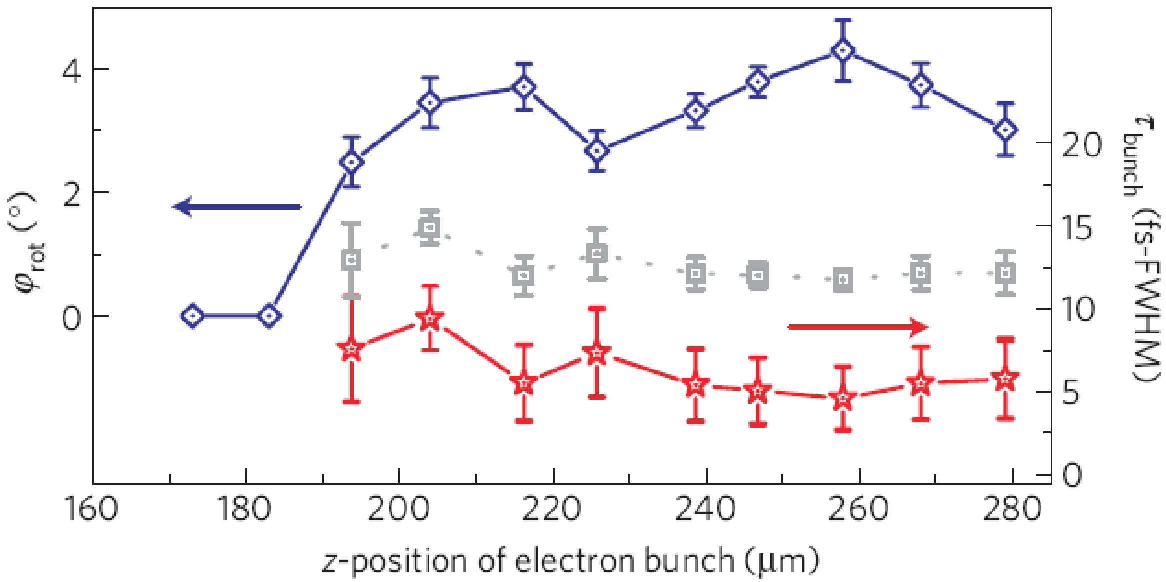
M. Schwab, MCK *et al.,* Applied Physics Letters **103,** 191118 (2013)
D. Adolph, MCK *et al.,* Applied Physics Letters **110,** 081105 (2017)

Laser Wakefield Acceleration of Electrons: Optical probing



- Polarimetry:
  Visualization of e-bunches via B-fields

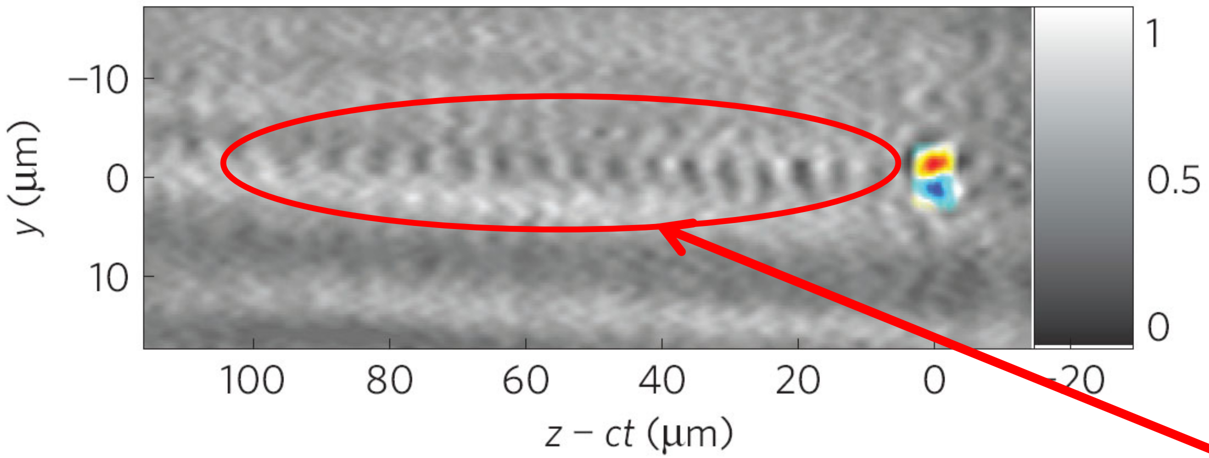
- Variation of delay between pump and probe pulse:
  ⇒ Evolution of e-pulse generation!



- First online observation of e-bunch generation!

A. Buck, MCK *et al.,* Nature Physics **7,** 543 (2011)

Laser Wakefield Acceleration of Electrons: Optical probing



- Polarimetry:
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  Visualization of the plasma wave

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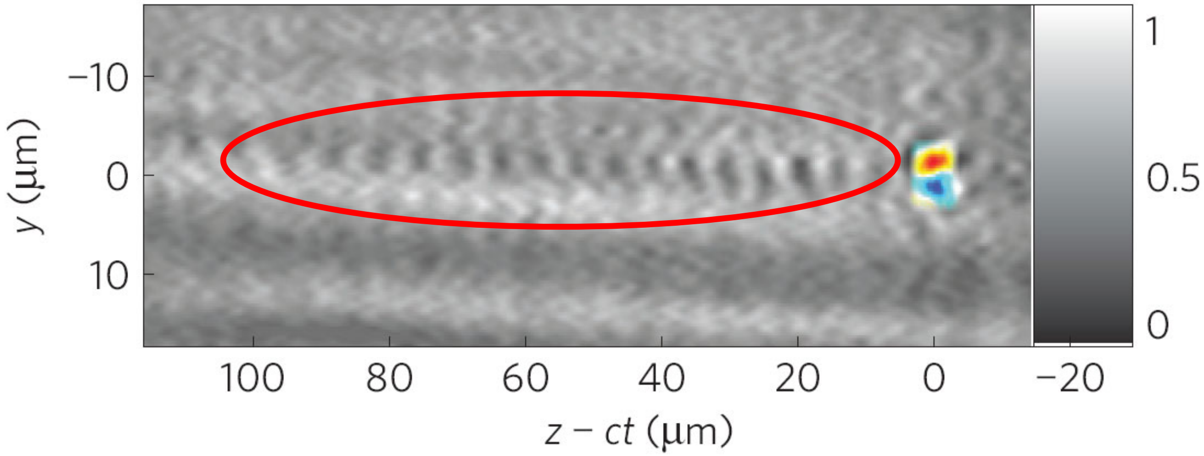

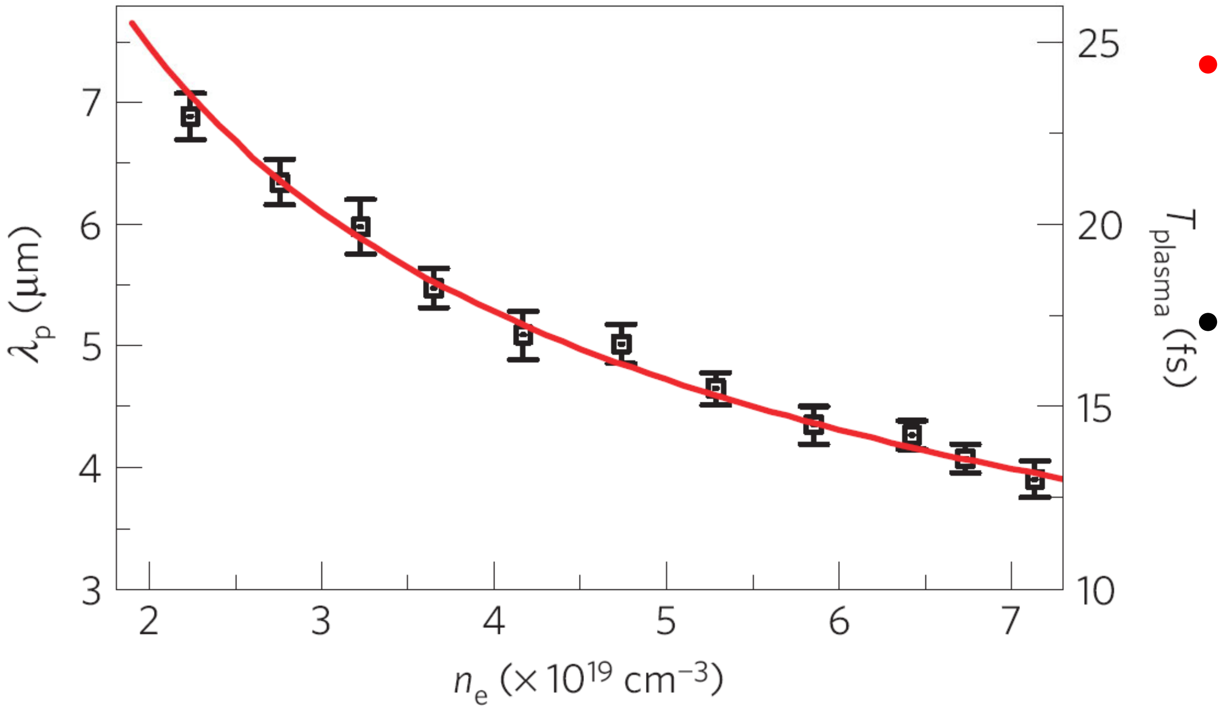

- Shadowgraphy: Visualization of the plasma wave
- Variation of plasma density $\Rightarrow$ change of plasma wave length

$$\lambda_p = v_{ph} T_p \approx \frac{2\pi c}{\omega_p} = 2\pi c \sqrt{\frac{\varepsilon_0 m_e}{n_e e^2}}$$

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Laser Wakefield Acceleration of Electrons: Optical probing

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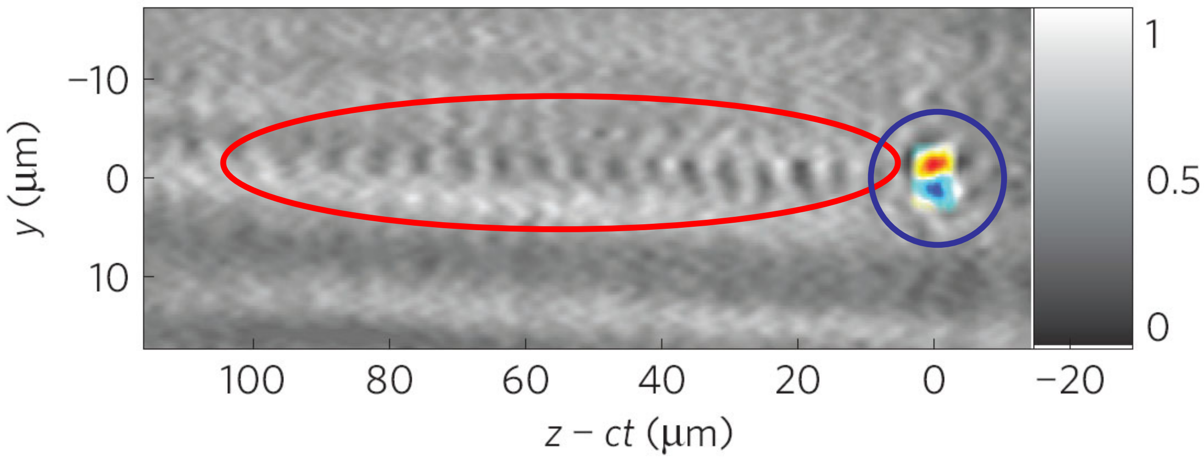

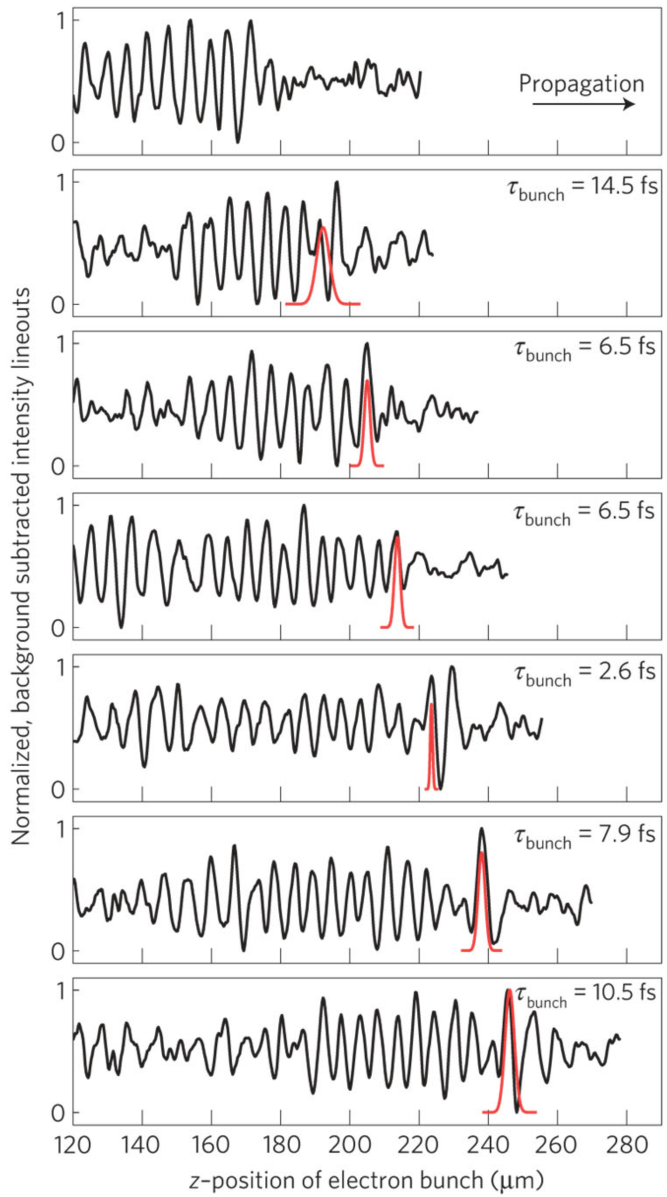

- Polarimetry + Shadowgraphy:

  Measurement of e-bunch position within the plasma wave:

  e-pulse is indeed accelerated within the 1st wave period!

A. Buck, MCK *et al.,* Nature Physics **7,** 543 (2011)

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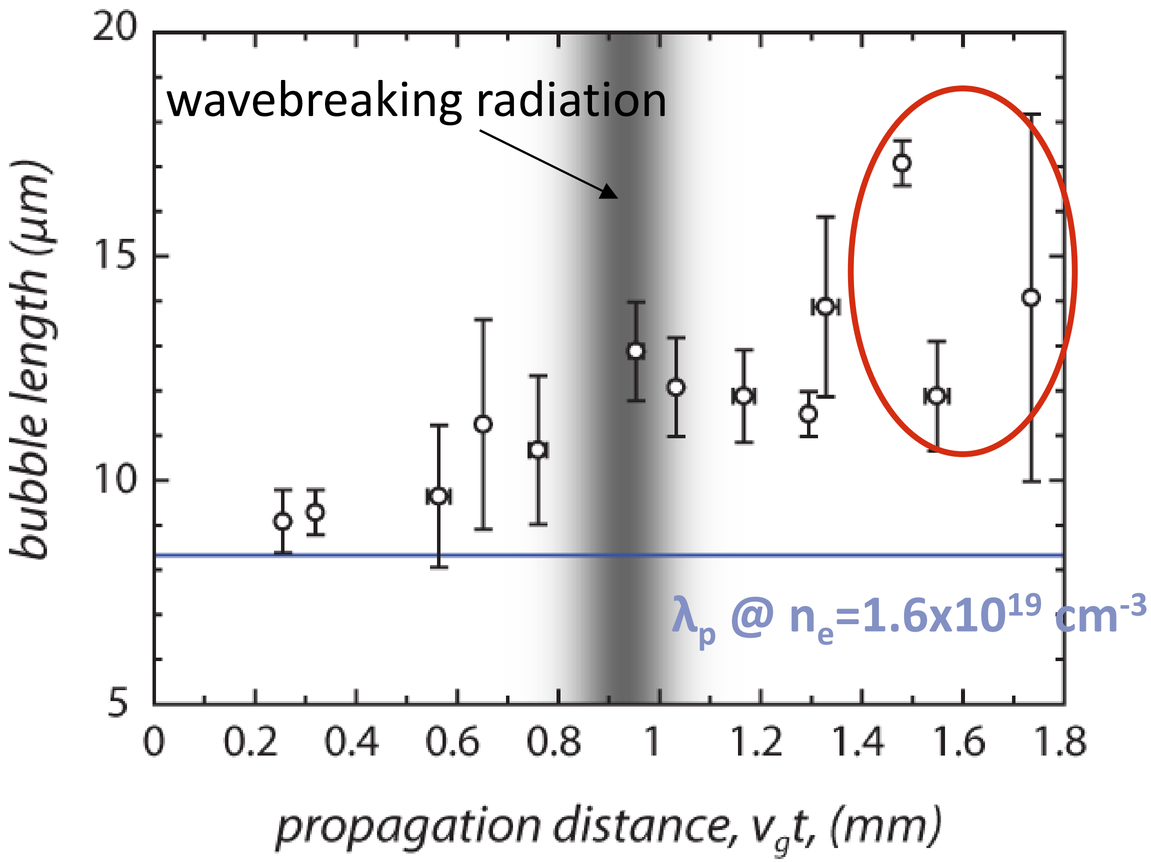
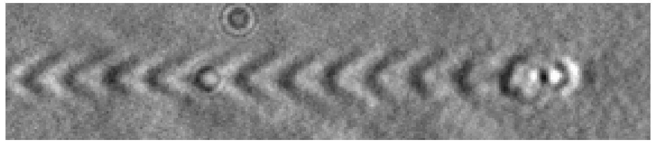
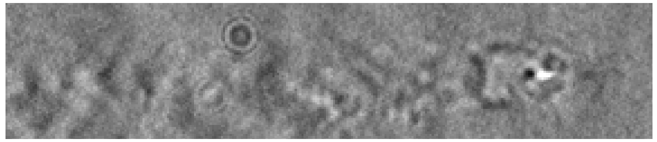
Laser Wakefield Acceleration of Electrons @ JETI: Optical probing



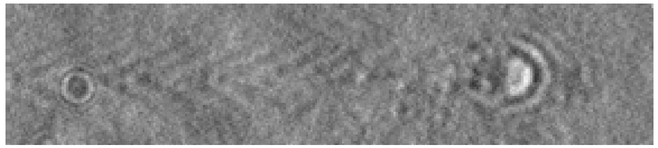
„well behaved"



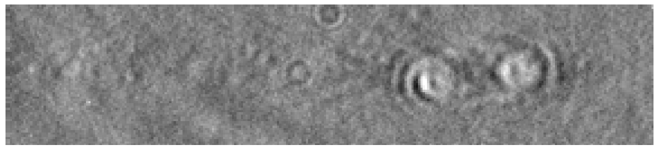
„beam loading" dominated



„single bubble" regime



„multi bubble" regime



Elongation of 1st plasma wave period starts before injection of electrons.

no „beam loading" but main pulse amplification.

$$\lambda_p^* \approx \lambda_p \left(1 + \frac{a_0^2}{2}\right)^{1/4}$$

A. Sävert, MCK *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

Laser Wakefield Acceleration of Electrons @ JETI: Optical probing

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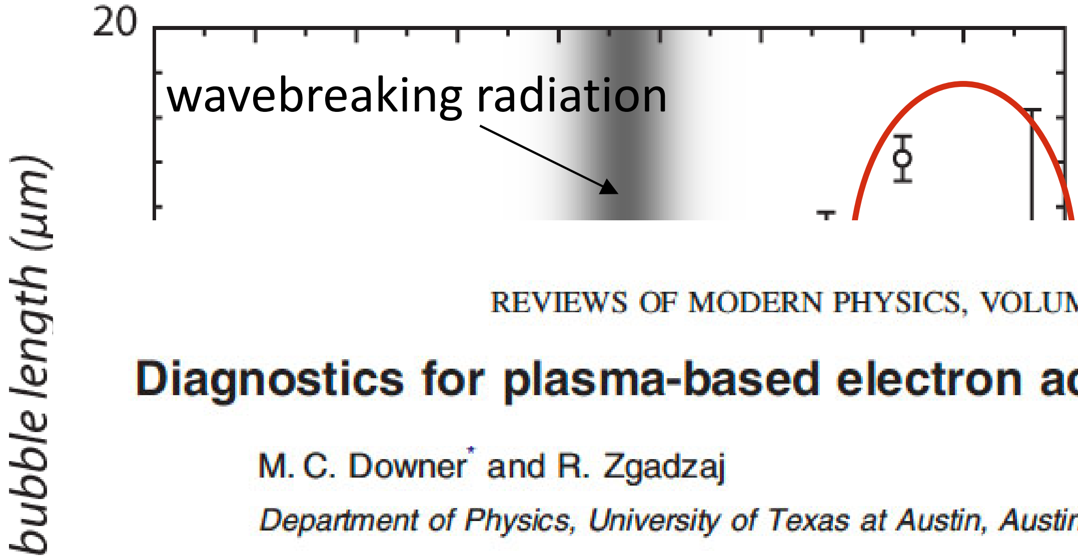

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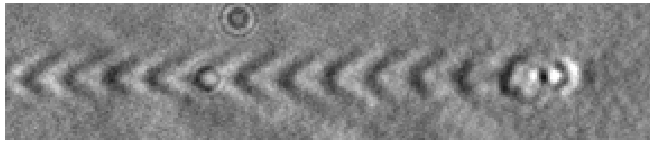

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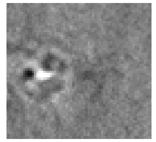

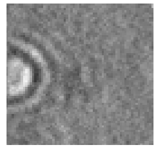

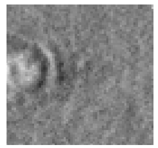

REVIEWS OF MODERN PHYSICS, VOLUME 90, JULY–SEPTEMBER 2018

Diagnostics for plasma-based electron accelerators

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(published 8 August 2018)

Plasma-based accelerators that impart energy gain as high as several GeV to electrons or positrons within a few centimeters have engendered a new class of diagnostic techniques very different from

$$\lambda_p^* \approx \lambda_p \left(1 + \frac{a_0^2}{2}\right)^{1/4}$$

A. Sävert, MCK *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

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