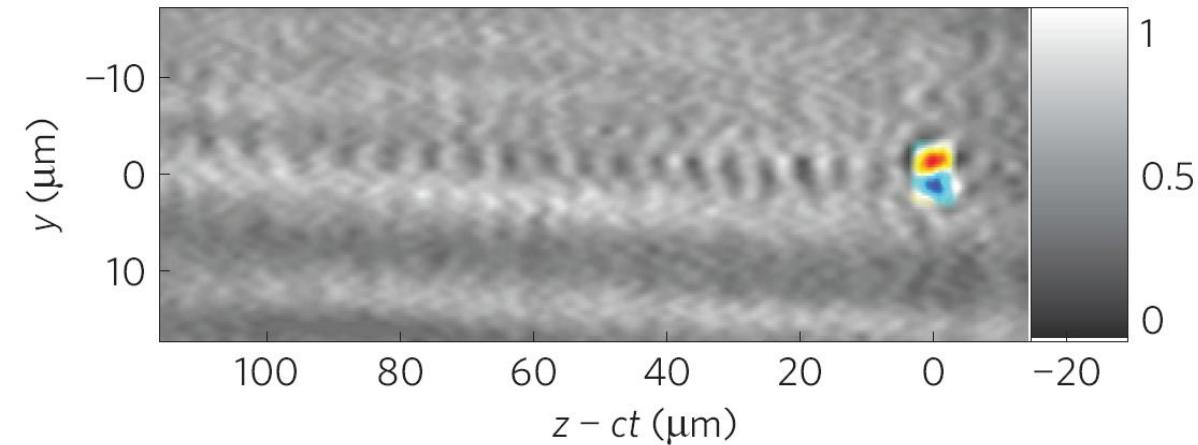
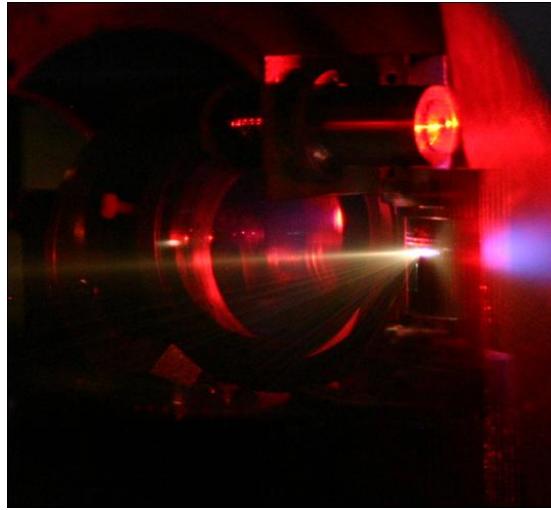


# Diagnostic Tools for Plasma-Electron Accelerators



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*Institute of Optics and Quantum Electronics  
Helmholtz-Institute Jena  
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# Motivation and Outline

- Compact laser-driven plasma-electron accelerators:
  - plasma formation and modulation induced by high-intensity laser pulse
  - electrons are accelerated by fields of laser-generated plasma wave („wakefield“)
  - electron pulse parameters determined by details of interaction
  - generation and evolution of this wakefield?
  - acceleration dynamics?
- High relevance for future plasma-electron accelerators
  - plasma-wakefield accelerators (e.g. beam-driven): realize compact high-energy plasma-based accelerators (e.g. at DESY or at SLAC)
- Pump-probe geometry well suited for investigation:
  - accelerator driven („pumped“) by main pulse,
  - can be characterized („probed“) using synchronized probe pulse
- Generate synchronized probe pulses:  
investigate details of interaction with high temporal and spatial resolution

# Laser Wakefield Acceleration

## Principle of the acceleration

- Plasma wave excited by  $F_{\text{pond}}$  of high-intensity laser pulse  
= modulation of  $n_e$  against ion background ( $v_{\text{ph,plasma}} = v_{\text{gr,laser}}$ )  
⇒ longitudinal E-fields ( $\sim 0.1 \dots 1 \text{ TV/m}$ )

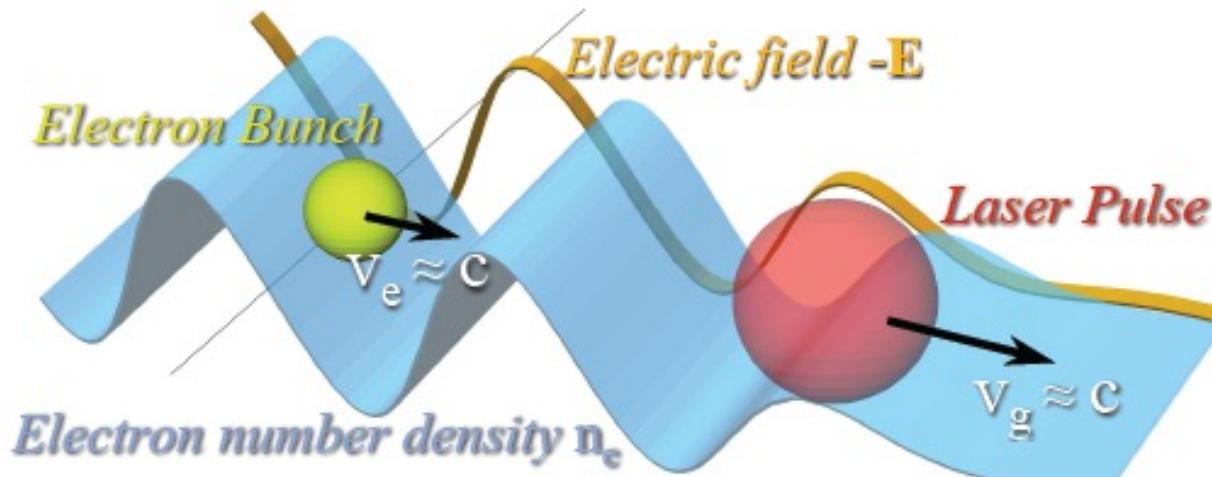
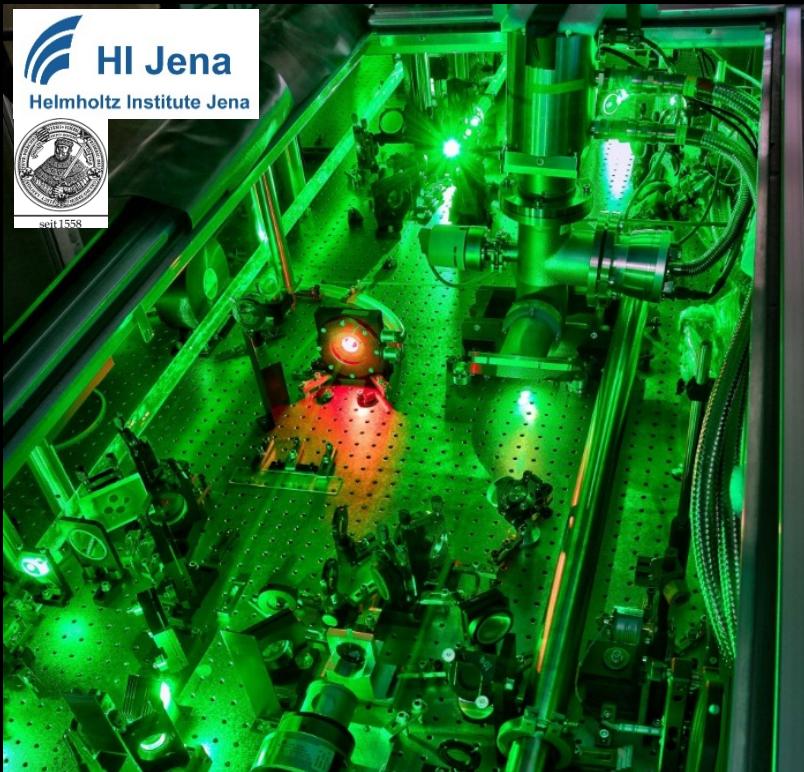


Image courtesy of A.G.R. Thomas

- Injection of electrons into the wave (e.g. by wave breaking)  
⇒ relativistic electron current  $\Leftrightarrow$  azimuthal B-fields

# JETI @ FSU Jena and LWS 20 @ MPQ Garching



10...30-TW Ti:Sapphire Laser

pulse duration: 85 ... 35 fs

pulse energy: 750 mJ

focus diameter: 14 μm

max. intensity:  $2\ldots6\times10^{18}$  W/cm<sup>2</sup>



Multi-TW OPCPA Laser

pulse duration: 8.5 fs

pulse energy: 65 mJ

focus diameter: 7.2 μm

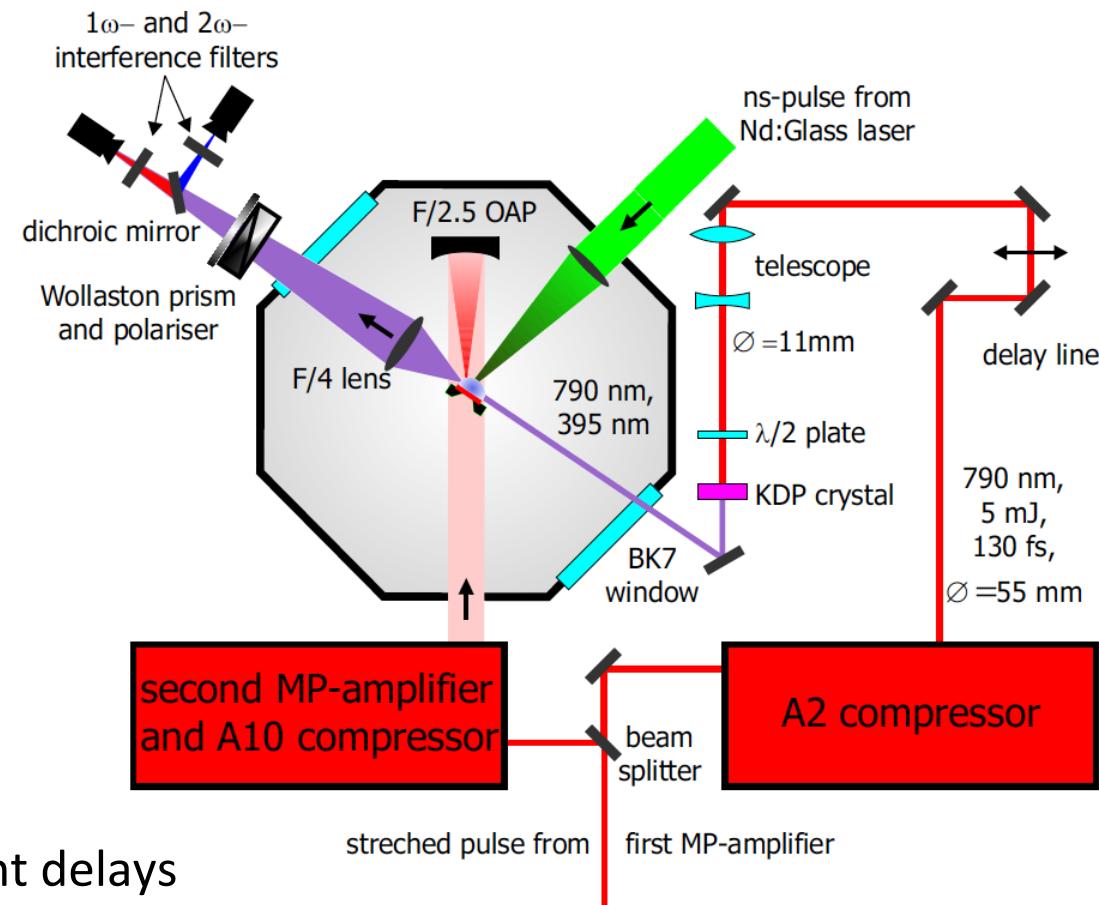
max. intensity:  $6\times10^{18}$  W/cm<sup>2</sup>

# Electromagnetic Probe Pulses

## Probe-pulse generation

- Generation of synchronized optical probe pulses:
  - split off part of the main pulse
  - guide it towards interaction along different path
  - adjust temporal delay

⇒ perfect synchronization  
⇒ probe pulse duration similar to main pulse  
⇒ record movie from subsequent shots at different delays  
(requires good shot-to-shot stability!)



# Electromagnetic Probe Pulses

## Probing of plasma wakefield acceleration process

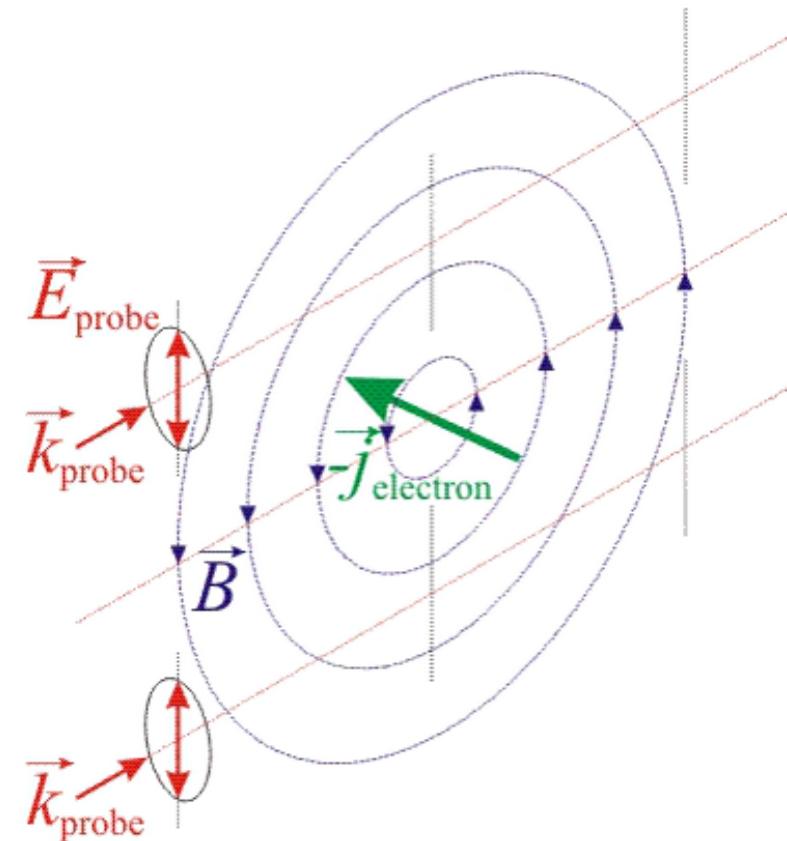
- Transverse probing of B-fields in underdense plasma with linearly-polarized probe pulse:  
if  $\vec{k}_{\text{probe}} \parallel \vec{B}$   $\Rightarrow$  B-field induced difference of  $\eta$  for circularly- polarized probe components

$\Rightarrow$  rotation of probe polarization:

$$\phi_{\text{rot}} = \frac{e}{2m_e c} \int \frac{n_e(\vec{r})}{n_{\text{cr}}} \vec{B}(\vec{r}) \cdot \frac{\vec{k}_{\text{probe}}}{k_{\text{probe}}} ds$$

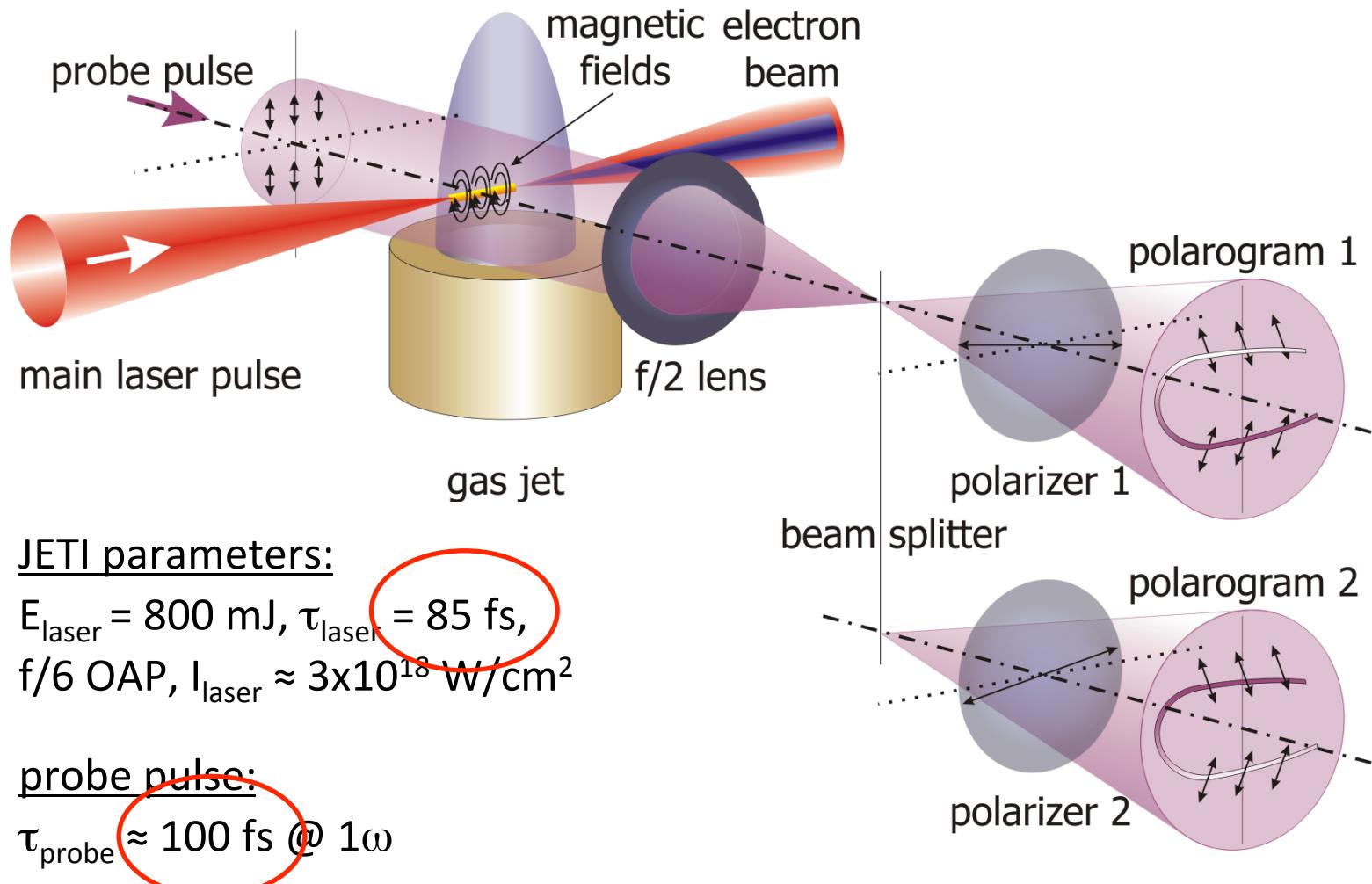
$\Rightarrow$  measure  $\phi_{\text{rot}}$  to get signature of B-fields, measure  $n_e$  to get amplitude!

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



# Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

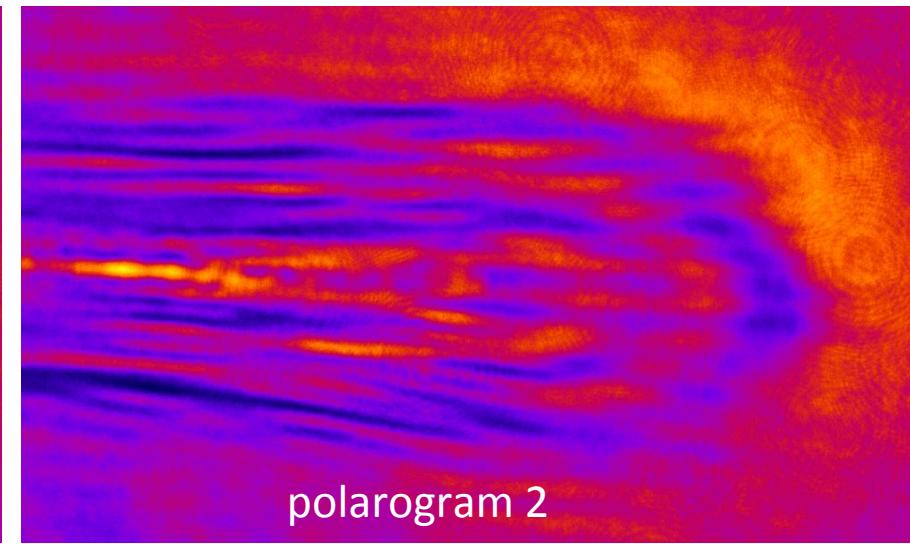
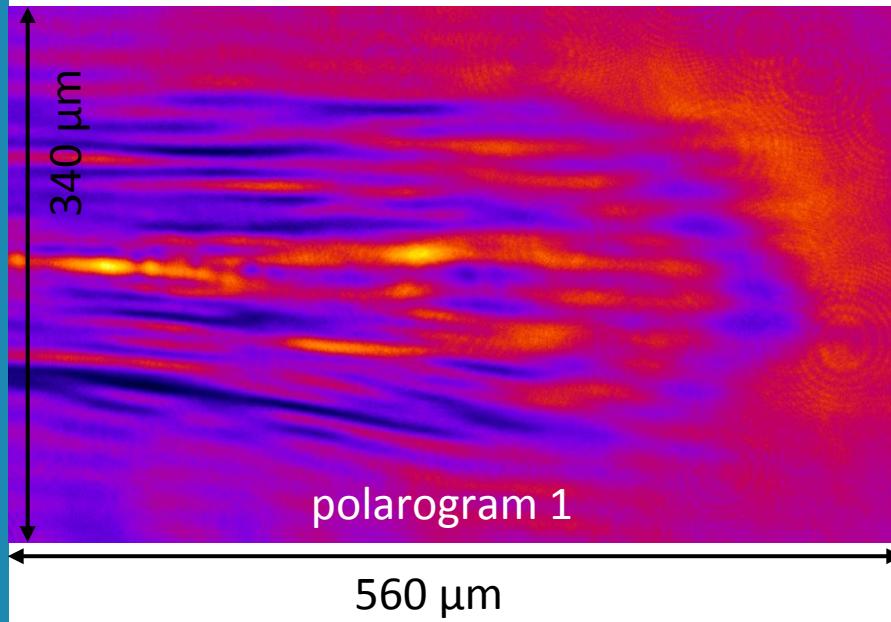




# Electromagnetic Probe Pulses

## Probing of plasma wakefield acceleration process

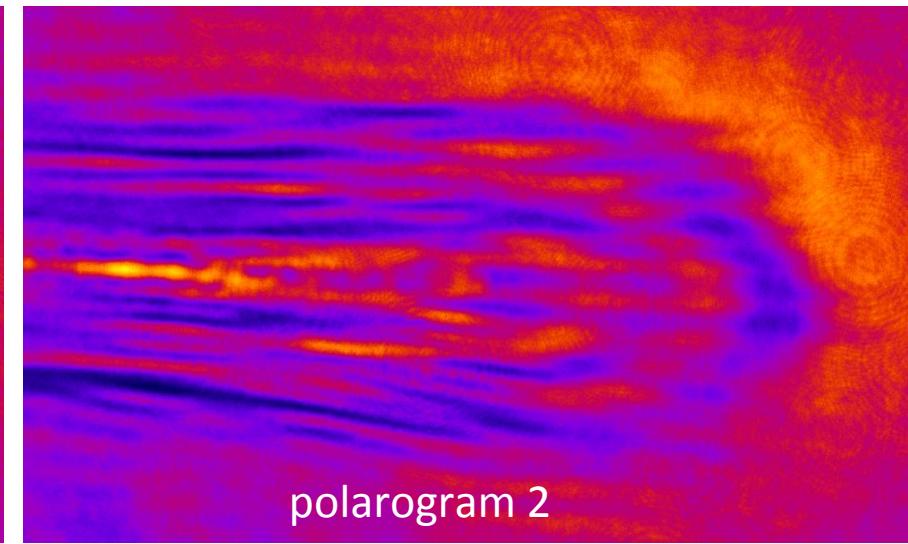
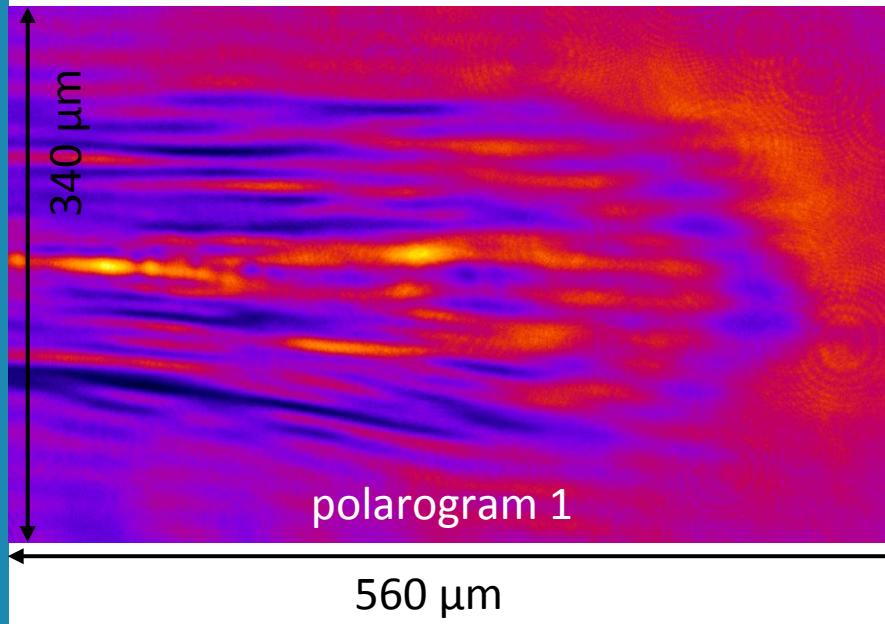
Two polarograms from two (almost) crossed polarizers:



# Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

Two polarograms from two (almost) crossed polarizers:



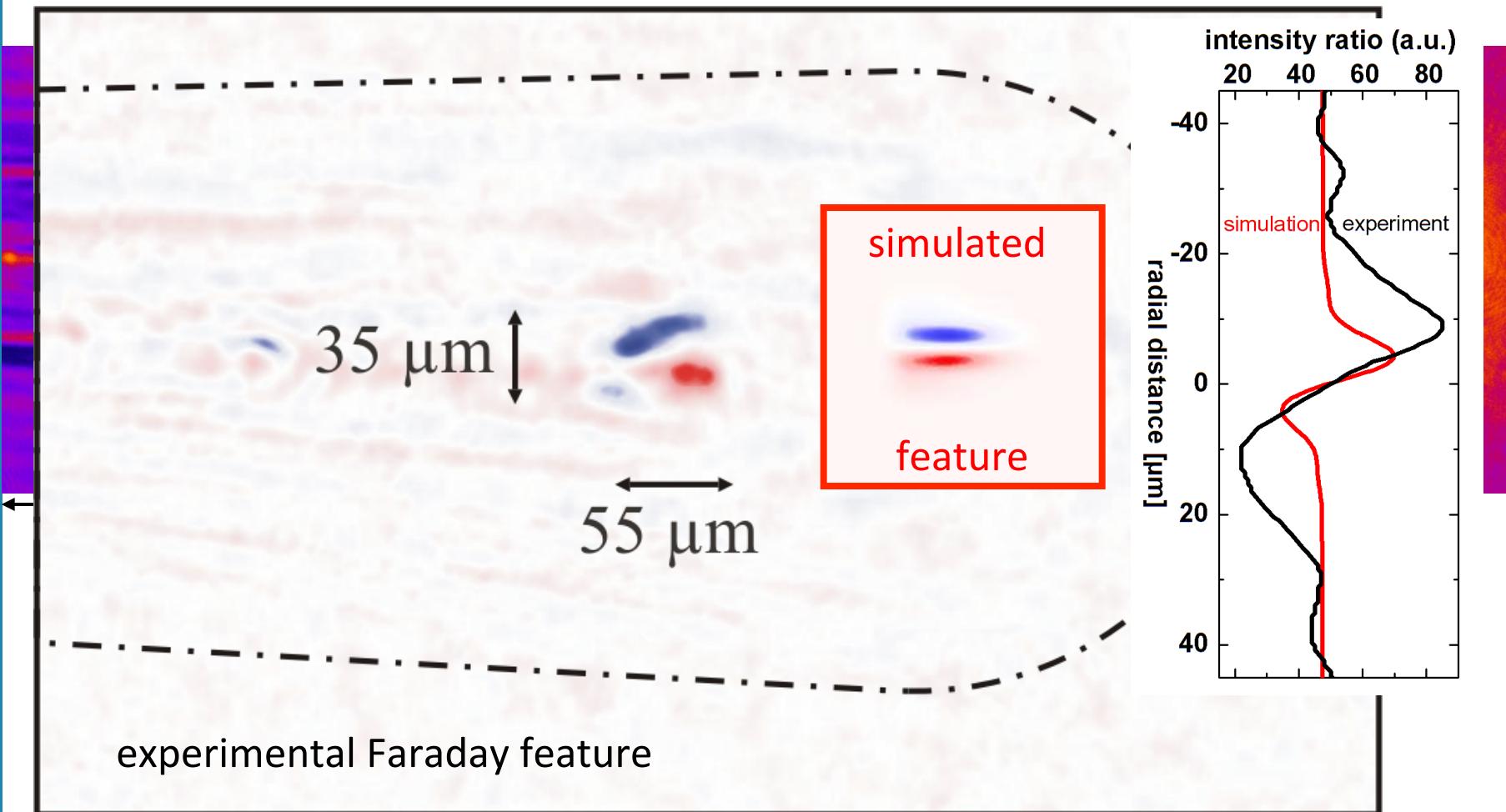
$$I_{\text{pol1}} = I_0 [1 - \beta_1 \sin^2(90^\circ - \theta_{\text{pol1}} - \phi_{\text{rot}})] \quad I_{\text{pol2}} = I_0 [1 - \beta_2 \sin^2(90^\circ + \theta_{\text{pol2}} - \phi_{\text{rot}})]$$

Deduce rotation angle  $\phi_{\text{rot}}$  from pixel-by-pixel division of  
polarogram intensities:

$$I_{\text{pol1}}(x, y) / I_{\text{pol2}}(x, y)$$

# Electromagnetic Probe Pulses

## Probing of plasma wakefield acceleration process

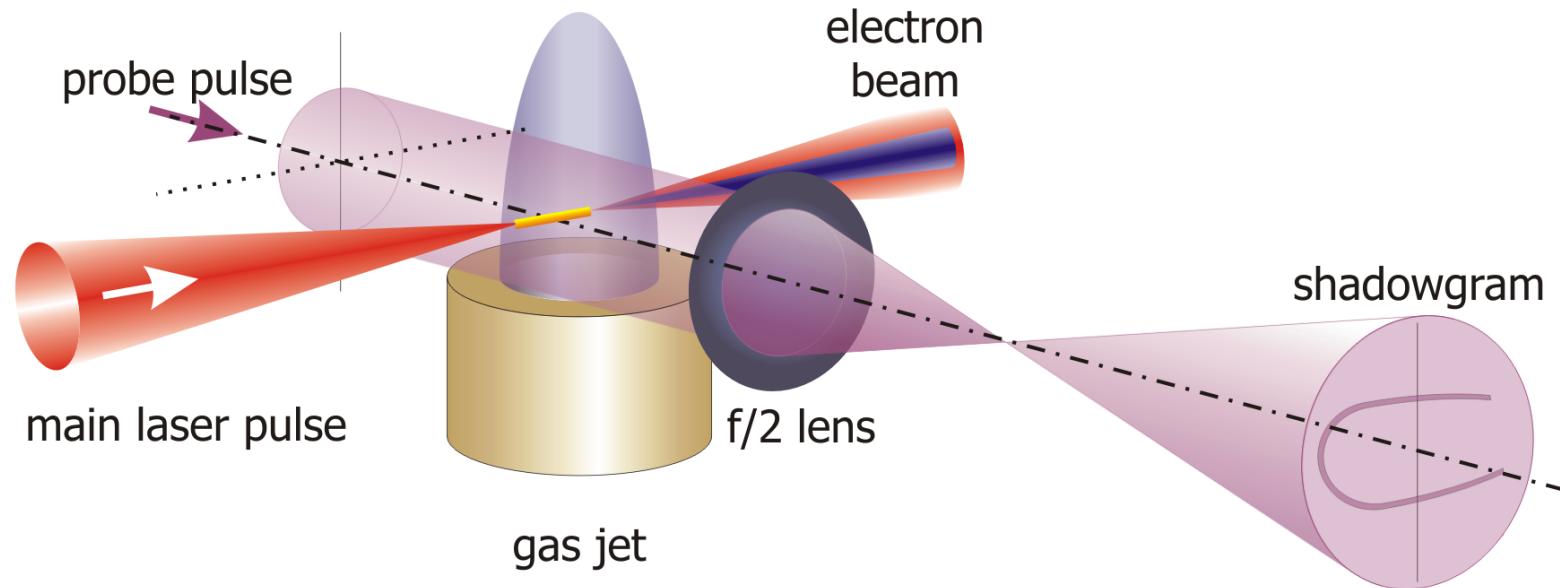


Experimental evidence for B-fields from MeV electrons and bubble!

MCK *et al.*, Physical Review Letters **105**, 115002 (2010)

# Electromagnetic Probe Pulses

## Probing of plasma wakefield acceleration process



### JETI parameters:

$E_{\text{laser}} = 800 \text{ mJ}$ ,  $\tau_{\text{laser}} = 85 \text{ fs}$ ,  
 $f/6 \text{ OAP}$ ,  $I_{\text{laser}} \approx 3 \times 10^{18} \text{ W/cm}^2$

### probe pulse:

$\tau_{\text{probe}} \approx 100 \text{ fs}$  @  $1\omega$

### LWS-20 parameters:

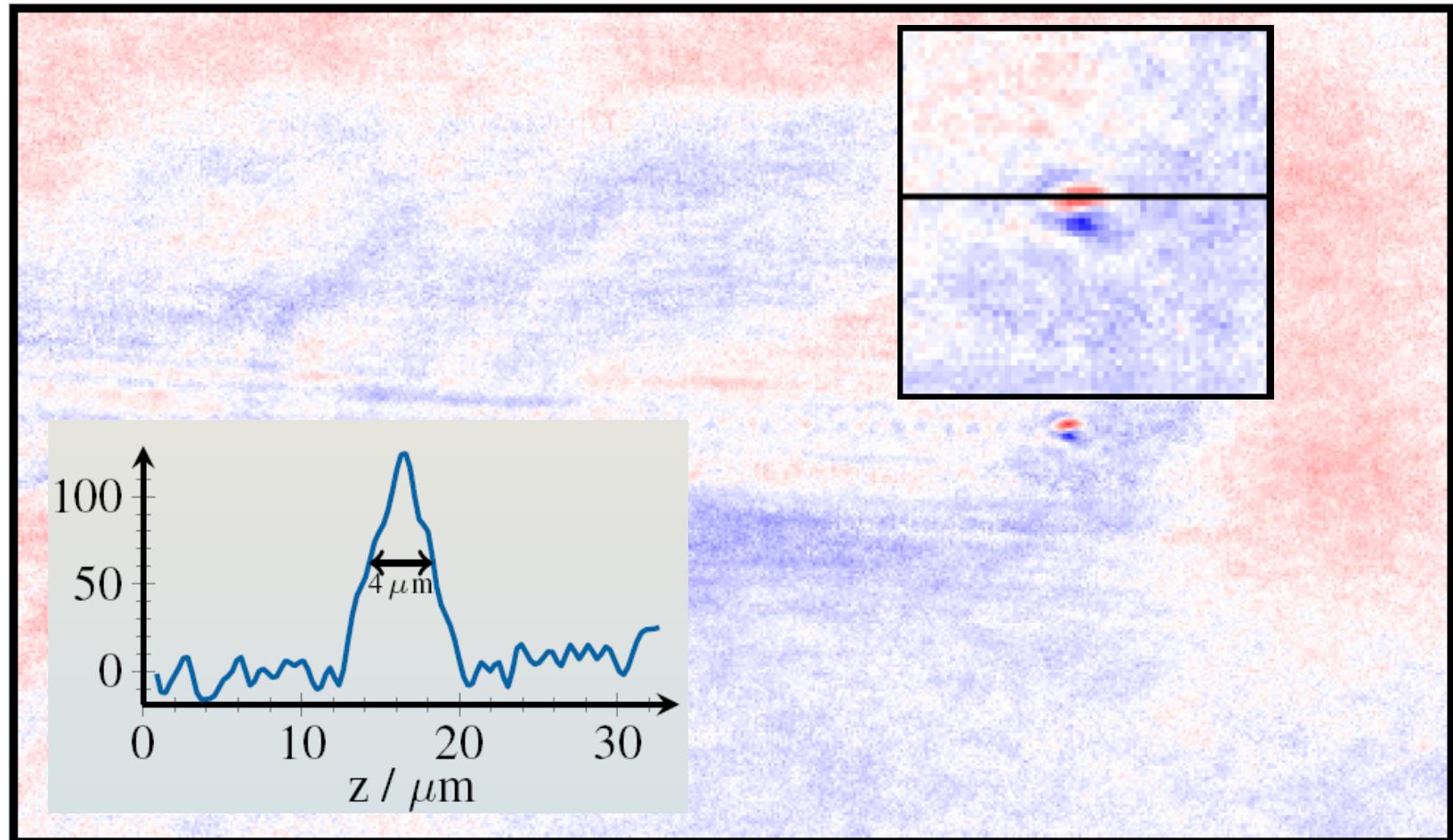
$E_{\text{laser}} = 80 \text{ mJ}$ ,  $\tau_{\text{laser}} = 8.5 \text{ fs}$ ,  
 $f/6 \text{ OAP}$ ,  $I_{\text{laser}} \approx 6 \times 10^{18} \text{ W/cm}^2$

### probe pulse:

$\tau_{\text{probe}} = 8.5 \text{ fs}$  @  $1\omega$

# Electromagnetic Probe Pulses

## Probing of plasma wakefield acceleration process

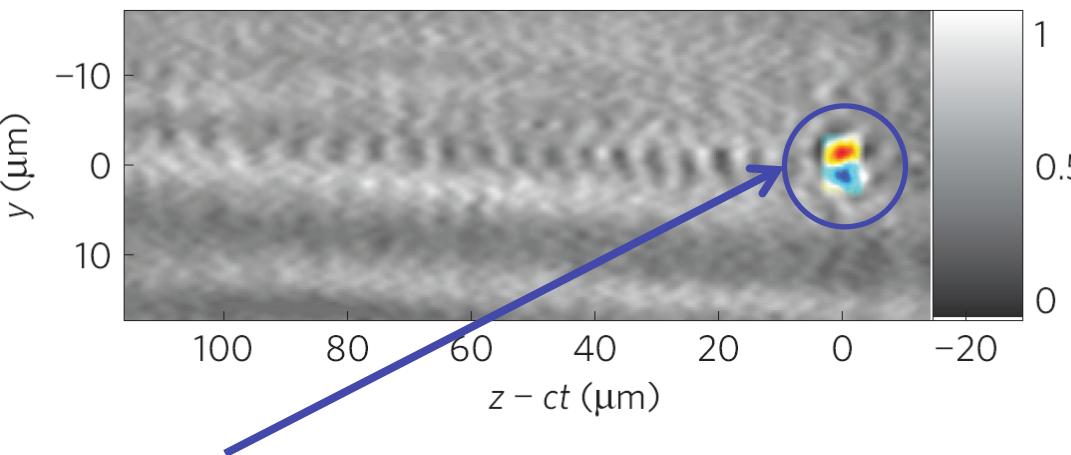


Electron bunch length:  $\Delta z = 4 \mu\text{m}$

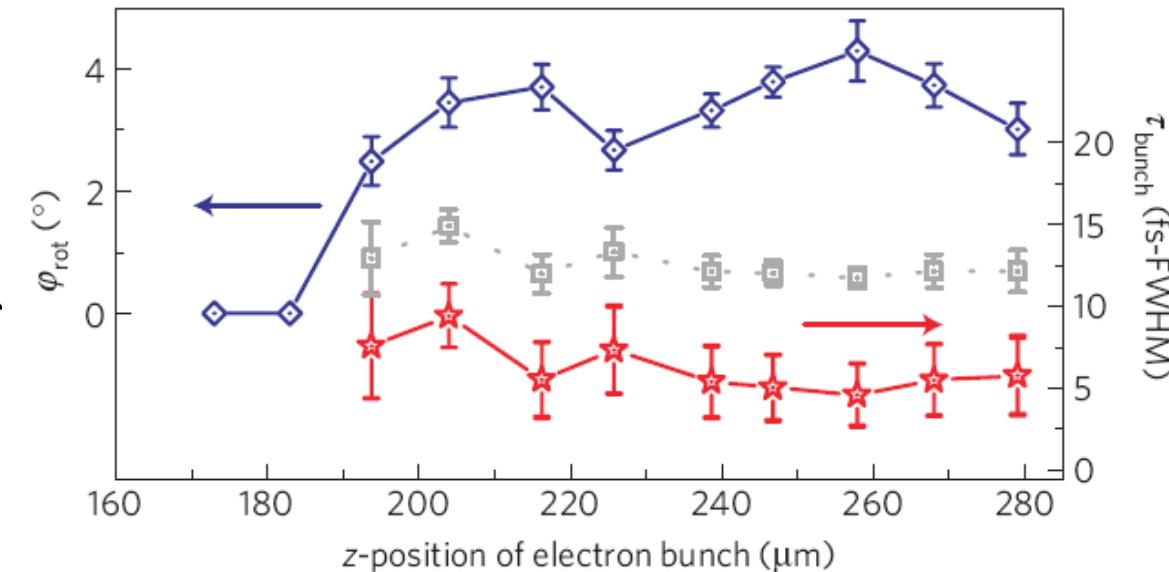
$\tau_{\text{FWHM}} = (6 \pm 2) \text{ fs}$ ,  $\tau_{\text{RMS}} = (2.5 \pm 0.9) \text{ fs}$

# Electromagnetic Probe Pulses

## Probing of plasma wakefield acceleration process



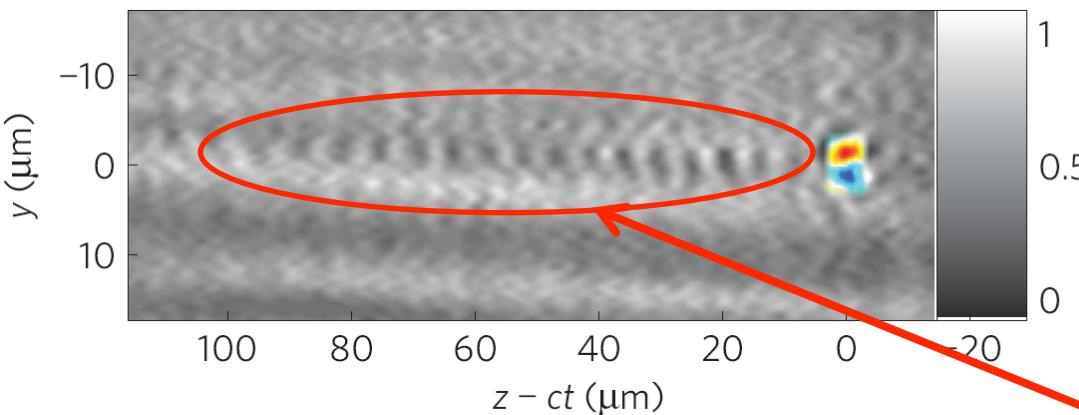
- Polarimetry:  
visualize e-bunch via  
associated B-fields
- change delay between pi  
and probe  
⇒ movie of e-bunch  
formation



- observe e-bunch formation on-line!
- A. Buck *et al.*, Nature Physics 7, 543 (2011)

# Electromagnetic Probe Pulses

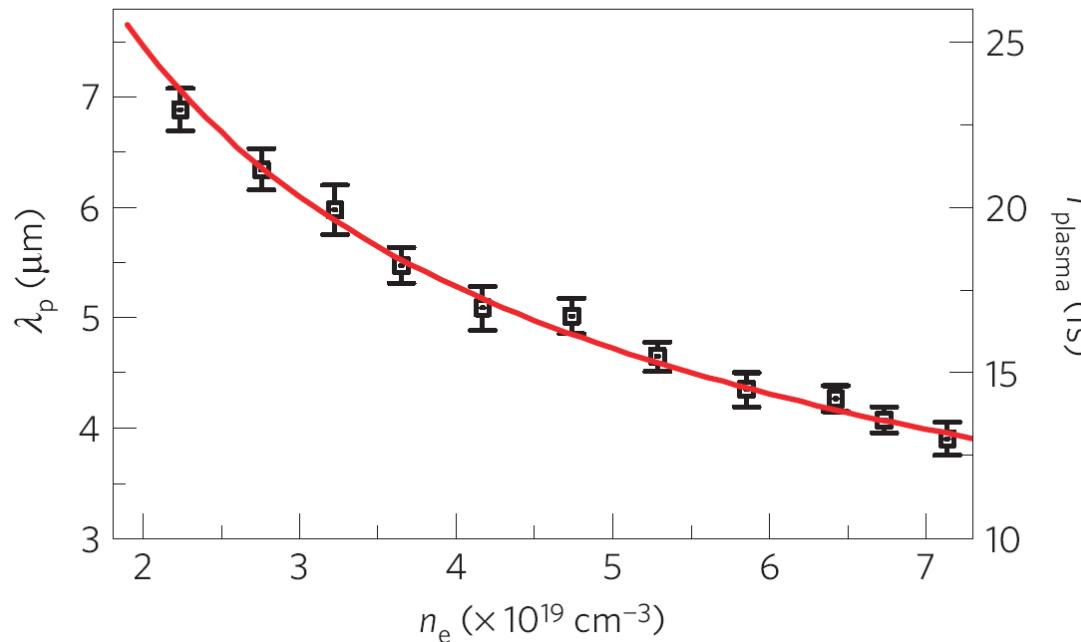
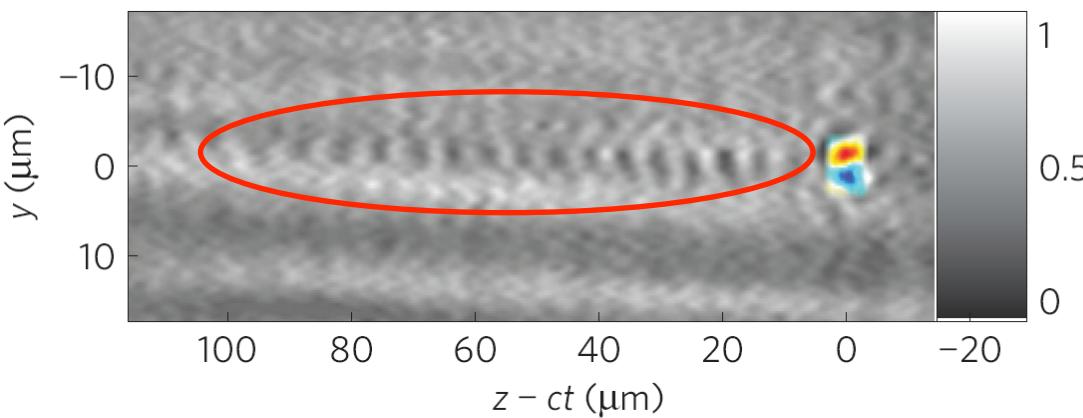
## Probing of plasma wakefield acceleration process



- **Polarimetry:**  
visualize e-bunch via  
associated B-fields
- change delay between pump  
and probe  
⇒ movie of e-bunch  
formation
- observe e-bunch formation on-line!  
A. Buck *et al.*, Nature Physics 7, 543 (2011)
- **Shadowgraphy:**  
visualize plasma wave
- change electron density ⇒  
change plasma wavelength

# Electromagnetic Probe Pulses

## Probing of plasma wakefield acceleration process



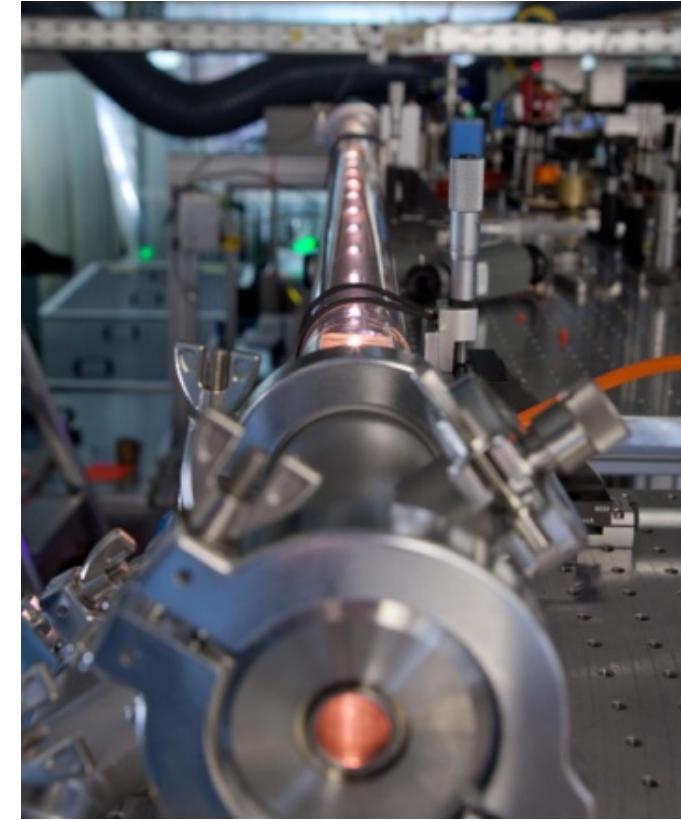
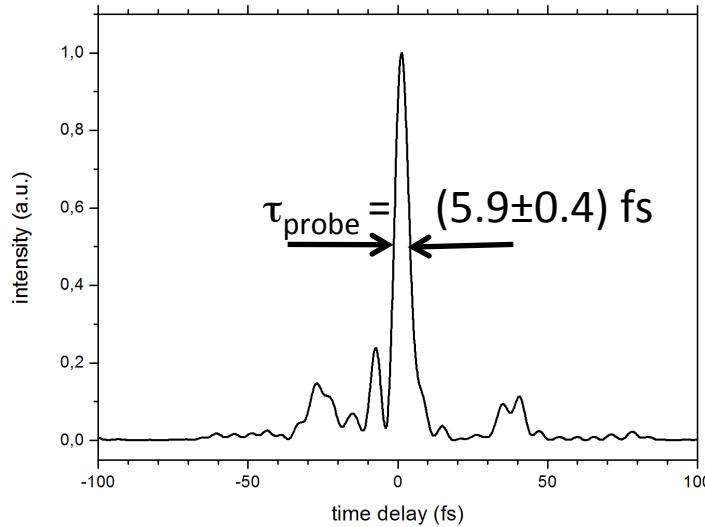
- **Shadowgraphy:** visualize plasma wave
- change electron density  $\Rightarrow$  change plasma wavelength

$$\lambda_p = v_{\text{ph}} T_p \approx \frac{2\pi c}{\omega_p} = 2\pi c \sqrt{\frac{\epsilon_0 m_e}{n_e e^2}}$$

# Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

- Experiments with 30-TW JETI-laser system
  - Similar resolution, but with 35-fs driver laser:
  - frequency-broadening of probe pulse  
(in gas-filled hollow fiber)
- ⇒ shorter  $\tau_{\text{probe}}$



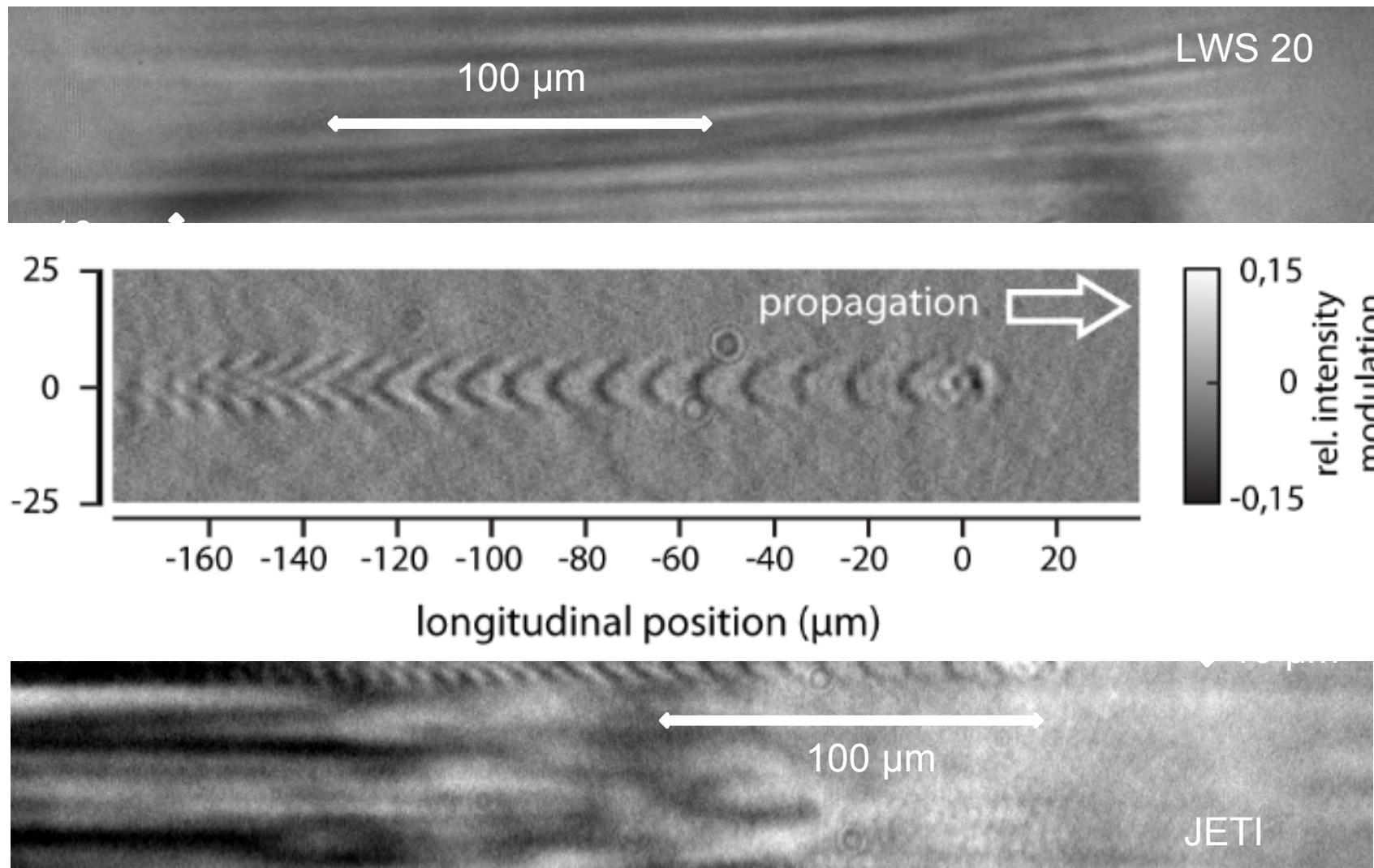
⇒ sub-main pulse temporal resolution,  
1.1 μm spatial resolution with optimized imaging system

M. Schwab *et al.*, Appl. Phys. Lett. **103**, 191118 (2013)

# Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

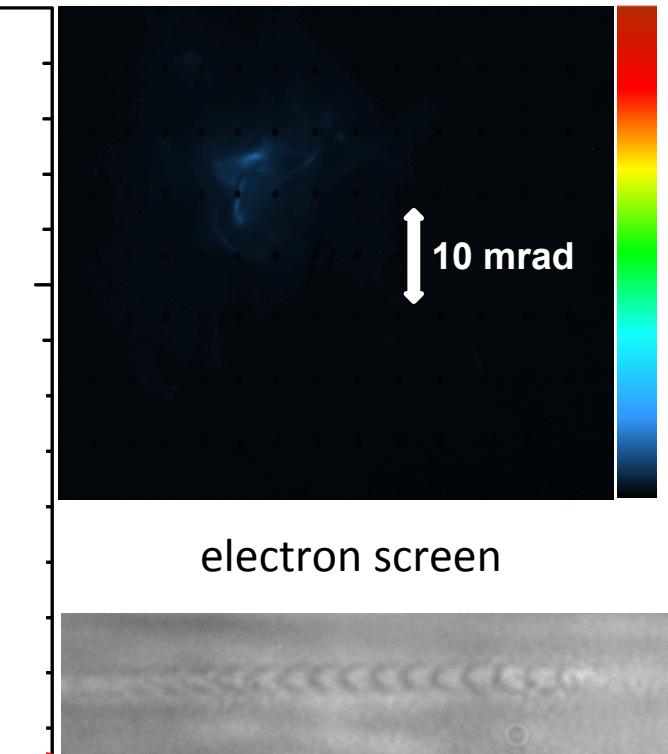
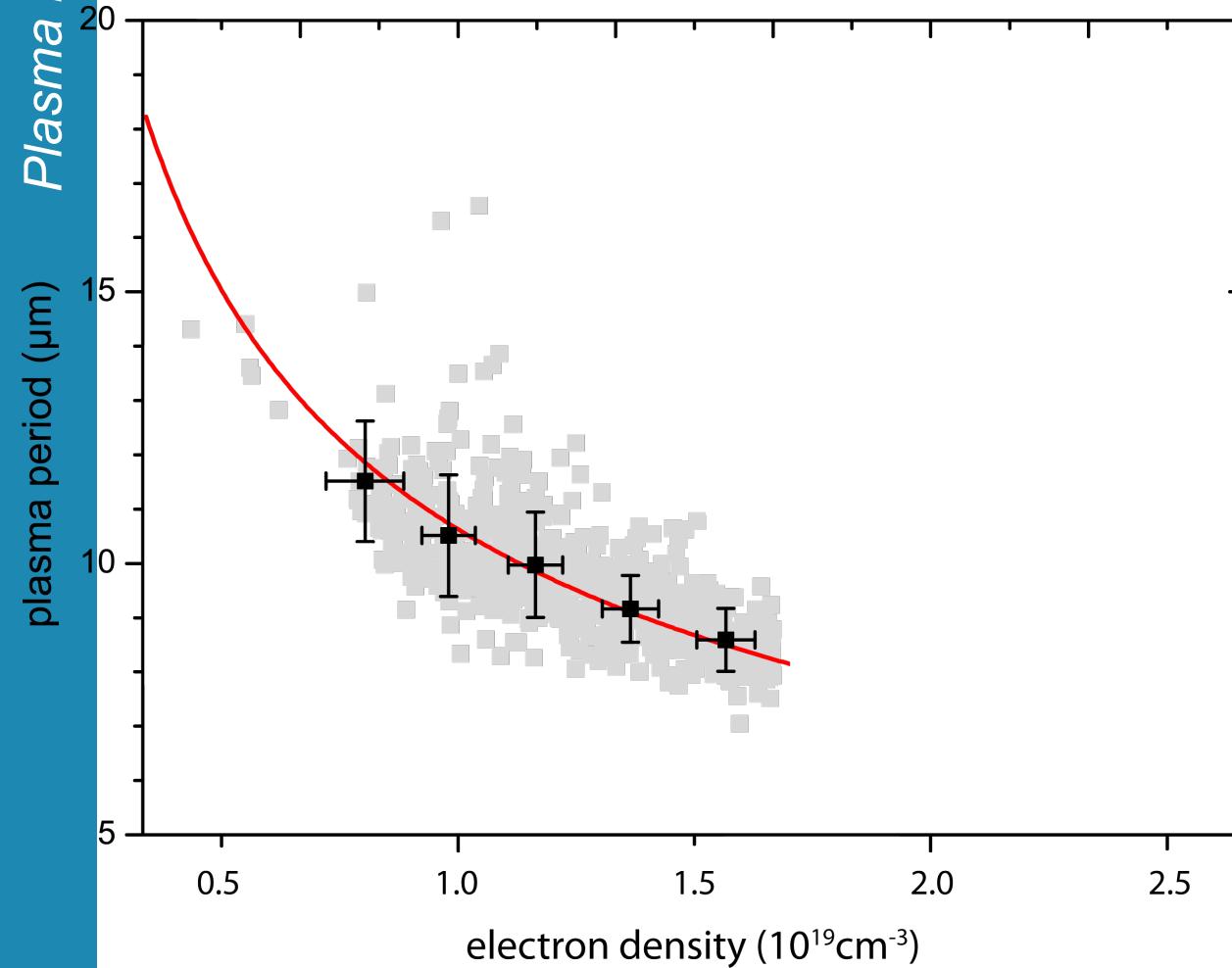
- Few-cycle probe pulses



# Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

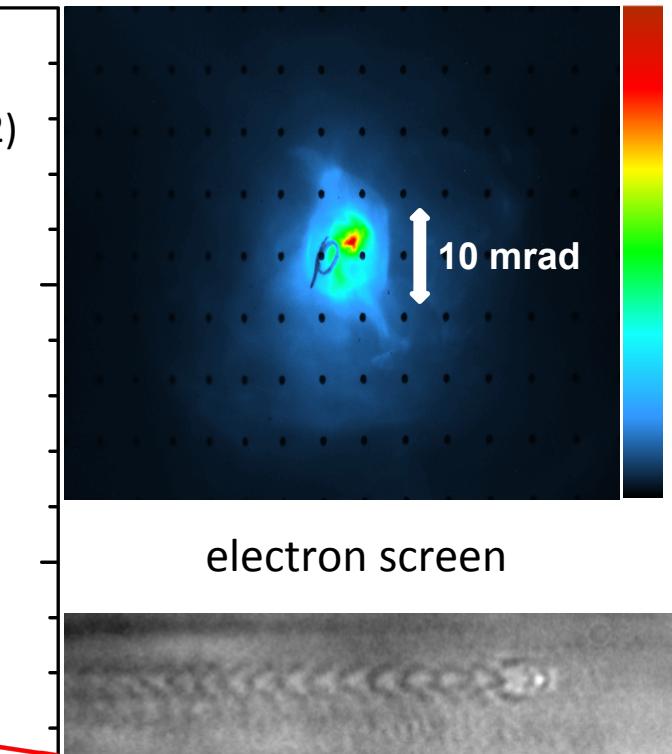
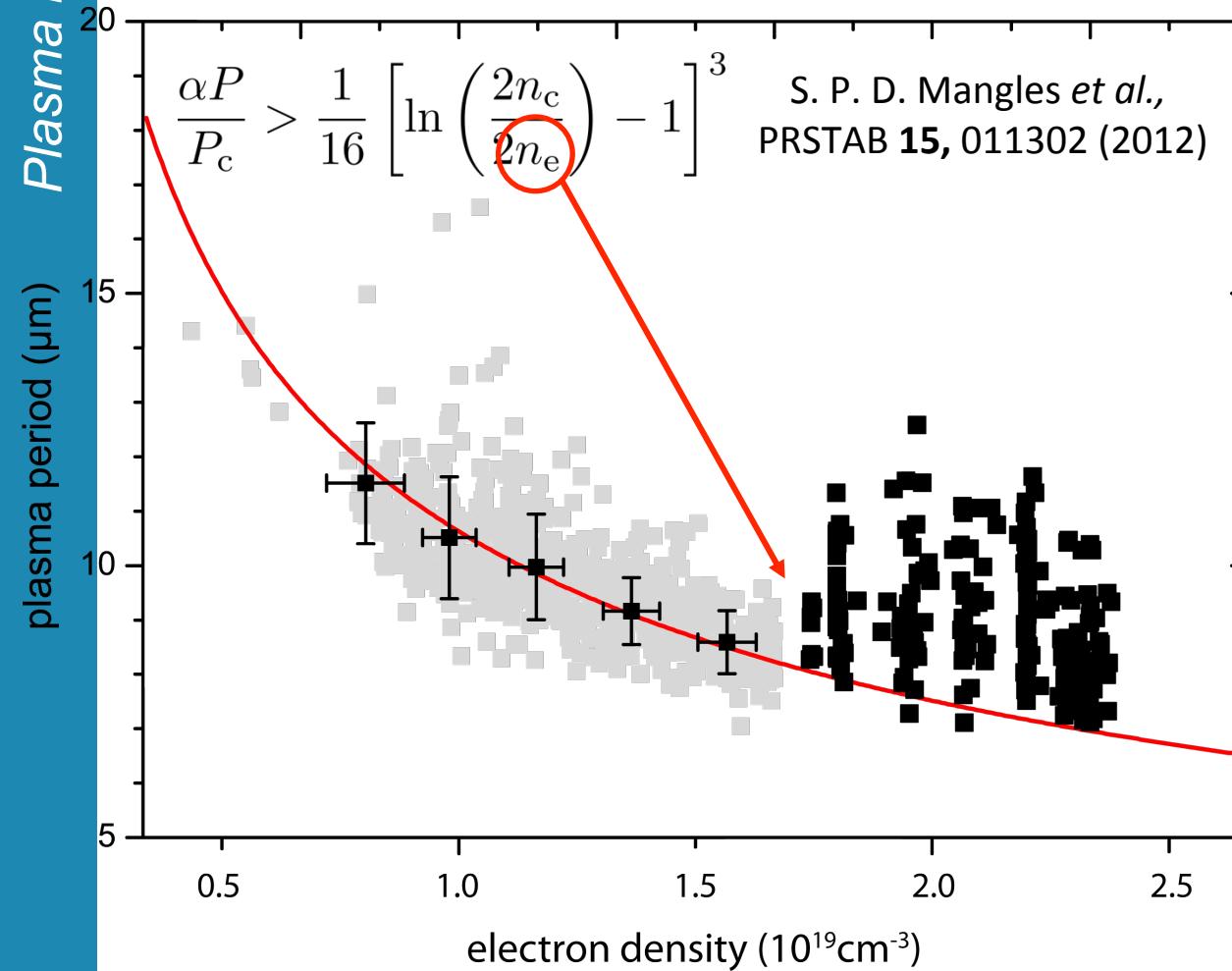
- Length of 2<sup>nd</sup> plasma period vs. density after  $\sim 1.1$  mm propagation



# Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

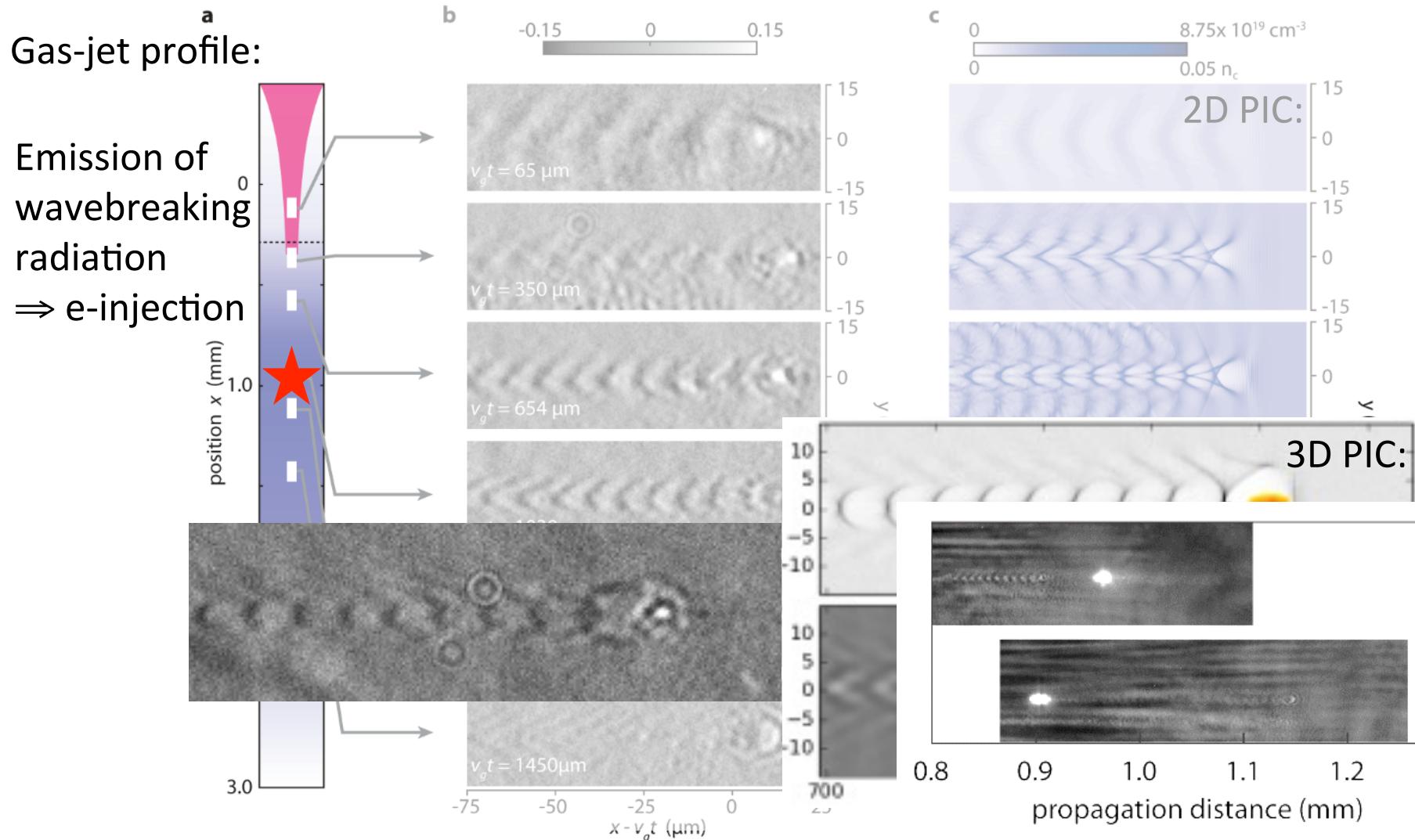
- Length of 2<sup>nd</sup> plasma period vs. density after  $\sim 1.1$  mm propagation



Above threshold: increase of  $\lambda_p$  (beam loading)

# Electromagnetic Probe Pulses

## Probing of plasma wakefield acceleration process

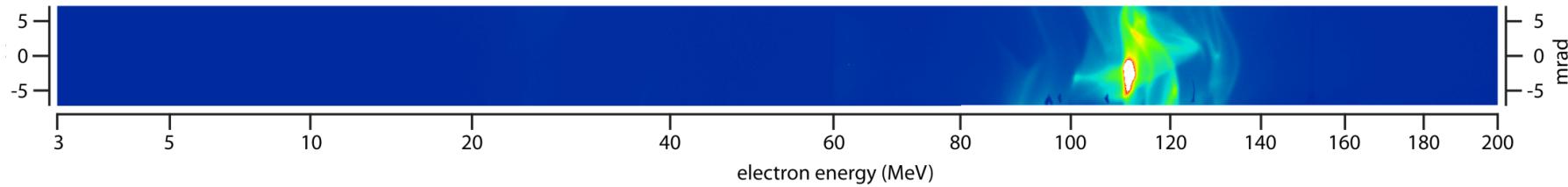
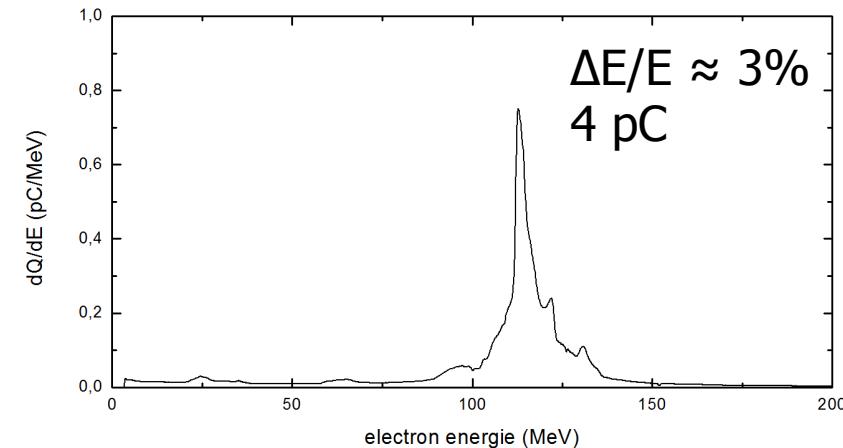
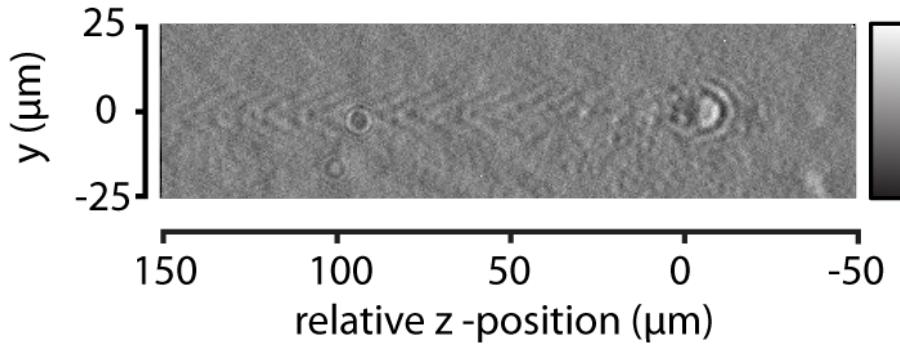


A. Sävert et al., arXiv 1402.3052

# Electromagnetic Probe Pulses

## Probing of plasma wakefield acceleration process

- After plasma wave evolution into single bubble:



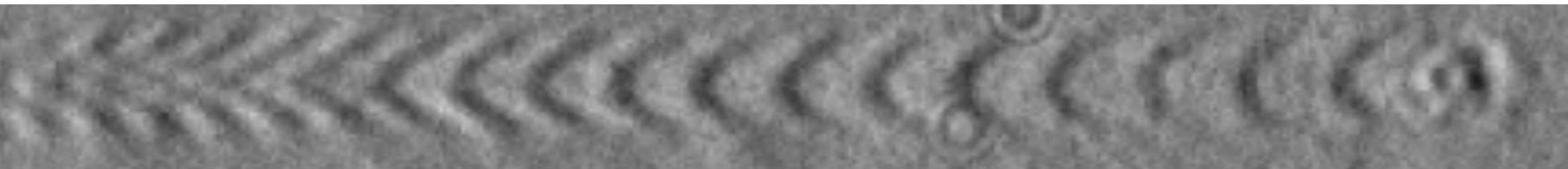


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# Electromagnetic Probe Pulses

Probing of plasma waves at lower background densities

- when reducing  $n_e$



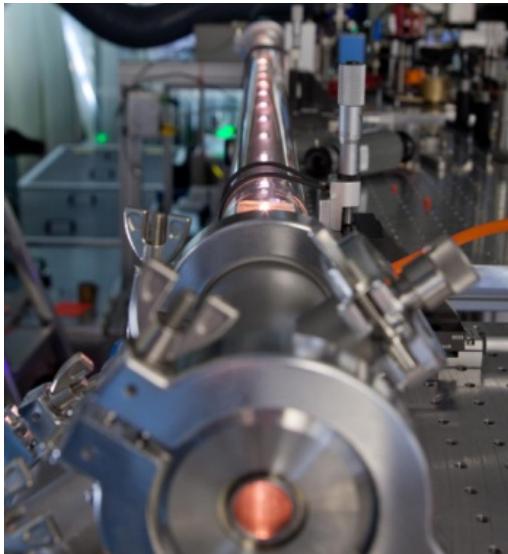
- plasma wave length  $\lambda_{pl}$  increases (less spatial resol. required)  
but diagnostics' sensitivity ( $\sim \lambda_{pr}/\lambda_{pl}$ ) needs to remain constant
- ⇒ use synchronized **few-cycle mid-IR pulses**,  
adapt diagnostic components (lenses, cameras, polarizers,...)

# Electromagnetic Probe Pulses

Probing of plasma waves at lower background densities

**near-IR:**  $\lambda_{\text{pr}}$  @ 800 nm

spectral broadening  
+ compression



synchr. few-cycle, **near-IR probe**

**works @  $n_e = 0.5 \dots 1 \times 10^{19} \text{ cm}^{-3}$**

M. Schwab et al., APL 103, 191118 (2013)

**mid-IR:**  $2 \mu\text{m} \leq \lambda_{\text{pr}} \leq 10 \mu\text{m}$

shift  $\lambda_{\text{pr}}$   
(+ amplification in an OPA)  
+ spectral broadening  
+ compression



synchr. few-cycle, **mid-IR probe**

**works @  $n_e = 3 \times 10^{16} \dots 1 \times 10^{18} \text{ cm}^{-3}$**

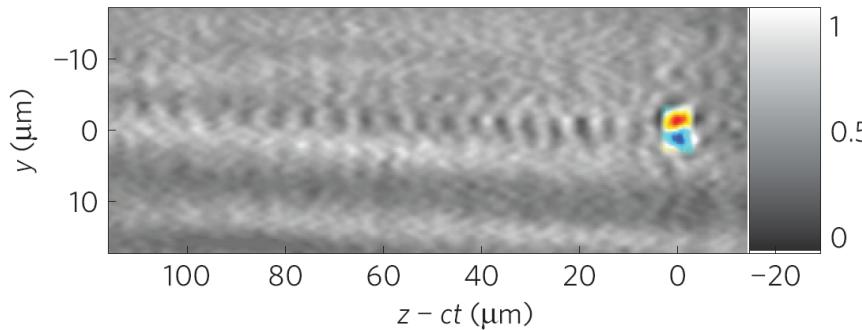
# Electromagnetic Probe Pulses

Probing of plasma waves at lower background densities

- when reducing  $n_e$



- plasma wave length  $\lambda_{pl}$  increases (less spatial resol. required)  
but diagnostics' sensitivity ( $\sim \lambda_{pr}/\lambda_{pl}$ ) needs to remain constant
- ⇒ use synchronized **few-cycle mid-IR pulses**,  
adapt diagnostic components (lenses, cameras, polarizers,...)
- ⇒ probe electrons' B-fields in plasma using Faraday-effect:

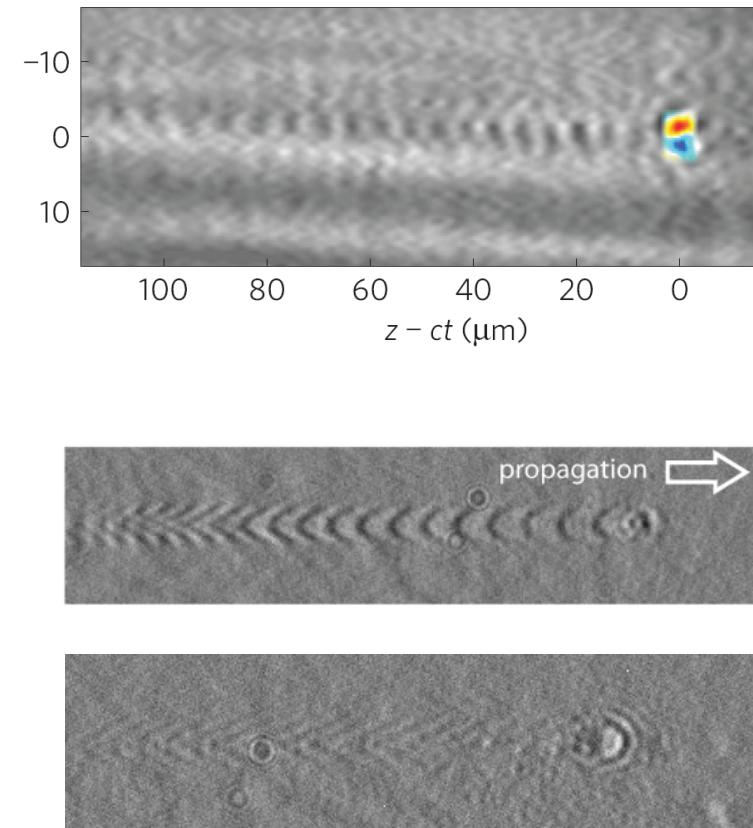


⇒ High-resolution diagnostic for  
**visualization of wake field** and for  
**synchronization** of e-bunch and driver  
for external injection

A. Buck et al., Nature Phys. 7, 543 (2011)

# Conclusions

- Probing diagnostics reveal detailed insight into laser-plasma accelerators
  - Electromagnetic pulses can be used to deduce density and accelerating field distributions in the plasma
  - Study non-linear evolution of plasma wave  
⇒ quantitative information about acceleration details
  - Use of these diagnostics might help to overcome current issues of plasma accelerators (stability/reproducibility) in the future
- ⇒ Further improve plasma diagnostics, their applicability and their resolution in the future!





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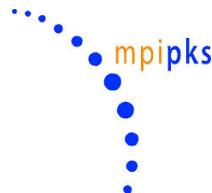
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Helmholtz-Institut Jena



Imperial College  
London



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