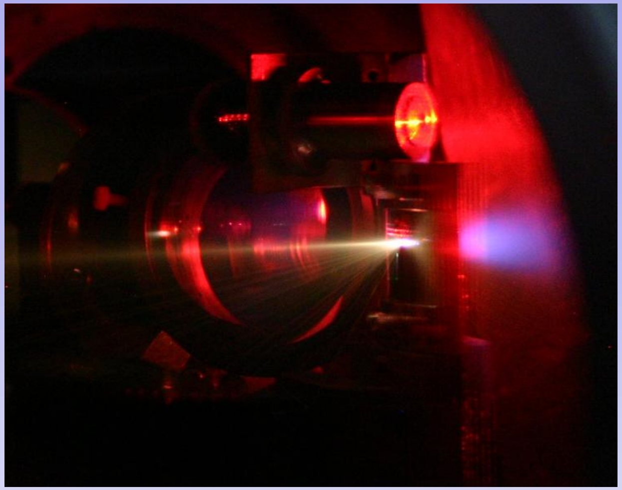
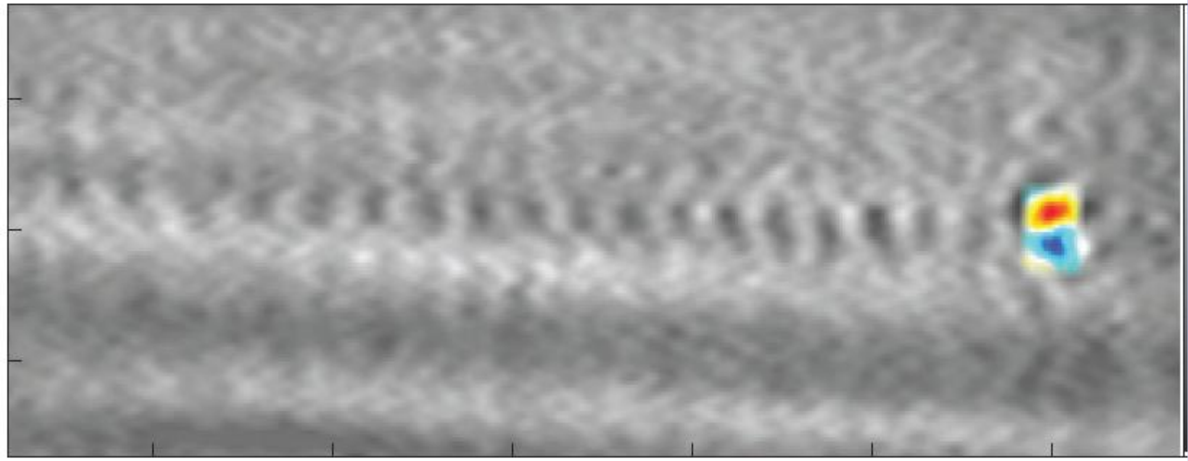
Optical Probing of Laser-Driven Electron-Acceleration





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Outline and Motivation

- Characterize laser-driven electron acceleration:
  - physics underlying the acceleration process: „Laser-Wakefield Acceleration“
  - parameters of the electron pulses: energy spectrum, pulse duration
  - study electron acceleration „in-situ“: visualize the bunch formation

Laser-Driven Electron Acceleration

- Interaction of a high-intensity laser pulse with plasma
  $\Rightarrow$ generation of a plasma wave via its ponderomotive force

Laser-Driven Electron Acceleration

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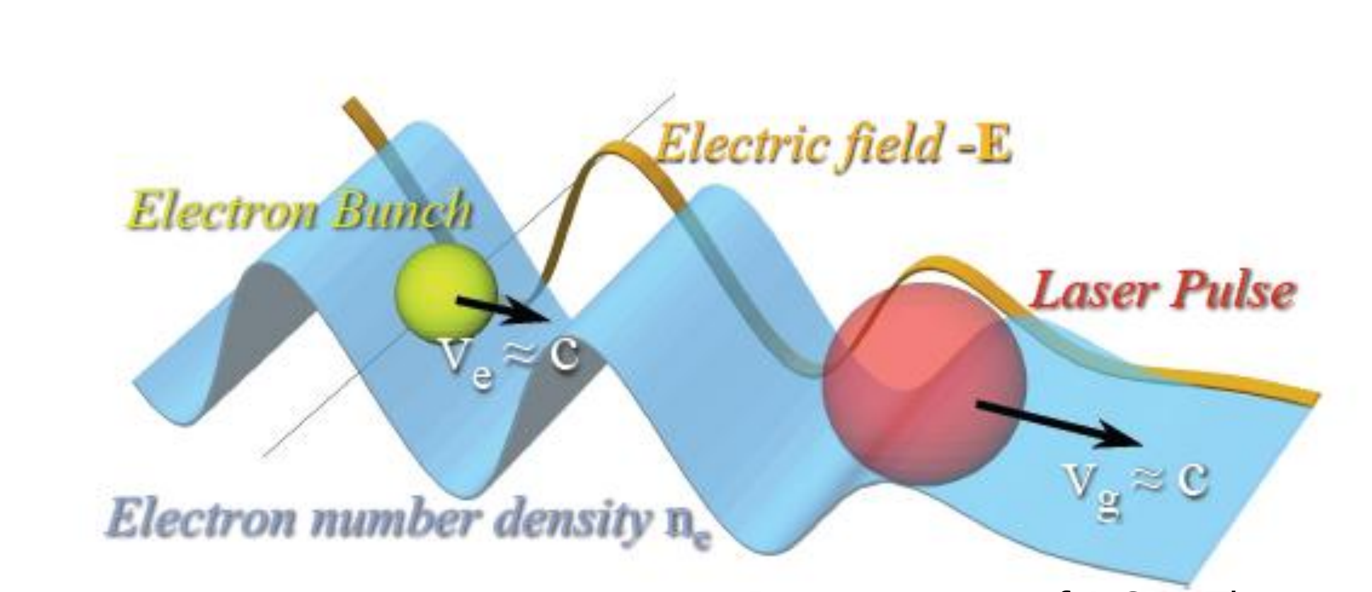


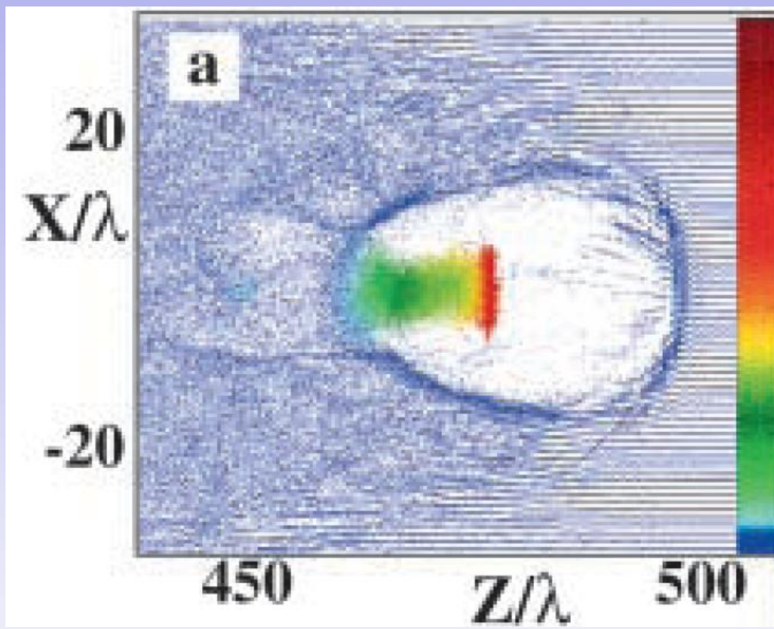
Image courtesy of A.G.R. Thomas

- Plasma wave ($v_{ph,plasma} = v_{gr,laser}$) ≡ modulation of n_e with respect to ion background,

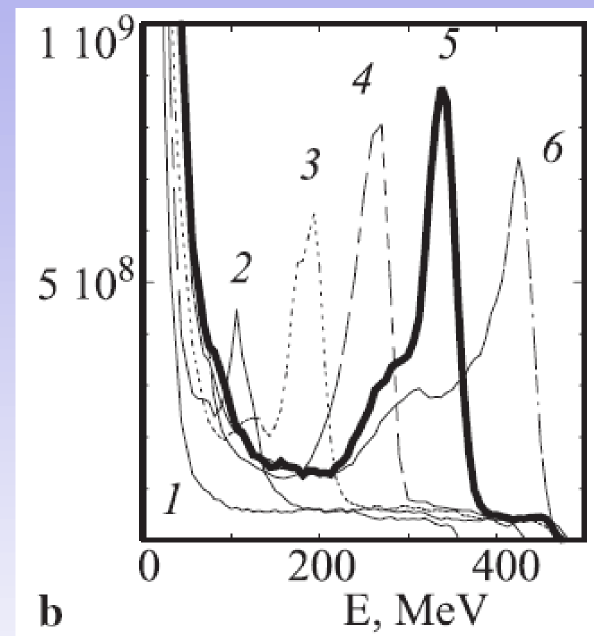
⇒ Very strong local charge separation,

⇒ Very strong longitudinal E-field (~ 0.1...1 TV/m)

- When plasma wave breaks, it forms a "bubble-like" plasma cavity
- Electrons are injected into the bubble and are accelerated to relativistic energies exhibiting quasi-monoenergetic spectra

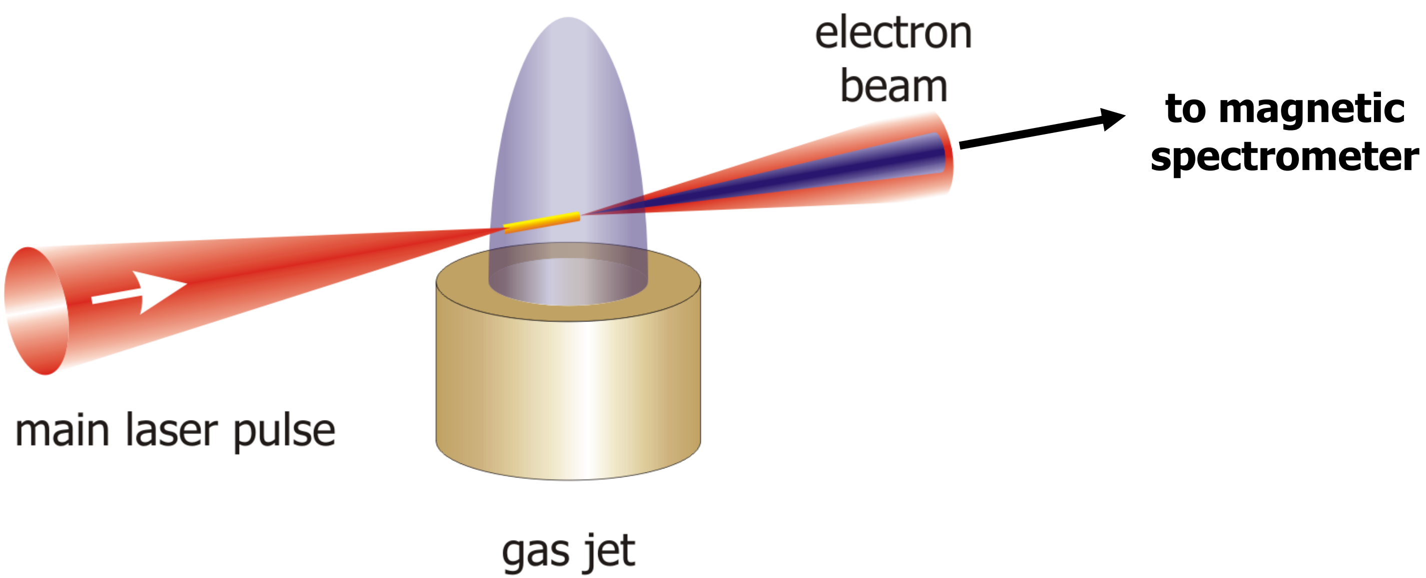


A. Pukhov and J. Meyer-ter-Vehn, APB (2002)



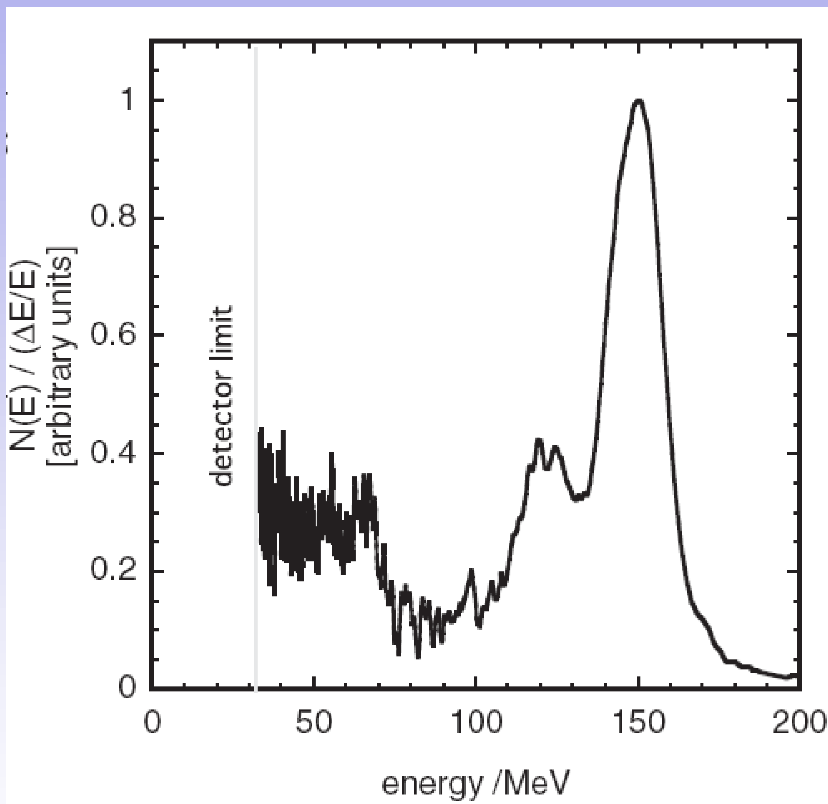
- First experimental verification: S.P.D. Mangles *et al.,* J. Faure *et al.,* C.G.R. Geddes *et al.,* Nature (2004)

Experimental Setup



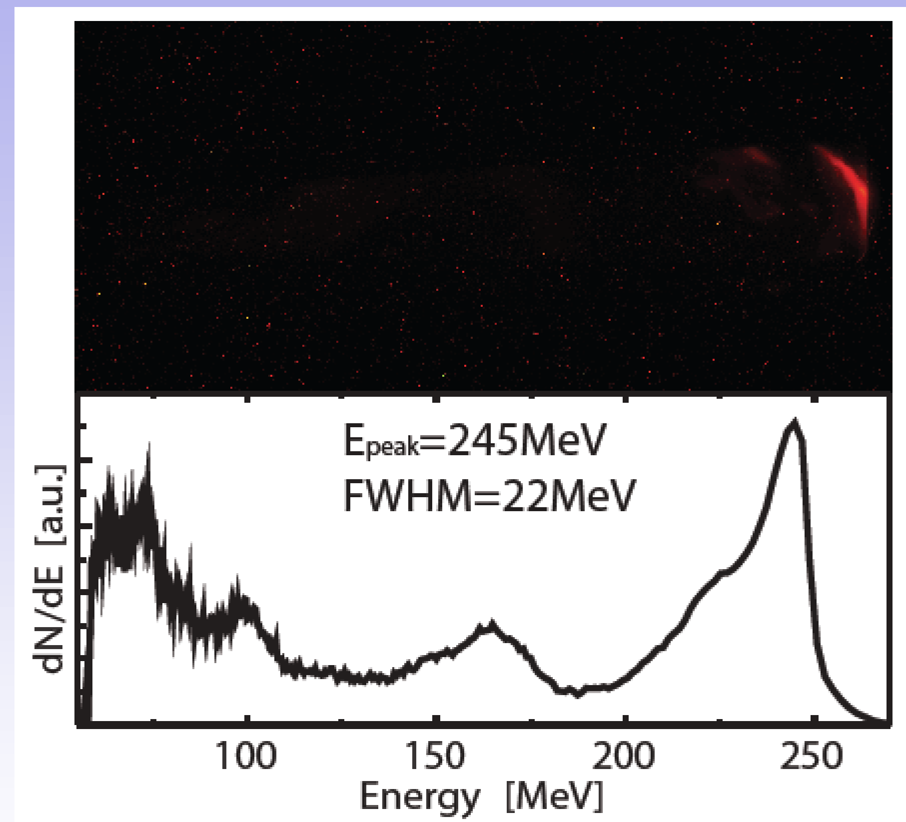
Results: Monoenergetic Spectra

- Previous experiments in Lund, Sweden in 2005/06 (τ_L=32 fs, E_L=600 mJ):



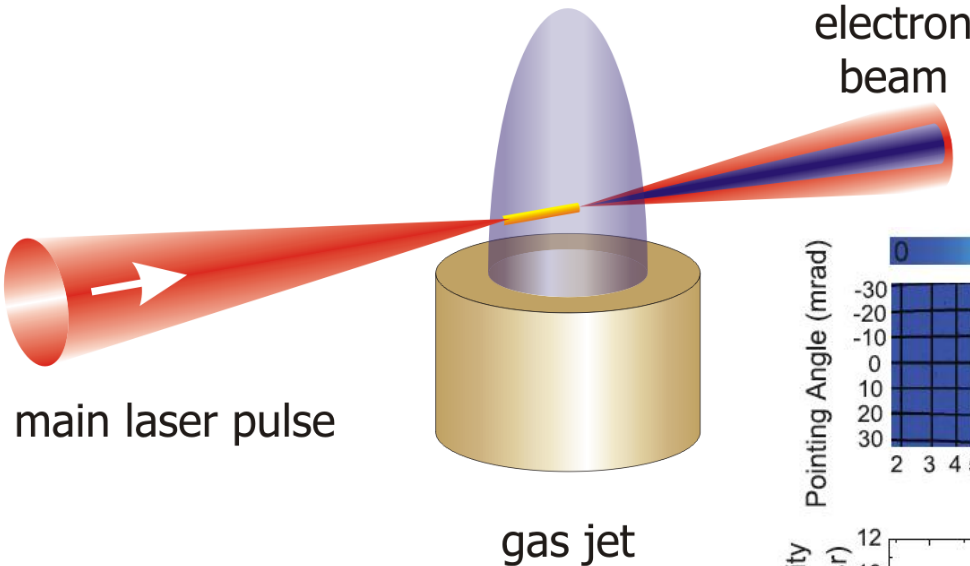
S. P. D. Mangles, A. G. R. Thomas, MCK *et al.*, Phys. Rev. Lett. **96,** 215001 (2006)

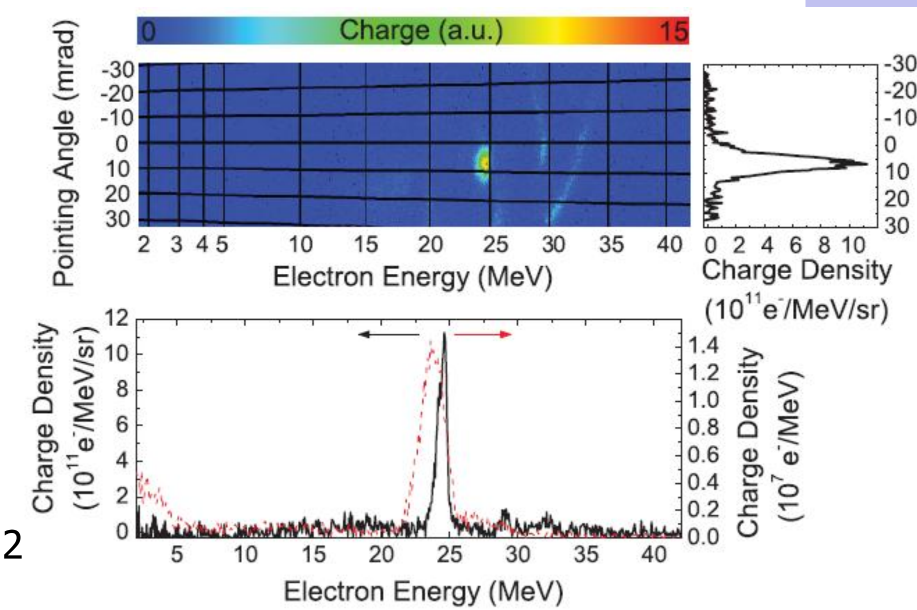
- Recent experiment with JETI, (τ_L=30 fs, E_L=800 mJ, gas-jet optimized, gas dependence):



A. Sävert, M. Nicolai, M. Schnell, MCK *et al.*, under preparation (2011)

Experimental Setup



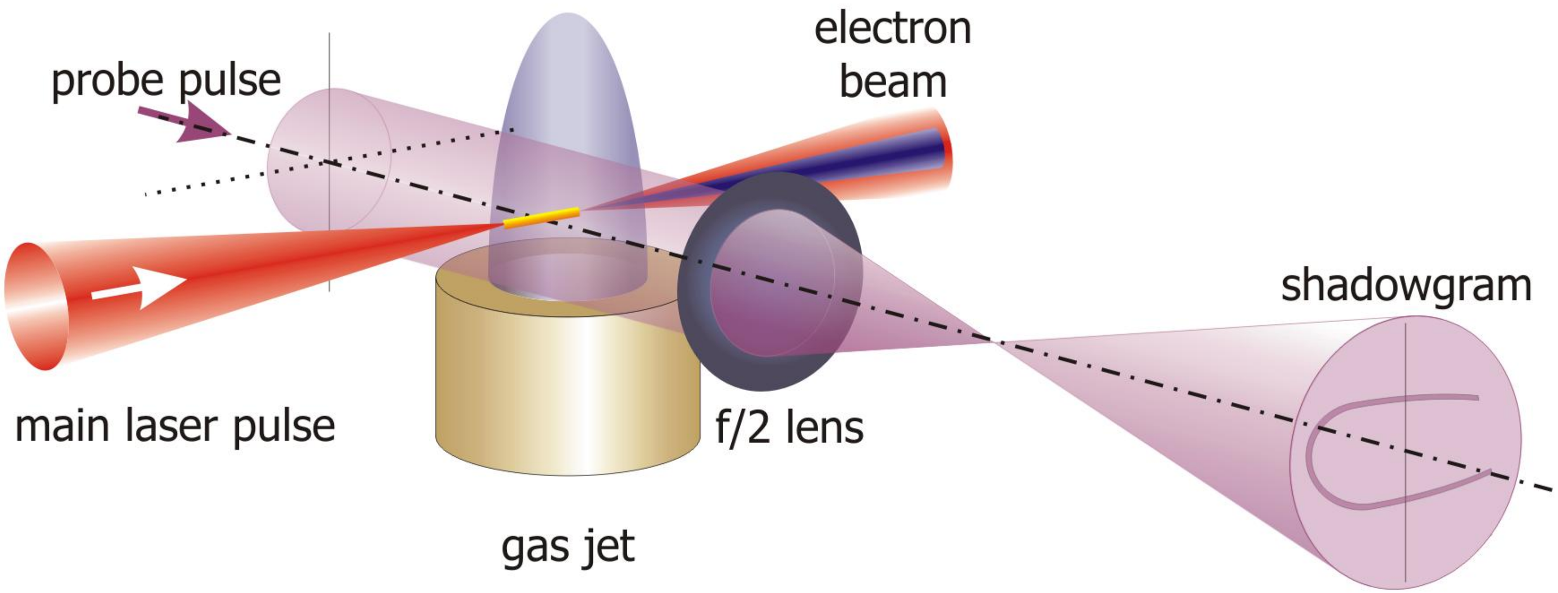


<u>LWS-20 laser parameters:</u>

E_{laser} = 80 mJ, τ_{laser} = 8.5 fs,
f/6 OAP, $I_{laser} \approx 6\times10^{18}$ W/cm^2

K. Schmid *et al.,* Phys. Rev. Lett. **102,** 124801 (2009)

Experimental Setup



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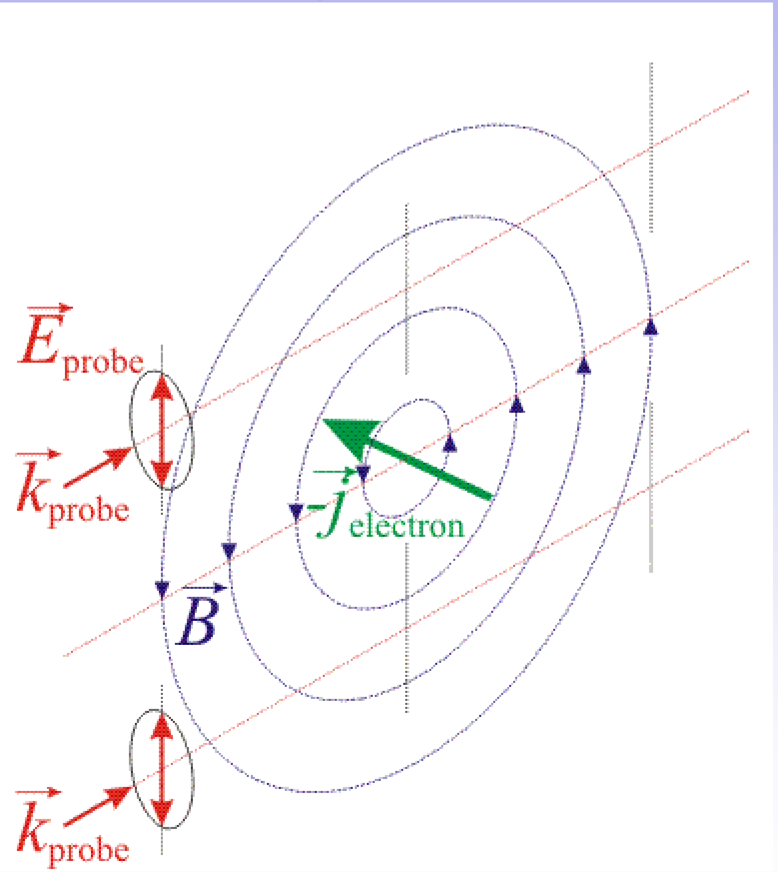
<u>probe pulse:</u>

$\tau_{probe} \approx$ 8.5 fs, λ_{probe} = 800 nm

Faraday-Rotation

- 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 η for circularly-polarized probe components



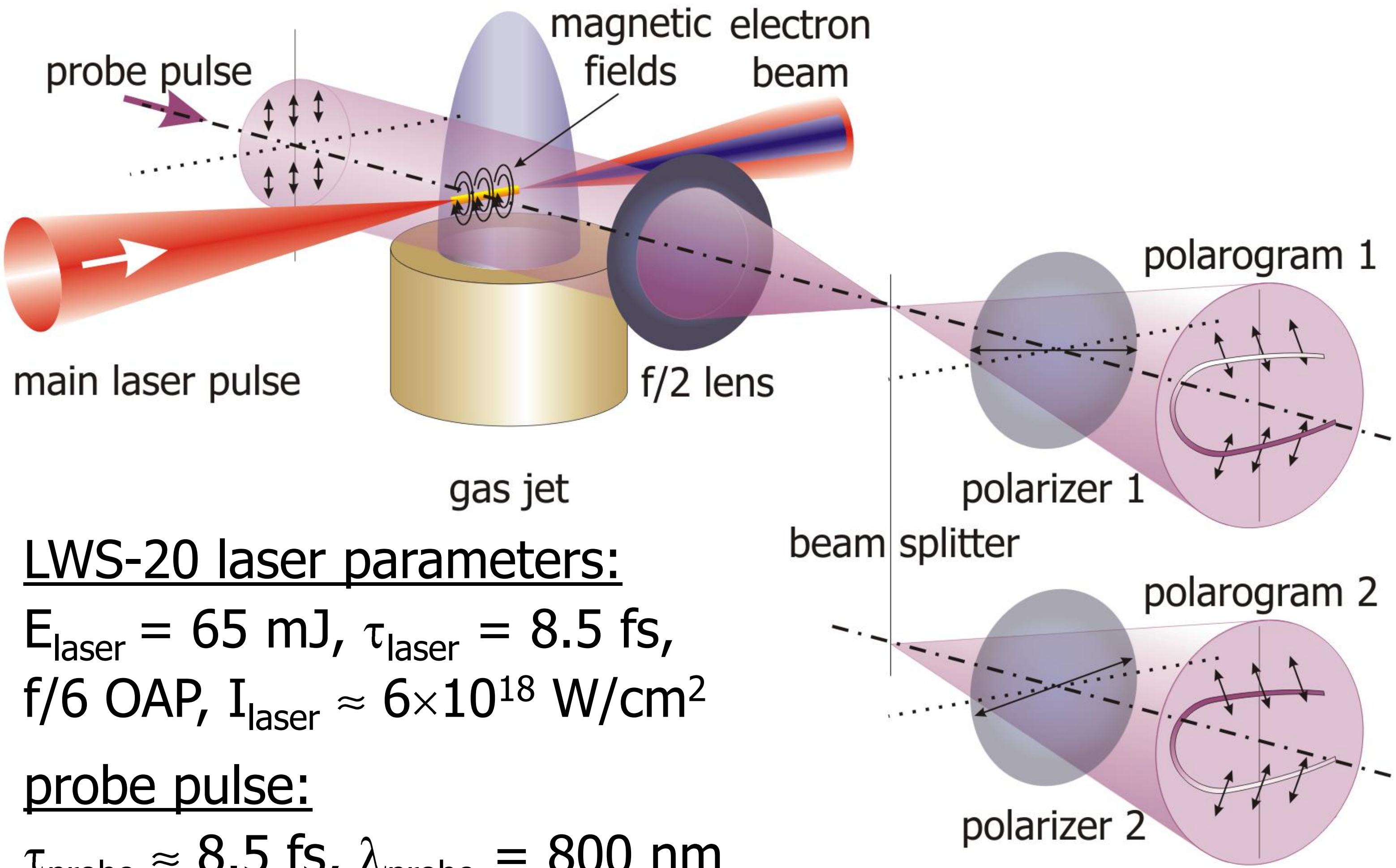
$\Rightarrow$ rotation of probe polarization:

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

$\Rightarrow$ measure ϕ_{rot} to get signature of B-fields!

J. Stamper *et al.* Phys. Rev. Lett. (1975)

Experimental Setup



<u>LWS-20 laser parameters:</u>

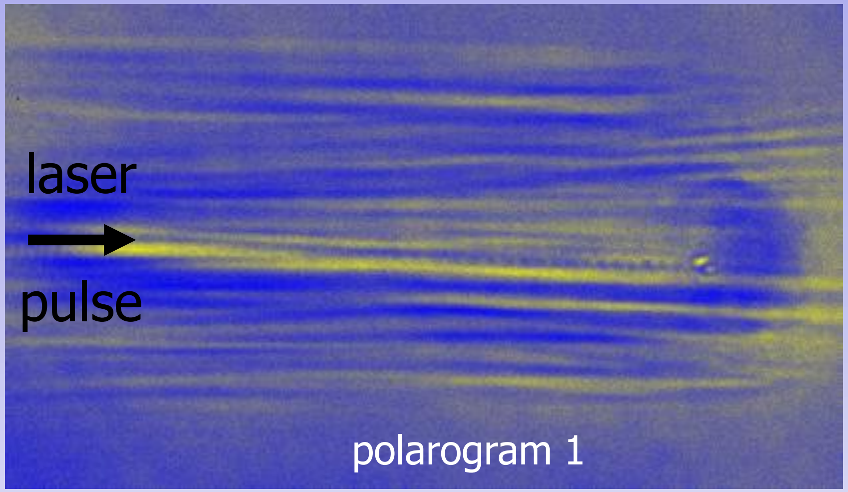
E_{laser} = 65 mJ, τ_{laser} = 8.5 fs,
f/6 OAP, $I_{laser} \approx 6\times10^{18}$ W/cm^2

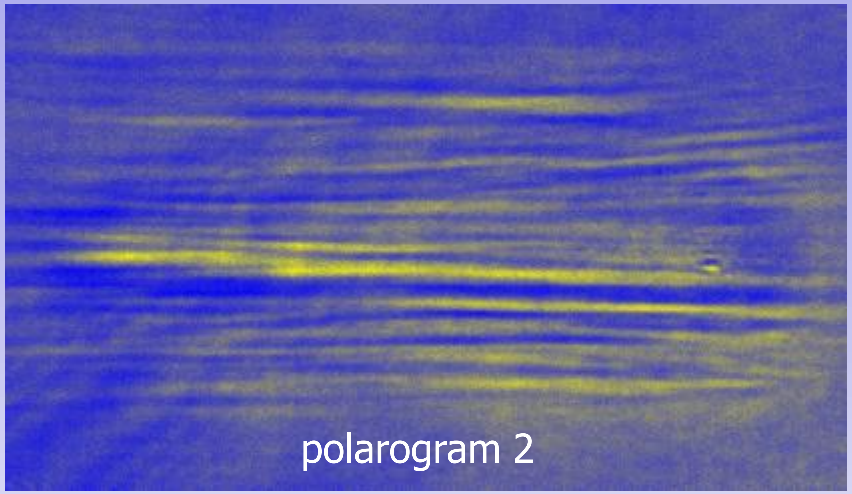
<u>probe pulse:</u>

$\tau_{probe} \approx$ 8.5 fs, λ_{probe} = 800 nm

Results: Faraday-Rotation

Two polarograms from two (almost) crossed polarizers:





$$I_{\mathrm{pol}1} = I_0[1 - \beta_1 \sin^2(90° - \theta_{\mathrm{pol}1} - \phi_{\mathrm{rot}})]$$

$$I_{\mathrm{pol}2} = I_0[1 - \beta_2 \sin^2(90° + \theta_{\mathrm{pol}2} - \phi_{\mathrm{rot}})]$$

Results: Faraday-Rotation

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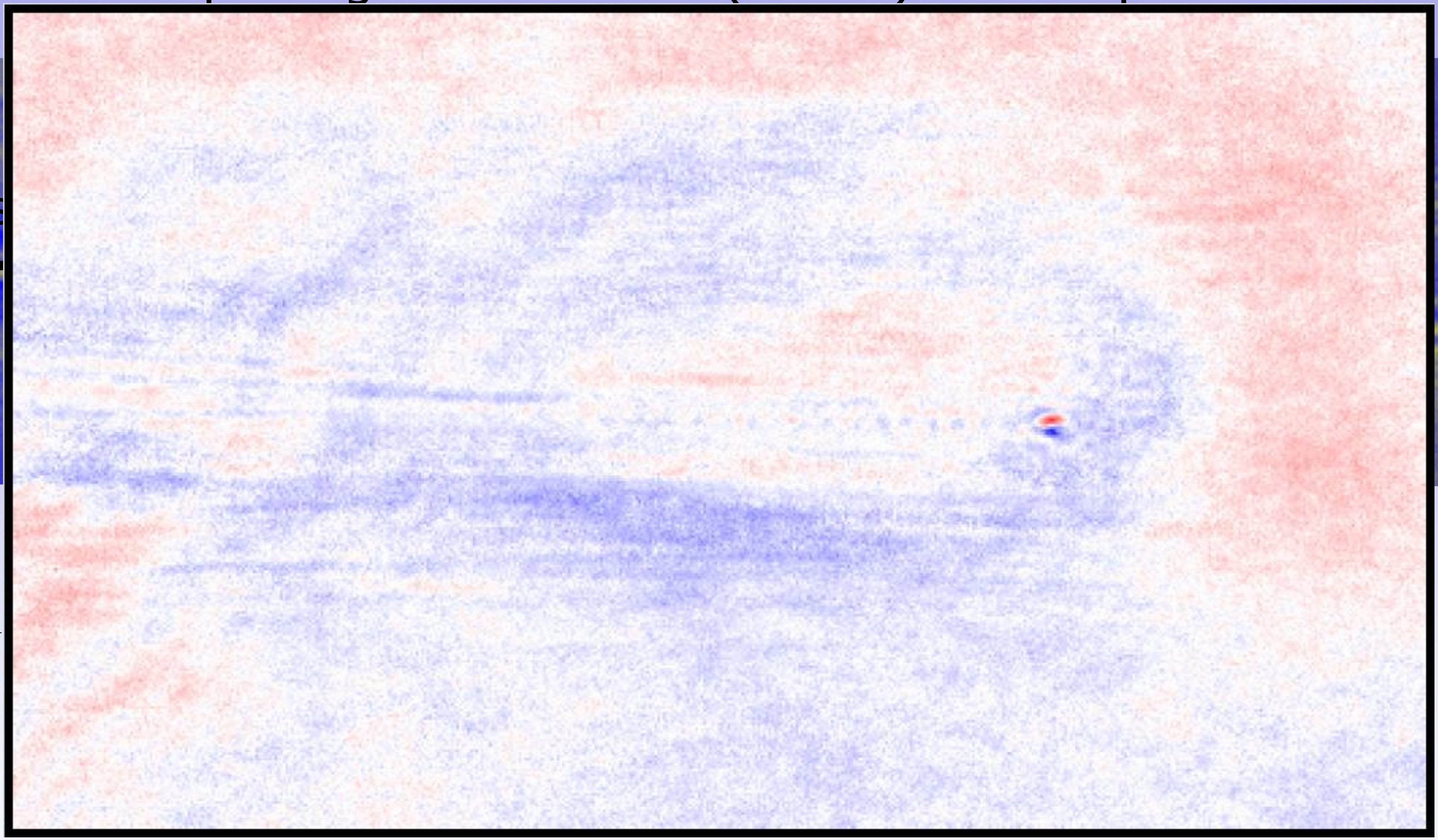

$$I_{pol1}(x,y)/I_{pol2}(x,y)$$

Results: Faraday-Rotation

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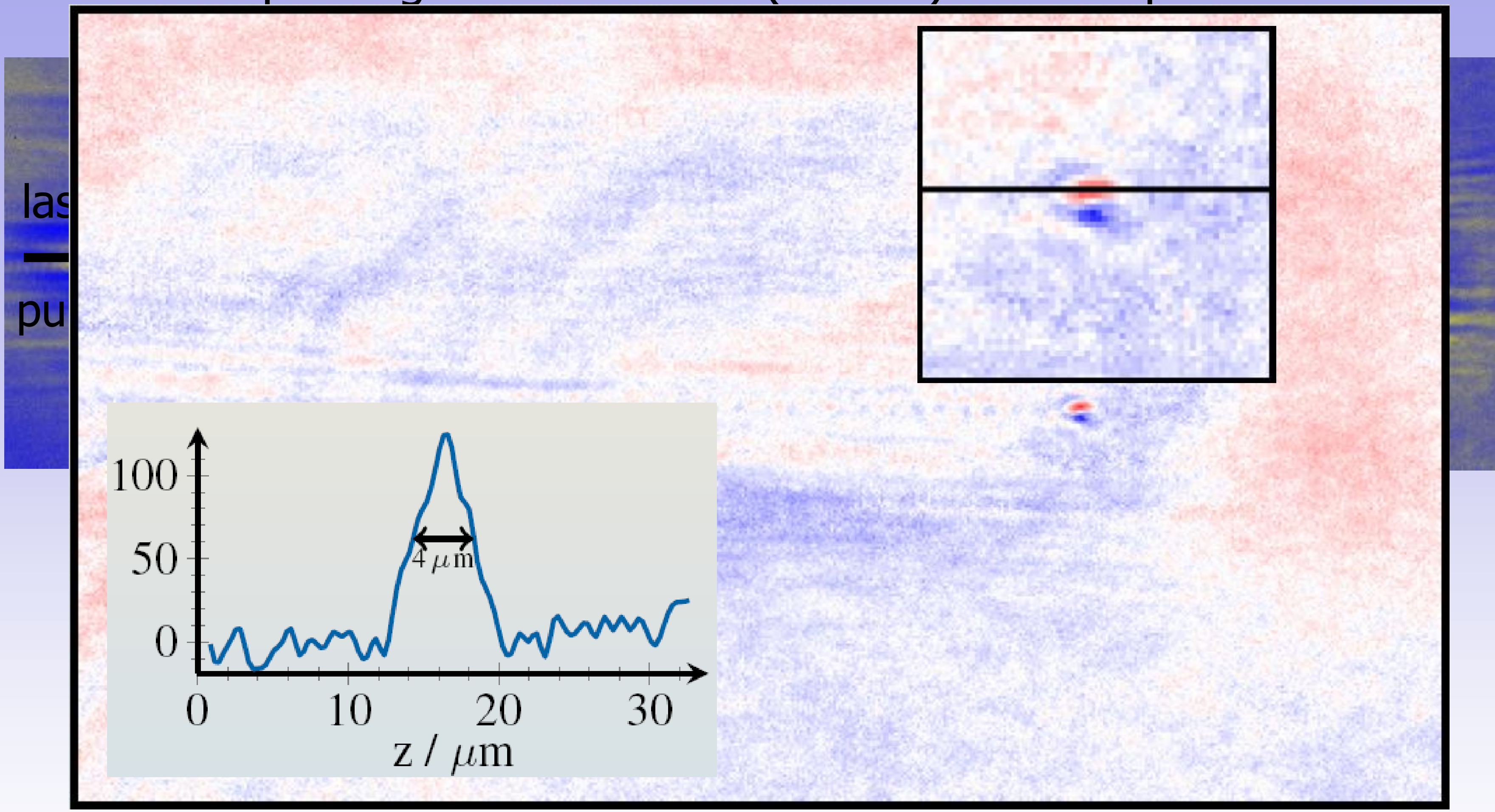
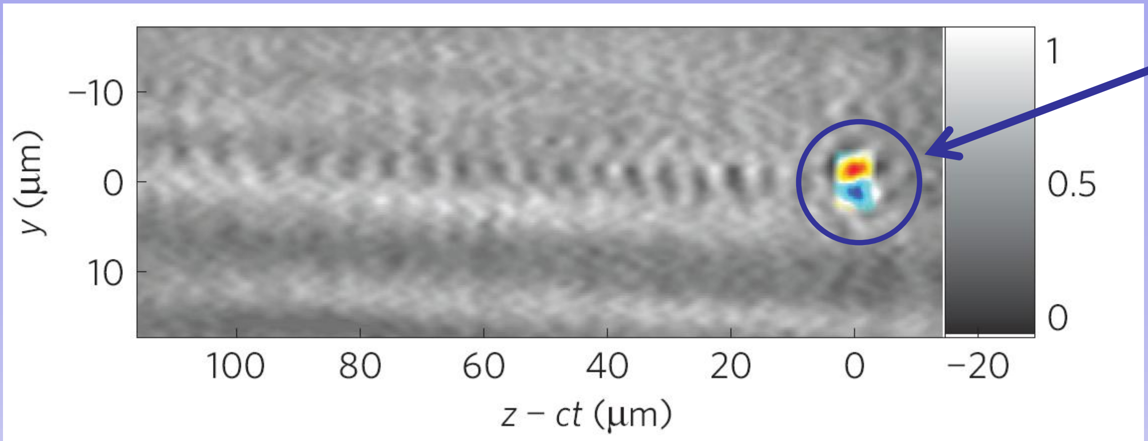
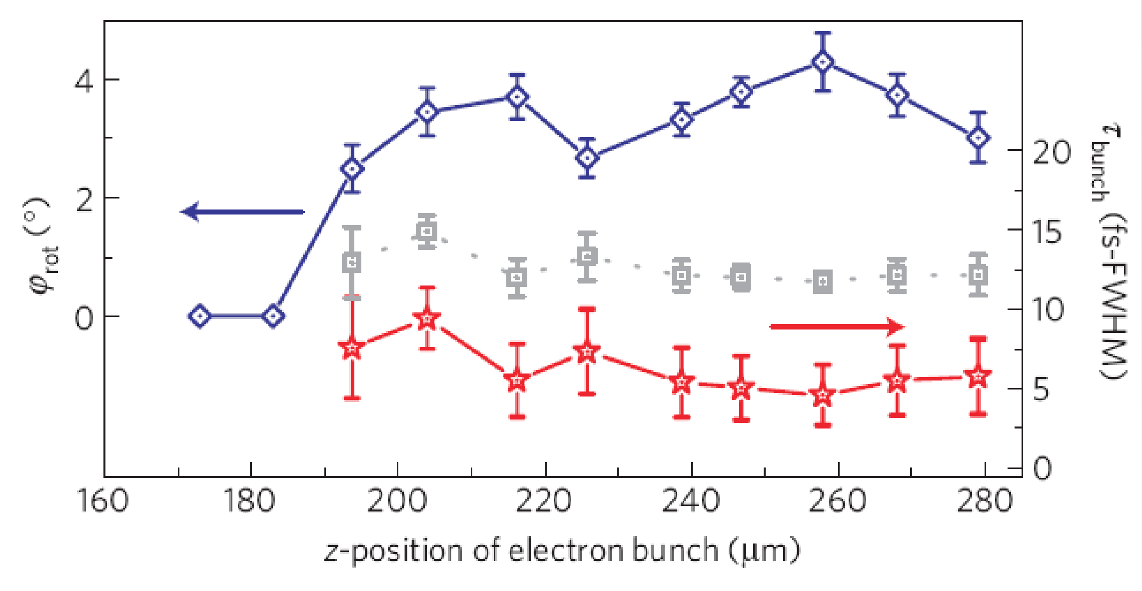


<u>Electron bunch length:</u>

$\Delta z = 4\ \mu m \Rightarrow \Delta\tau = 13\ fs \Rightarrow$ **$\Delta\tau_{deconvolved} = (6 \pm 2)\ fs$**

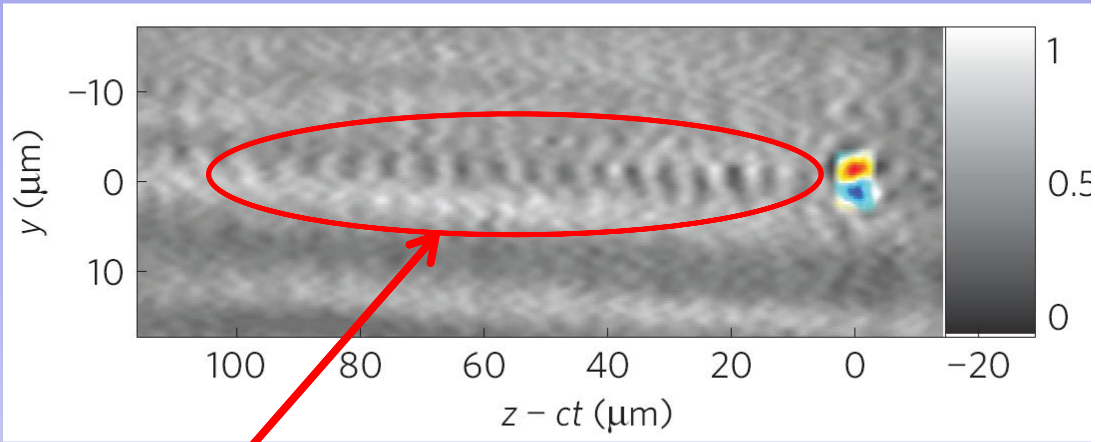
Visualization of e-Bunch Formation

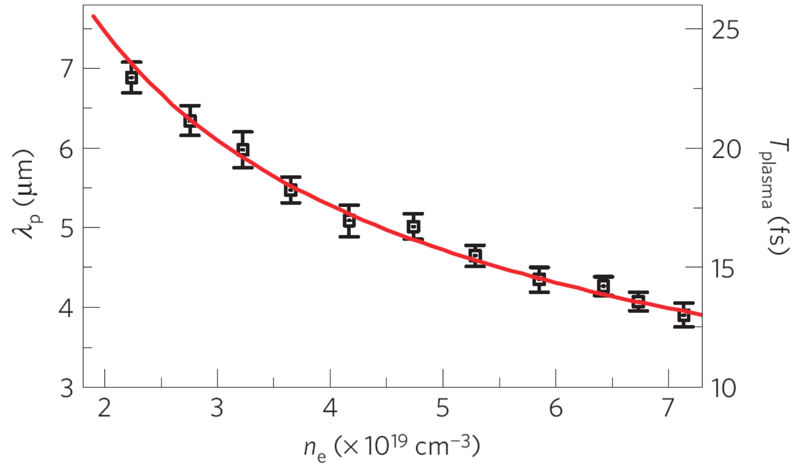


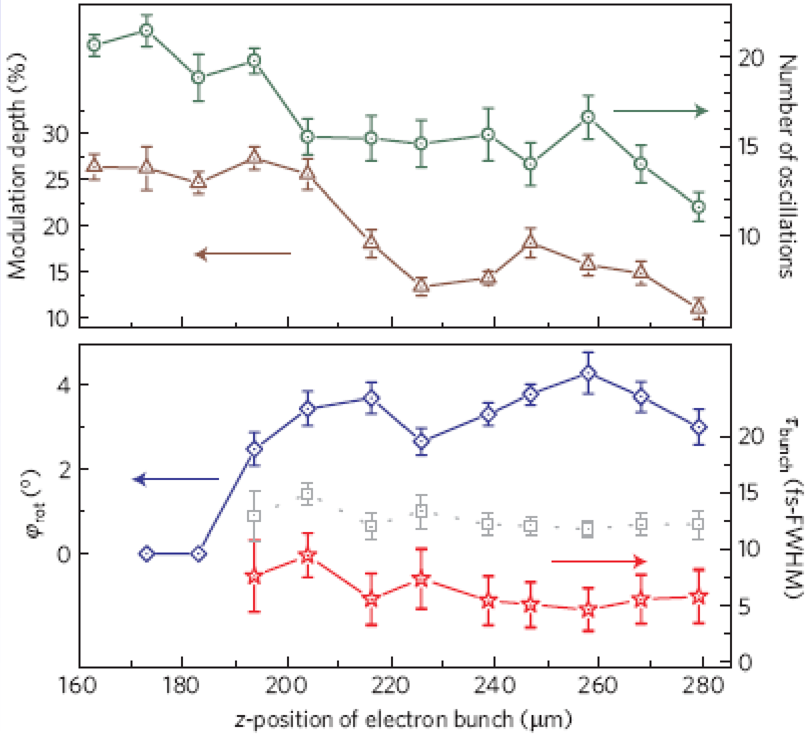


- **Polarimetry:** visualize e-bunch via associated B-fields
- change delay between pump and probe $\Rightarrow$ movie of e-bunch formation
- observe electron acceleration on-line!

Visualization of the Plasma Wave







- Shadowgraphy:
  visualize plasma wave
- change electron density
  ⇒ plasma wavelength changes

$$\lambda_p = cT_p = \frac{2\pi c}{\omega_p} = 2\pi c\sqrt{\frac{\varepsilon_0 m_e}{n_e e^2}}$$

- after injection:
  ⇒ plasma wave amplitude and number of oscillations reduces

Conclusions

- Measurement of B-field distributions during laser-driven electron acceleration in underdense plasma using Faraday-effect
- Highly localized B-field structures:

  v_{struct} ~ $v_{group,L}$, closely following main pulse

  τ_{struct} ~ (6 ± 2) fs
- Signature of electron bunch,
  visualization of the electron acceleration process,
- Direct time-resolved observation evolution of the plasma wave and its evolution
- Reduction of plasma wave amplitude observed after injection
- Position of the accelerated electron bunch within the first period of the plasma wave

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