Laser-driven electron acceleration – how to get insight into the acceleration process

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Outline

1. Laser wakefield acceleration
   - Theory and setup of the experiment
   - the JETI laser system
2. Influence of experimental parameters on electron stability
   - Laser energy, plasma density, pulse duration, pulse front tilt
   - Spectra of the electrons
3. Optical probing of the acceleration process
   - Polarimetry and Faraday effect
   - Light Wave Synthesizer 20
4. Visualization of the acceleration process
   - Duration of the electron bunches
   - Plasma wave

Laser wakefield acceleration

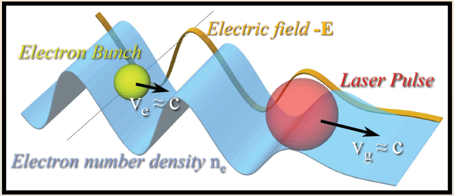


Image courtesy of A. G. R. Thomas

idea

T. Tajima *et al.*, PRL 43 (1979)

monoenergetic electrons

J. Faure *et al.*, C. G. R. Geddes *et al.*, S. P. D. Mangles *et al.*, Nature (2004)

- laser intensity $> 10^{18}$ W/cm^2
- electron energy up to 1 GeV
- acceleration distance in the range of millimeters
- energy and pointing stability is still an issue

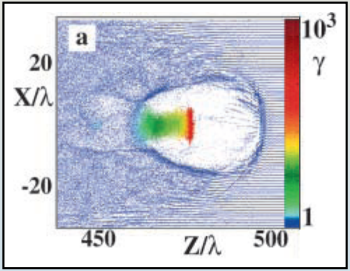
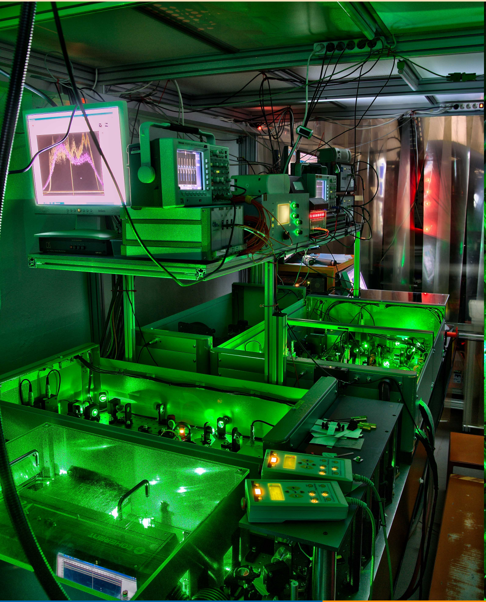
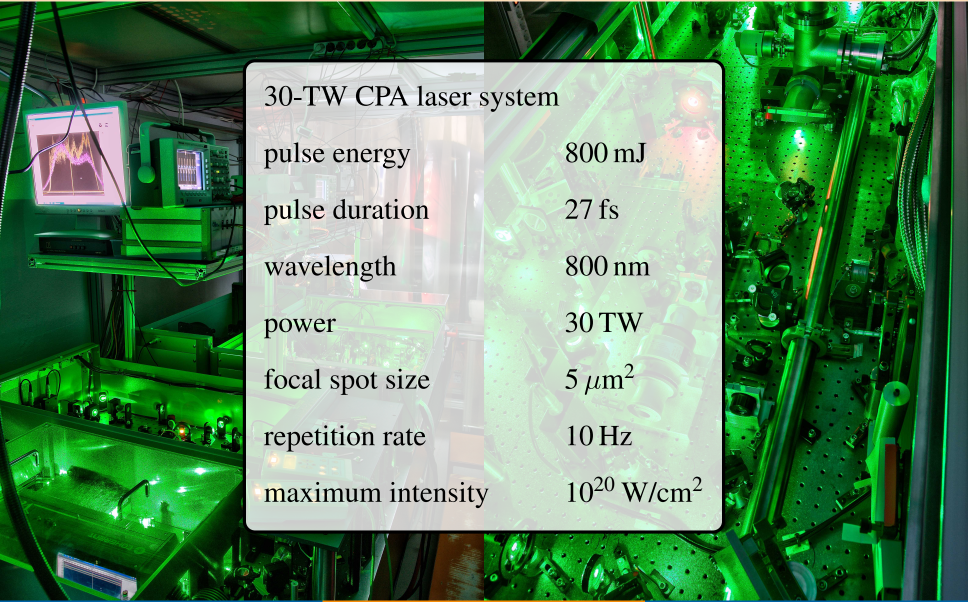


Image courtesy of A. Pukhov *et al.*, Appl. Phys. B 74 (2002)

JETI: the Jena Ti:Sapphire laser system



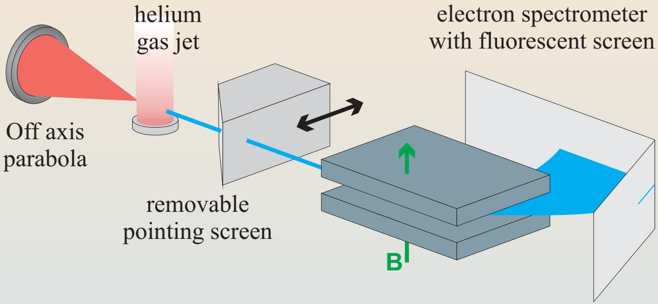
JETI: the Jena Ti:Sapphire laser system



30-TW CPA laser system

pulse energy	800 mJ
pulse duration	27 fs
wavelength	800 nm
power	30 TW
focal spot size	5 μm^2
repetition rate	10 Hz
maximum intensity	10^{20} W/cm^2

Setup for laser electron acceleration



JETI laser system

$$E_{\text{target}} = 700\,\text{mJ} \qquad \lambda_{\text{laser}} = 800\,\text{nm}$$

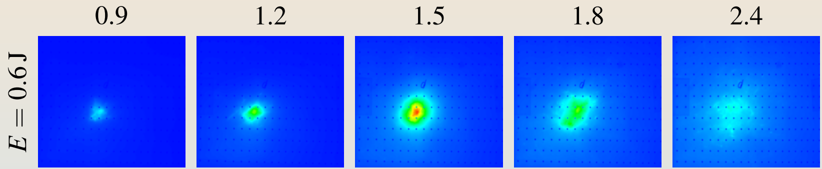
$$\tau_{\text{laser}} = 31\,\text{fs} \qquad f_{\text{rep}} = 10\,\text{Hz}$$

$$A_{\text{focus}} \approx 220\,\mu\text{m}^2 \qquad I_{\text{laser}} = 6 \cdot 10^{18}\,\text{W/cm}^2$$

Influence of laser energy and plasma density

averaged images of the electron beam profile

n_e / 10^{19} cm^{-3}



Influence of laser energy and plasma density

averaged images of the electron beam profile

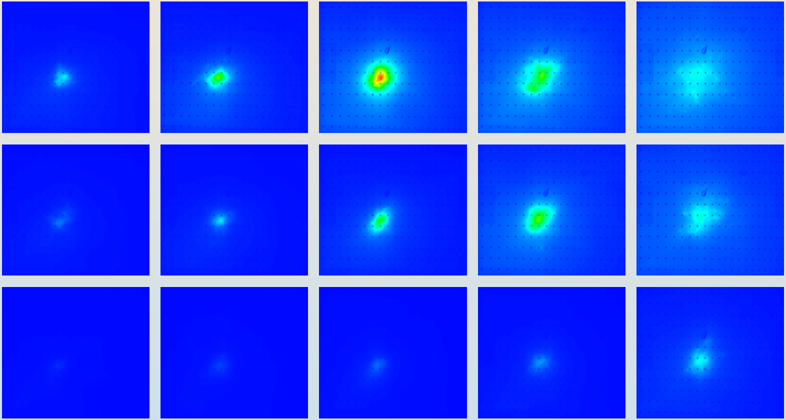
n_e / 10^{19} cm^{-3}

0.9 1.2 1.5 1.8 2.4

$E = 0.6$ J

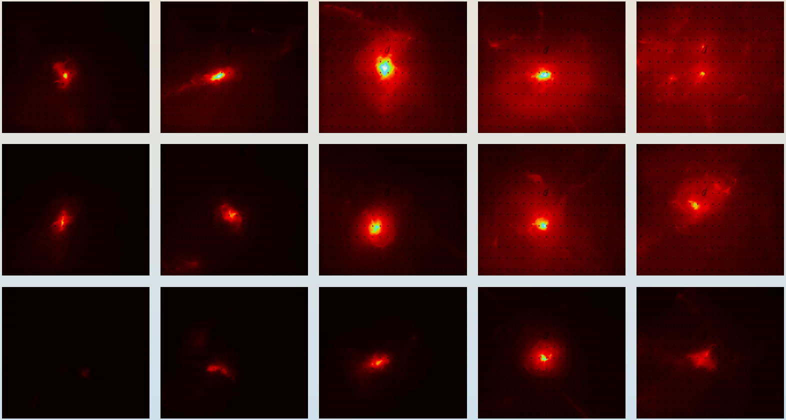
$E = 0.45$ J

$E = 0.3$ J

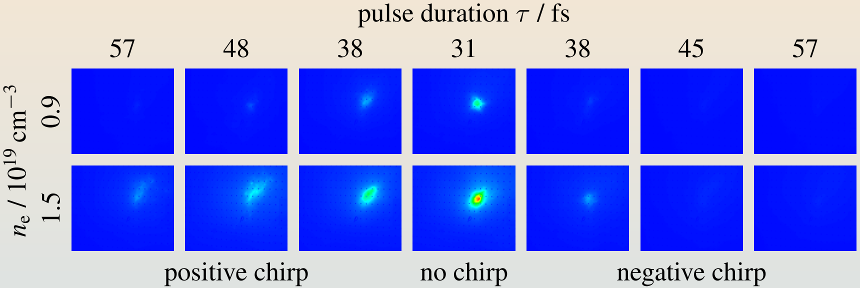


Influence of laser energy and plasma density

exemplary images for single shots



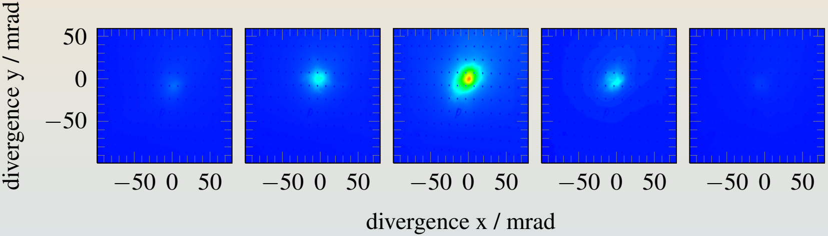
Influence of pulse duration



- best electrons for shortest pulse duration
- clear difference between positive and negative chirp
- high order dispersion influences pulse duration and shape

Influence of pulse front tilt

$C_{a,x}$	1.2 μrad/nm	0.3 μrad/nm	0 μrad/nm	-0.3 μrad/nm	-0.7 μrad/nm
α	0.9 mrad	0.2 mrad	0 mrad	-0.2 mrad	-0.5 mrad
$\Delta\tau_g$	184 fs	46 fs	0 fs	39 fs	105 fs



- electron beam parameters get worse even for a small pulse front tilt due to pulse elongation and an asymmetric acceleration structure

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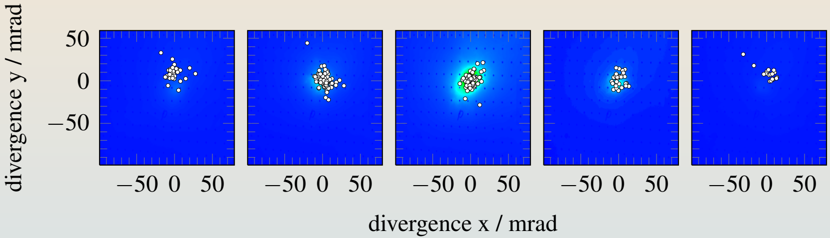
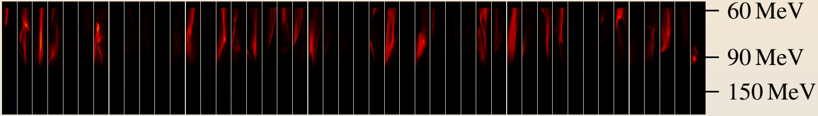
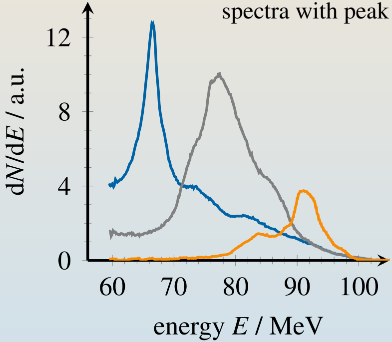
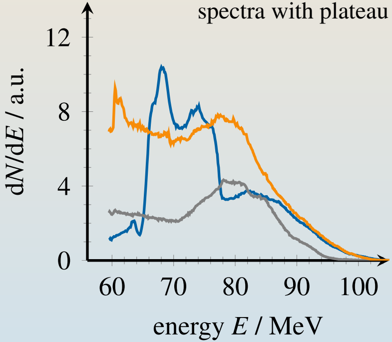


- electron beam parameters get worse even for a small pulse front tilt due to pulse elongation and an asymmetric acceleration structure
- no change in electron direction observable

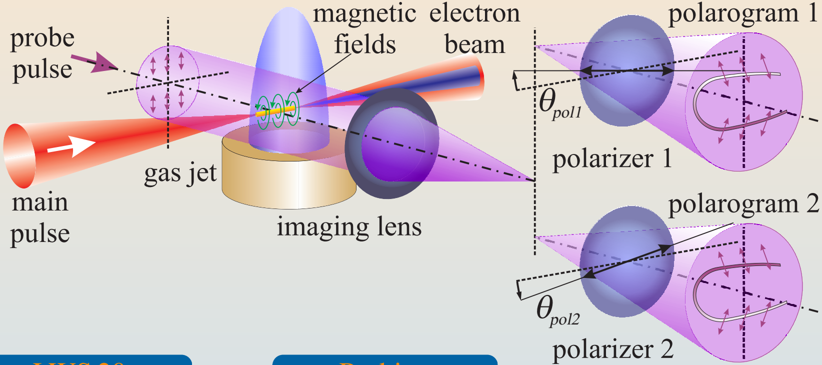
Spectra of the electrons







Plasma observation – Polarimetry



LWS 20

$E_{\text{target}} = 65\,\text{mJ}$

$\tau_{\text{laser}} = 8\,\text{fs}$

$I_{\text{laser}} = 6 \cdot 10^{18}\,\text{W/cm}^2$

Probing

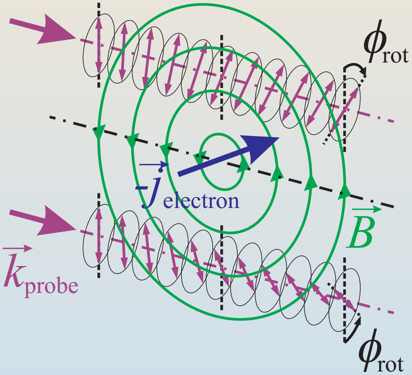
apochromatic objective	$f =$	$20\,\text{mm}$
achromatic lens	$f =$	$250\,\text{mm}$
resolution		$2\,\mu\text{m}$

Faraday effect

Observing the acceleration process directly requires diagnostics with high temporal und spatial resolution.

Faraday effect

- rotates the polarization of an electromagnetic wave in a magnetic field
- $$\phi_{\mathrm{rot}} = \frac{e}{2\, m_{\mathrm{e}}\, c} \int_{\mathrm{plasma}} \frac{n_{\mathrm{e}}}{n_{\mathrm{crit}}}\, \vec{B} \cdot \mathrm{d}\vec{l}$$
- the magnetic field can be calculated from ϕ_{rot} and n_{e} via Abel inversion



Light Wave Synthesizer 20 – LWS 20

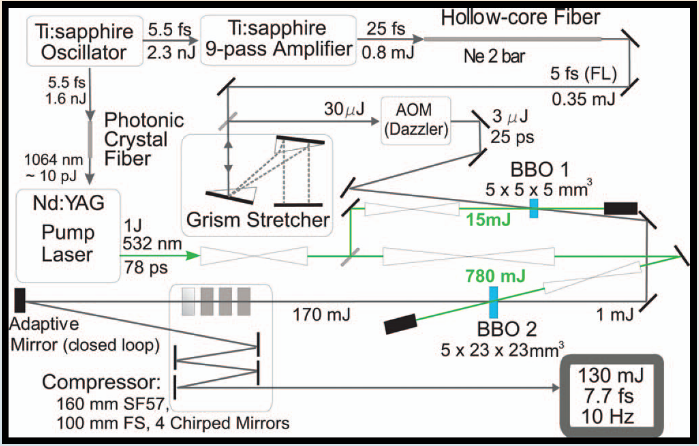
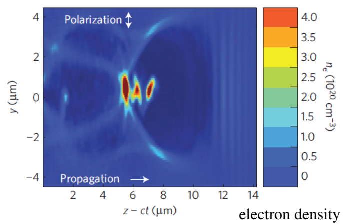


Image courtesy of D. Herrmann, Opt. Lett. (2009)

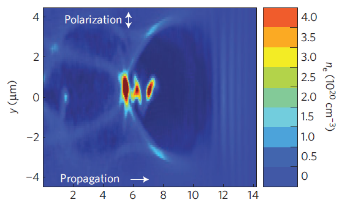
16-TW OPCPA laser system at MPQ in Garching

PIC-Simulation



electron density

PIC-Simulation



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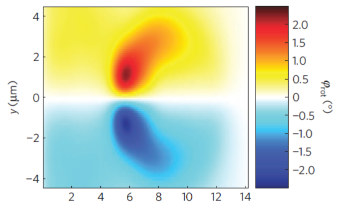
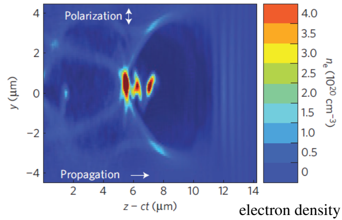
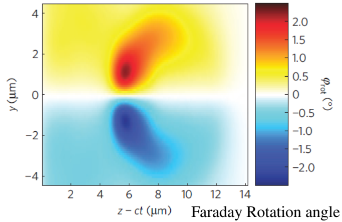


Faraday Rotation angle

PIC-Simulation



electron density



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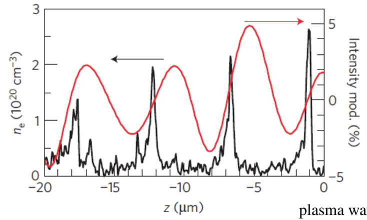
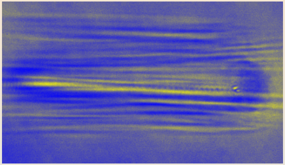


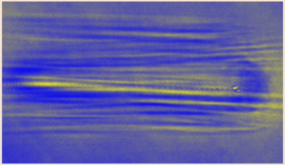
plasma wave

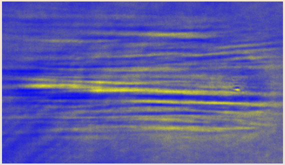
Determination of the Faraday Rotation angle



$$I_1 = I_0 \left(1 - \beta_1 \sin^2\left(90^\circ + \phi_{\text{rot}} - \theta_{\text{pol1}}\right)\right)$$

Determination of the Faraday Rotation angle





$$I_1 = I_0\left(1 - \beta_1 \sin^2\left(90^\circ + \phi_{\text{rot}} - \theta_{\text{pol1}}\right)\right) \quad I_2 = I_0\left(1 - \beta_2 \sin^2\left(90^\circ + \phi_{\text{rot}} - \theta_{\text{pol2}}\right)\right)$$

2 images from the same shot with different polarizer settings

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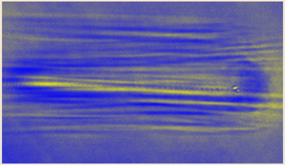

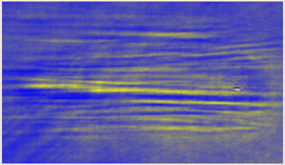

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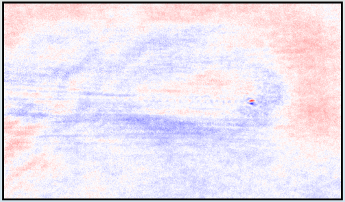

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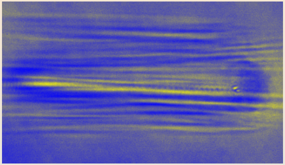

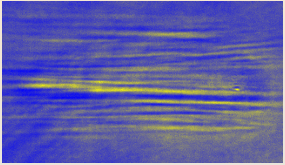

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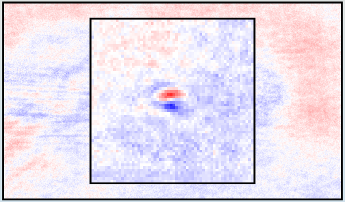
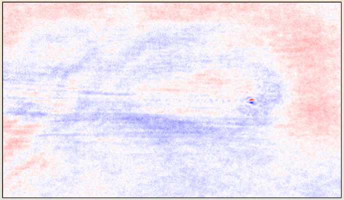


$$\frac{I_1}{I_2} = \frac{1 - \beta_1 \sin^2\left(90^\circ + \phi_{rot} - \theta_{pol1}\right)}{1 - \beta_2 \sin^2\left(90^\circ + \phi_{rot} - \theta_{pol2}\right)}$$

Duration of the electron bunches



A. Buck, M. Nicolai *et al.*, “Real-time observation of laser-driven electron acceleration”, Nature Physics, DOI 10.1038/NPHYS1942

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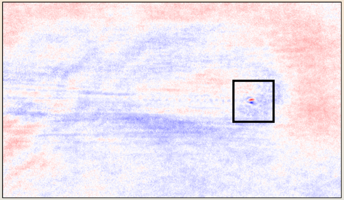

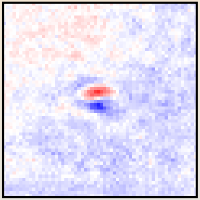

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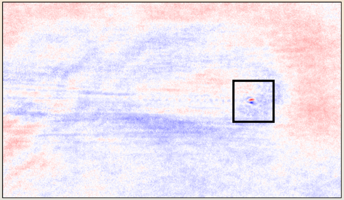

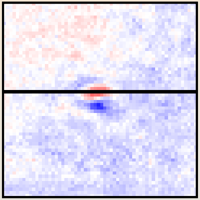

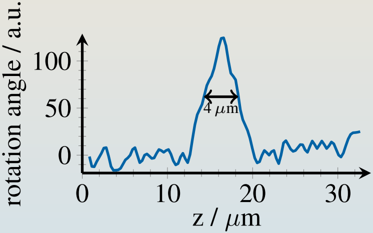

$$s_{\text{electrons}} \approx 4\,\mu\text{m}$$

$$t_{\text{electrons}} \approx 13\,\text{fs}$$

$$t_{\text{deconvolved}} = (6 \pm 2)\,\text{fs}$$

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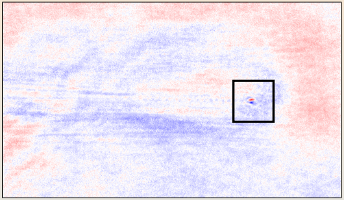

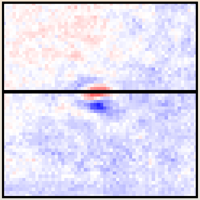

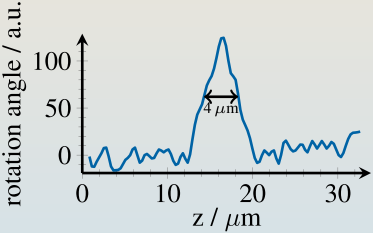

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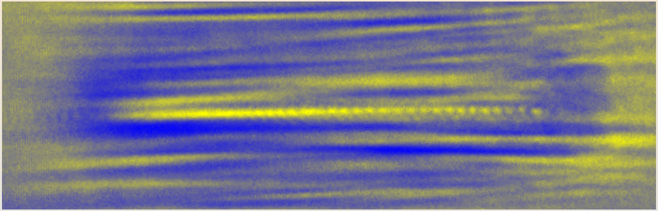
shortest direct measurement of the duration of a laser accelerated electron bunch

A. Buck, M. Nicolai *et al.*, “Real-time observation of laser-driven electron acceleration”, Nature Physics, DOI 10.1038/NPHYS1942

Observation of the plasma wave



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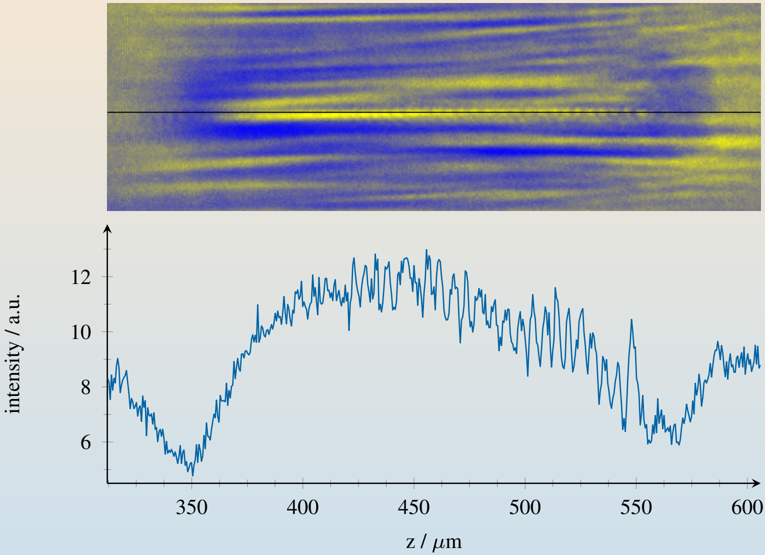

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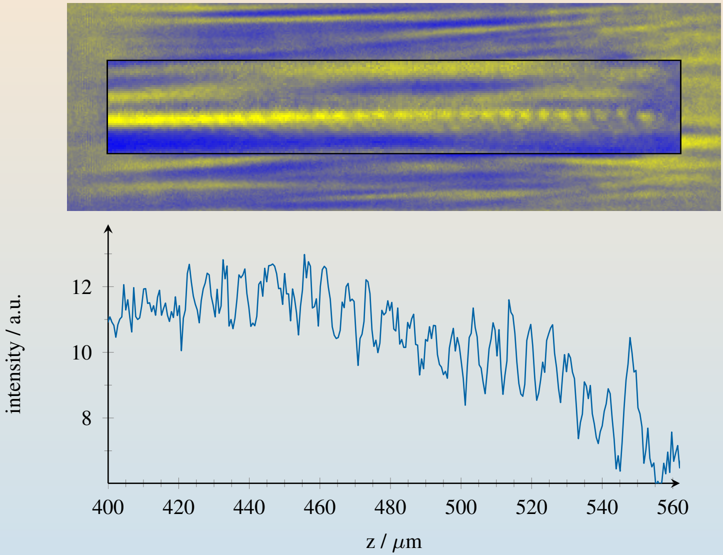
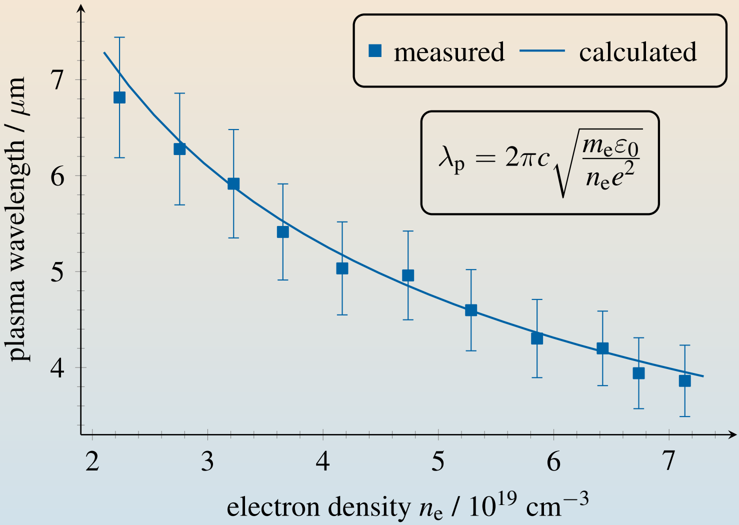
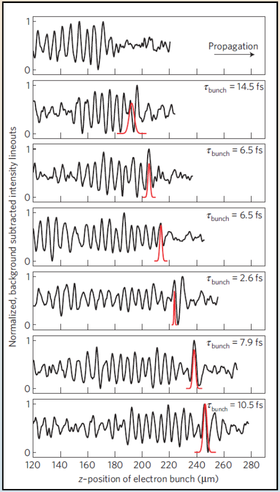


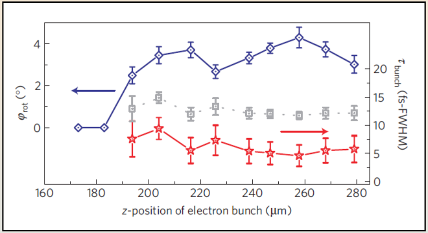
Plasma wavelength

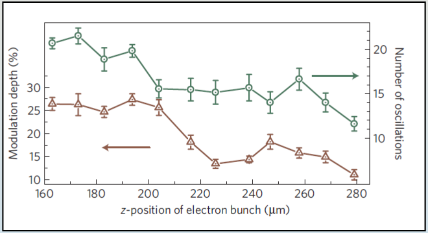


$$\lambda_p = 2\pi c \sqrt{\frac{m_e \varepsilon_0}{n_e e^2}}$$

Insight into the acceleration process







Conclusion

- Laser wakefield acceleration with state-of-the-art 30 TW-laser
- Parameters of laser-accelerated electrons are strongly depending on experimental conditions
- Large shot-to-shot variations even under optimized conditions

- Measurement with an 8 fs OPCPA laser system
- Visualization of the acceleration process with high temporal and spatial resolution $\rightarrow$ also a possibility to measure the duration of electron bunches of conventional accelerators
- Electron bunch duration was measured to be as short as 6 ± 2 fs $\rightarrow$ shortest direct measured laser-driven electron bunch duration
- First direct observation of the plasma wave

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