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Diagnostics Tools for Laser-Driven Plasma-Accelerators

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Outline

- Motivation: Why plasma diagnostics necessary
- Pump-probe scenarios:
  Which different types of probe pulses can be applied?
- Electro-magnetic probe pulses:
  - Shadowgraphy
  - Interferometry
  - E- and B-field sensitive techniques
- Particle probe pulses:
  - Proton probing
  - Detection of magnetic and electric field distributions

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Motivation

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- Laser-produced plasmas:
  - formation and modulation occuring on time scales of driving laser
  - density distribution?
  - temperature?
  - internal fields?
- High relevance for particle accelerators
  - plasma-wakefield accelerators: detect details of plasma wave
  - plasma ion accelerators: e.g. sheath field of accelerating fields from solid targets
- Pump-probe geometry well suited: probe interaction driven („pumped“) by main pulse

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Electromagnetic Probe Pulses

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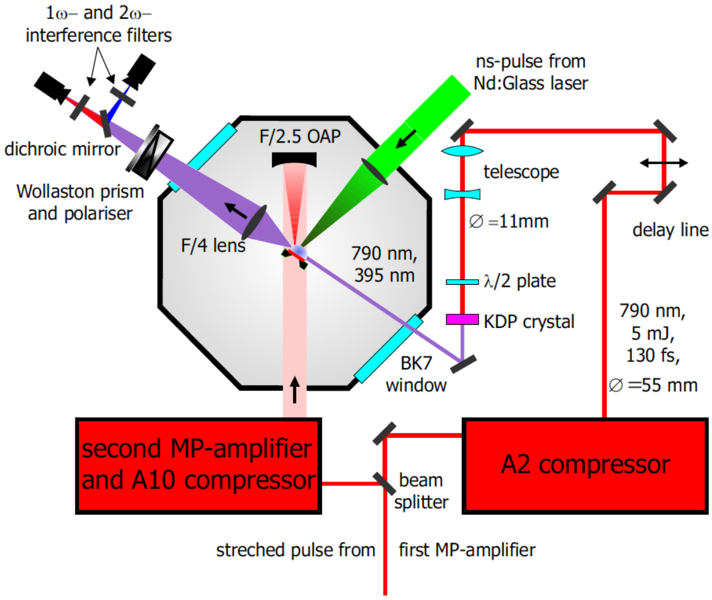
- Generation of synchronized optical probe pulses:
  - split off part of the main pulse
  - guide it towards interaction along different path
  - adjust temporal delay

➔ perfect synchronization

➔ probe pulse duration similar to main pulse

➔ record movie from subsequent shots at different delays



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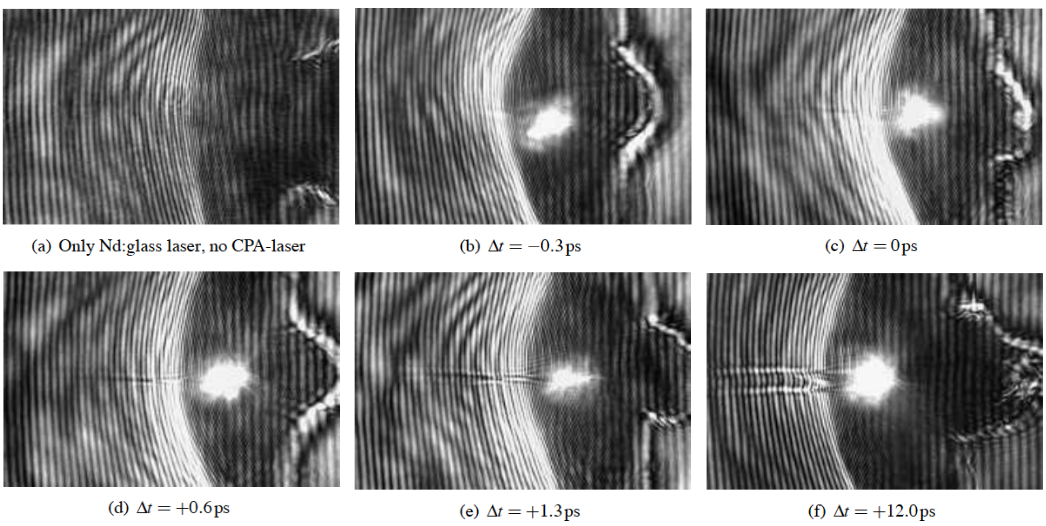
- Delay scan of interaction of 10-TW laser pulse with preformed plasma at different shots:



(a) Only Nd:glass laser, no CPA-laser
(b) $\Delta t = -0.3$ ps
(c) $\Delta t = 0$ ps
(d) $\Delta t = +0.6$ ps
(e) $\Delta t = +1.3$ ps
(f) $\Delta t = +12.0$ ps

- How can we deduce the plasma density from these images?
- Use interferometry!

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Interferometry

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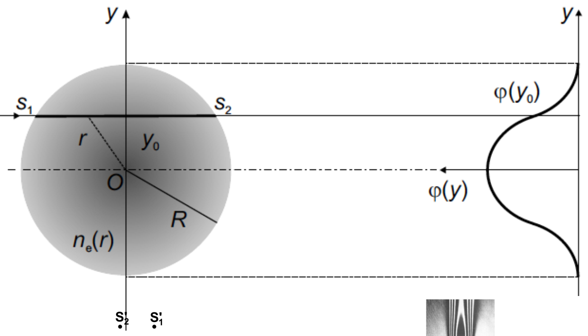
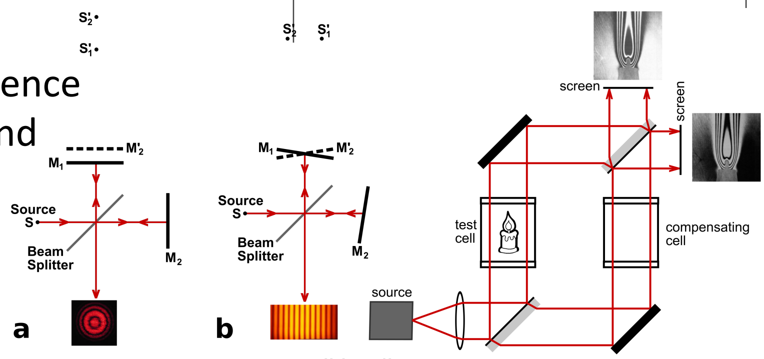
- Refractive index of a plasma:

$$\eta = \sqrt{1 - (\omega_\mathrm{p}/\omega_\mathrm{L})^2} = \sqrt{1 - n_\mathrm{e}/n_\mathrm{c}}$$

- Integrated optical path length or integrated phase φ depends on plasma density distribution seen by light rays:



- Visualize phase difference between probe ray and ray going through vacuum: **interferometer**



www.wikipedia.com

- Challenge for short pulses: rays‘ path lengths need to be identical within pulse length (few μm)! easier: Wollaston prism

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Interferometry

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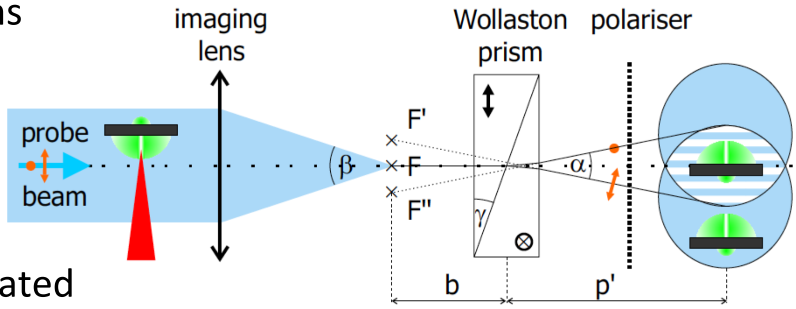
- Wollaston prism = polarizing beam splitter, combination of two birefringent prisms
- Probe pulse: polarization under 45° w.r.t. both optical axes



- Two replica separated by α, polarized perpendicularly to each other
- Imaging system: generation of two images shifted transversely
- Polarizer under 45°: interference between to replica possible, „mixing“ of beam parts going through interaction region and through vacuum
- Separation distance i of fringes on CCD: $i = \frac{\lambda_\mathrm{probe}}{\alpha}\frac{p'}{b}$

Interferometry

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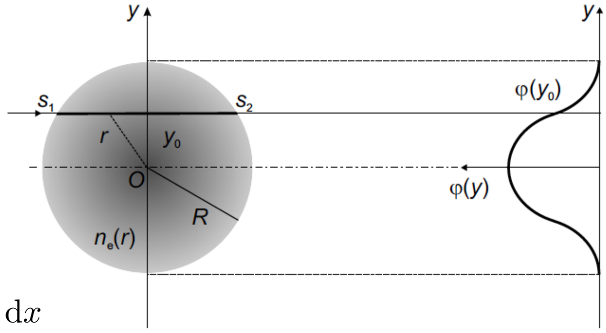
- Deduce plasma density distribution by assuming cylindrical symmetry:
- Phase shift difference between ray going through the plasma and through vacuum:



$$\Delta\varphi(y_0) = \Phi(y_0) = \frac{2\pi}{\lambda_L}\int_{x_1}^{x_2}[1-\eta(x)]\,dx$$

$$\approx \frac{\pi}{n_{cr}\lambda_L}\int_{x_1}^{x_2} n_e(x)dx = \frac{2\pi}{n_{cr}\lambda_L}\int_{y_0}^{R}\frac{n_e(r)r}{\sqrt{r^2-y_0^2}}dr$$

- Deduce plasma density via Abel inversion:

$$n_e(r) = -\frac{n_{cr}\lambda_L}{\pi^2}\int_r^R \frac{d\Phi(y)}{dy}\cdot\frac{dy}{\sqrt{y^2-r^2}}.$$

Interferometry

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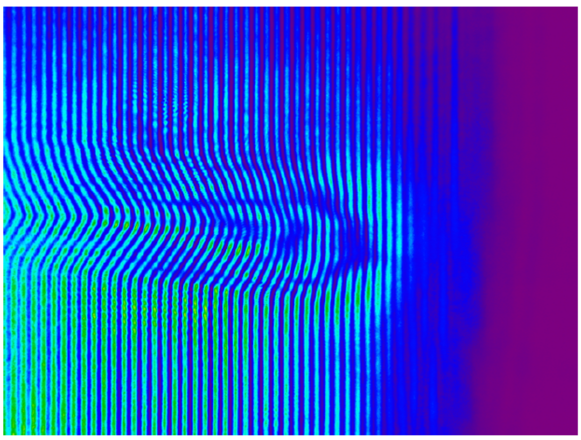
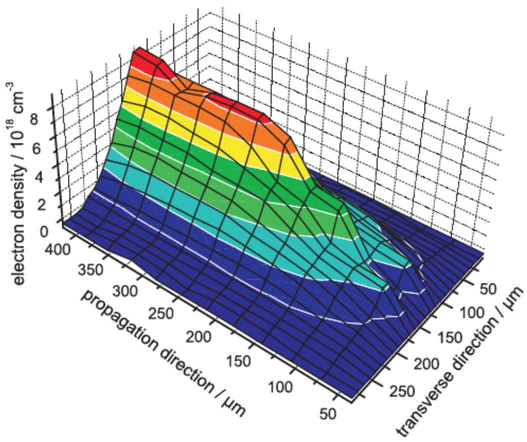
- Deduce plasma density distribution by assuming cylindrical symmetry:

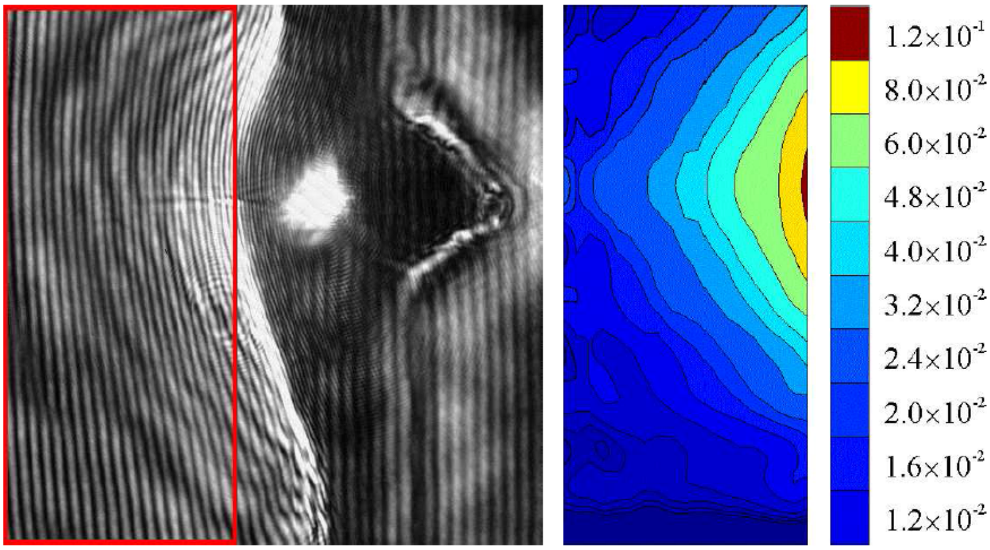




H.-P. Schlenvoigt, PhD thesis, Uni Jena (2009)

Interferometry

- Deduce plasma density distribution by assuming cylindrical symmetry:

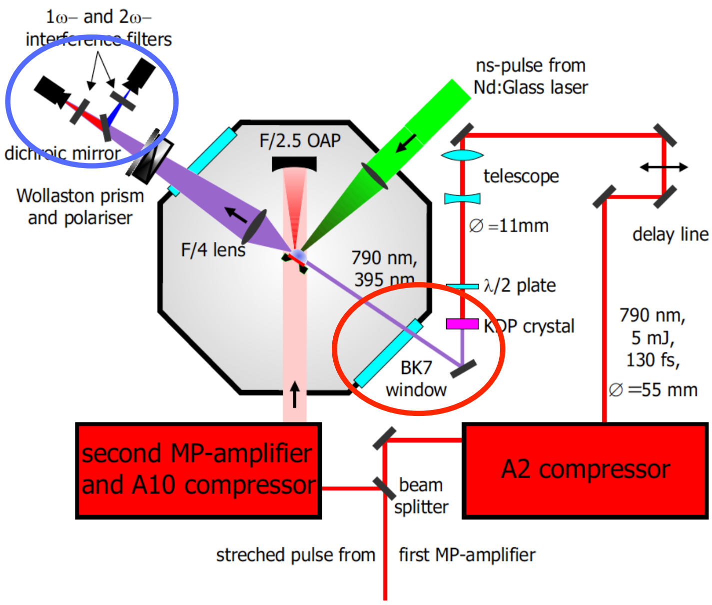


(a) (b)

- Density given in units of n_{cr}

Electromagnetic Probe Pulses

- 2-color probe pulses:
  visualize different time steps of evolution during a single shot by taking 2 images at different times
- 2 pulses (1ω and 2ω) go through window at different speed (GVD) => separation by few ps
- Separate pulses after interaction:
  get 2 images of the same interaction at 2 different times



Electromagnetic Probe Pulses

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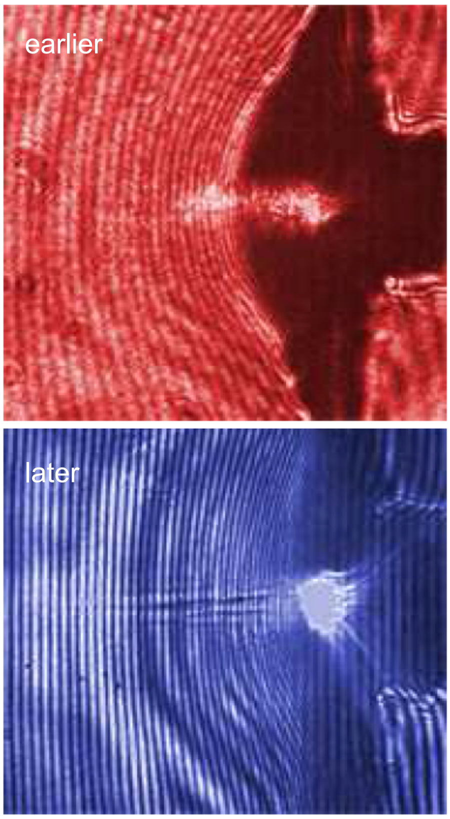
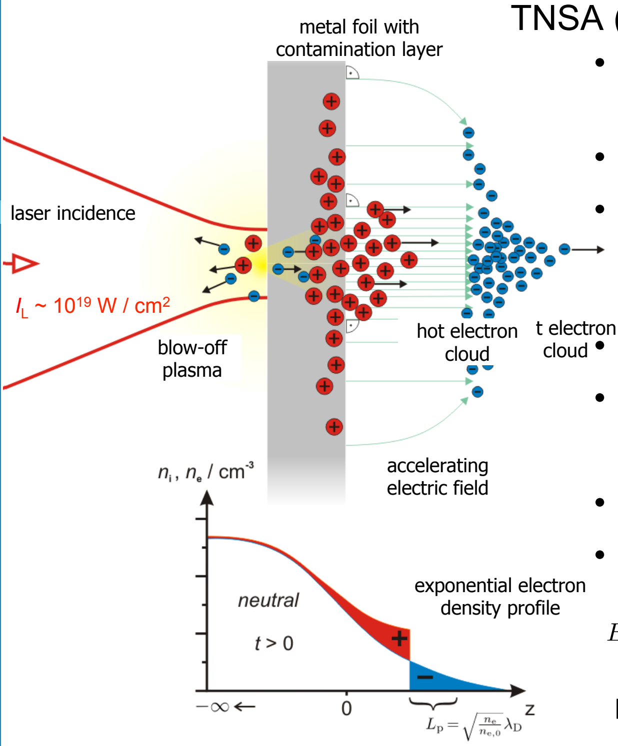


Electromagnetic Probe Pulses



TNSA (**T**arget **N**ormal **S**heath **A**cceleration)

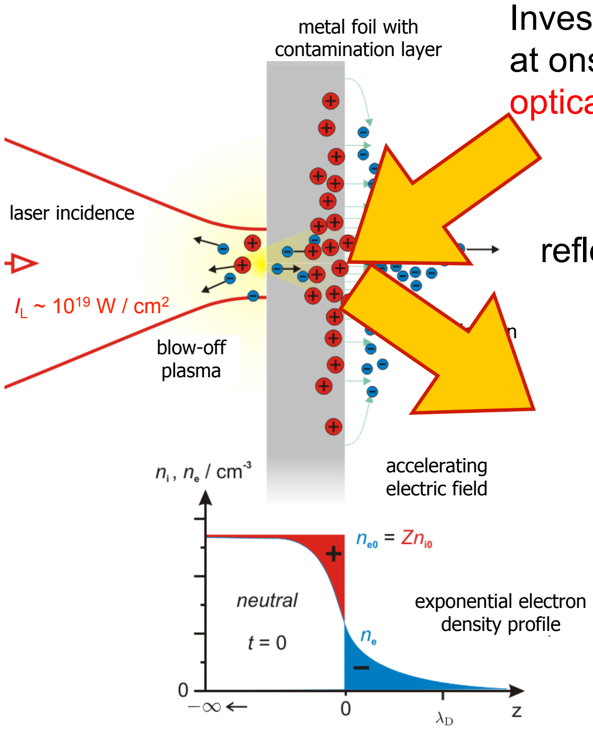
- laser pulse generates relativistic electrons,
- they propagate through the foil and
- form an electric sheath field
  ~ TV/m $\mathcal{E}_{\mathrm{front}}(t) \approx 2\sqrt{\frac{k_B T_e n_e}{\varepsilon_0(2e_N + \omega_{pi}^2 t^2)}}$
- charge distribution starts to expand,
- acceleration length ~ µm
  ~ Debye-length $\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}}$
- lifetime of electric field ~ $f(\tau_L)$
- max. ion energies

$$E_{\max} = 2Zk_B T_e \left[\ln\left(\frac{\omega_{pi}t}{\sqrt{2e_N}} + \sqrt{\left(\frac{\omega_{pi}t}{\sqrt{2e_N}}\right)^2 + 1}\right)\right]^2$$

P. Mora, PRL **90,** 185002 (2003)

Electromagnetic Probe Pulses

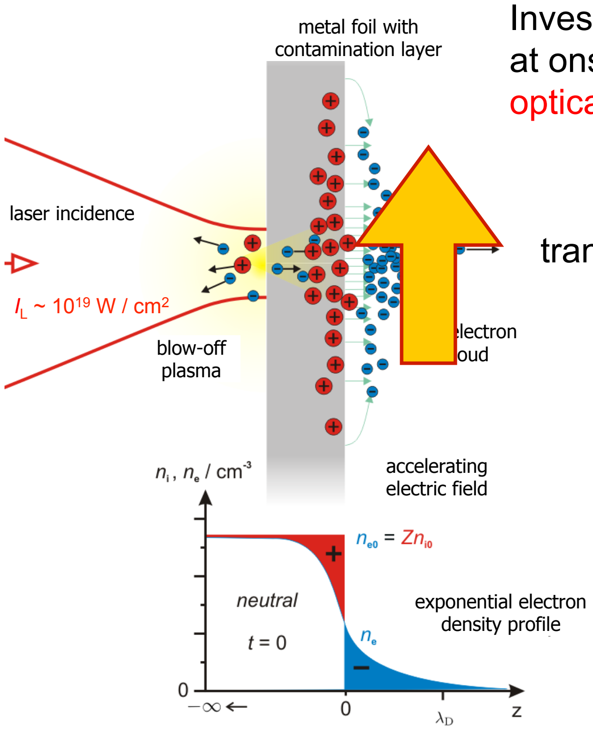
Investigation of rear-surface TNSA-sheath at onset of acceleration process:
optical probing with fs and µm resolution



reflective geometry

Electromagnetic Probe Pulses

Investigation of rear-surface TNSA-sheath at onset of acceleration process:
optical probing with fs and µm resolution



transverse geometry

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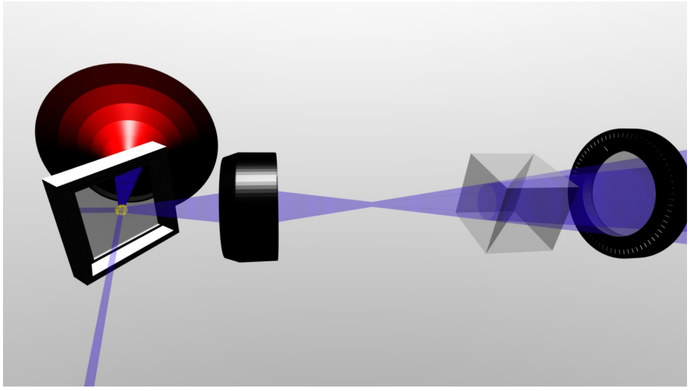
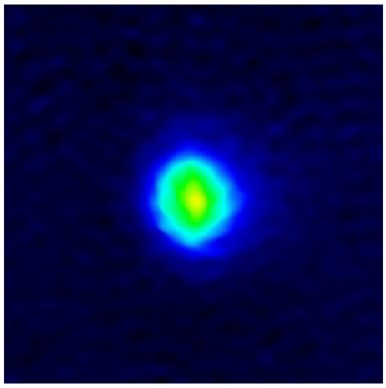
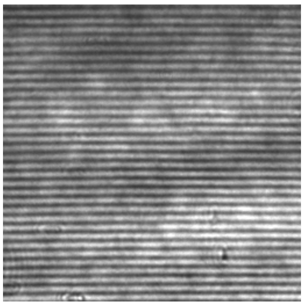
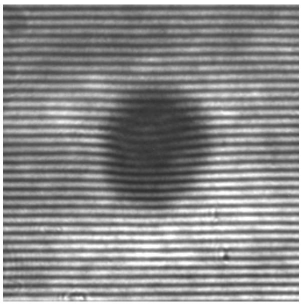


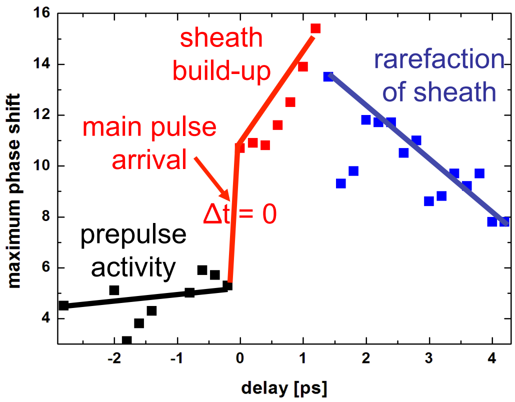




without main pulse



with main pulse



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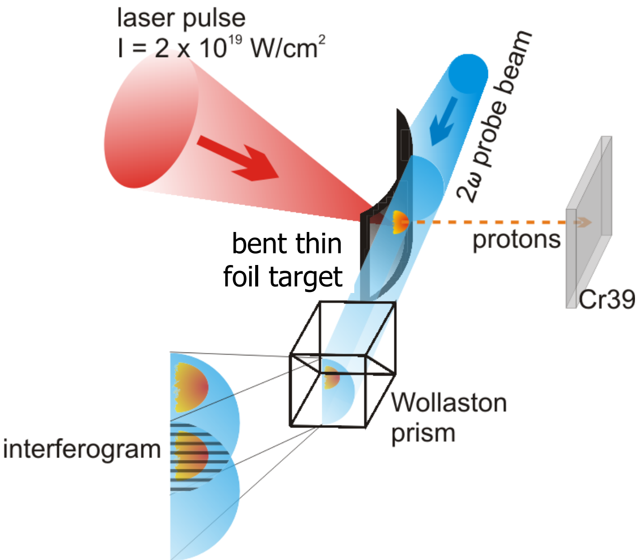

phase shift (measured tangentially) ⇒ 2D signal

$$\Delta\phi = \frac{\omega}{c}\int(\eta - 1)\mathrm{d}s = \frac{\omega}{c}\int\left(\sqrt{1-\frac{n_e}{n_c}} - 1\right)\mathrm{d}s$$
$$\approx \frac{\omega}{2cn_c}\int n_e \mathrm{d}s$$

Abel inversion

$$h(y) = 2\int_y^R f(y)\frac{r}{\sqrt{r^2 - y^2}}\mathrm{d}r$$

3D electron density distribution (cylindrical symmetry)

$$n_e(r,z,t) \sim \exp\left[-\frac{r(t)^2}{w_0^2}\right]\exp\left[-\frac{z(t)}{\lambda_D}\right]$$

<u>Nomarski interferometer:</u>
f/2 imaging onto 12-bit CCD
Wollaston prism + polarizer

- spatial resolution ~ 1.1 µm
- temporal resolution ~ 100 fs

⇒ match dimensions of accel. process!

R. Benattar *et al.* (1979); G. Pretzler *et al.* (1992)

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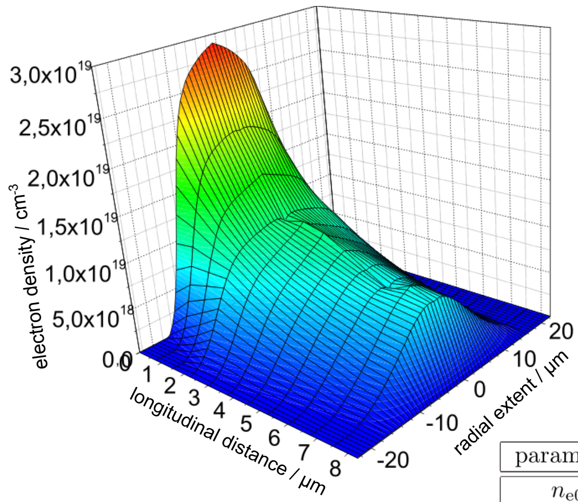
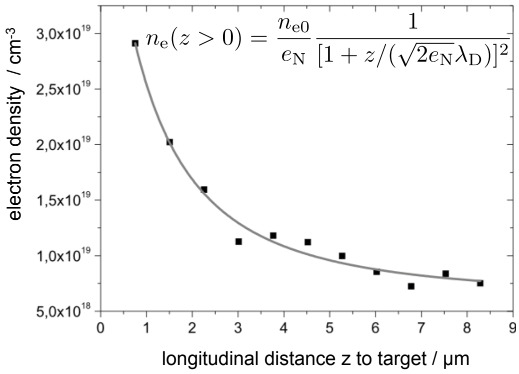
1st all-optical measurement of n_e-distribution driving laser ion acceleration!



at t = 0
(onset of acceleration process)

J. Crow *et al.*, J. Plasma Phys. (1975)



parameter	experimental data	theoretical prediction
n_{e0}	$(8.4 \pm 0.4) \times 10^{19}\,\mathrm{cm}^{-3}$	$9.44 \times 10^{19}\,\mathrm{cm}^{-3}$
λ_D	$(1.0 \pm 0.2)\,\mu\mathrm{m}$	$0.64\,\mu\mathrm{m}$
w_{back}	$(21 \pm 1)\,\mu\mathrm{m}$	$8.1\,\mu\mathrm{m}$
$k_B T_e$	$(1.5 \pm 0.4)\,\mathrm{MeV}$	$0.71\,\mathrm{MeV}$
E_{TNSA}	$(1.3 \pm 0.4)\,\mathrm{TV/m}$	$1.1\,\mathrm{TV/m}$

O. Jäckel, MCK *et al.,* New Journal of Physics **12,** 103027 (2010)

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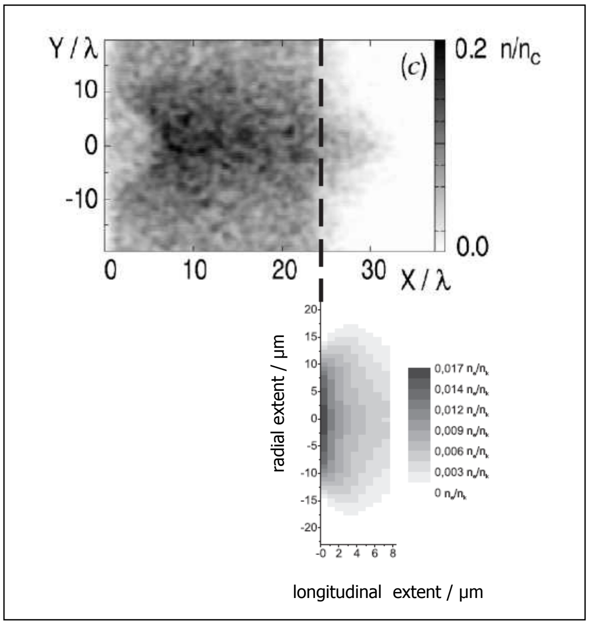
Comparsion with numerical simulations



3D-PIC results by A. Pukhov for comparable laser conditions

⇒ comparable shape
⇒ deviation of absolute numbers (measured density smaller by a factor of 5)

A. Pukhov, PRL **86,** 16 (2001)

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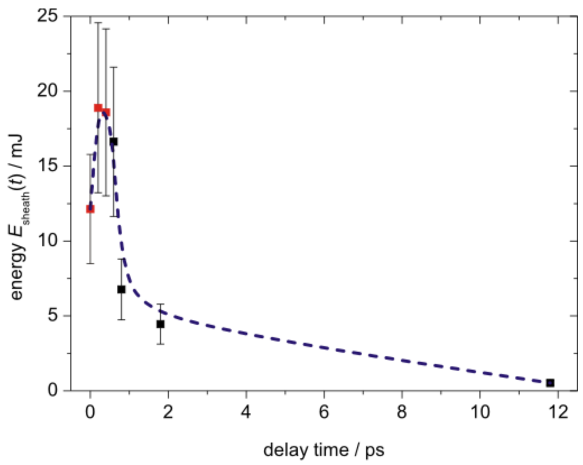
Energy content of electron sheath: $E_{e^-} = k_\mathrm{B} T_\mathrm{e} N_\mathrm{e}$



Conversion efficiency
$E_{laser} \Rightarrow$ hot electrons:

$$\eta = \frac{E_{e^-}}{E_\mathrm{L,eff}} = \frac{k_\mathrm{B} T_\mathrm{e} N_\mathrm{e}}{E_\mathrm{L,eff}}$$

$$\eta_\mathrm{sheath} = (3.7 \pm 1.2)\%$$

$$\eta_\mathrm{total} = (9 \pm 3)\%$$

(deduced from sheath's electron density and radial extent, assuming similar hot-e-density inside the target)

O. Jäckel, MCK *et al.,* New Journal of Physics **12,** 103027 (2010)

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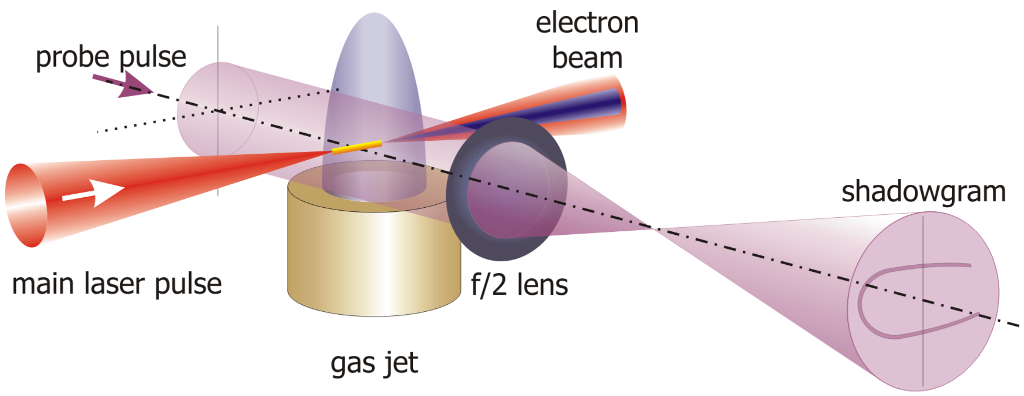


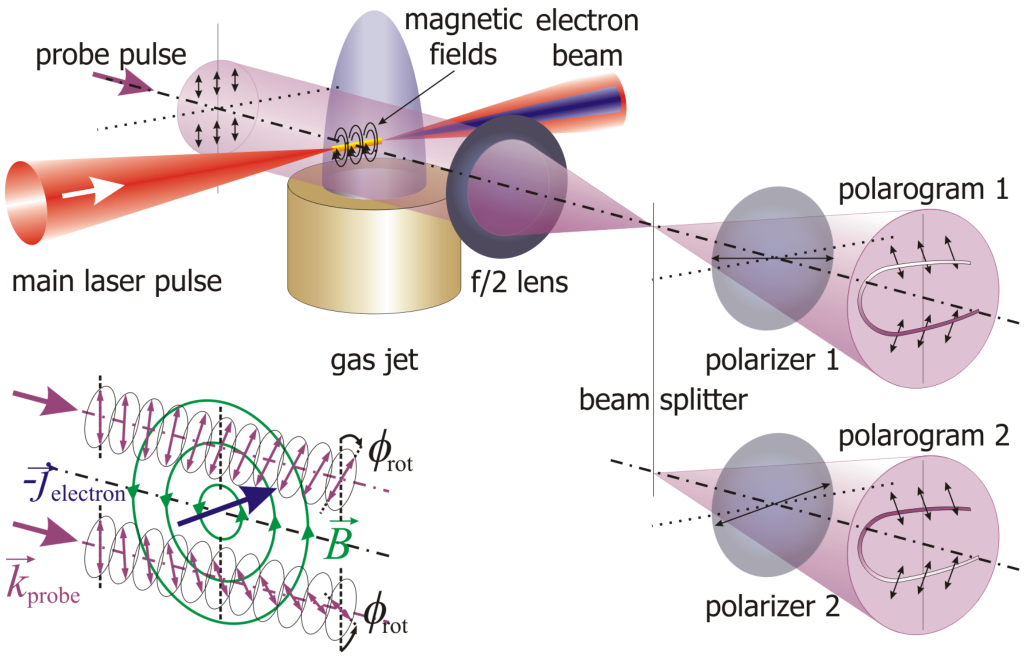
<u>JETI parameters:</u>
E_{laser} = 800 mJ, τ_{laser} = 85 fs,
f/6 OAP, $I_{laser} \approx 3\times10^{18}$ W/cm^2

<u>probe pulse:</u>
$\tau_{probe} \approx$ 100 fs @ 1ω

<u>LWS-20 parameters:</u>
E_{laser} = 80 mJ, τ_{laser} = 8.5 fs,
f/6 OAP, $I_{laser} \approx 6\times10^{18}$ W/cm^2

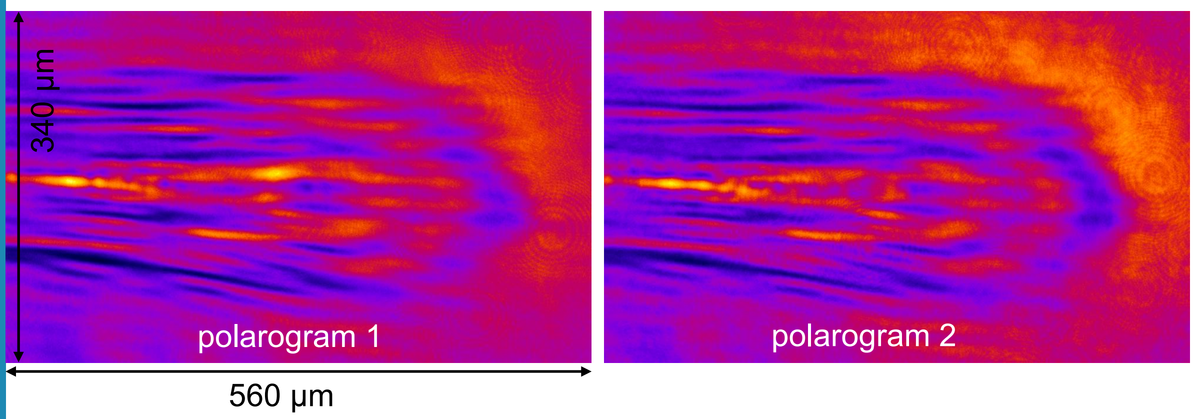
<u>probe pulse:</u>
$\tau_{probe} \approx$ 8.5 fs @ 1ω

Electromagnetic Probe Pulses



Electromagnetic Probe Pulses

Two polarograms from two (almost) crossed polarizers:



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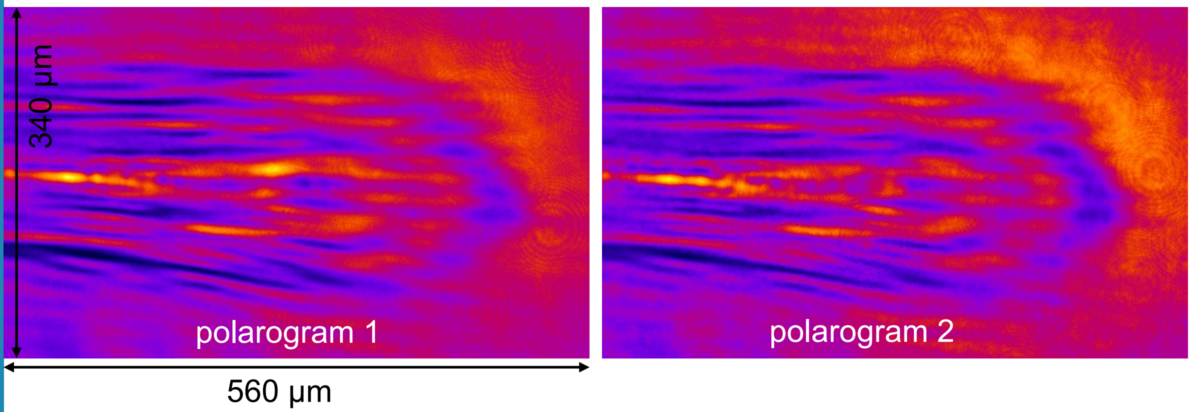

$$I_{\mathrm{pol1}} = I_0 \left[1 - \beta_1 \sin^2(90^\circ - \theta_{\mathrm{pol1}} - \phi_{\mathrm{rot}})\right] \quad I_{\mathrm{pol2}} = I_0 \left[1 - \beta_2 \sin^2(90^\circ + \theta_{\mathrm{pol2}} - \phi_{\mathrm{rot}})\right]$$

Deduce rotation angle ϕ_{rot} from pixel-by-pixel division of polarogram intensities:

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

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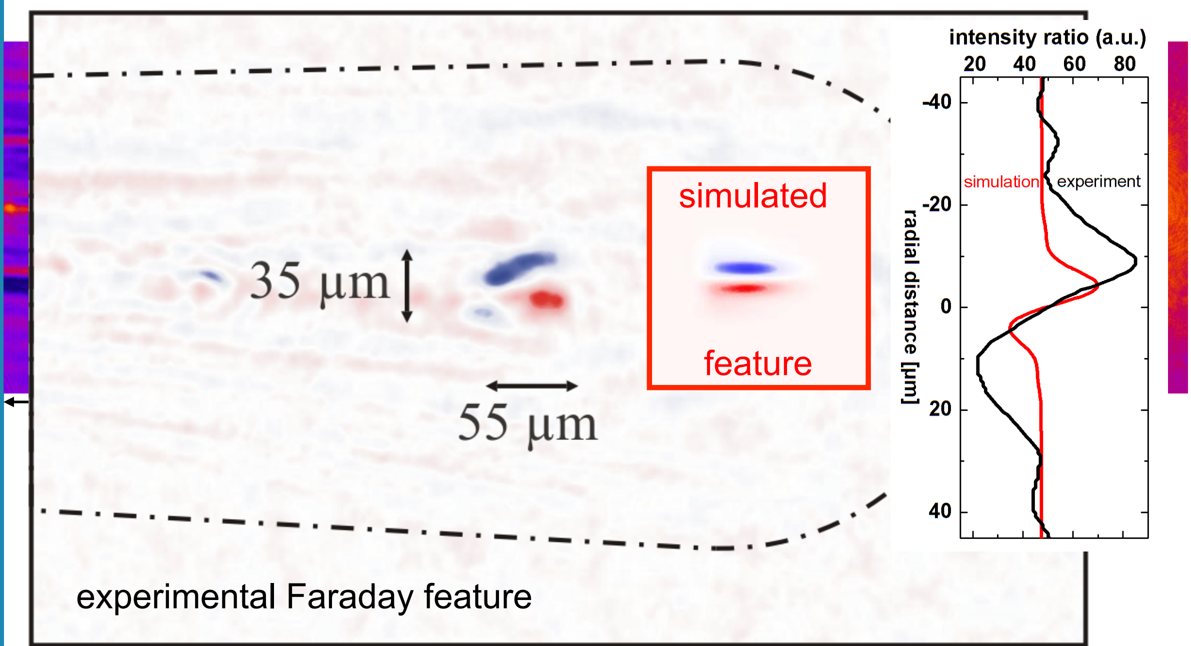

Experimental evidence for B-fields from MeV electrons and bubble!

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

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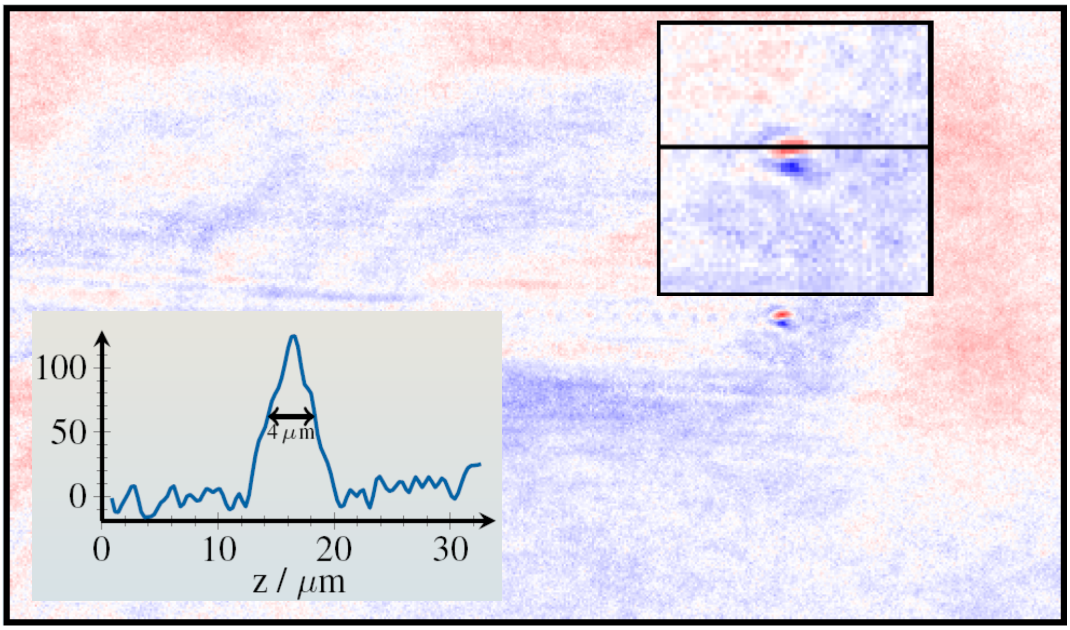

Electron bunch length: Δz = 4 μm

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

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

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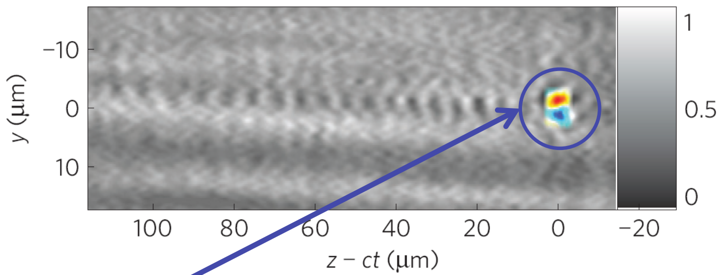
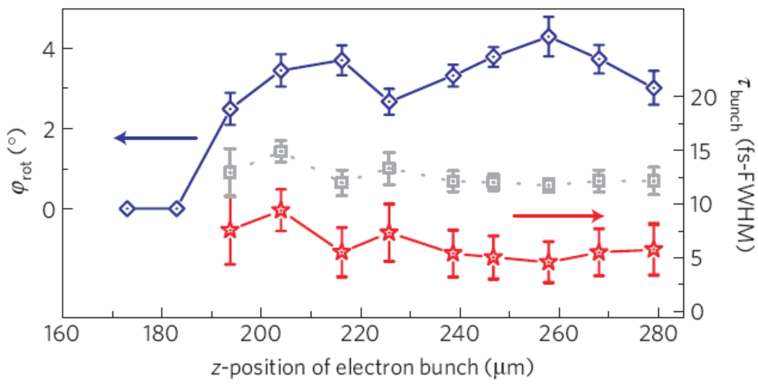


- Polarimetry: visualize e-bunch via associated B-fields
- change delay between pump and probe ⇒ movie of e-bunch formation



- observe e-bunch formation on-line!

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

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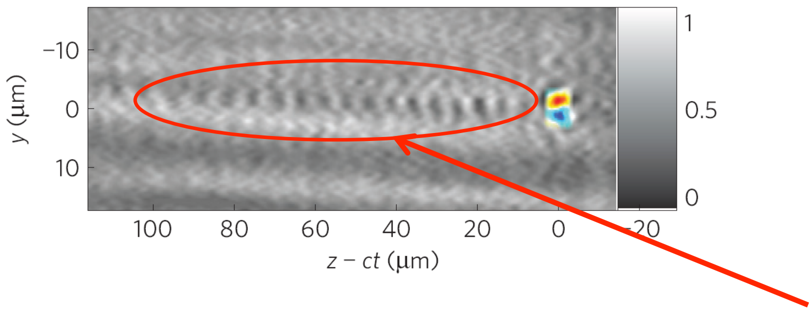

- Polarimetry:
  visualize e-bunch via associated B-fields
- change delay between pump and probe
  ⇒ movie of e-bunch formation

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

- observe e-bunch formation on-line!

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

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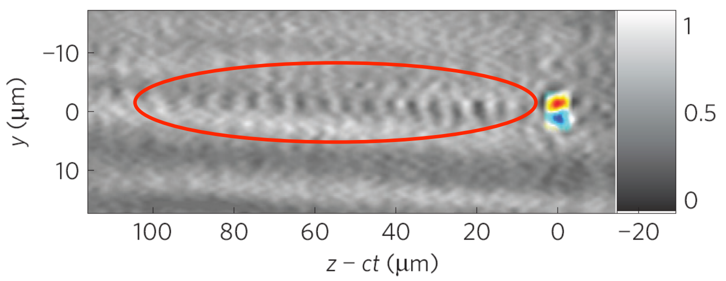

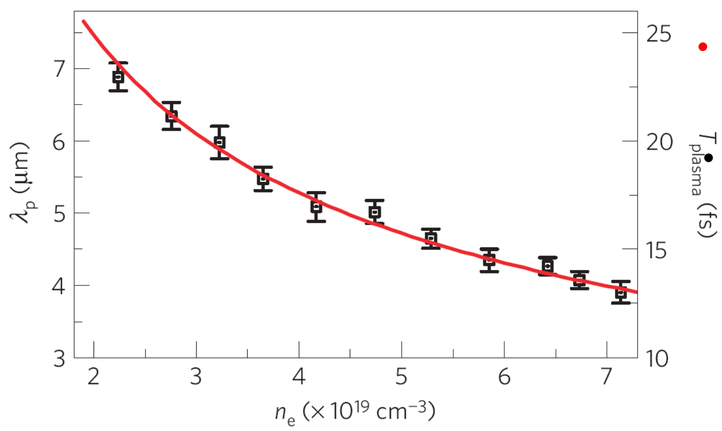

- Shadowgraphy:
  visualize plasma wave
- change electron density ⇒ change plasma wavelength

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

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

Electromagnetic Probe Pulses

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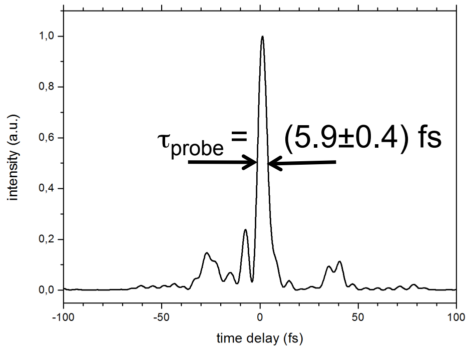
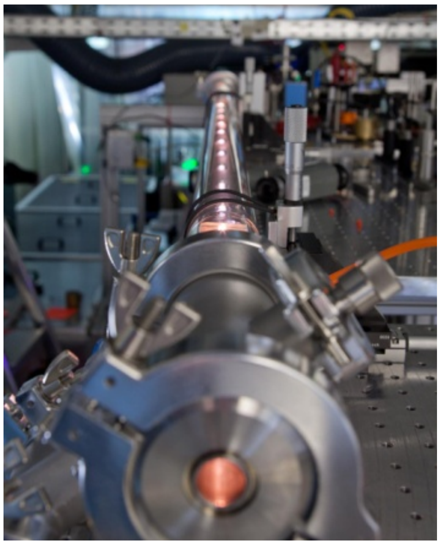
- Few-cycle probe pulses

- Similar resolution with 35-fs driver laser:
- frequency-broadening of probe pulse (in gas-filled hollow fiber)

⇒ shorter τ_{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)

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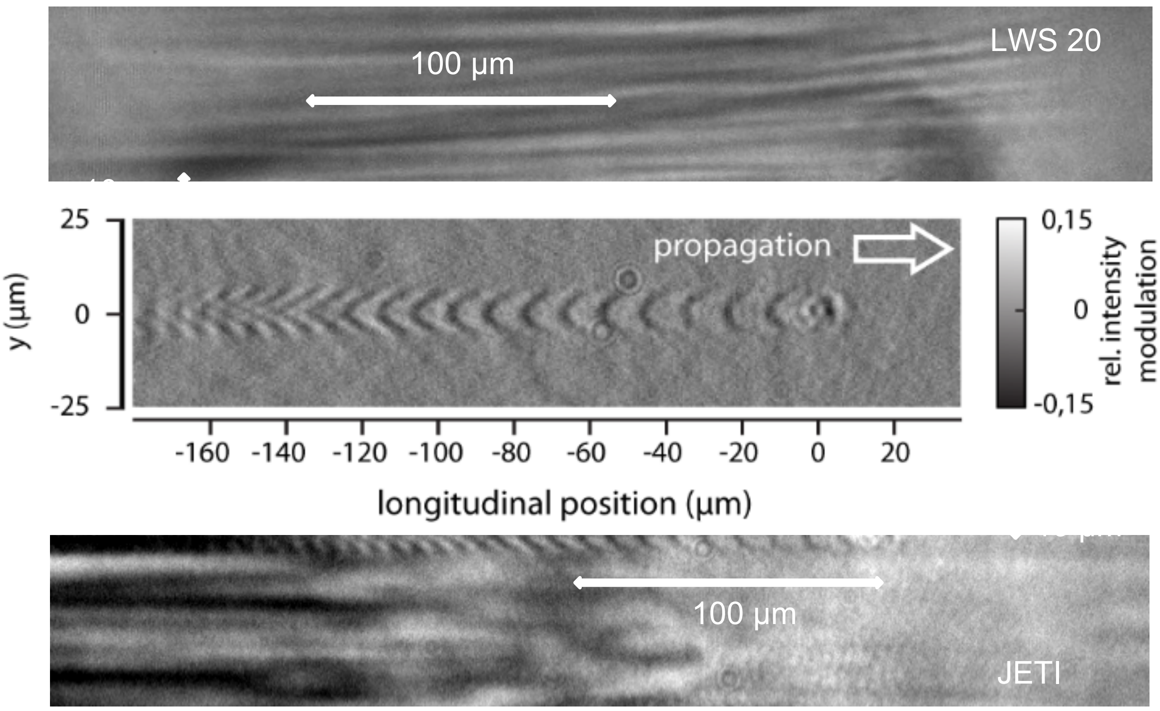
- Few-cycle probe pulses



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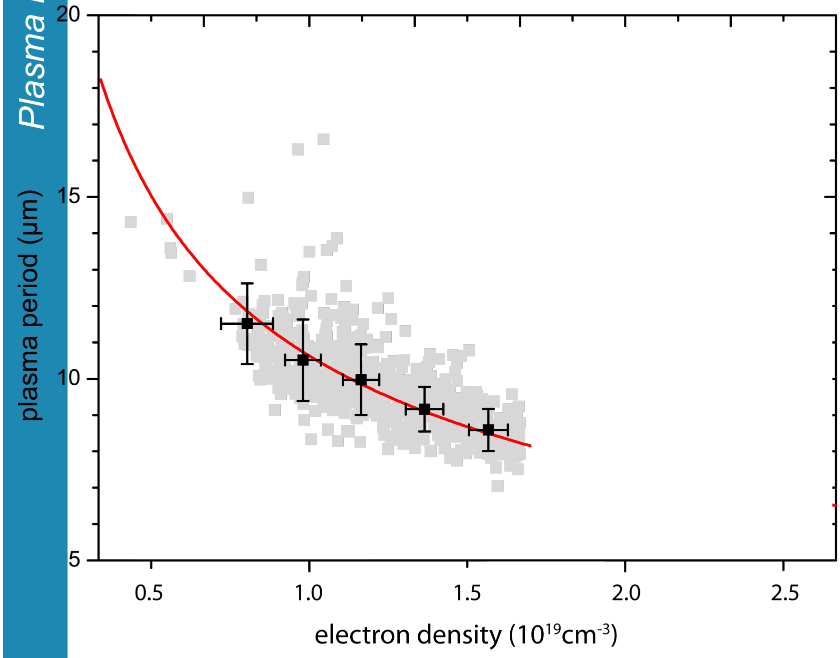
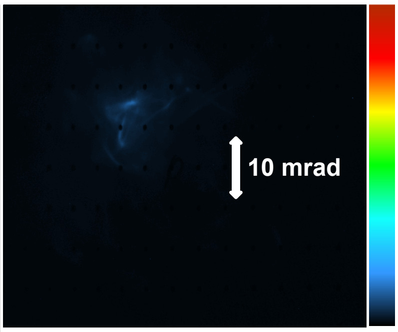
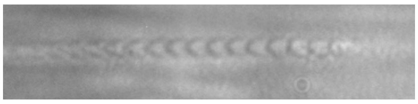
- Length of 2nd plasma period vs. density after ~ 1.1 mm propagation





electron screen



sideview

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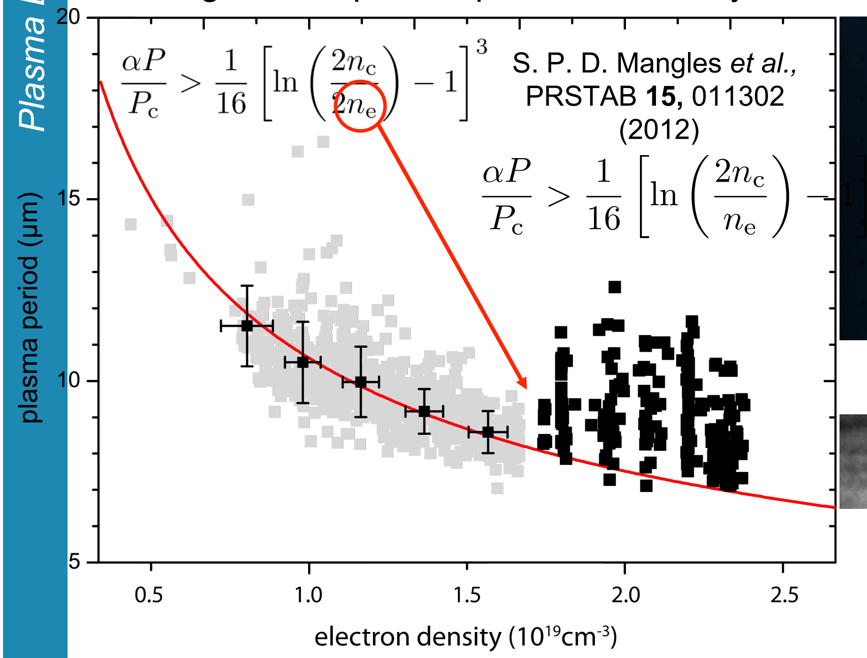
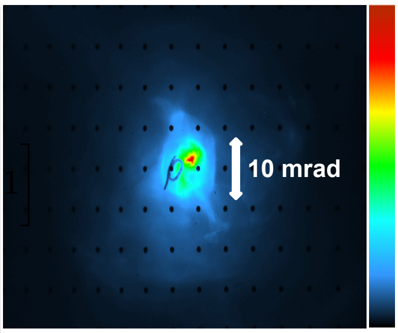
- Length of 2nd plasma period vs. density after ~ 1.1 mm propagation





electron screen

sideview

Above threshold: increase of λ_p (beam loading)

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Electromagnetic Probe Pulses

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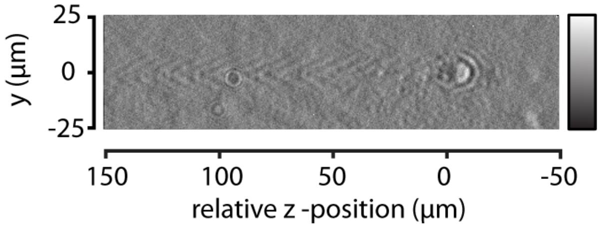
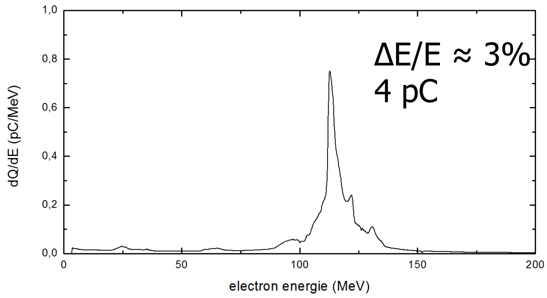
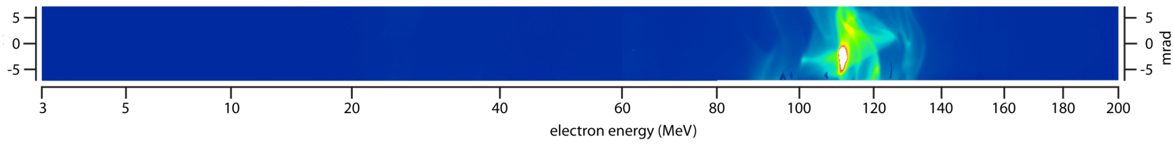
- After plasma wave evolution into single bubble:







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Outline

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- Motivation: Why plasma diagnostics necessary
- Pump-probe scenarios:
  Which different types of probe pulses can be applied?
- Electro-magnetic probe pulses:
  - Shadowgraphy
  - Interferometry
  - E- and B-field sensitive techniques
- Particle probe pulses:
  - Proton probing
  - Detection of magnetic and electric field distributions

Particle Probe Pulses

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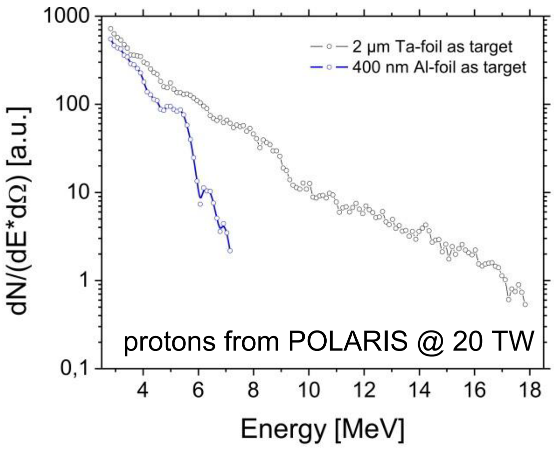
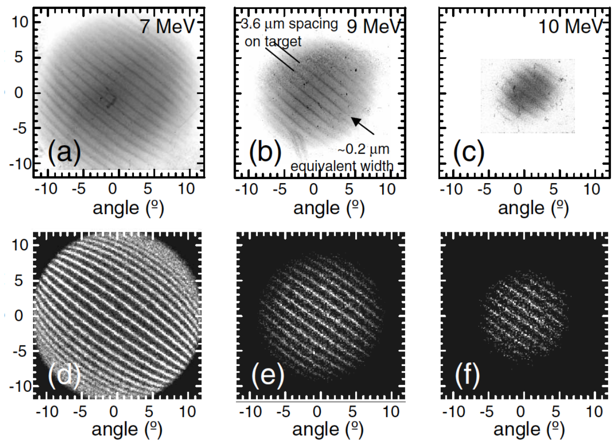
- Probing with laser-accelerated proton beams:
  - broad energy spectrum (up to few 10‘s of MeV)
  - laminar flow -> excellent imaging properties

Energy spectrum in forward direction



Transverse beam profile for different energies



T. E. Cowan, PRL (2004)

Particle Probe Pulses

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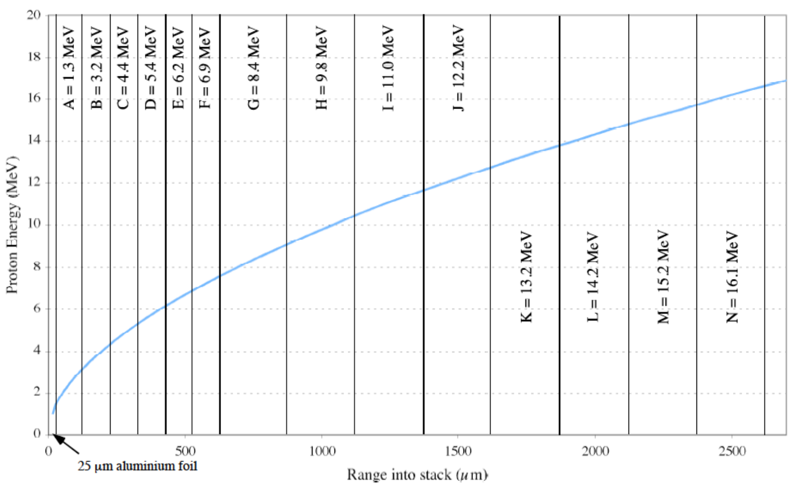
- Probing with laser-accelerated proton beams:
  - broad energy spectrum (up to few 10‘s of MeV),
  - laminar flow -> excellent imaging properties
  - energies detected separately in radiochromic film stack



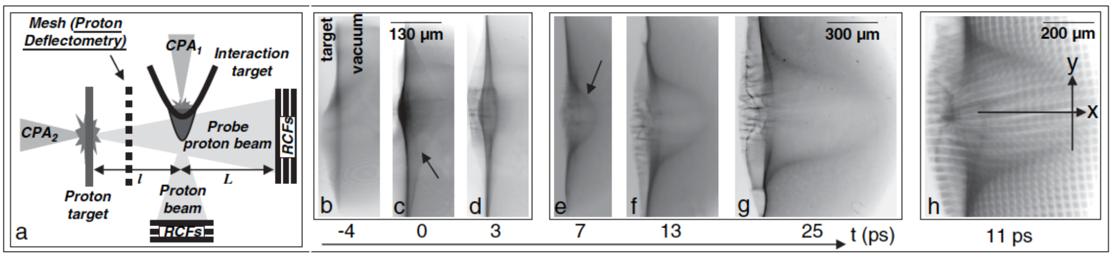
L. Willingale, PhD thesis
Imperial College (2007)

Particle Probe Pulses

- Probing with laser-accelerated proton beams:
  - broad energy spectrum (up to few 10's of MeV)
  - laminar flow -> excellent imaging properties
  - energies detected separately in radiochromic film stack
  - initial duration ≈ few times laser pulse duration, stretching due to different velocities
- Different images from different proton energies = snapshots from different times during the interaction
- Record movie of evolution of field distribution!

Particle Probe Pulses

- Transverse probing with laser-accelerated proton beams:
  - proton deflection mainly due to electric fields

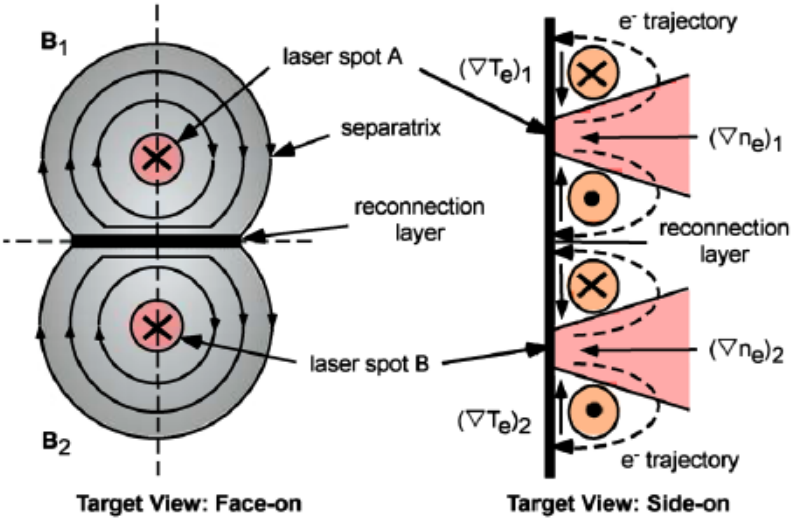


L. Romagnani, PRL (2005)

  - record TNSA-sheath evolution in single shot,
  - deduce sheath-field strength from mesh warping: $E_{TNSA} \geq 3\text{x}10^{10}$ V/m

Particle Probe Pulses

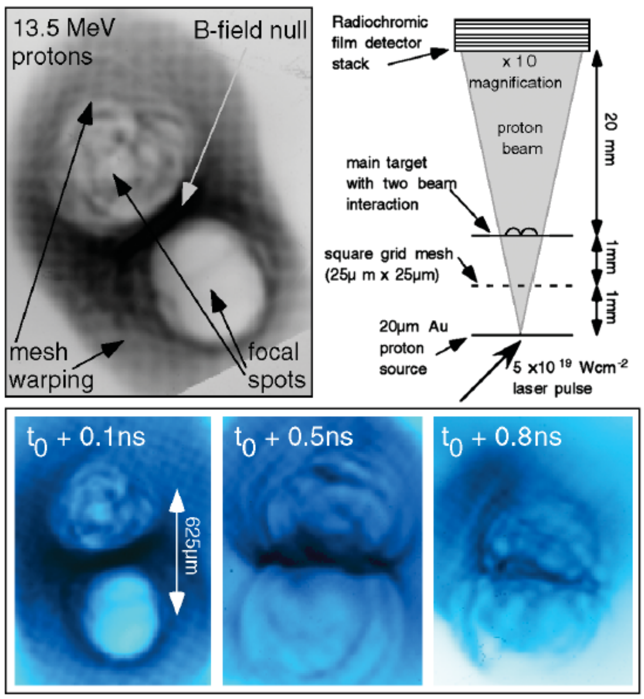
- Longitudinal probing with laser-accelerated proton beams:
  - proton deflection mainly due to magnetic fields



P. Nilson, PRL (2006)

Particle Probe Pulses

- Longitudinal probing with laser-accelerated proton beams:
  - visualize B-field geometry in 2-beam interaction
  - see merging of B-field structures between two plasma plumes
  - example of magnetic reconnetion



P. Nilson, PRL (2006)

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