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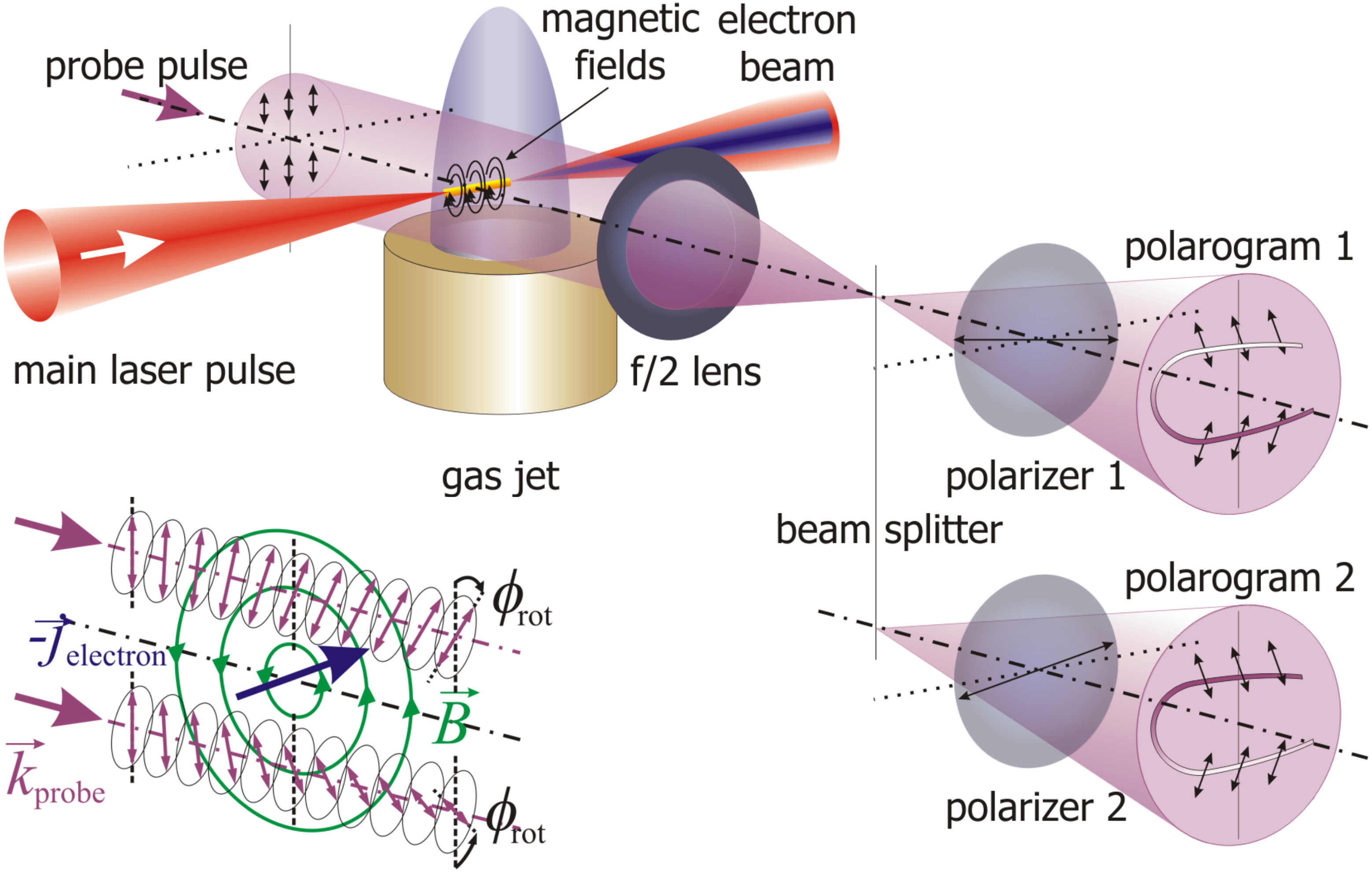
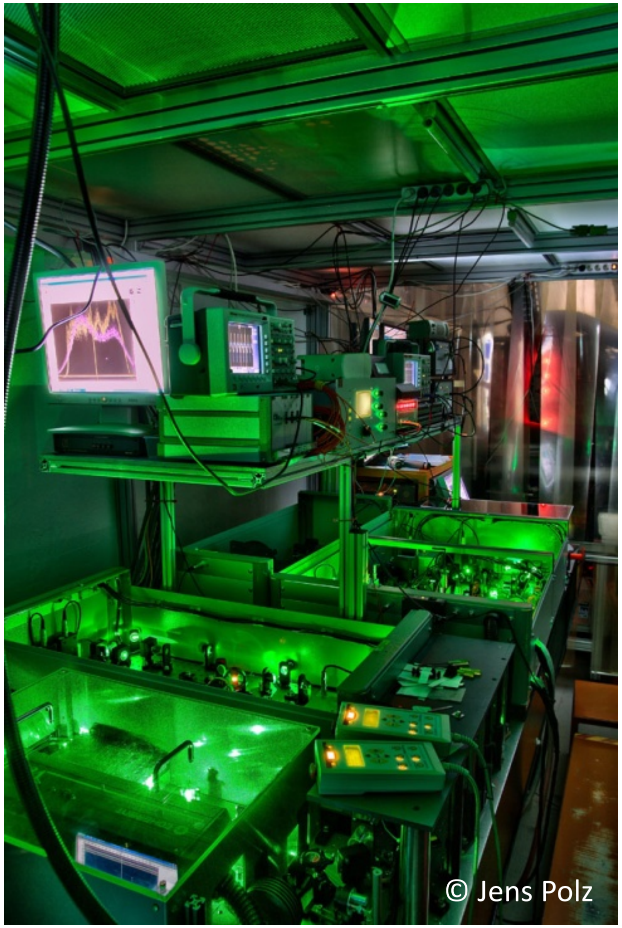
Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process



Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process



Frontend of the JETi laser

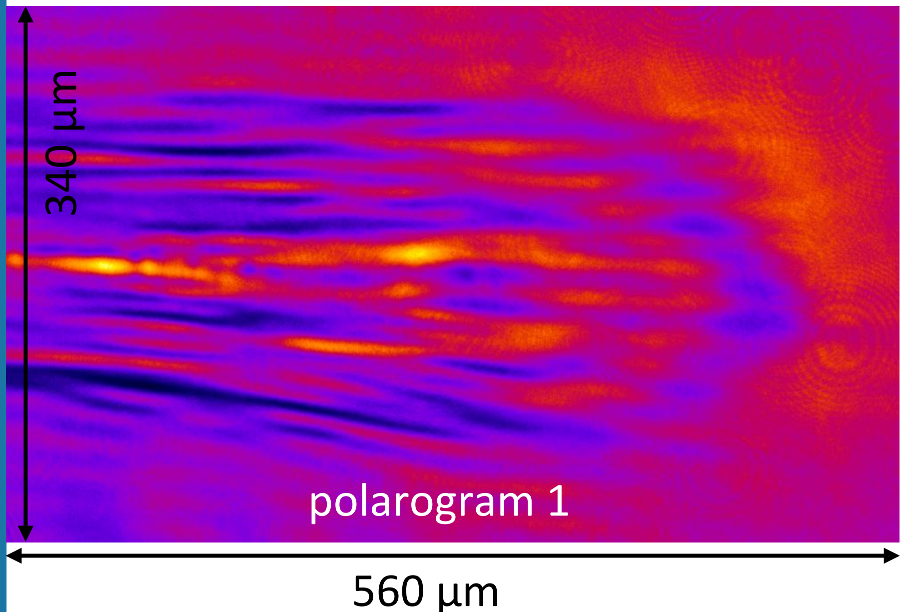
Power amplifier of the JETi laser

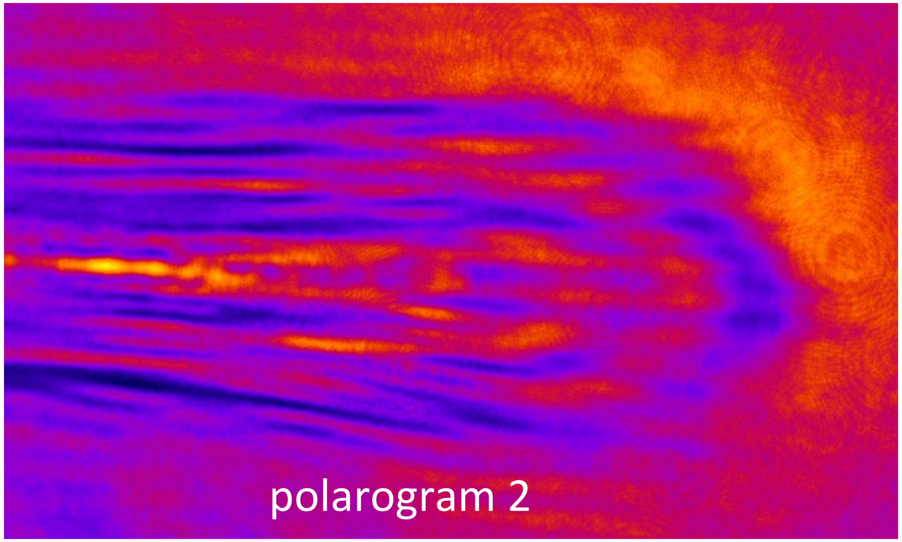
85 fs, 850 mJ, (10 TW peak power), $1\text{x}10^{20}$ W/cm^2 peak intensity, 10 Hz

Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

Two polarograms from two (almost) crossed polarizers:





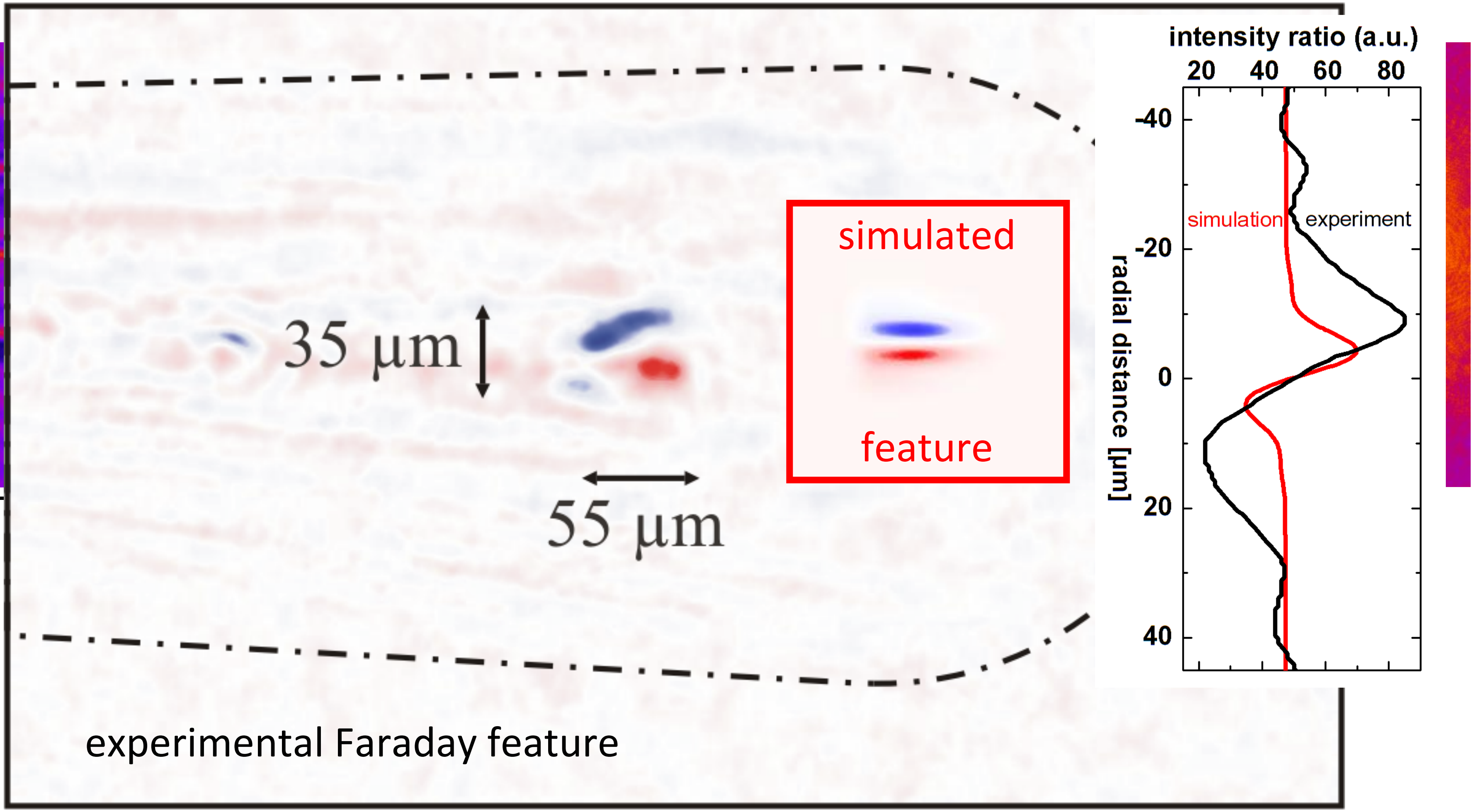
$$I_{\text{pol1}} = I_0 \left[1 - \beta_1 \sin^2(90^\circ - \theta_{\text{pol1}} - \phi_{\text{rot}})\right] \quad I_{\text{pol2}} = I_0 \left[1 - \beta_2 \sin^2(90^\circ + \theta_{\text{pol2}} - \phi_{\text{rot}})\right]$$

Deduce rotation angle ϕ_{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

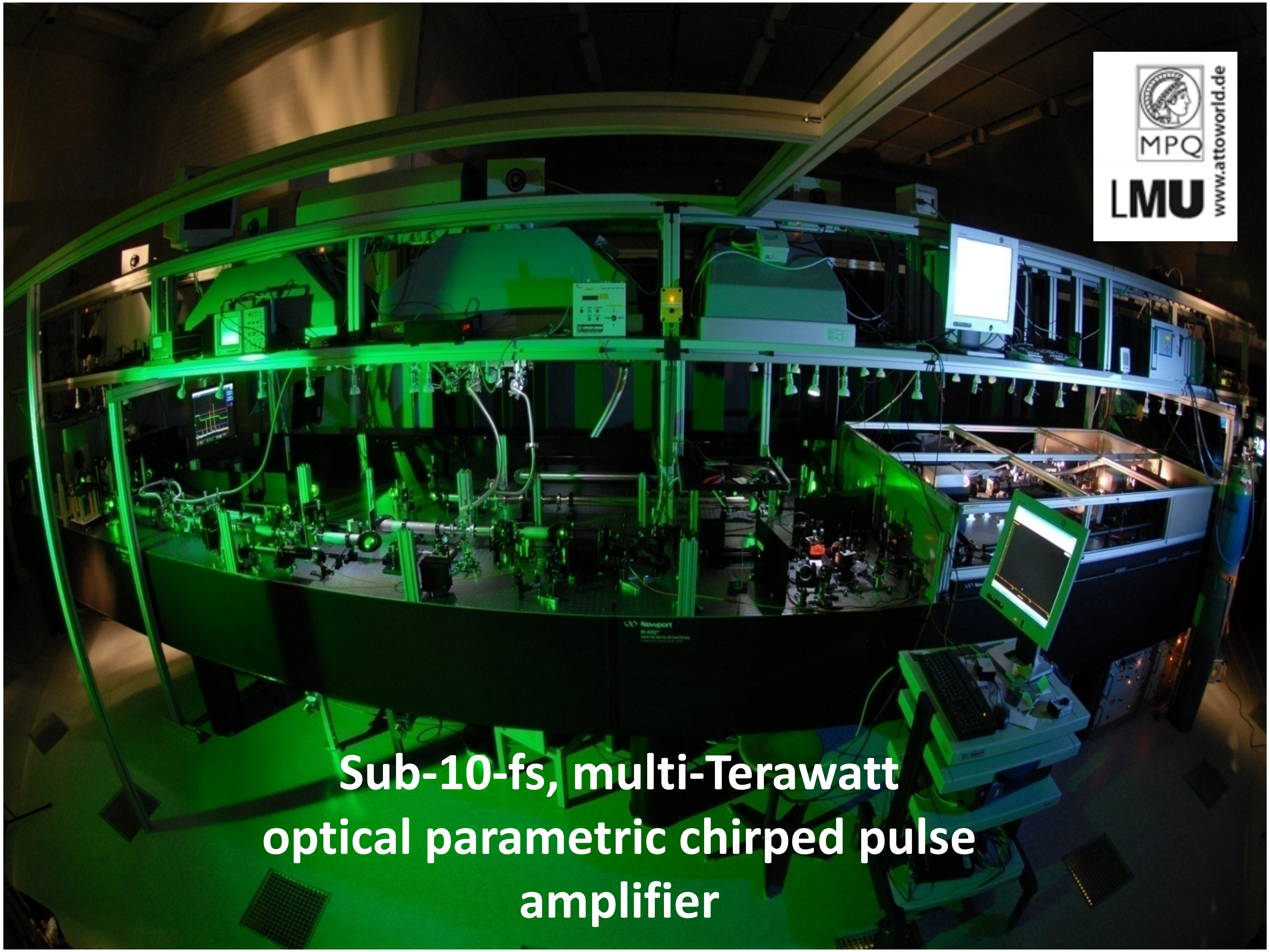


Experimental evidence for B-fields from MeV electrons and bubble!

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

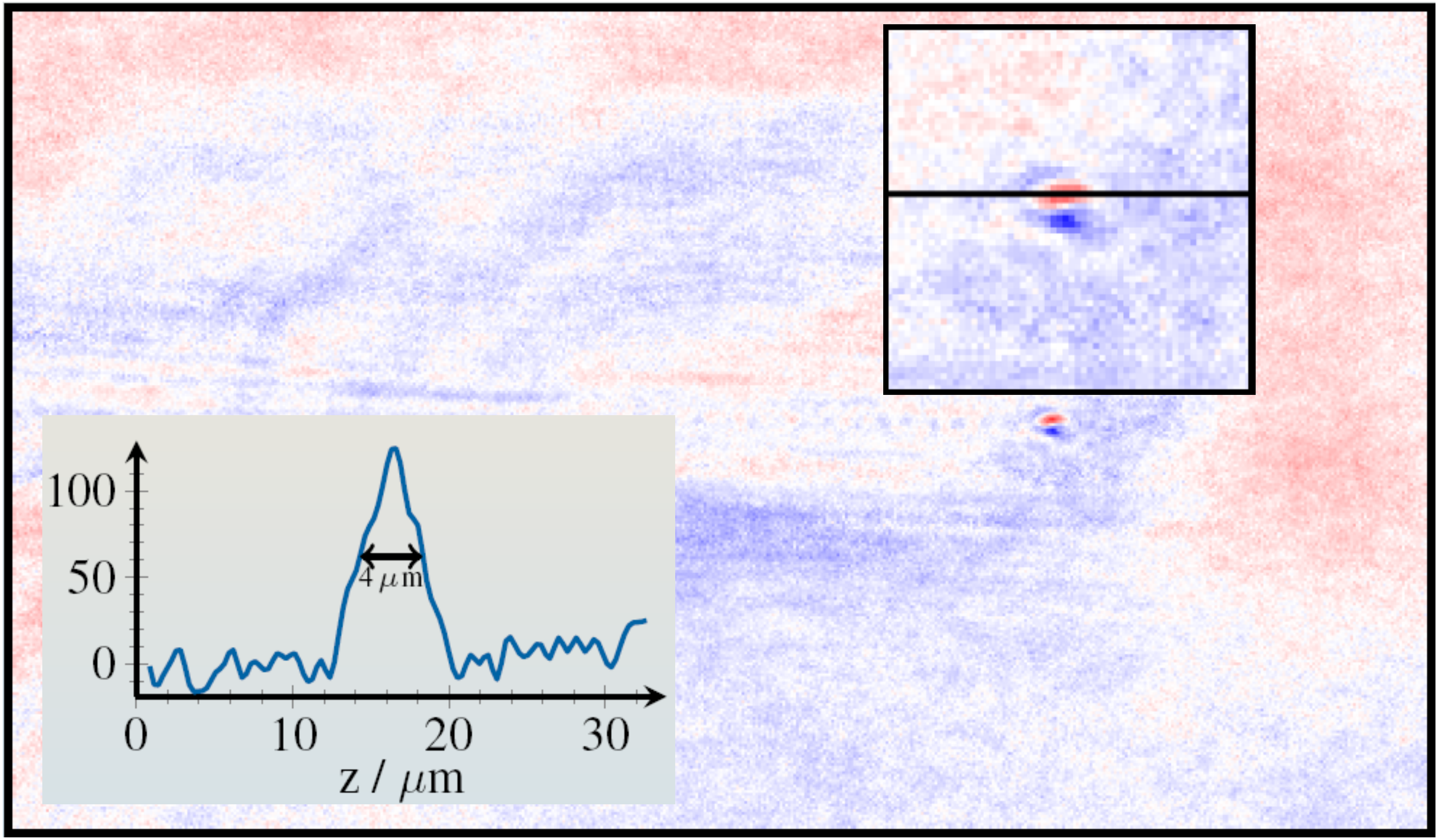
Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process



Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process



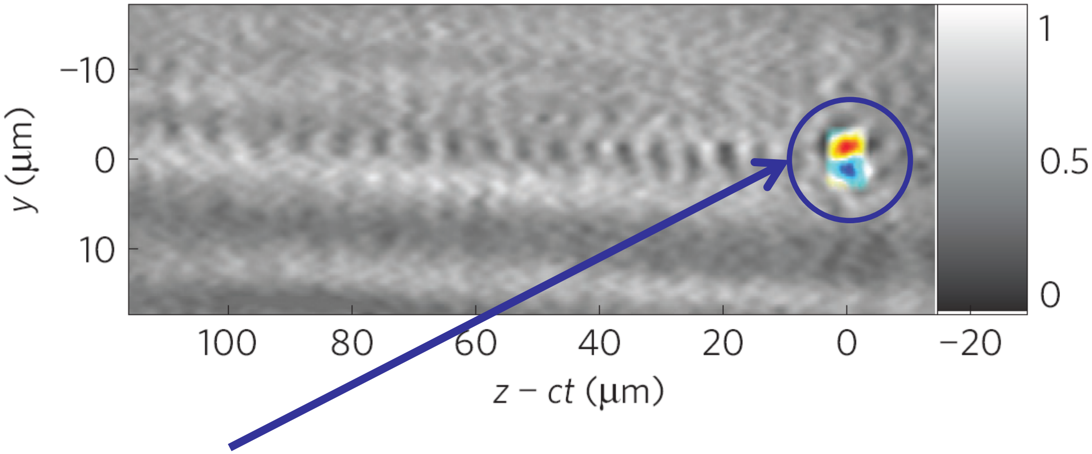
Electron bunch length: $\Delta z = 4\ \mu m$

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

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

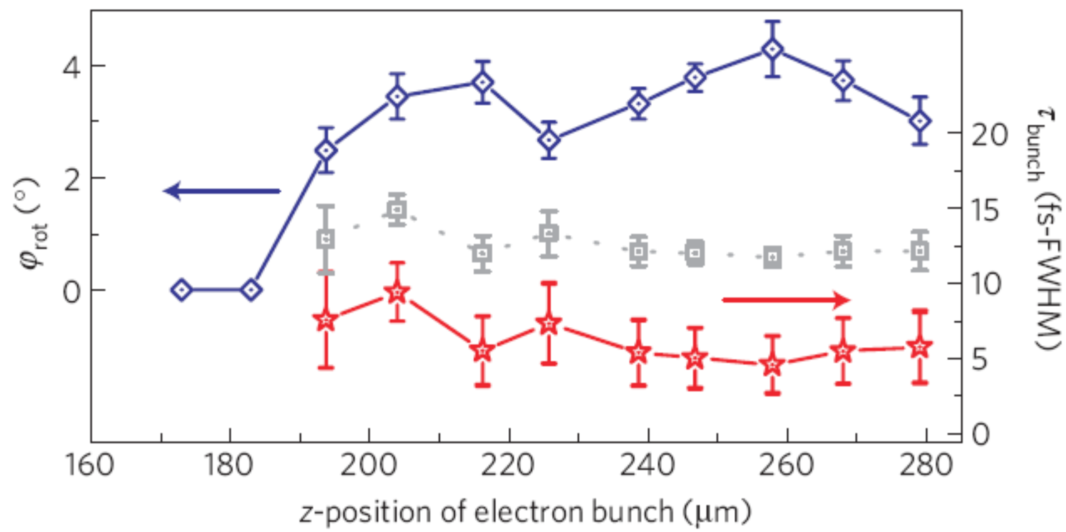
Electromagnetic Probe Pulses

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

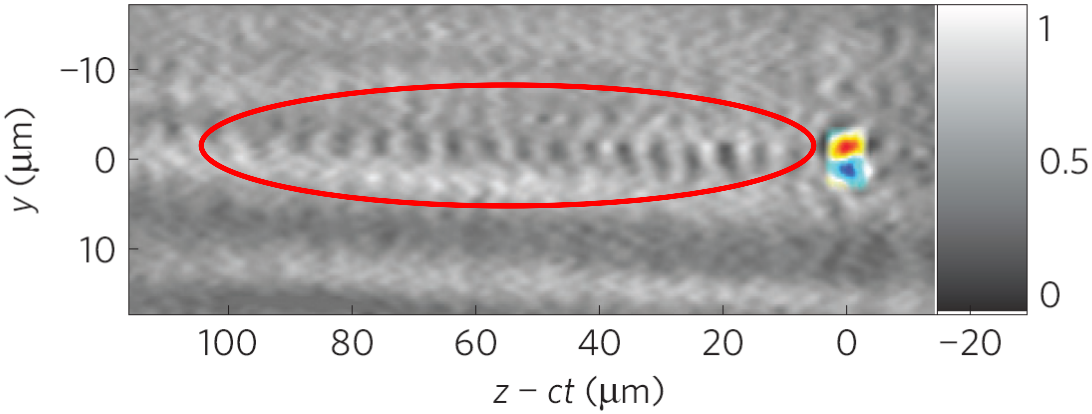


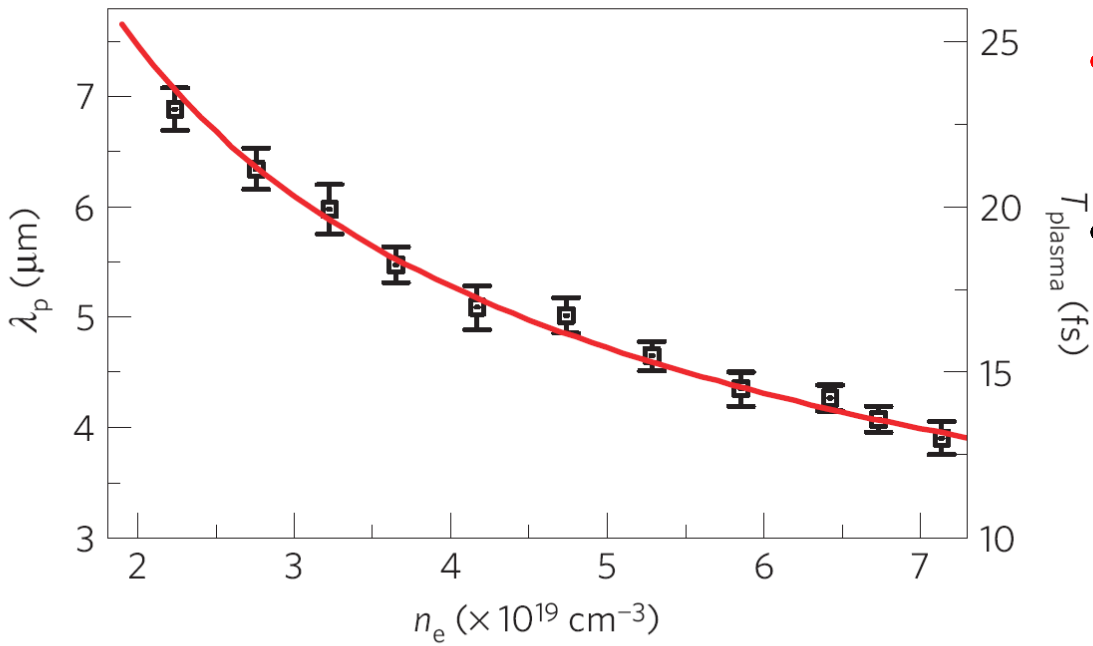
- observe e-bunch formation on-line!

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

Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process





- 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)

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Electromagnetic Probe Pulses

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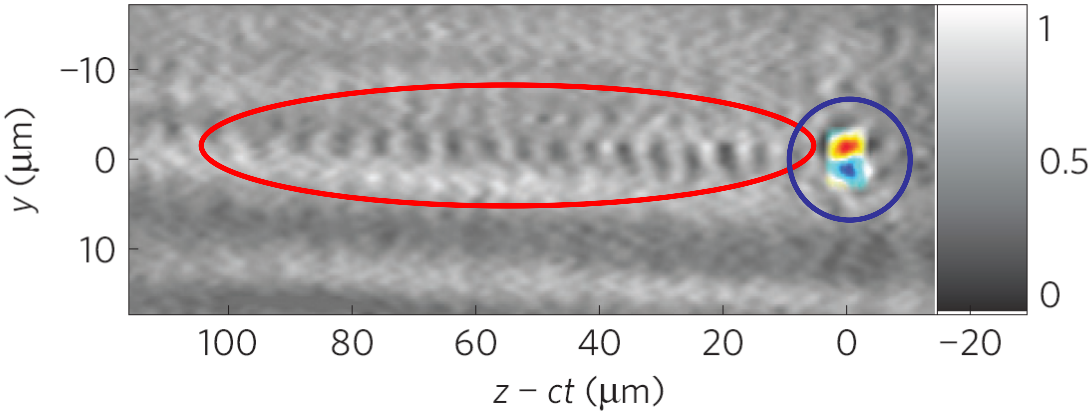
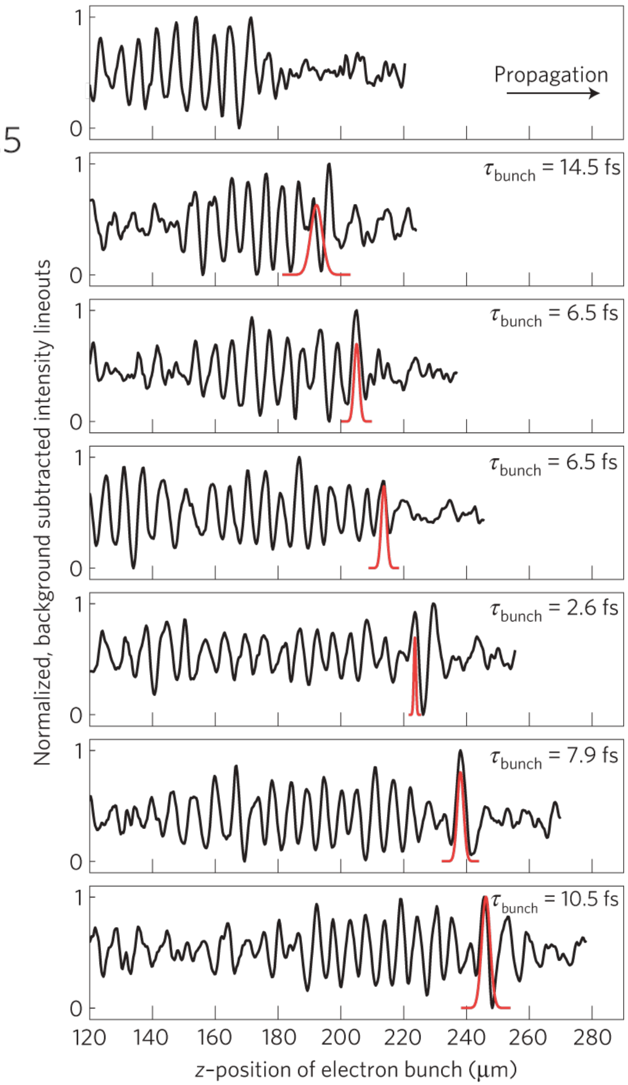
Probing of plasma wakefield acceleration process





- Polarimetry + Shadowgraphy:

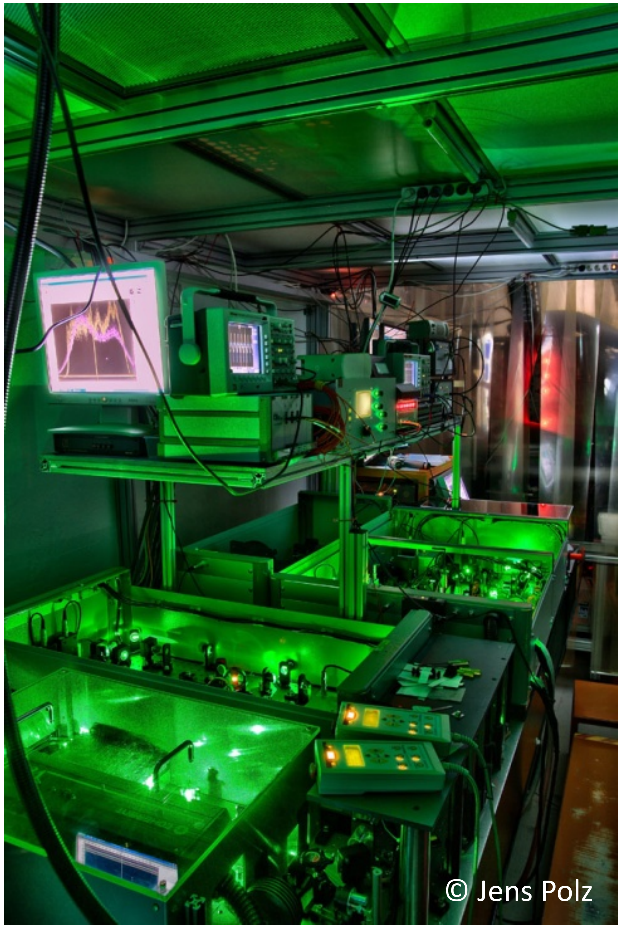
  Locate position of accelerated electron bunch in the plasma wave

  Accelerated electron bunch is situated within the first plasma-wave oscillation

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

Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process



Frontend of the JETi laser

Power amplifier of the JETi laser

30 fs, 850 mJ, (30 TW peak power), 3×10^{20} W/cm^2 peak intensity, 10 Hz

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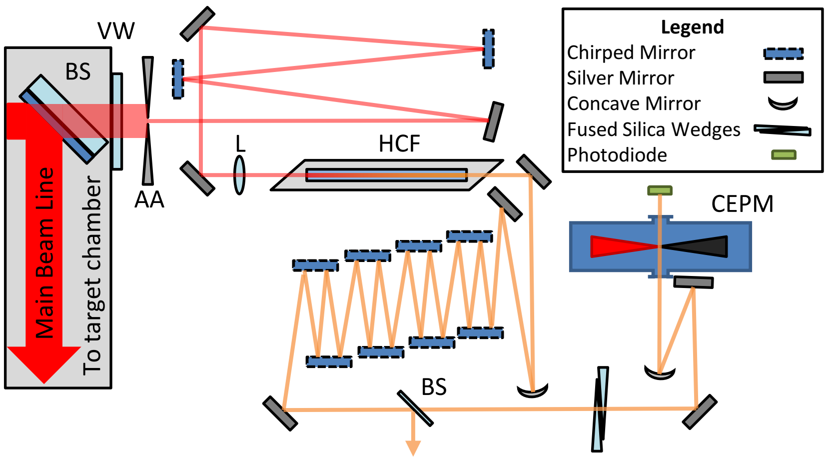
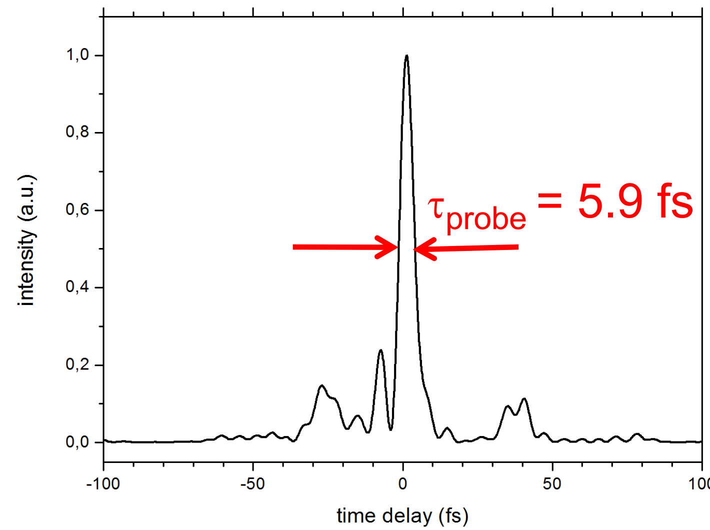
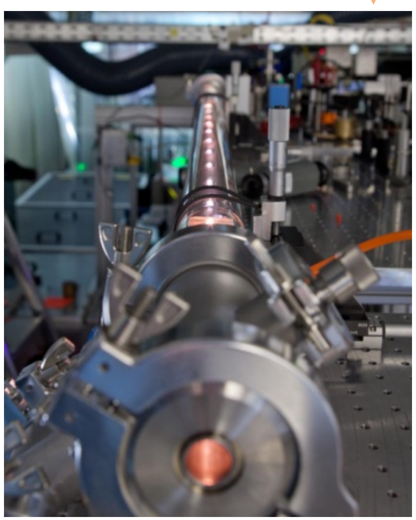
Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

- Few-cycle probe pulse generation at JETI via frequency-broadening







input pulses from JETI: 32 fs, ~1 mJ

⇒ (5.9±0.4) fs @ 300 µJ,

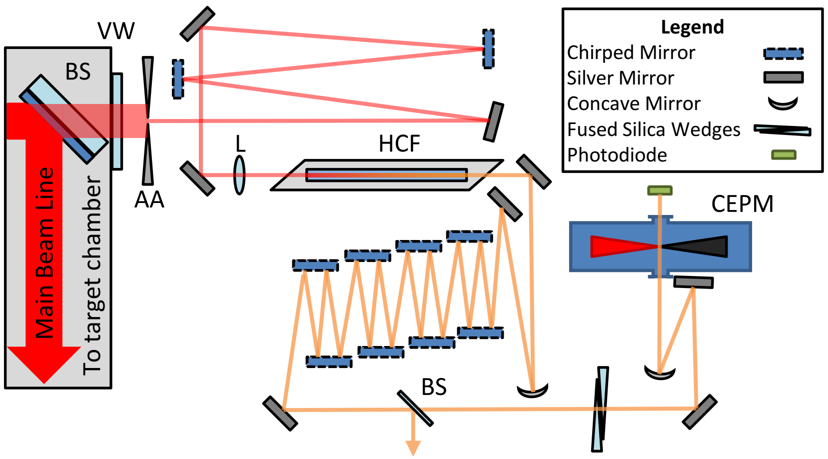
⇒ sufficient for shadowgraphy, Faraday-rotation, interferometry, …

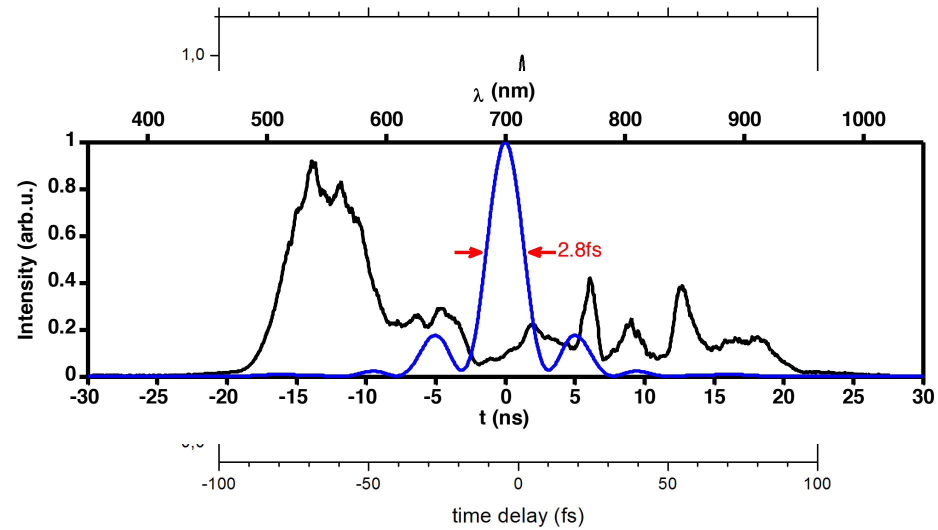
M. Schwab *et al.,* Applied Physics Letters **103,** 191118 (2013)
D. Adolph *et al.,* Applied Physics Letters **110,** 081105 (2017)

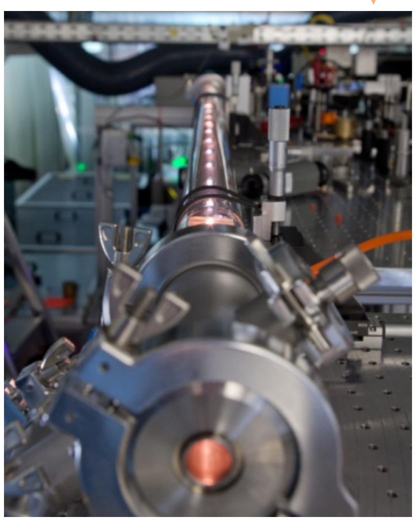
Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

- Few-cycle probe pulse generation at JETI via frequency-broadening







input pulses from JETI: 32 fs, ~1 mJ

⇒ (5.9±0.4) fs @ 300 μJ, (2.8±0.4) fs @ 200 μJ

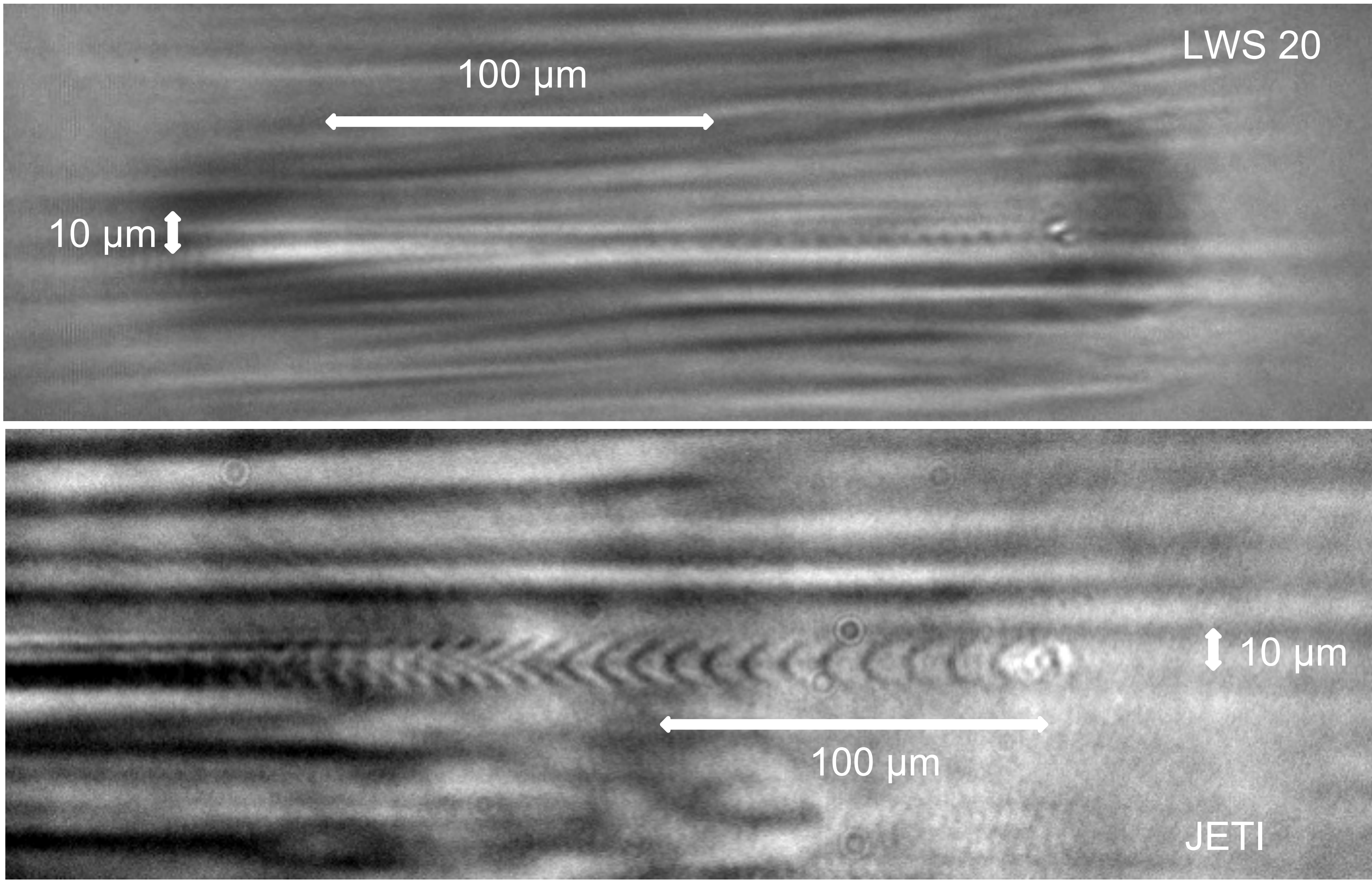
⇒ sufficient for shadowgraphy, Faraday-rotation, interferometry, …

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

Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

- Few-cycle probe pulses



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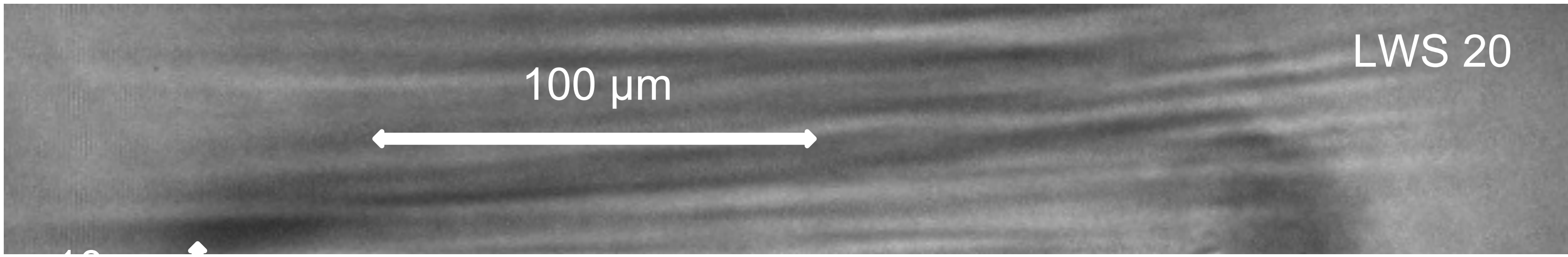
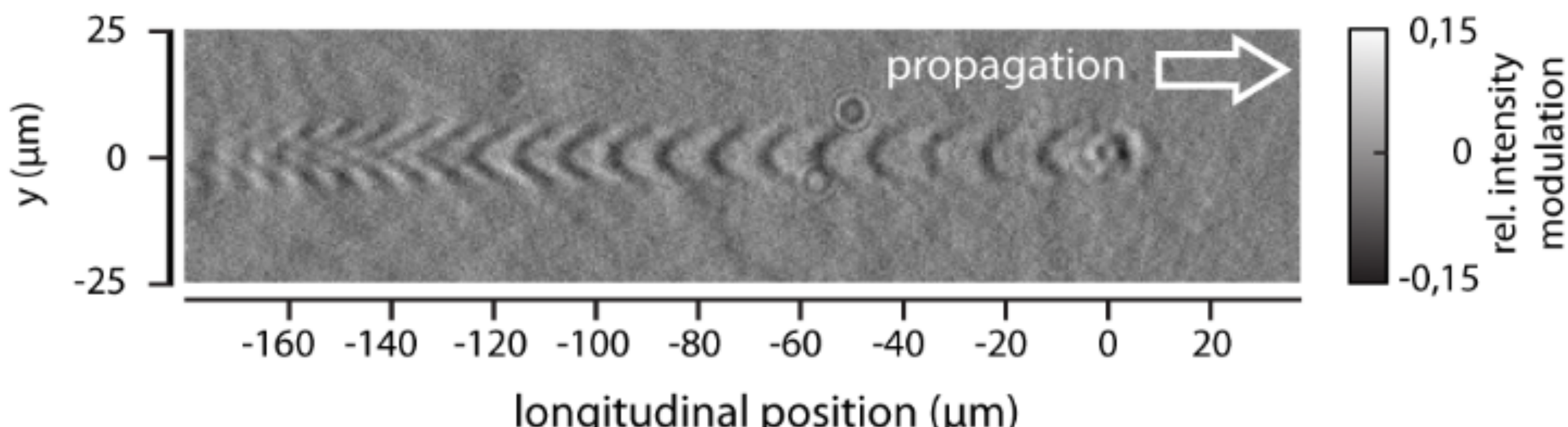
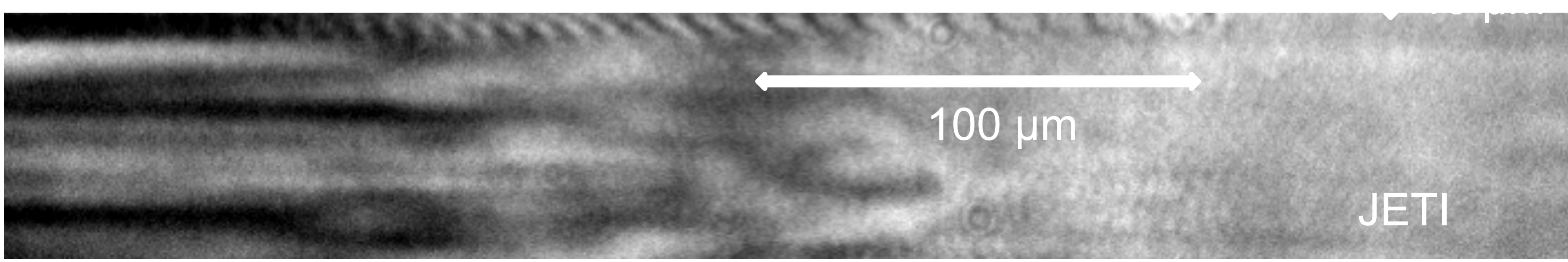
Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

- Few-cycle probe pulses







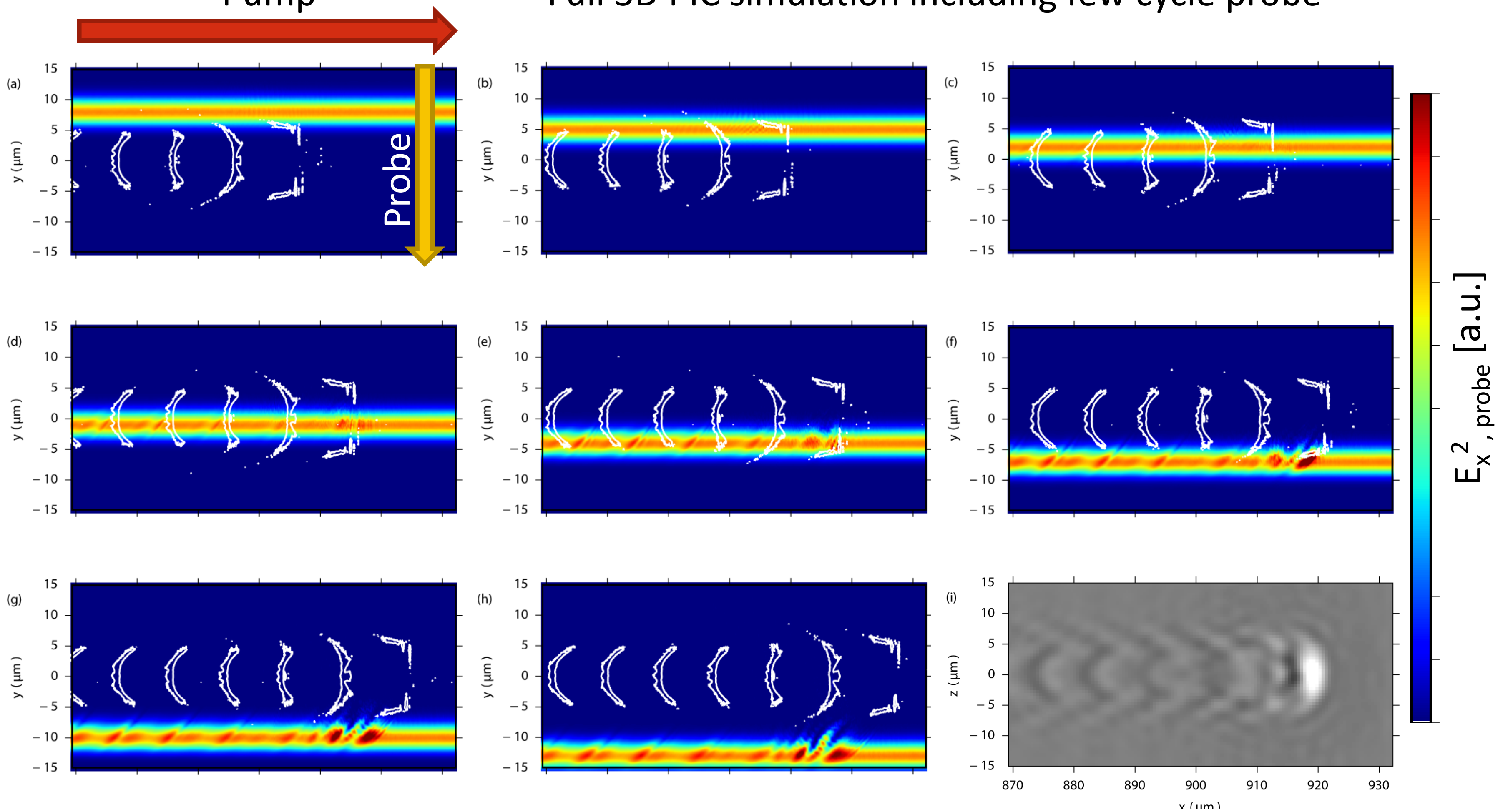
M. Schwab *et al.,* Appl. Phys. Lett. **103,** 191118 (2013)

Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

Pump

Full 3D PIC simulation including few cycle probe



Shadowgram is formed mostly in the center part.
High gradients & short pulse duration -> high contrast

Simulated shadowgram incl. imaging optics and detector

E. Siminos *et al.* Plasma Phys. Contr. Fusion **58**, 065004 (2016)

Electromagnetic Probe Pulses

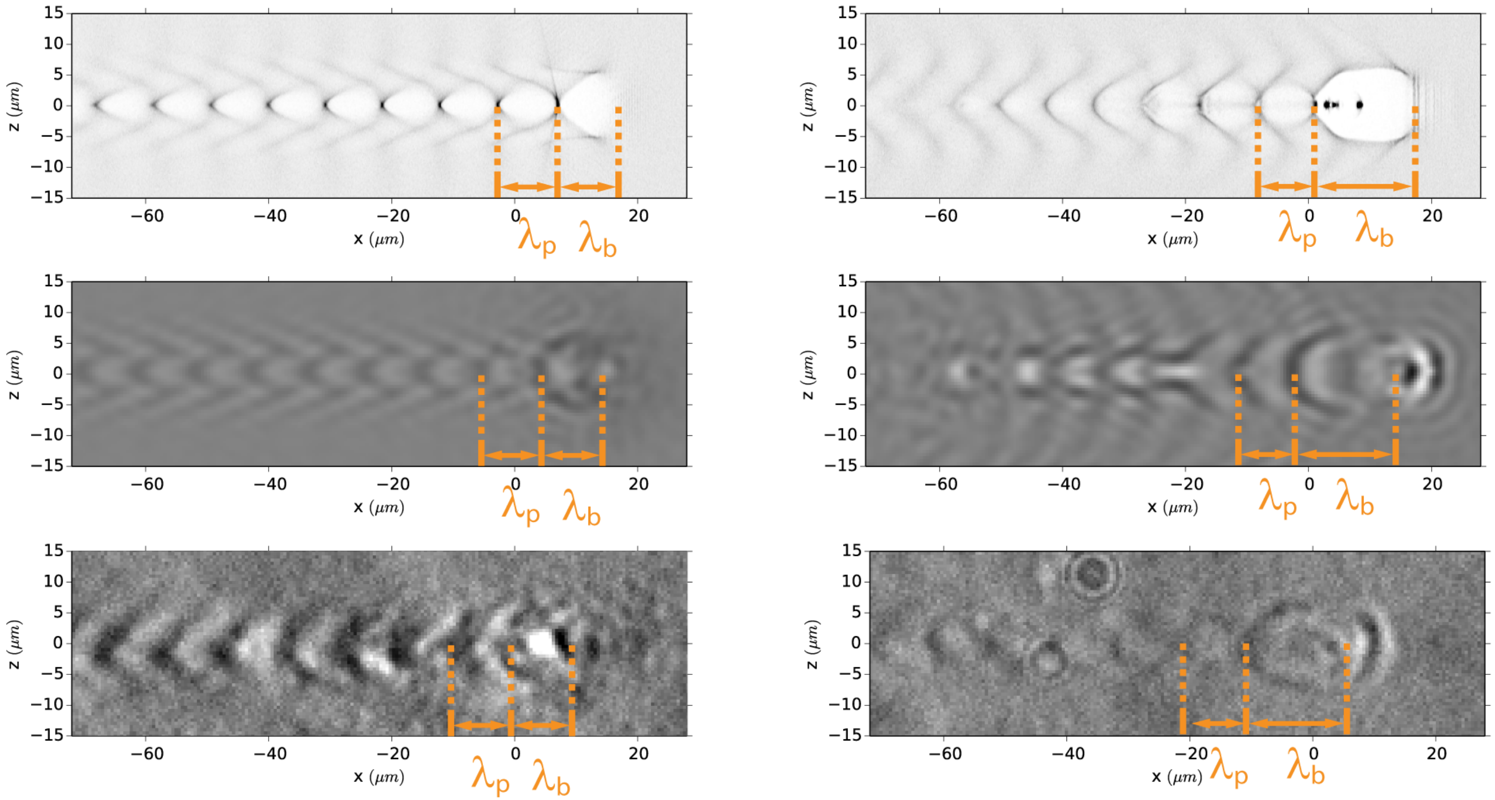
Probing of plasma wakefield acceleration process

$v_g t$=527 µm ***$v_g t$=1214 µm***

electron density:

computed shadowgram:

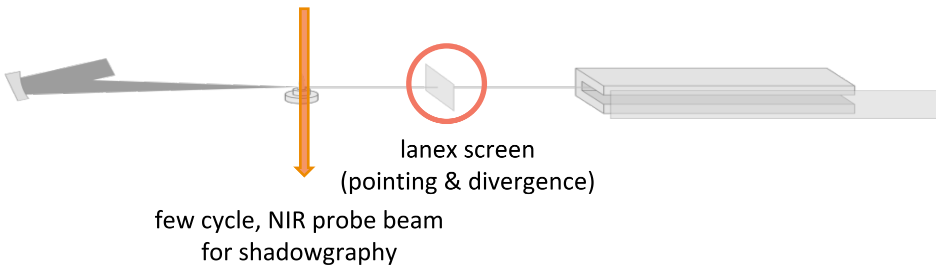
experiment:

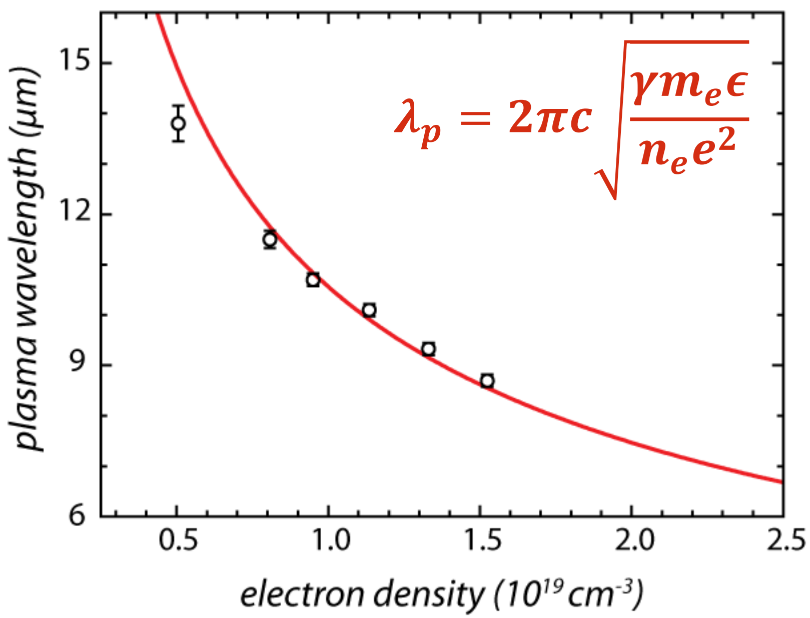


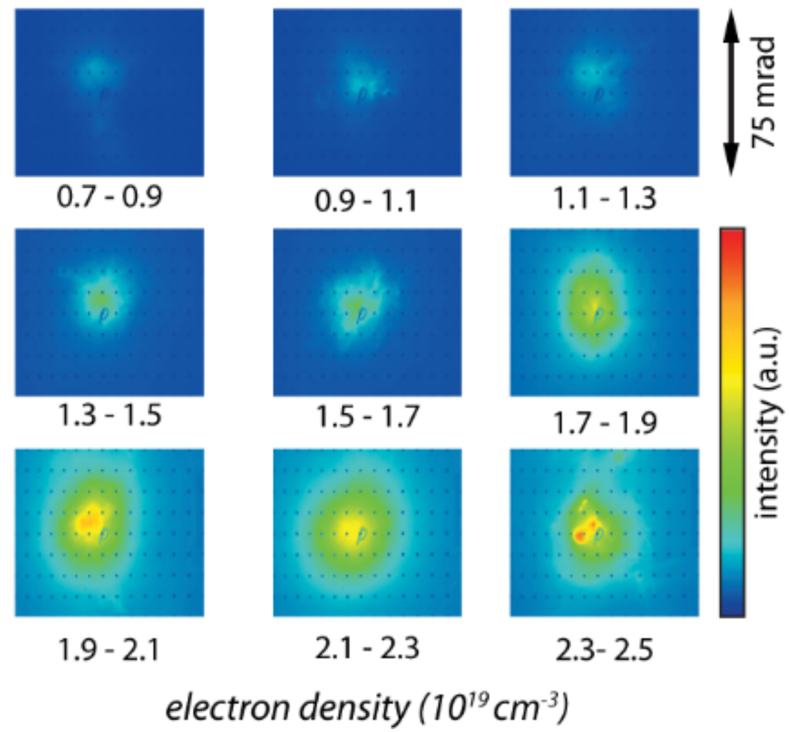
Bubble length and plasma period length are directly accessible!

Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process







critical power for self trapping:

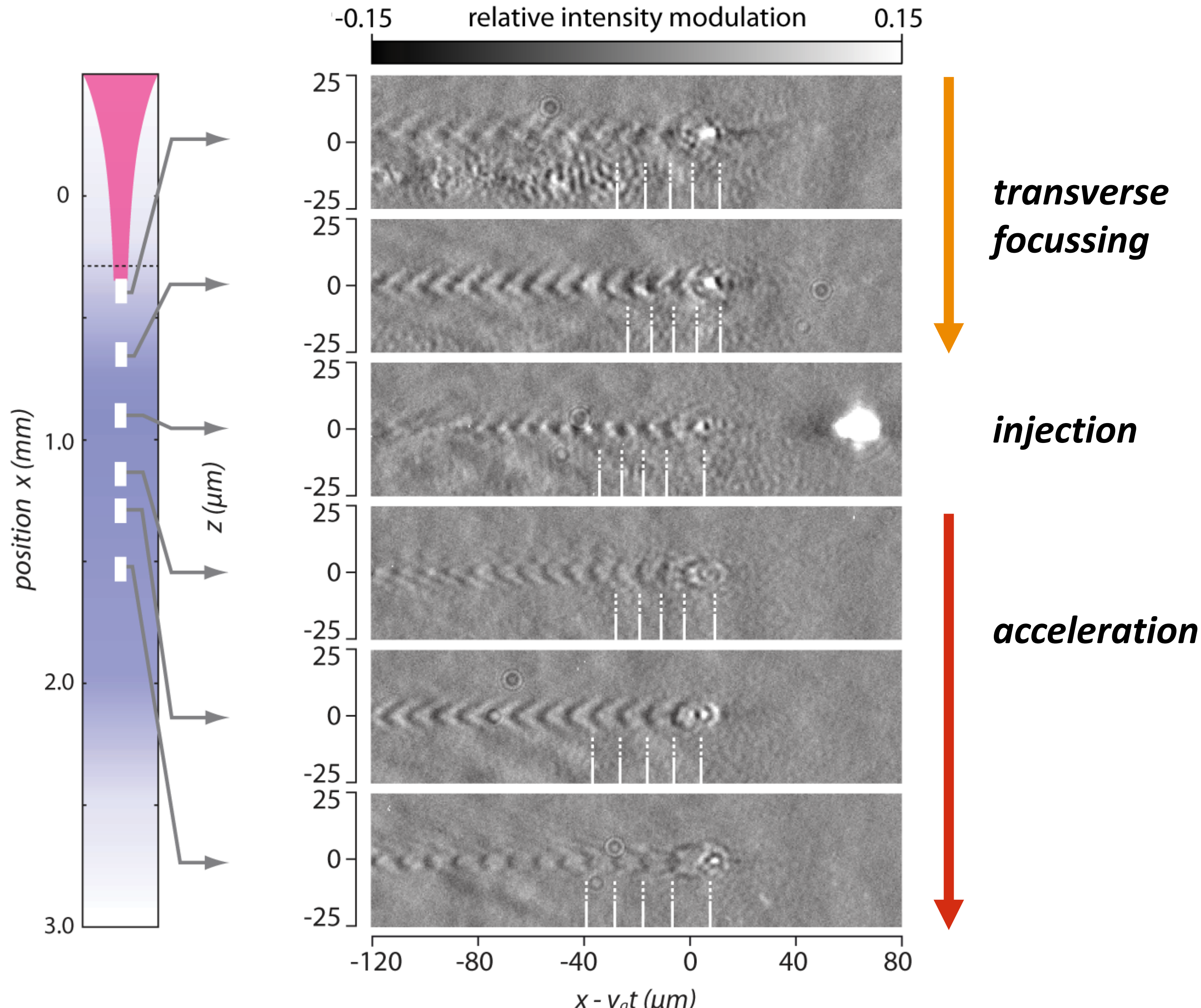
$$\frac{\alpha P}{P_c} > \frac{1}{16}\left[\ln\left(\frac{2n_c}{3n_e}\right) - 1\right]^3$$

for our parameters: $n_e >$ **1.5×10^{19}cm^{-3}**

S.P.D. Mangles *et al.* Phys. Rev. STAB **15**, 011302 (2012)
A. Sävert *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

Electromagnetic Probe Pulses

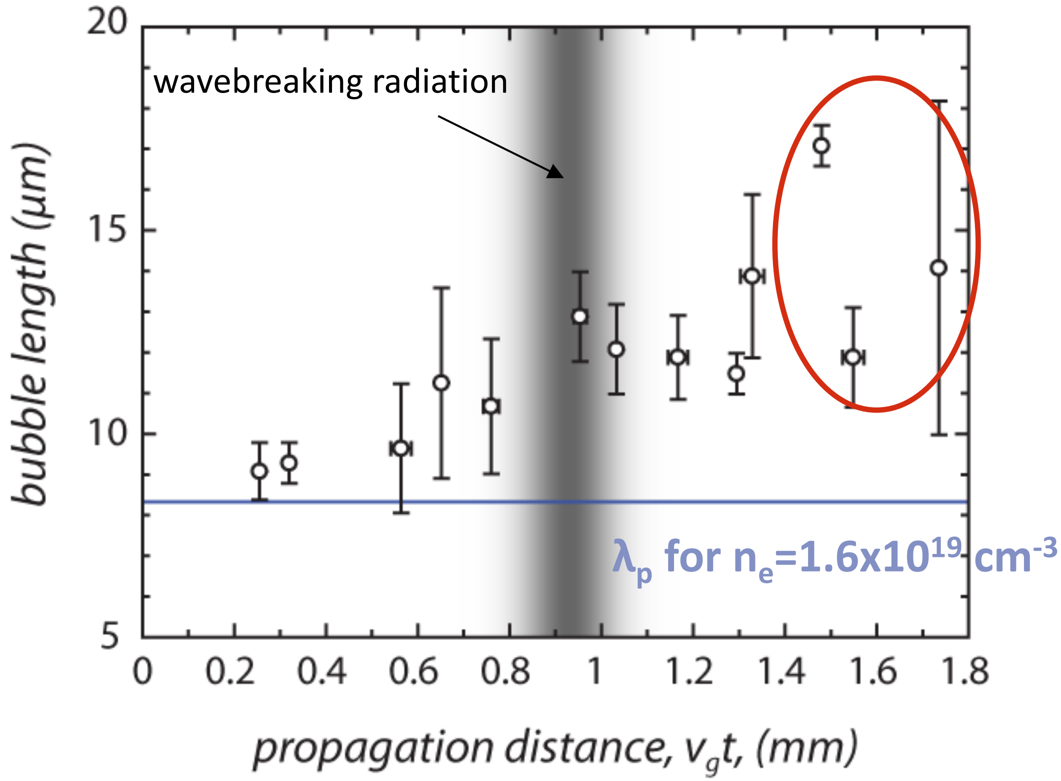
Probing of plasma wakefield acceleration process



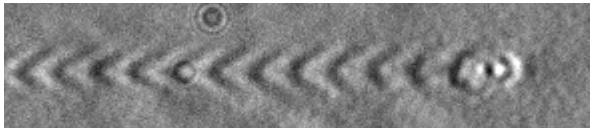
A. Sävert *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

Electromagnetic Probe Pulses

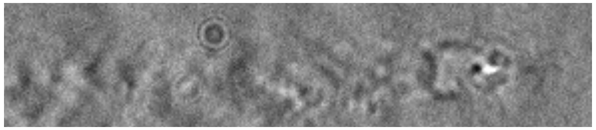
Probing of plasma wakefield acceleration process



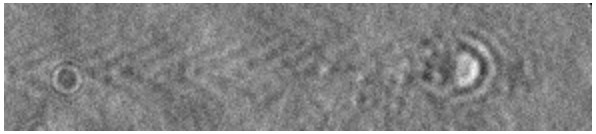
„well behaved“



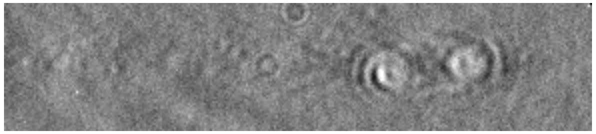
beam loading dominated



single bubble regime



multiple bubble regime



Bubble expansion starts before injection. → No beamloading but amplification of the pump pulse.

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

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

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Electromagnetic Probe Pulses

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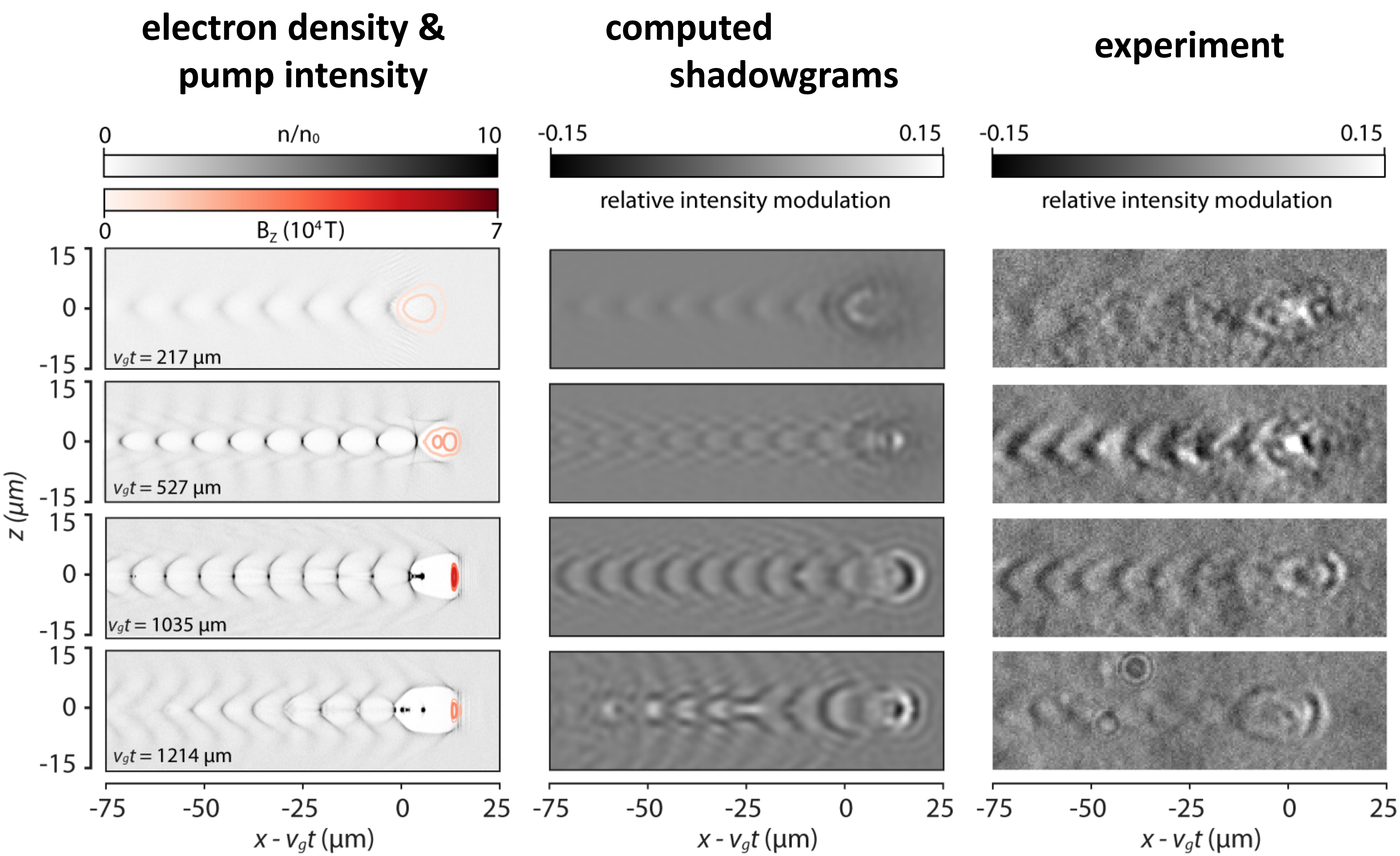
Probing of plasma wakefield acceleration process

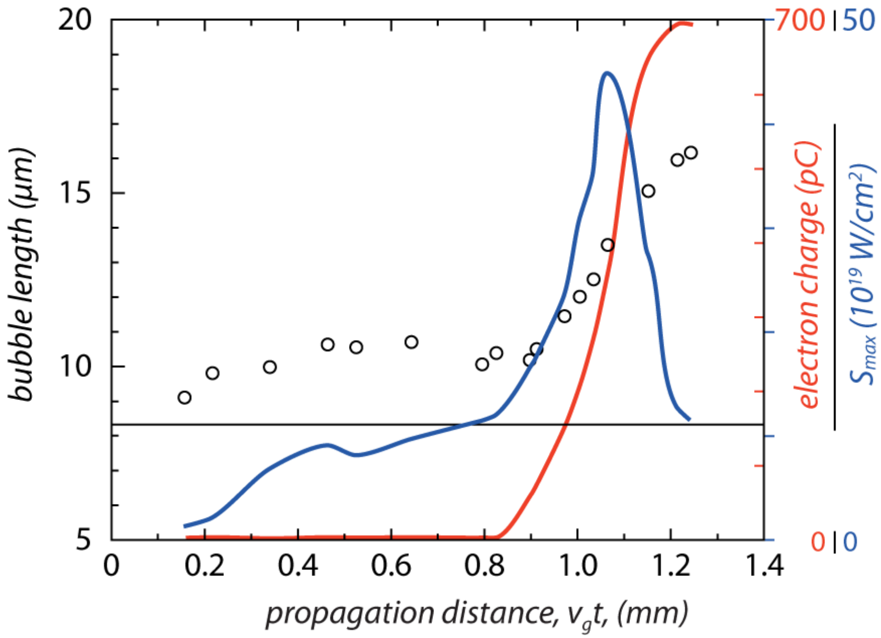


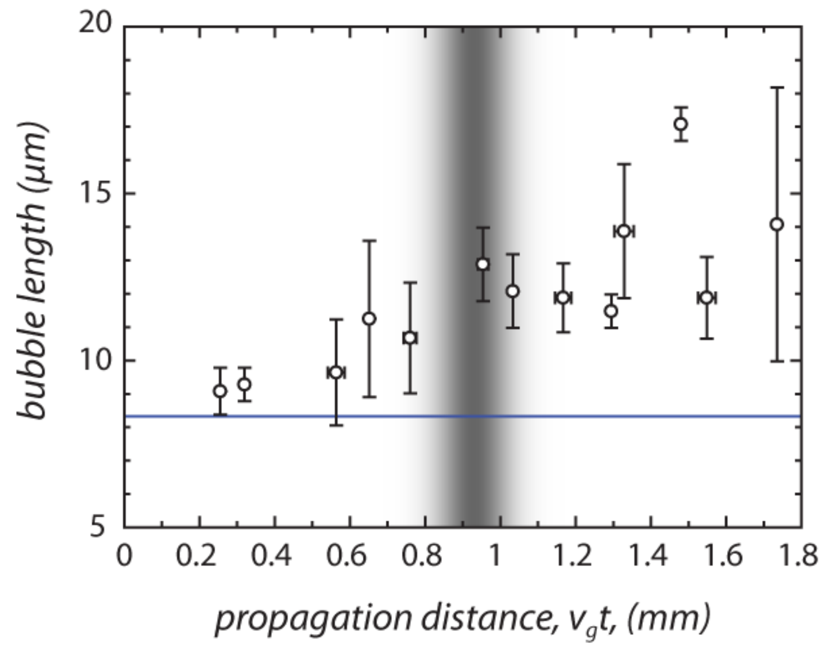
3D PIC simulation (EPOCH), 150x70x70 µm^3 sliding box
2700x525x525 cells

E. Siminos *et al.* Plasma Phys. Contr. Fusion **58**, 065004 (2016)

Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process





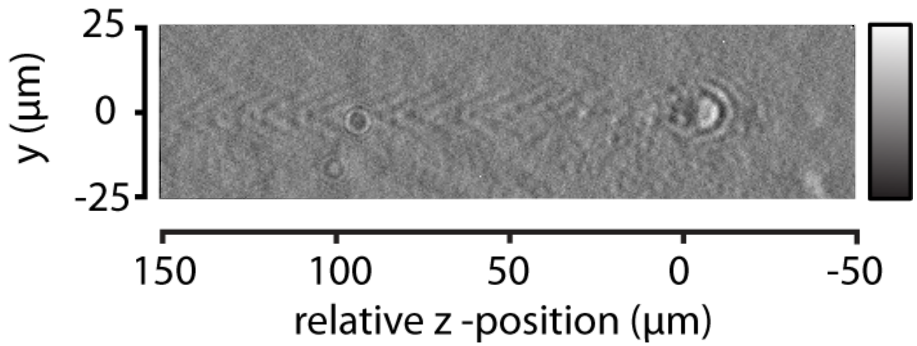
Bubble expansion starts before injection. → No beamloading but amplification of the pump pulse.

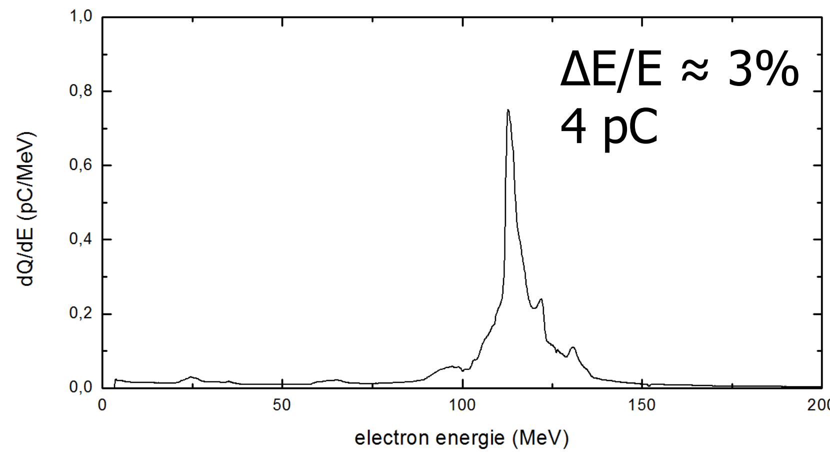
A. Sävert *et al.* Phys. Rev. Lett. **115**, 055002 (2015)

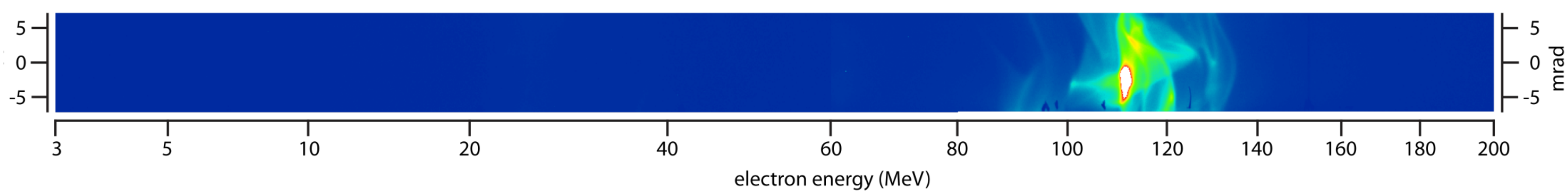
Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

- After plasma wave evolution into single bubble:







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Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

Energy gain

$$\Delta E[GeV] \cong 1.7 \left(\frac{P[TW]}{100}\right)^{1/3} \left(\frac{10^{18}}{n_p[cm^{-3}]}\right)^{2/3} \left(\frac{0.8}{\lambda_0[\mu m]}\right)^{4/3}$$

W. Lu et al. Phys. Rev. ST Accel. Beams 10, 061301

lower plasma density

↓

lower plasma frequency

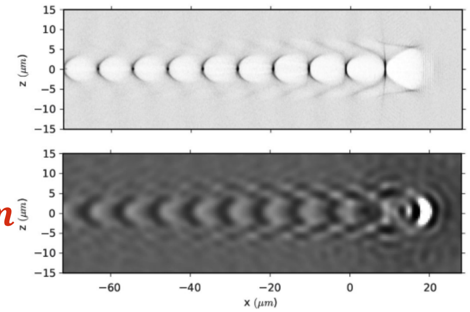
JETi 200: $P = 200\ TW$,
$\tau_L = 17\ fs$

pulse duration: $\tau_L \leq \lambda_p/2$

JETi40

$n_p = 1.6\times10^{19}\ cm^{-3}$

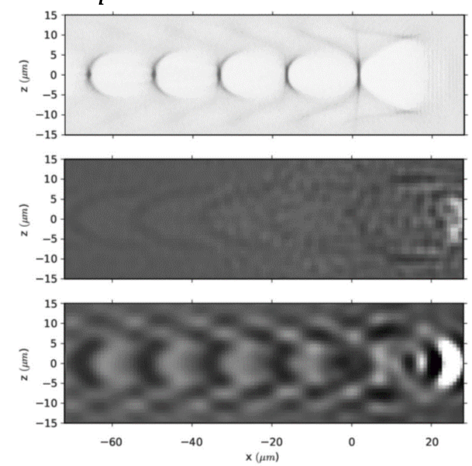
$\lambda_p = 750\ nm$



JETi200

$n_p = 0.4\times10^{19}\ cm^{-3}$

$\lambda_p = 1.4\ \mu m$



For probing techniques, the refractive index $n = \sqrt{1 - \frac{\omega_p^2}{\gamma\omega_{probe}^2}}$ defines the sensitivity!

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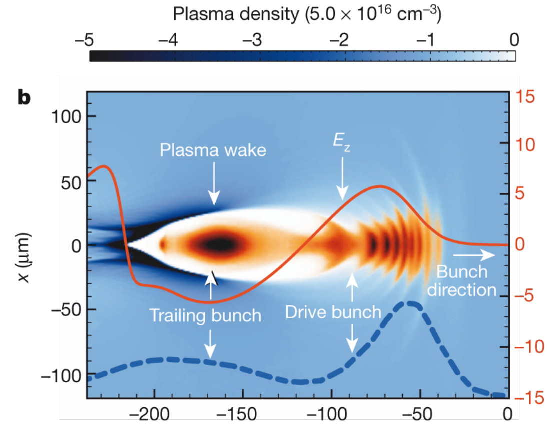
Probing of plasma wakefield acceleration process

$n_e = 7 \cdot 10^{18}\ cm^{-3}, \lambda_p = 12\ \mu m$

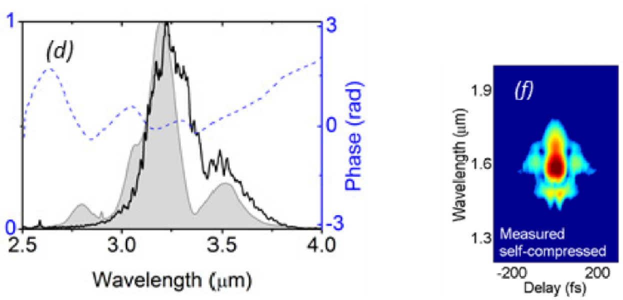
$\lambda_{probe} = 750\ nm$



M. Litos *et al.* Nature **515**, 92 (2014)

$\lambda_{probe} = 8\ \mu m$ required

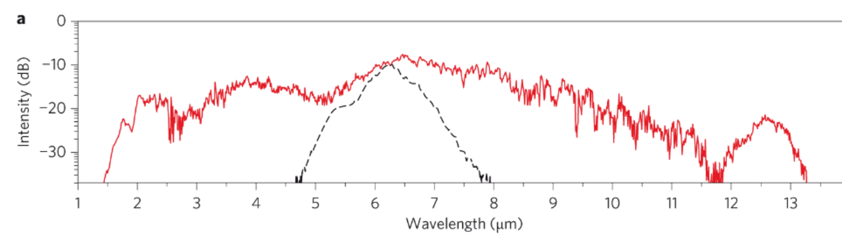
Sub 3-cycle laser pulses @ $\lambda_c = 3.1\ \mu m$



$E_{pulse} = 10\ \mu J\ @\ 160\ kHz$

M. Hemmer *et al.* Optics Express **21**, 28095 (2013)

Super continuum @ $\lambda_c = 6.5\ \mu m$



$E_{pulse} = 100\ nJ\ @\ 1\ kHz$

C.R. Petersen *et al.* Nat. Photon. **8**, 830 (2014)

All optical techniques like shadowgraphy (imaging wakefields), polarimetry (imaging magnetic fields) are feasible for PWFA experiments!

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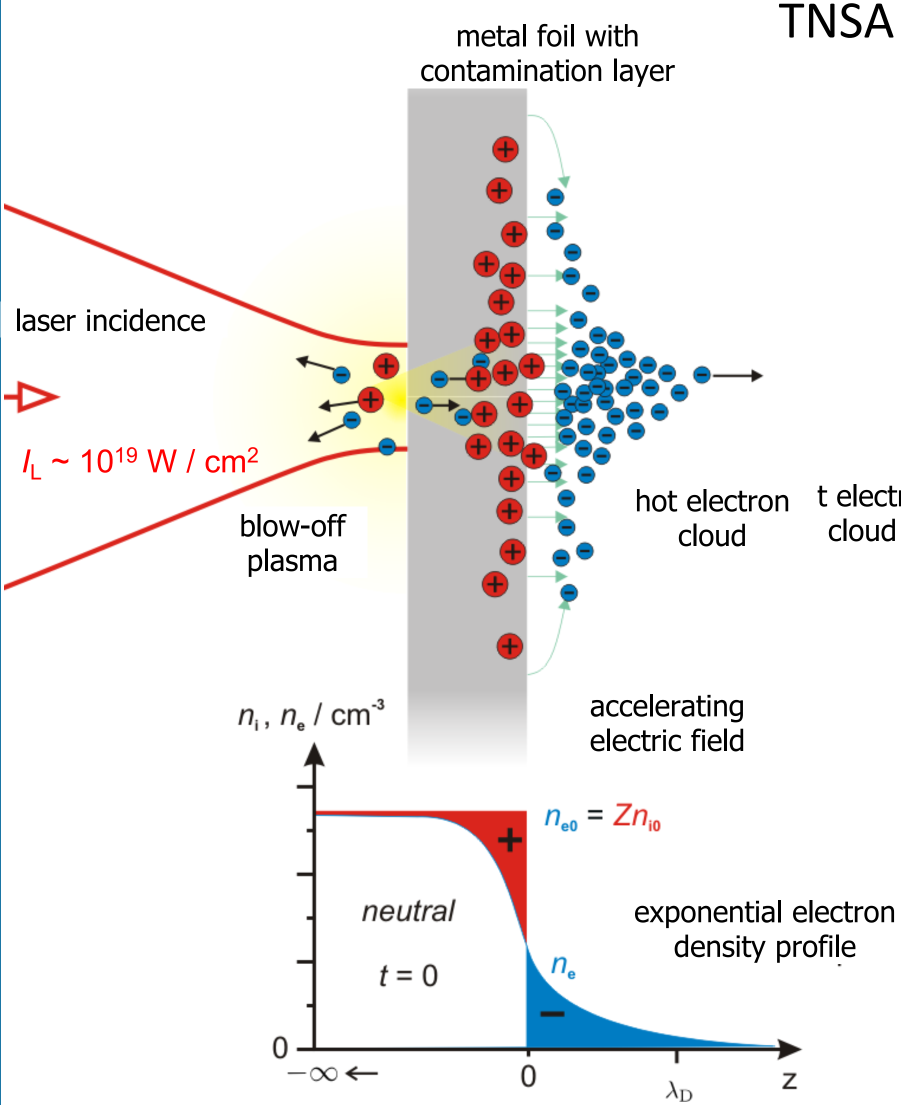
Electromagnetic Probe Pulses

Probing of laser-driven ion acceleration process



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 $\mathcal{E}_{\rm front}(t) \approx 2\sqrt{\frac{k_{\rm B}T_{\rm e}n_{\rm e}}{\varepsilon_0(2e_{\rm N}+\omega_{\rm pi}^2 t^2)}}$
- charge distribution starts to expand,
- acceleration length ~ µm

  ~ Debye-length $\lambda_{\rm D} = \sqrt{\frac{\varepsilon_0 k_{\rm B}T_{\rm e}}{n_{\rm e}e^2}}$
- lifetime of electric field ~ $f(\tau_L)$
- max. ion energies

$$E_{\rm max} = 2Zk_{\rm B}T_{\rm e}\left[\ln\left(\frac{\omega_{\rm pi}t}{\sqrt{2e_{\rm N}}}+\sqrt{\left(\frac{\omega_{\rm pi}t}{\sqrt{2e_{\rm N}}}\right)^2+1}\right)\right]^2$$

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

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Electromagnetic Probe Pulses

Probing of laser-driven ion acceleration process

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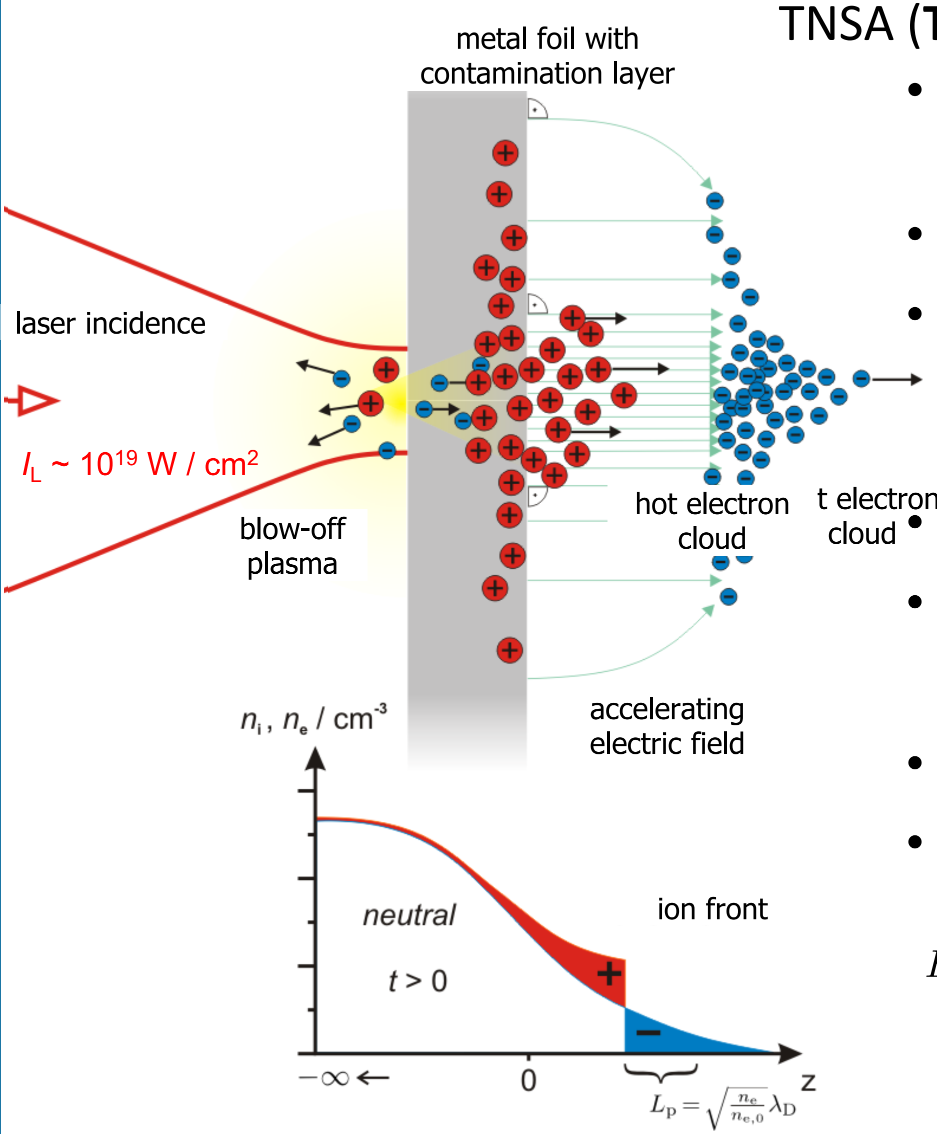

TNSA (**T**arget **N**ormal **S**heath **A**cceleration)

- laser pulse generates relativistic electrons,
- they propagate through the foil and
- form an electric sheath field

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- charge distribution starts to expand,
- acceleration length ~ µm

  ~ Debye-length $\quad \lambda_D = \sqrt{\dfrac{\varepsilon_0 k_B T_e}{n_e e^2}}$
- lifetime of electric field ~ $f(\tau_L)$
- max. ion energies

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

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

Electromagnetic Probe Pulses

Probing of laser-driven ion acceleration process

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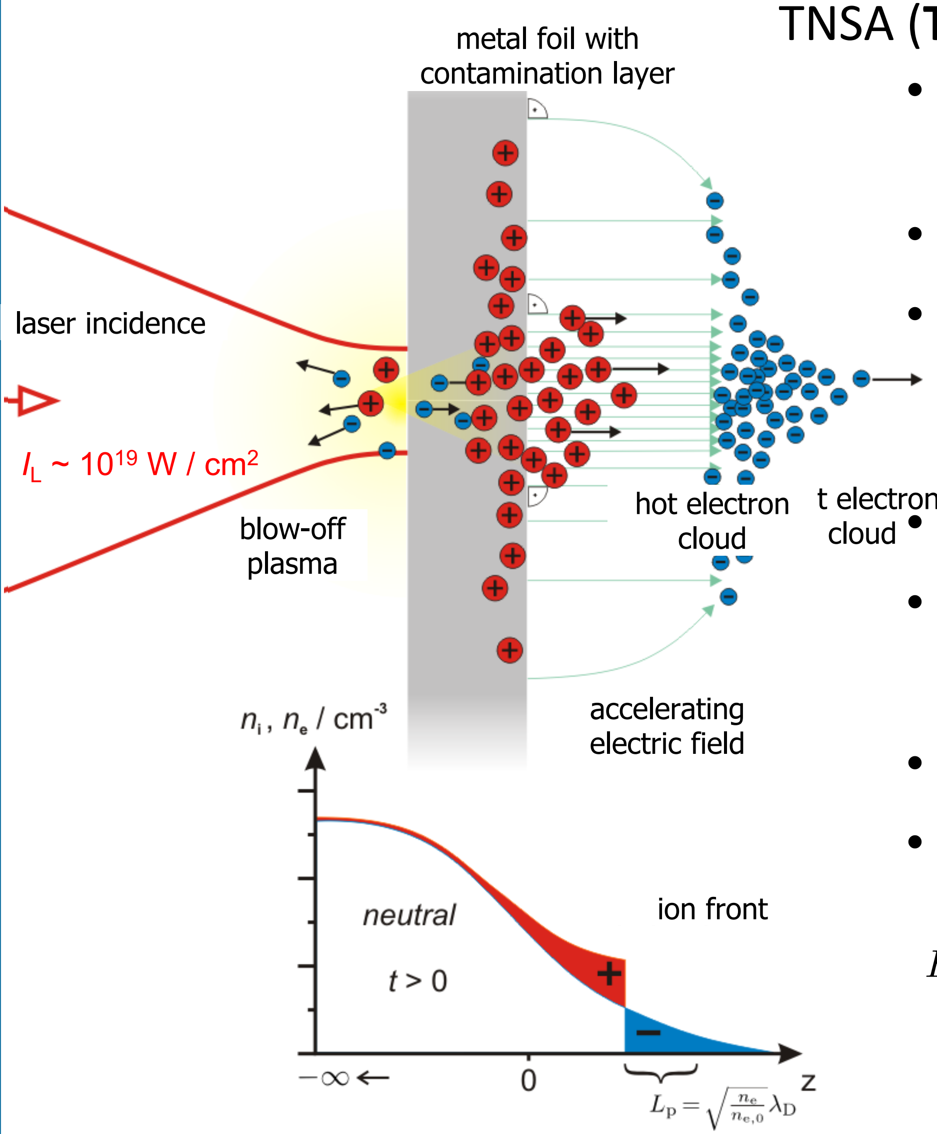
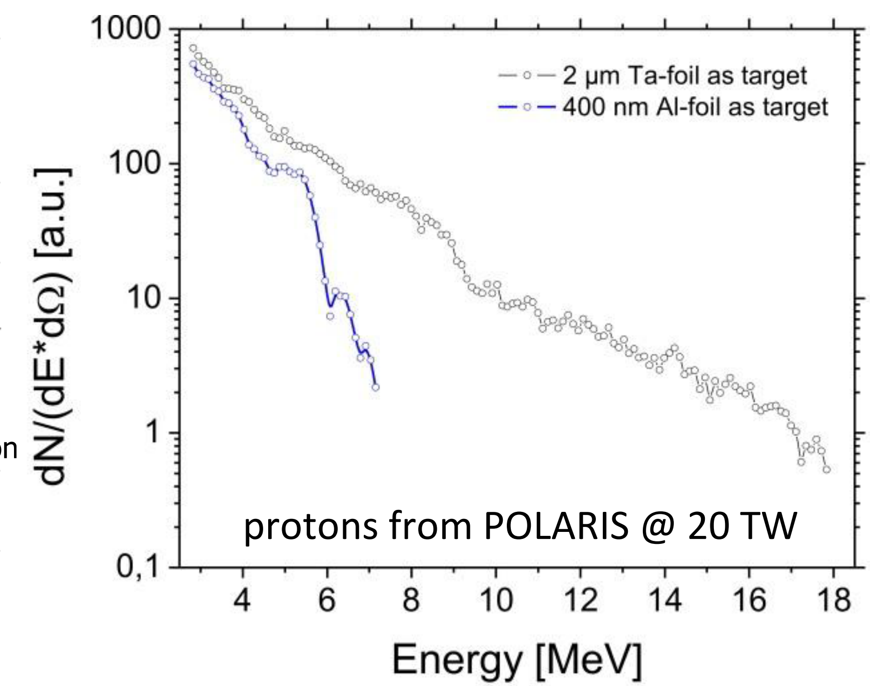


TNSA (**T**arget **N**ormal **S**heath **A**cceleration)



- lifetime of electric field ~ $f(\tau_L)$
- max. ion energies

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

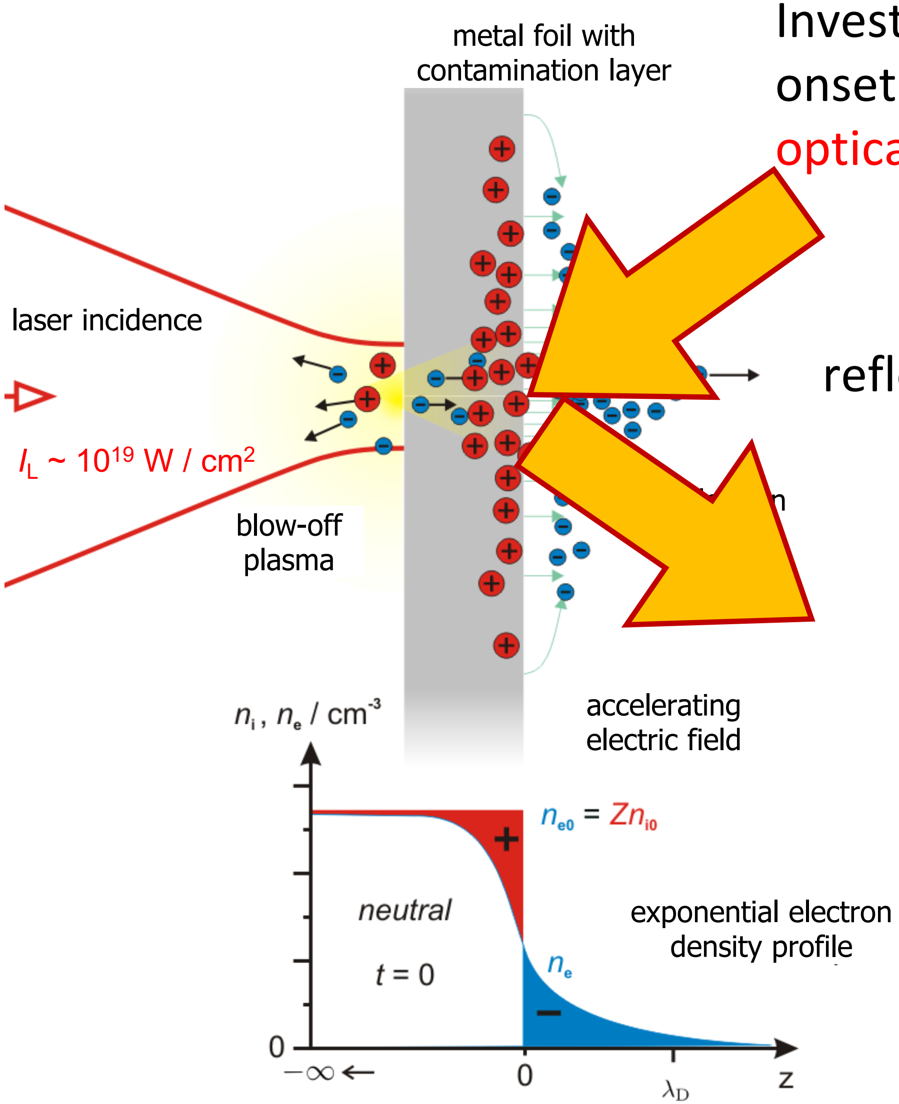
P. Mora, PRL **90,** 185002 (2003)

Electromagnetic Probe Pulses

Probing of laser-driven ion acceleration process

Investigation of rear-surface TNSA-sheath at onset of acceleration process:

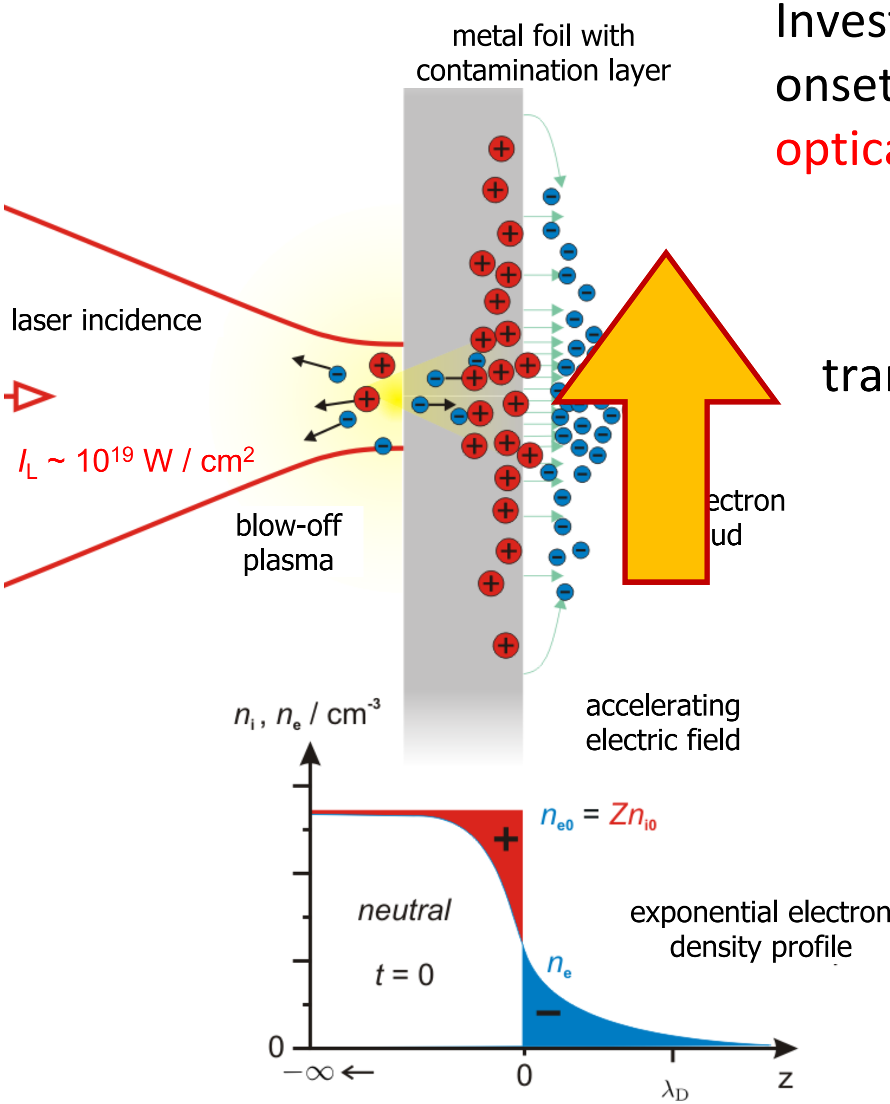
optical probing with fs and µm resolution



reflective geometry

Electromagnetic Probe Pulses

Probing of laser-driven ion acceleration process



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

transverse geometry

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Electromagnetic Probe Pulses

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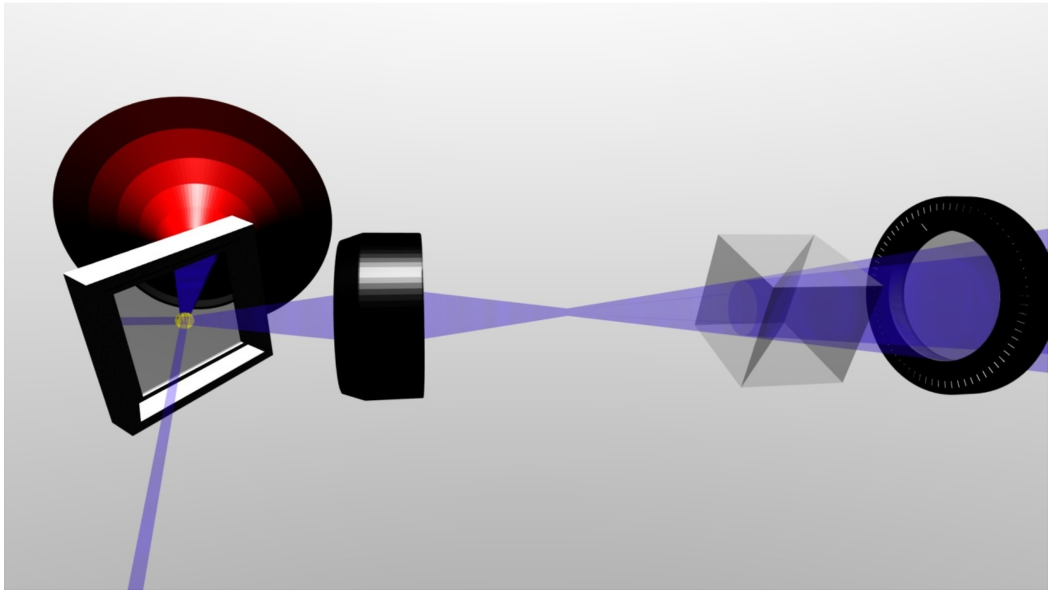
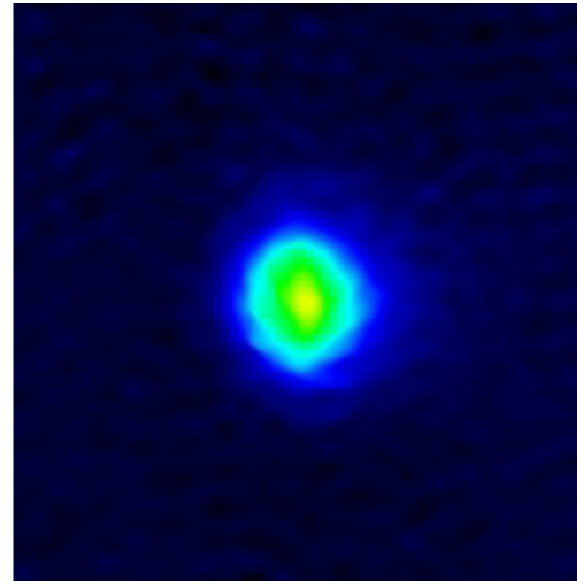
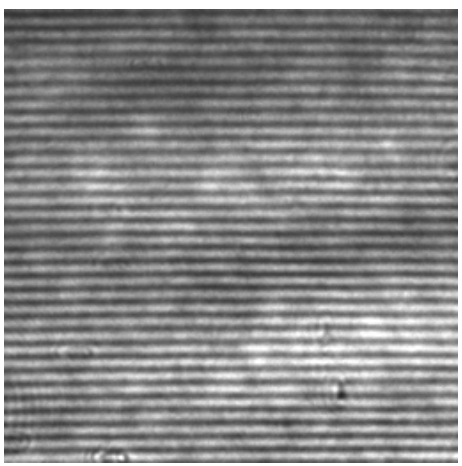
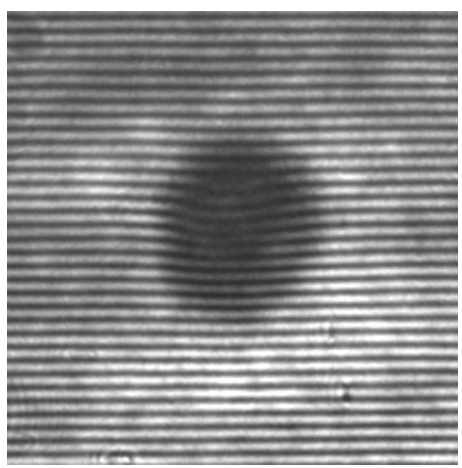
Probing of laser-driven ion acceleration process



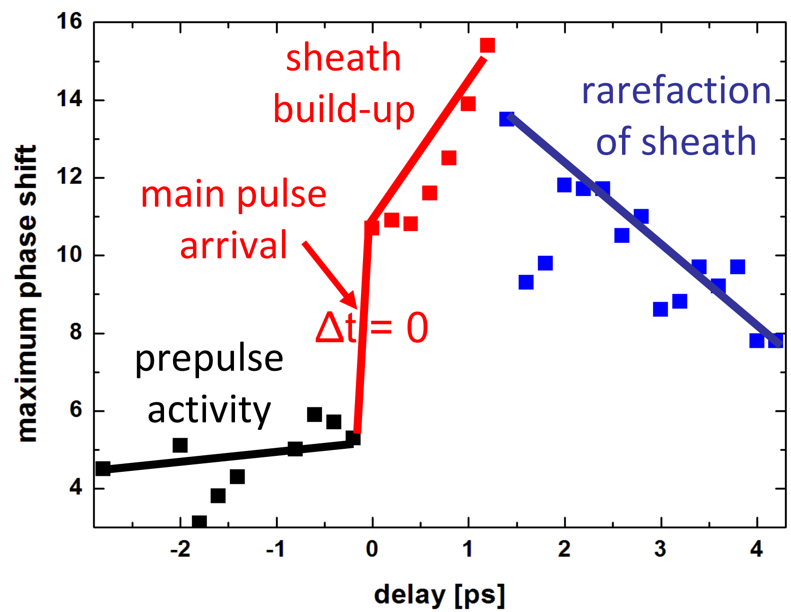




without main pulse



with main pulse



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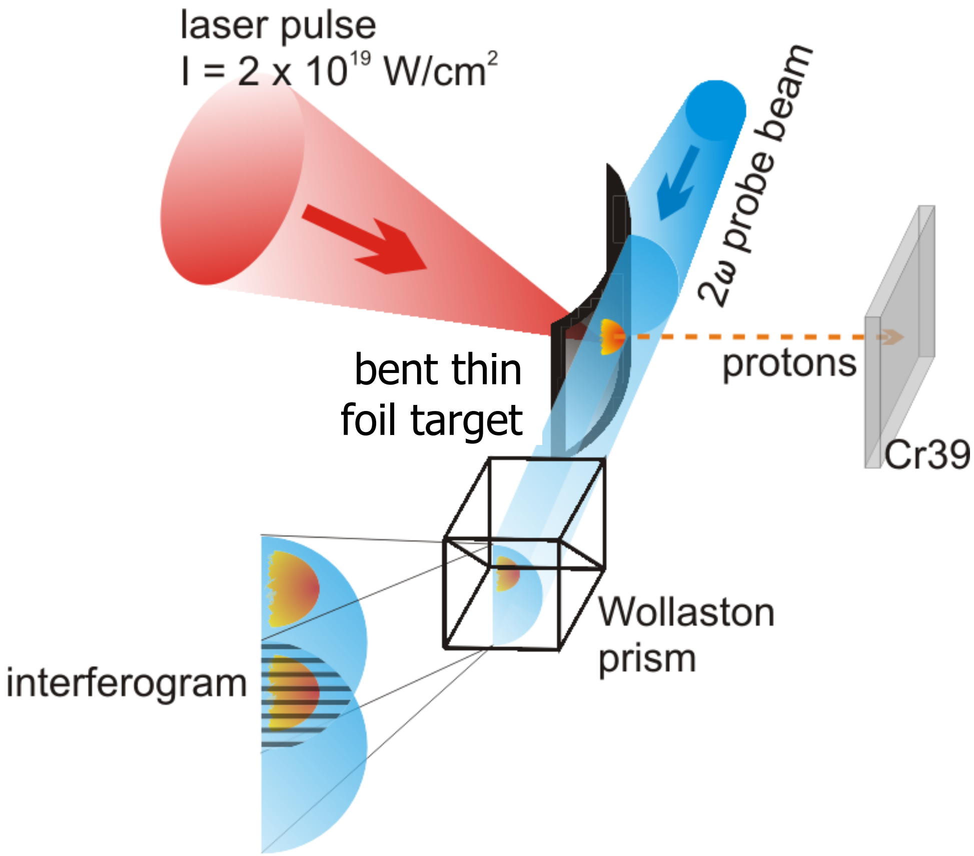
Probing of laser-driven ion acceleration process



phase shift (measured tangentially) $\Rightarrow$ 2D signal

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

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)

$$n_\mathrm{e}(r,z,t) \sim \exp\left[-\frac{r(t)^2}{w_0^2}\right]\exp\left[-\frac{z(t)}{\lambda_\mathrm{D}}\right]$$

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

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

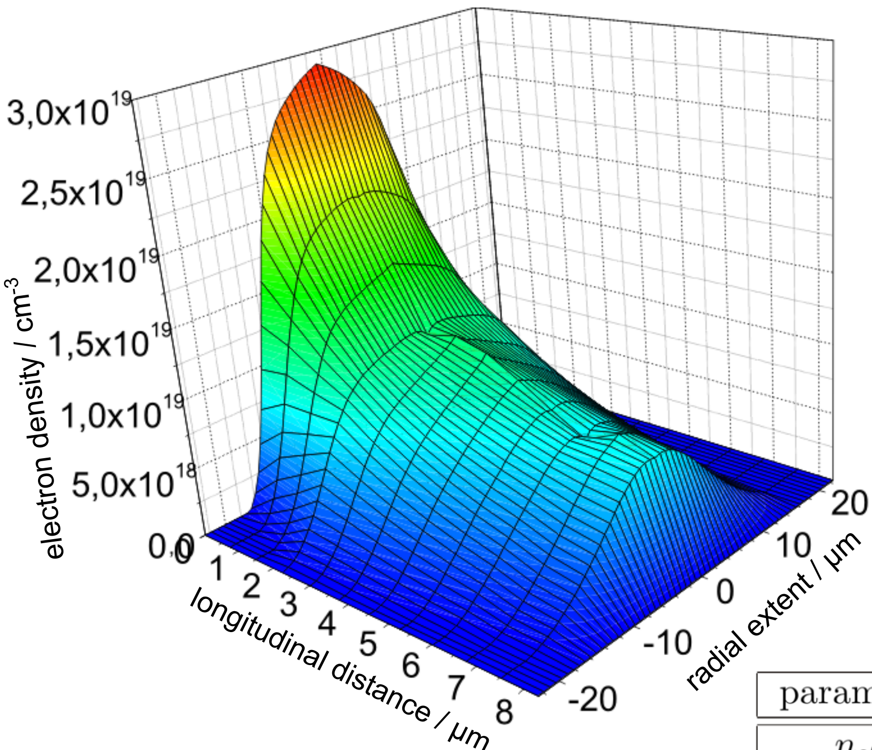
$\Rightarrow$ match dimensions of acceleration process!

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

Electromagnetic Probe Pulses

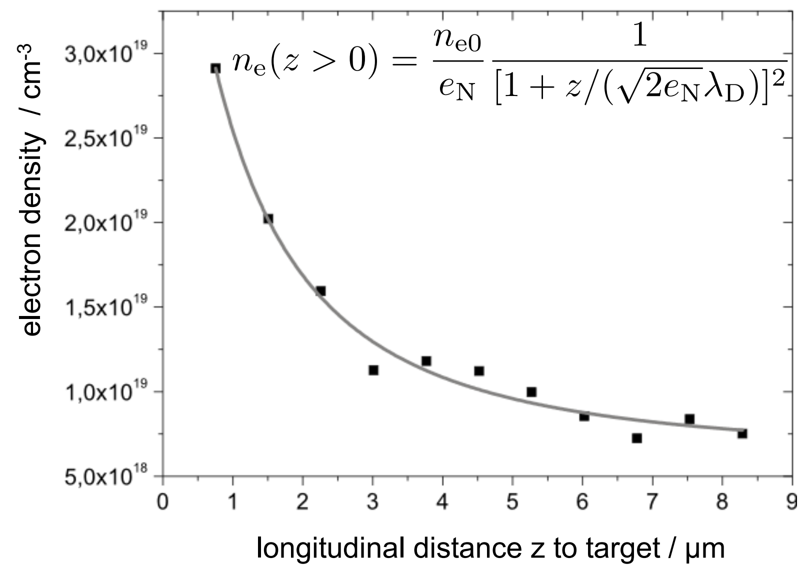
Probing of laser-driven ion acceleration process

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)



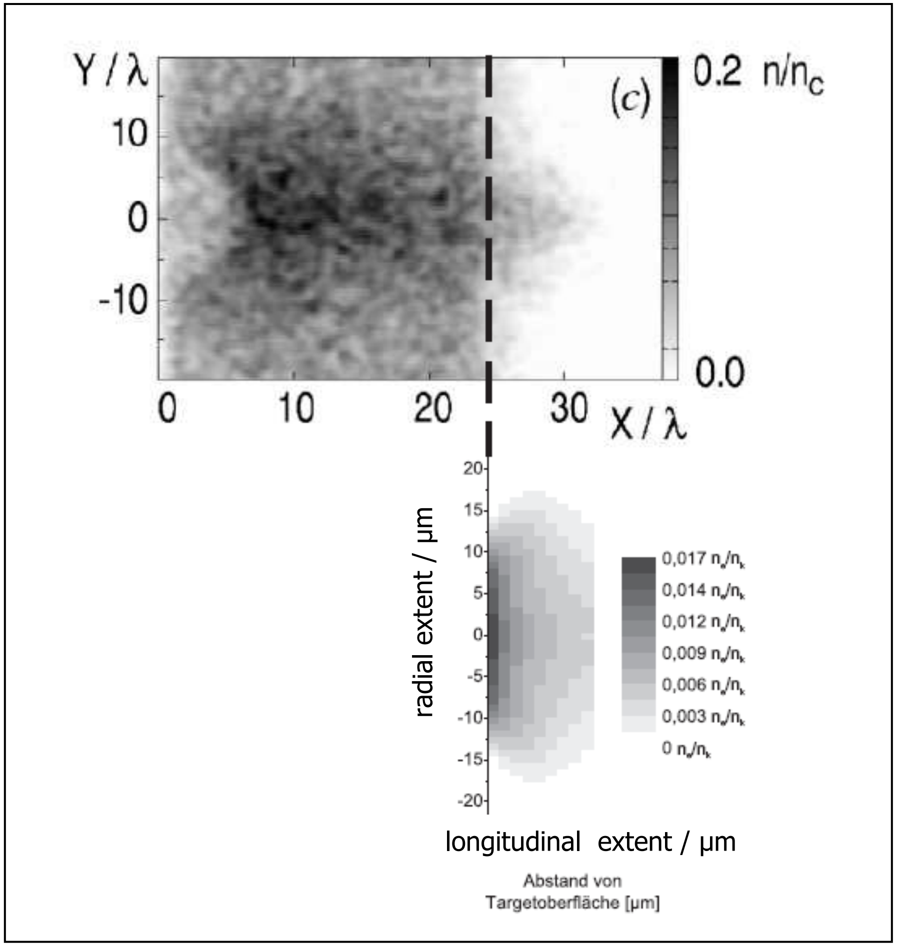
parameter	experimental data	theoretical prediction
n_{e0}	$(8.4 \pm 0.4) \times 10^{19}\,\mathrm{cm}^{-3}$	$9.44 \times 10^{19}\,\mathrm{cm}^{-3}$
λ_D	$(1.0 \pm 0.2)\,\mu\mathrm{m}$	$0.64\,\mu\mathrm{m}$
w_{back}	$(21 \pm 1)\,\mu\mathrm{m}$	$8.1\,\mu\mathrm{m}$
$\mathrm{k_B}T_e$	$(1.5 \pm 0.4)\,\mathrm{MeV}$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

Electromagnetic Probe Pulses

Probing of laser-driven ion acceleration process

Comparsion with numerical simulations



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

⇒ comparable shape

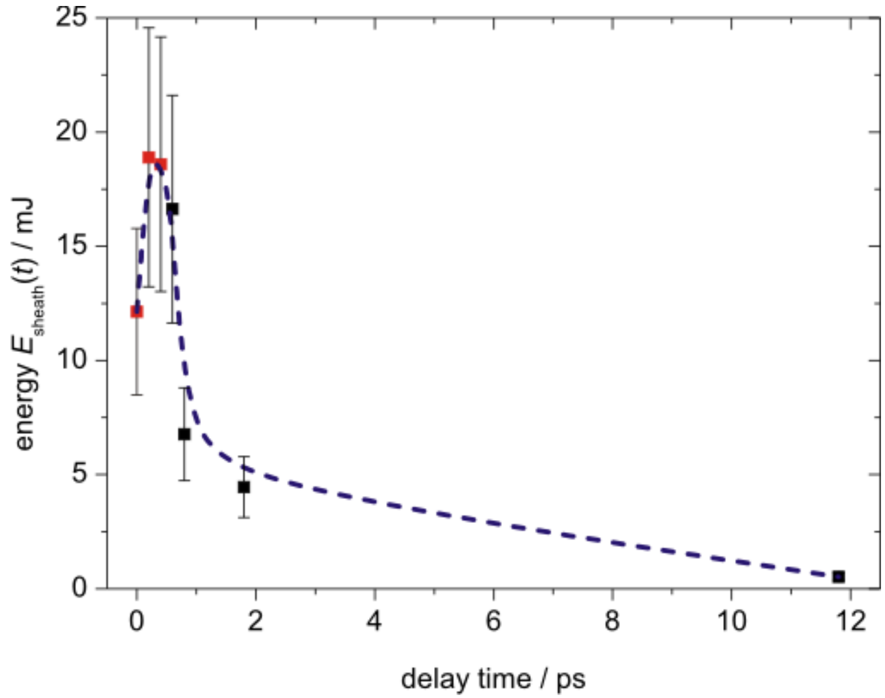
⇒ deviation of absolute numbers (measured density smaller by a factor of 5)

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

Electromagnetic Probe Pulses

Probing of laser-driven ion acceleration process

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



Conversion efficiency E_{laser} ⇒ hot electrons:

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

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

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

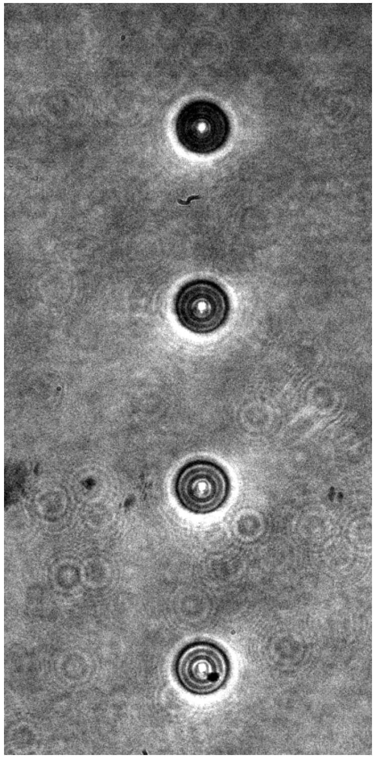
(deduced from sheath's electron density and radial extent, assuming similar hot-e-density inside the target)

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

Electromagnetic Probe Pulses

Probing of droplet targets for laser ion acceleration

Improvement of stability and understanding of acceleration process: visualize interaction in the experiment with synchronized probe pulses



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Electromagnetic Probe Pulses

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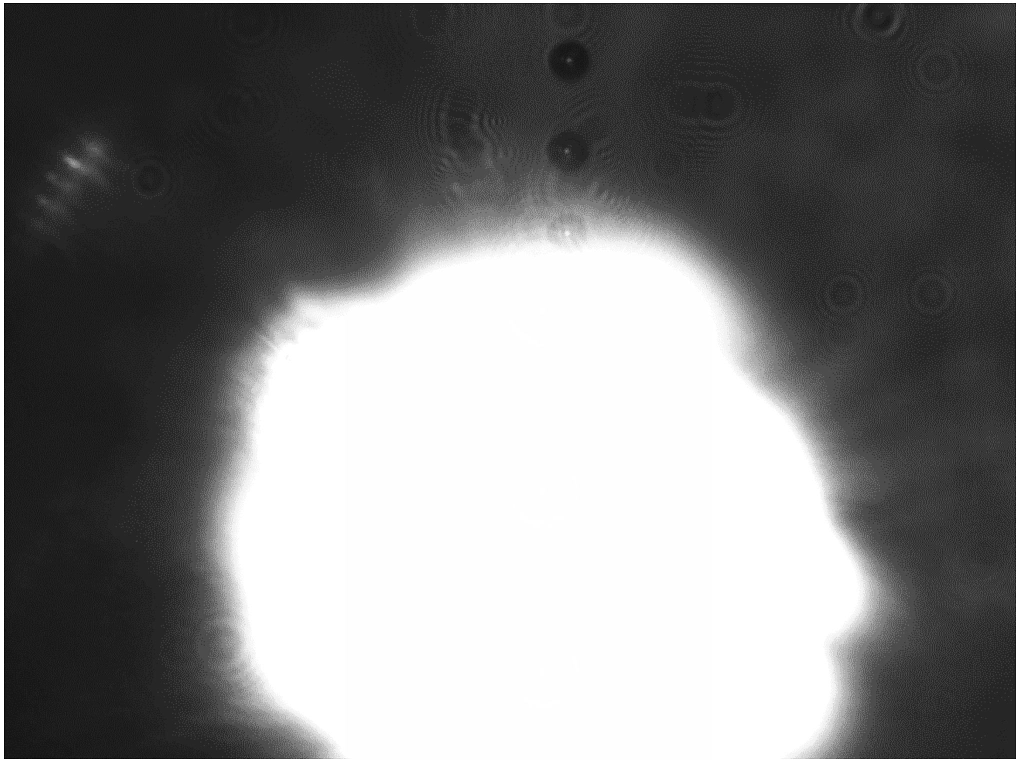
Probing of droplet targets for laser ion acceleration

Improvement of stability and understanding of acceleration process: visualize interaction in the experiment with synchronized probe pulses

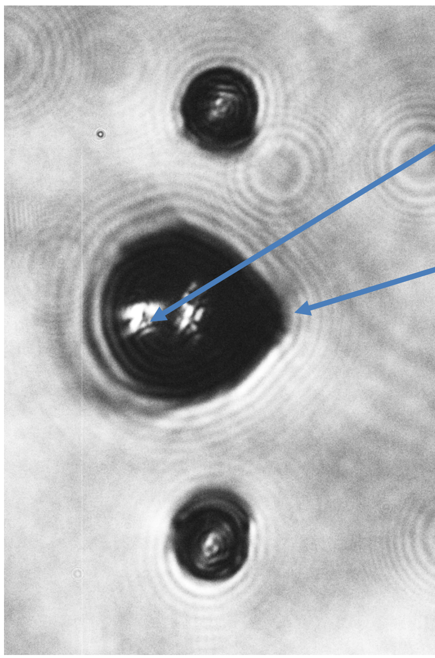


Problem:
Plasma self-emission outshines probe pulse
⟹ no observation possible!

Electromagnetic Probe Pulses

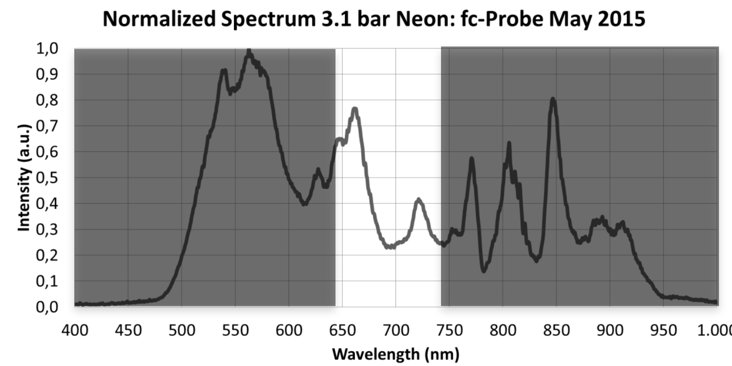
Probing of droplet targets for laser ion acceleration

Improvement of stability and understanding of acceleration process: visualize interaction in the experiment with synchronized probe pulses



Plasma emission strongly suppressed

Droplet expansion (and more) can be studied



Solution: main pulse @ 400 nm, synchronized few-cycle probe pulse @ 710 nm (+ color filter in front of CCD) ⟹ fs- and µm-resolution

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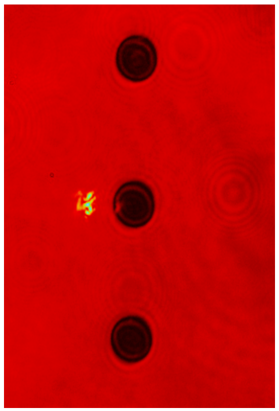
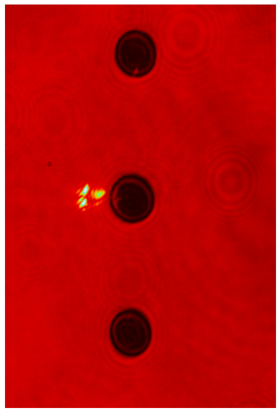
Electromagnetic Probe Pulses

Probing of droplet targets for laser ion acceleration

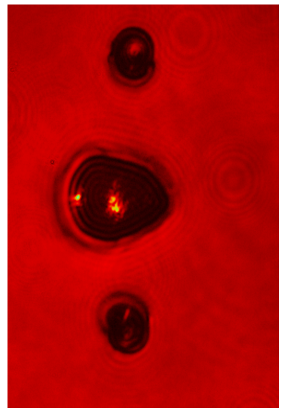
Improvement of stability and understanding of acceleration process: visualize interaction in the experiment with synchronized probe pulses



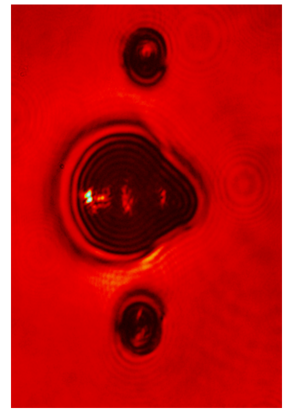
t_o + 100 fs



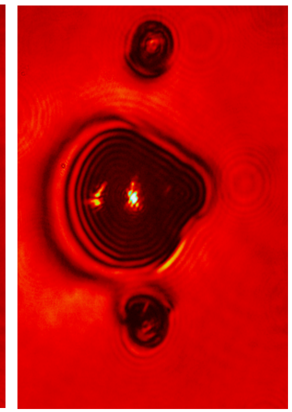
t_o + 2 ps



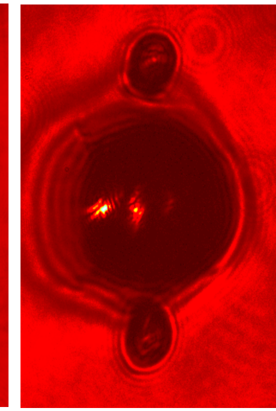
t_o + 64 ps



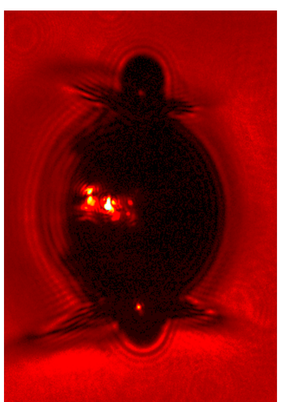
t_o + 100 ps



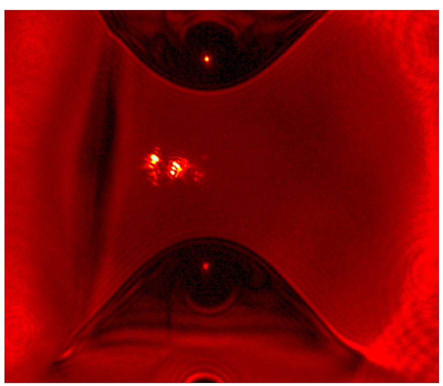
t_o + 150 ps



t_o + 285 ps



t_o + 440 ps



t_o + 1.275 ns

- online control of interaction possible,
- influence of focus position on the droplet,
- influence of additional fs-prepulse,
- observation of ion acceleration process,…

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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
  - Electron probing
  - Detection of magnetic and electric field distributions

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Particle Probe Pulses

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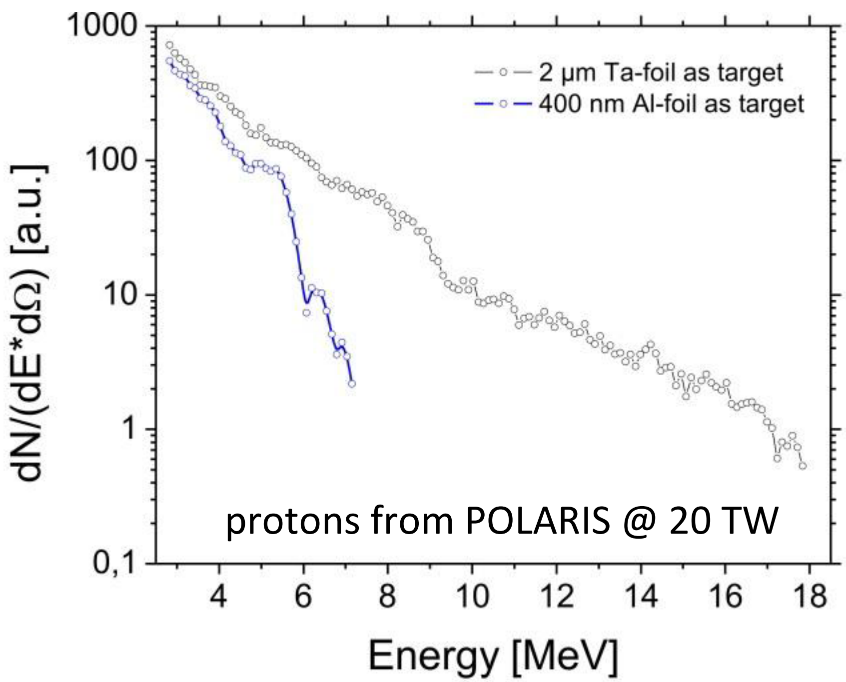
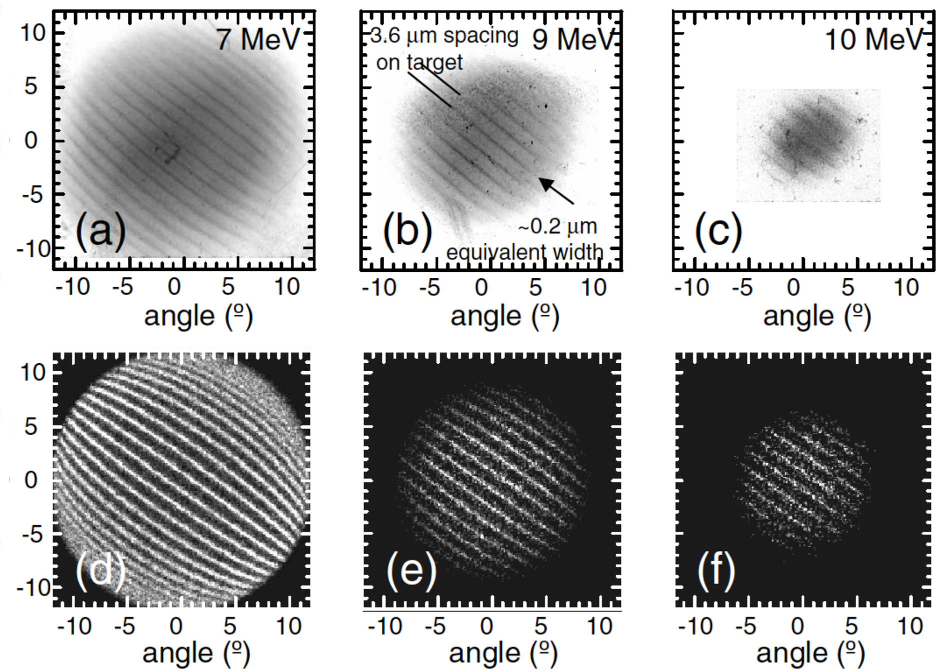
- Probing with laser-accelerated proton beams:
  - broad energy spectrum (up to few 10‘s of MeV)
  - laminar flow -> excellent imaging properties

Energy spectrum in forward direction



Transverse beam profile for different energies



T. E. Cowan, PRL (2004)

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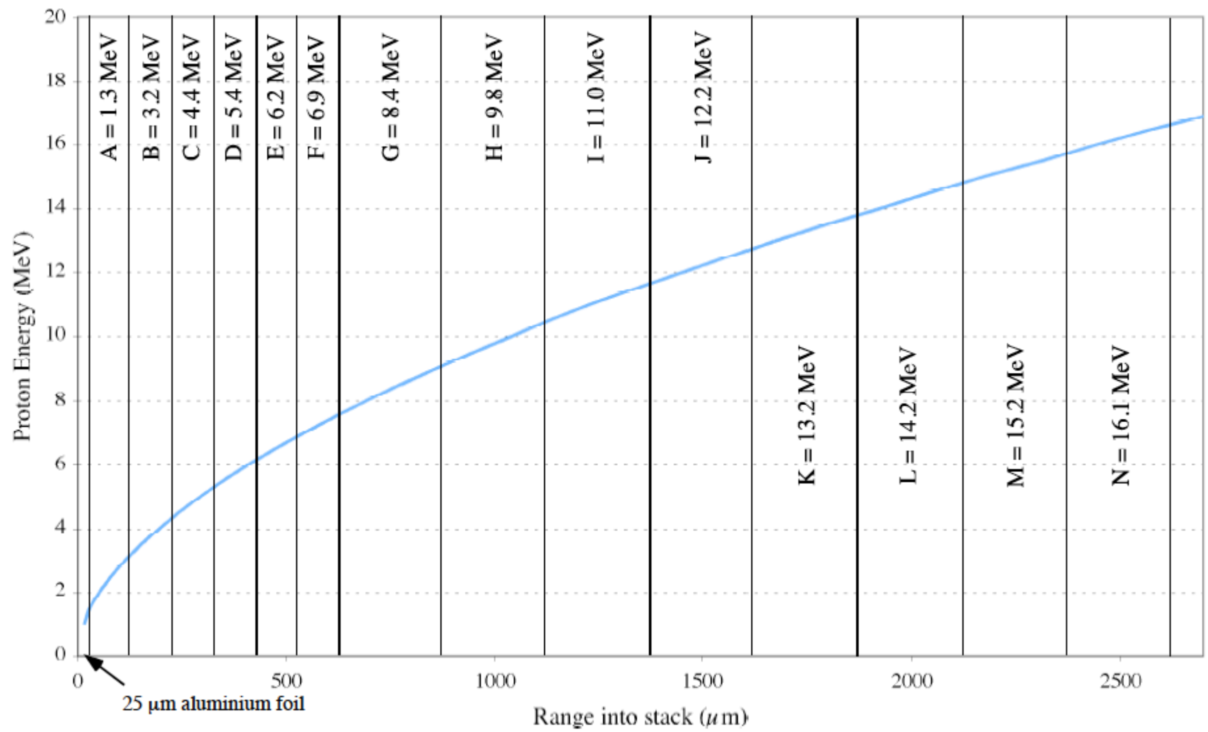
Particle Probe Pulses

- 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



L. Willingale, PhD thesis
Imperial College (2007)

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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

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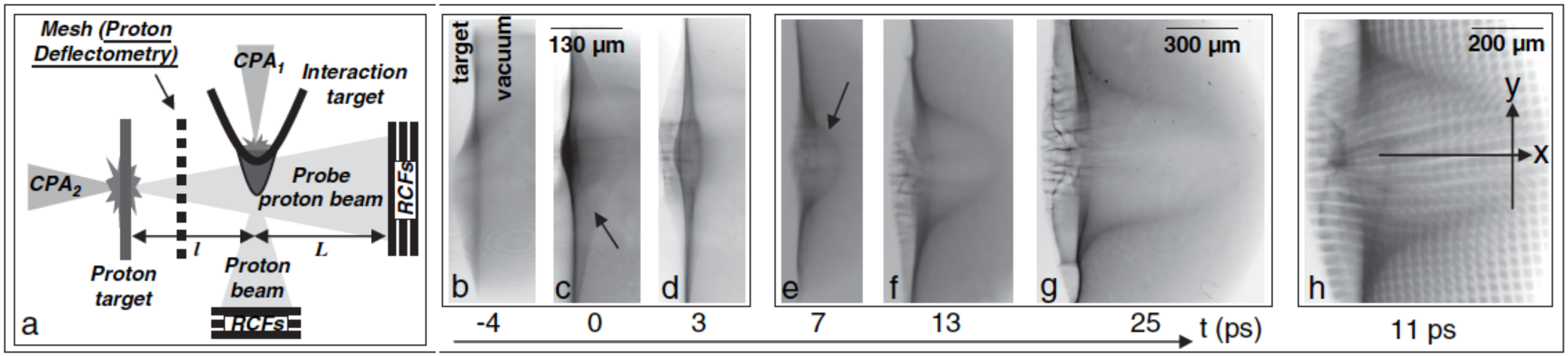
- **Transverse** probing with laser-accelerated proton beams:
  - proton deflection mainly due to electric fields



L. Romagnani, PRL (2005)

  - record TNSA-sheath evolution in single shot,
  - deduce sheath-field strength from mesh warping: $E_{TNSA} \geq 3x10^{10}$ V/m

Particle Probe Pulses

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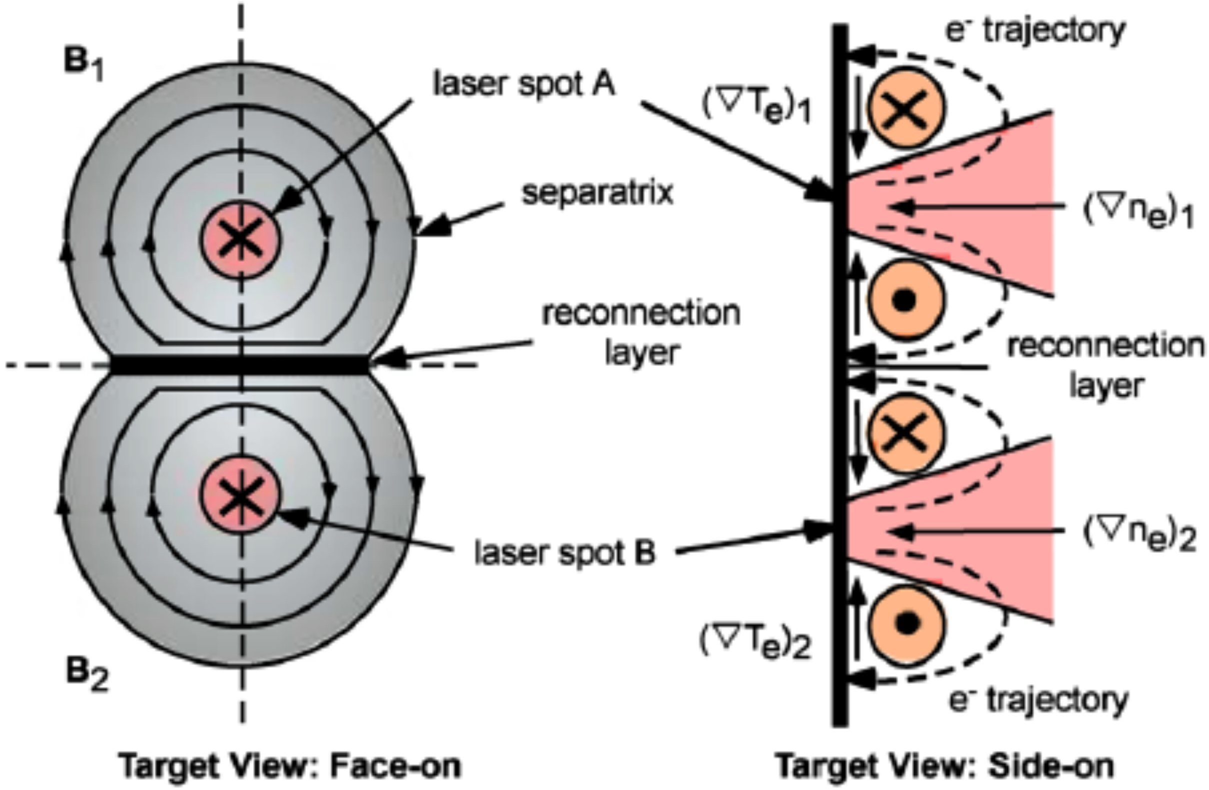
- **Longitudinal** probing with laser-accelerated proton beams:
  - proton deflection mainly due to magnetic fields



P. Nilson, PRL (2006)

Particle Probe Pulses

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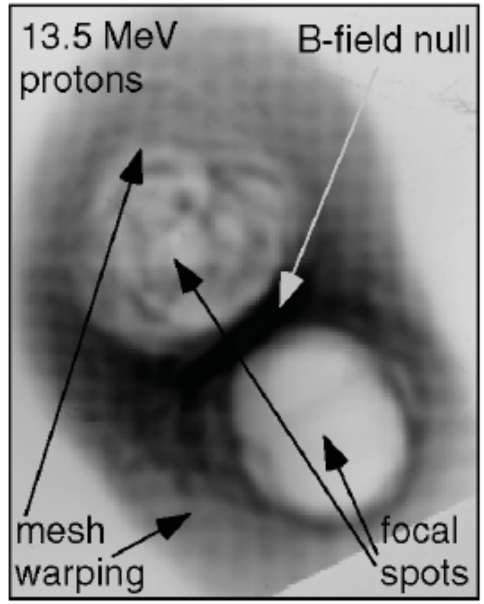
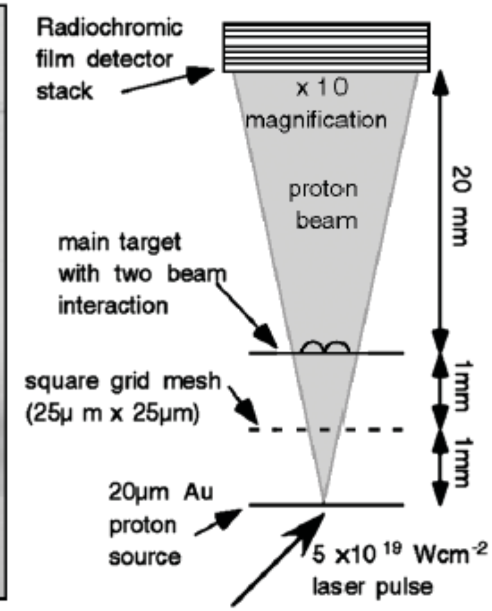
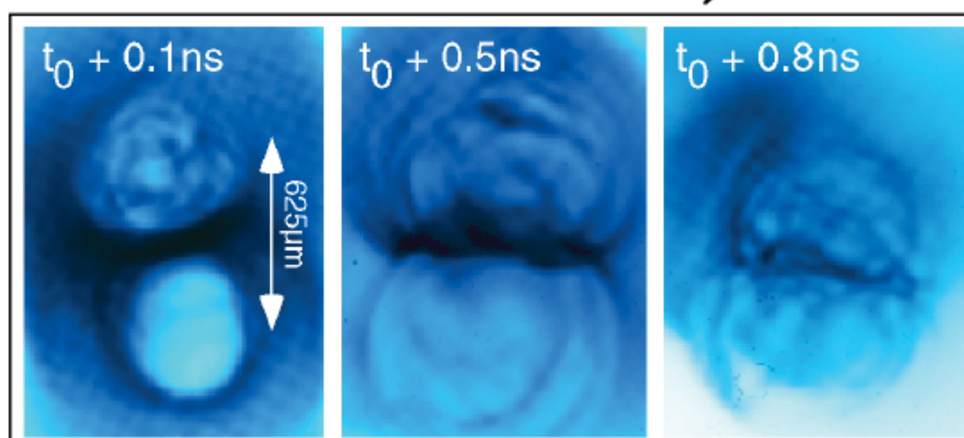
- **Longitudinal** probing with laser-accelerated proton beams:
  - visualize B-field geometry in 2-beam interaction
  - see merging of B-field structures between two plasma plumes
  - example of magnetic reconnetion







P. Nilson, PRL (2006)

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Conclusions

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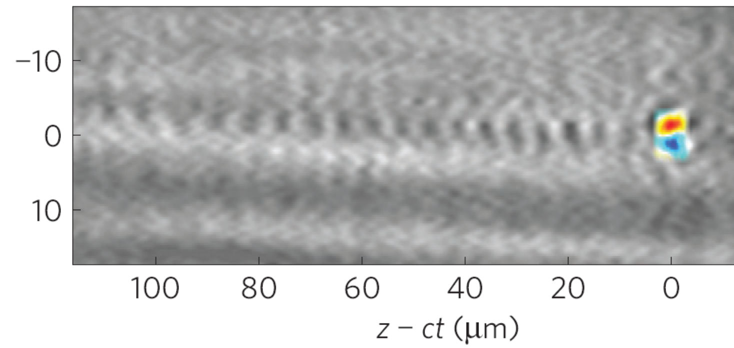
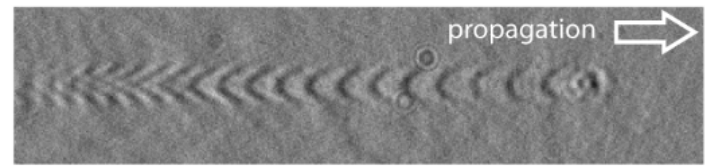
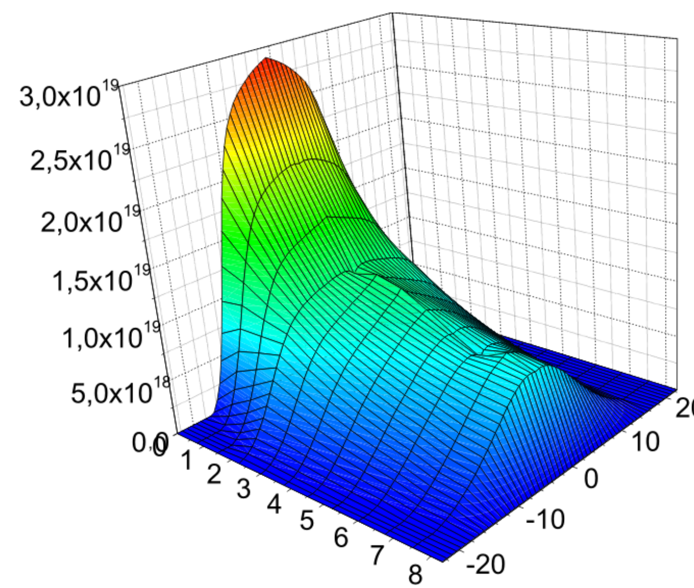
- Probing diagnostics reveal detailed insight into laser-plasma accelerators
- Electromagnetic and particle pulses can be used to deduce density and accelerating field distributions in the plasma
- Accelerating structures (TNSA-sheaths or plasma waves) can be visualized
- Use of these diagnostics might 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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