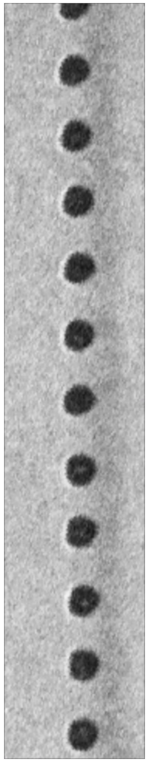
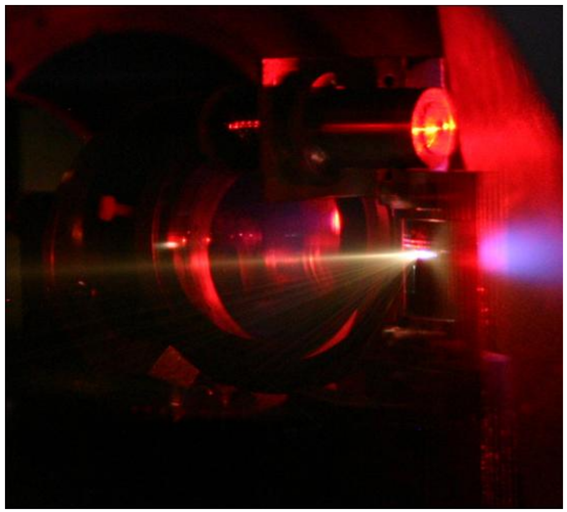
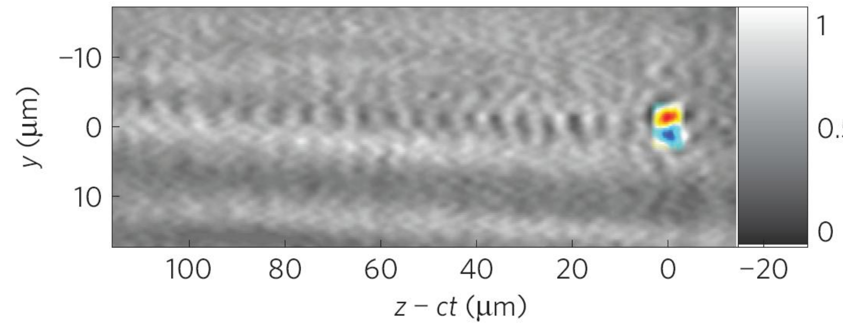
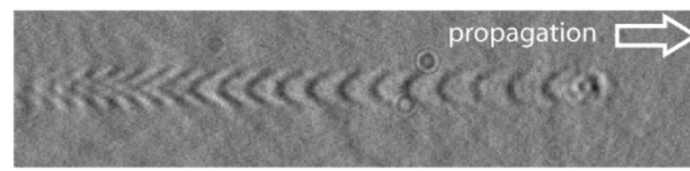
Ultrafast Imaging of Laser-Driven Plasma-Accelerators









Malte C. Kaluza

Institute of Optics and Quantum Electronics,
Friedrich-Schiller-Universität Jena, Germany
Helmholtz-Institute Jena

seit 1558

Outline

HI Jena
Helmholtz Institute Jena

- 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
  - Transverse vs. longitudinal probing
- Particle probe pulses:
  - Proton probing
  - Electron probing
  - Detection of magnetic and electric field distributions

seit 1558

Motivation

HI Jena
Helmholtz Institute Jena

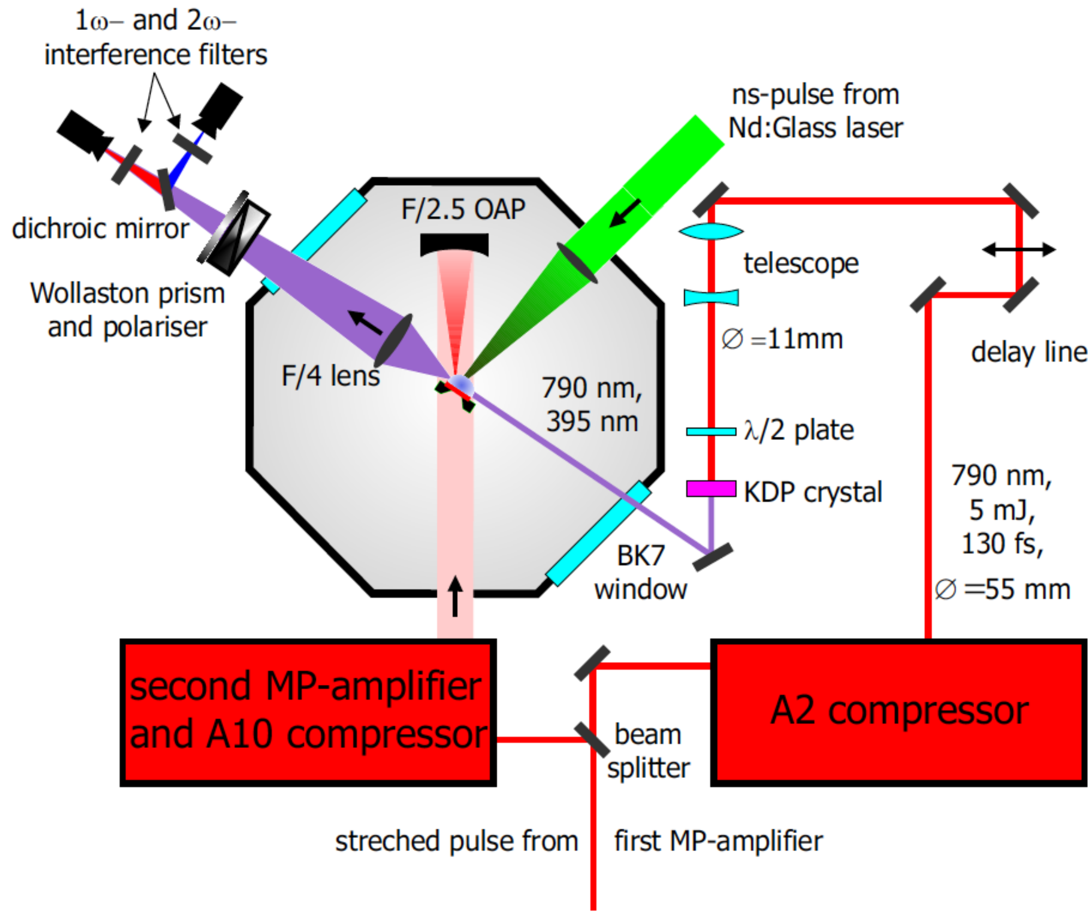
- Laser-produced plasmas:
  - formation and modulation occuring on time scales of driving laser
  - density distribution?
  - temperature?
  - internal fields?
- High relevance for particle accelerators
  - plasma-wakefield accelerators: detect details of plasma wave
  - plasma ion accelerators: e.g.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

Electromagnetic Probe Pulses

Probe-pulse generation

HI Jena
Helmholtz Institute Jena

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



$\Rightarrow$ perfect synchronization

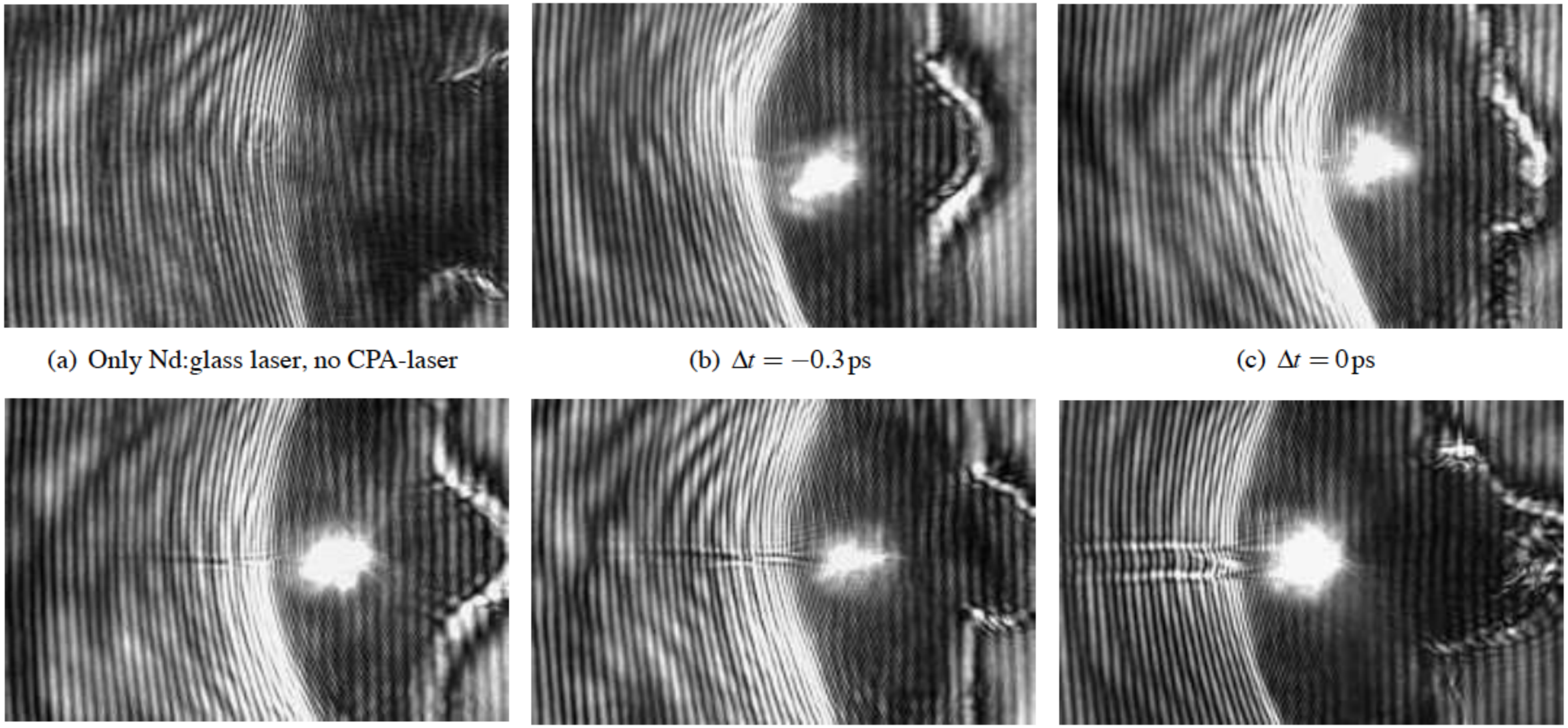
$\Rightarrow$ probe pulse duration similar to main pulse

$\Rightarrow$ record movie from subsequent shots at different delays (requires good shot-to-shot stability!)

Electromagnetic Probe Pulses

Probe-pulse generation

- Delay scan for interaction of 10-TW CPA-laser pulse with plasma preformed by Nd:glass laser from different shots:



(a) Only Nd:glass laser, no CPA-laser (b) $\Delta t = -0.3\,\text{ps}$ (c) $\Delta t = 0\,\text{ps}$

(d) $\Delta t = +0.6\,\text{ps}$ (e) $\Delta t = +1.3\,\text{ps}$ (f) $\Delta t = +12.0\,\text{ps}$

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

seit 1558

HI Jena
Helmholtz Institute Jena

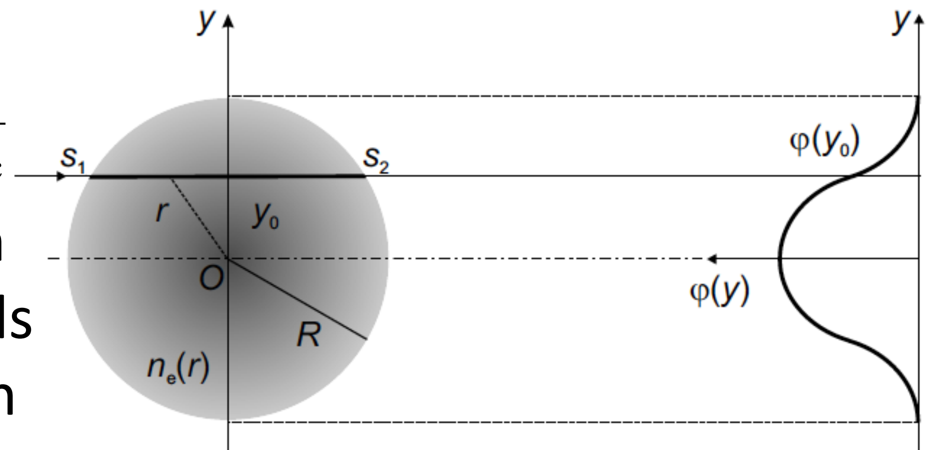
Electromagnetic Probe Pulses

Interferometry

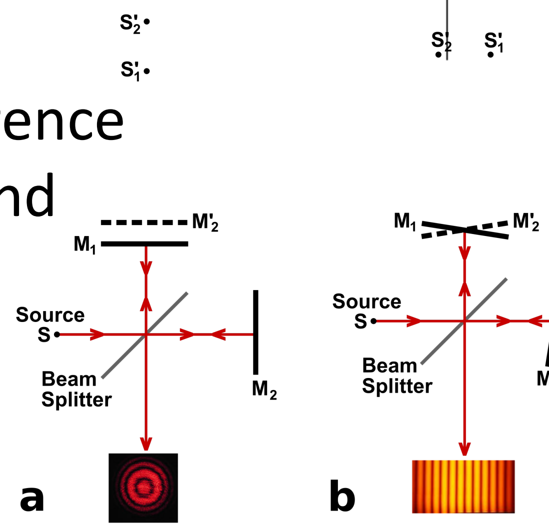
- Refractive index of a plasma:

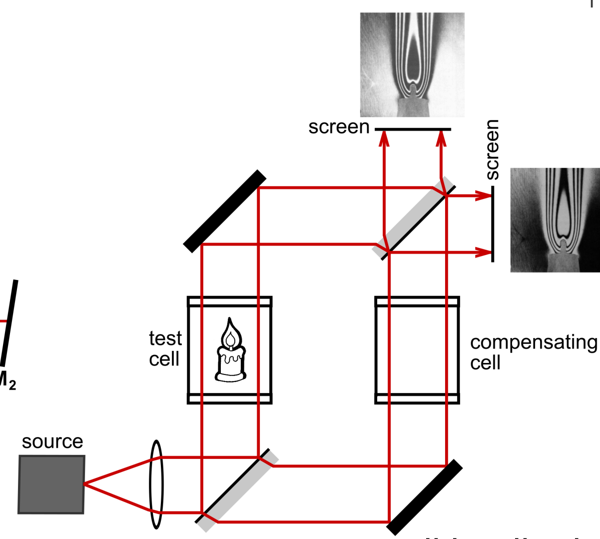
$$\eta = \sqrt{1-(\omega_\mathrm{p}/\omega_\mathrm{L})^2} = \sqrt{1-n_\mathrm{e}/n_\mathrm{c}}$$

- 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**





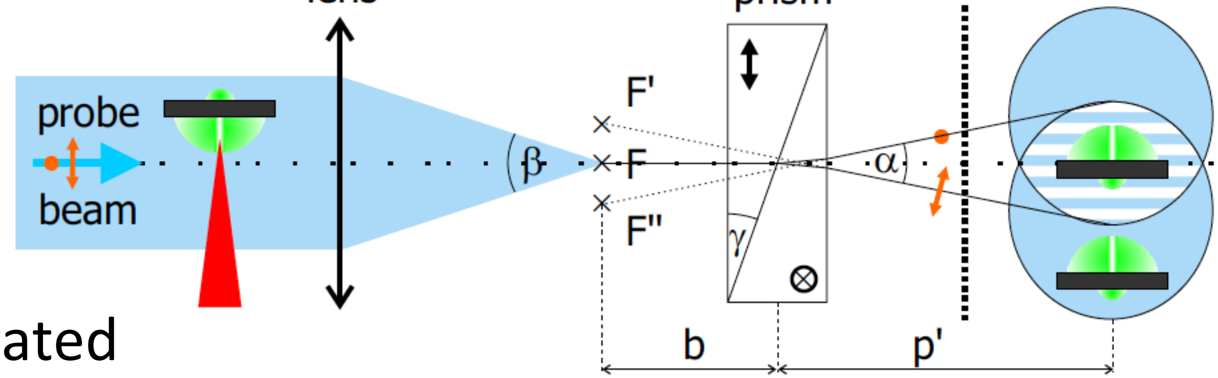
www.wikipedia.de

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

Electromagnetic Probe Pulses

Interferometry

- 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 laterally
- 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: $i = \frac{\lambda_{\mathrm{probe}}}{\alpha}\frac{p'}{b}$
- Fringe shift between data and reference $\Rightarrow$ phase difference $\Delta\varphi$

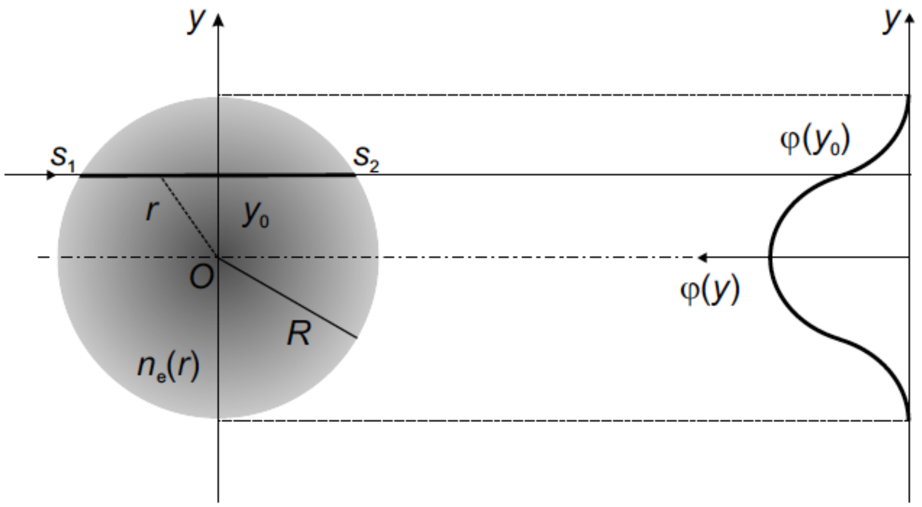
seit 1558

Electromagnetic Probe Pulses

Interferometry

HI Jena
Helmholtz Institute Jena

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



$$\Delta\varphi(y_0) = \frac{2\pi}{\lambda_L}\int_{x_1}^{x_2}[1-\eta(x)]\,\mathrm{d}x \qquad \eta(x) = \sqrt{1-n_e/n_{cr}} \approx 1 - n_e/2n_{cr}$$

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

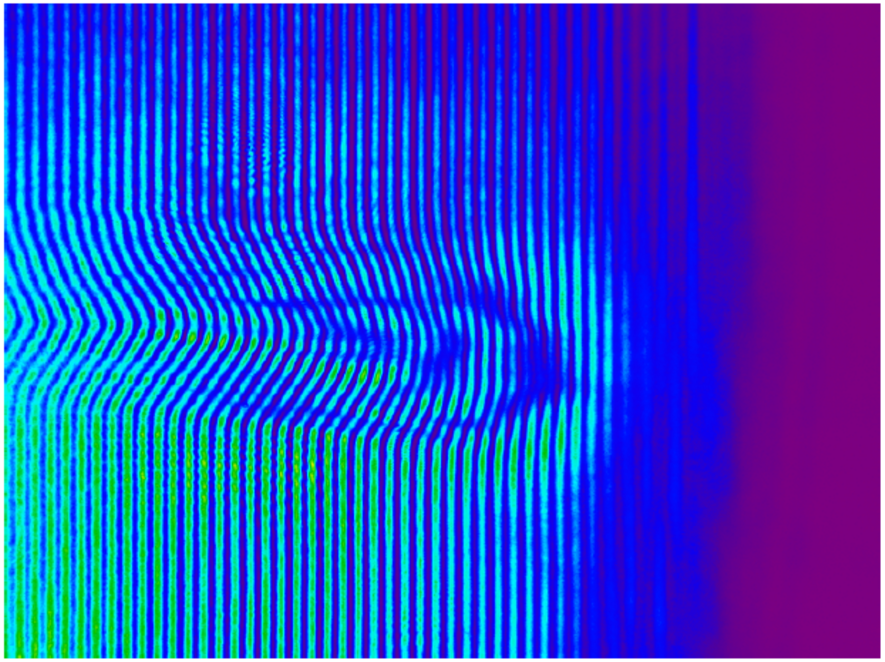
- Deduce plasma density via Abel inversion:

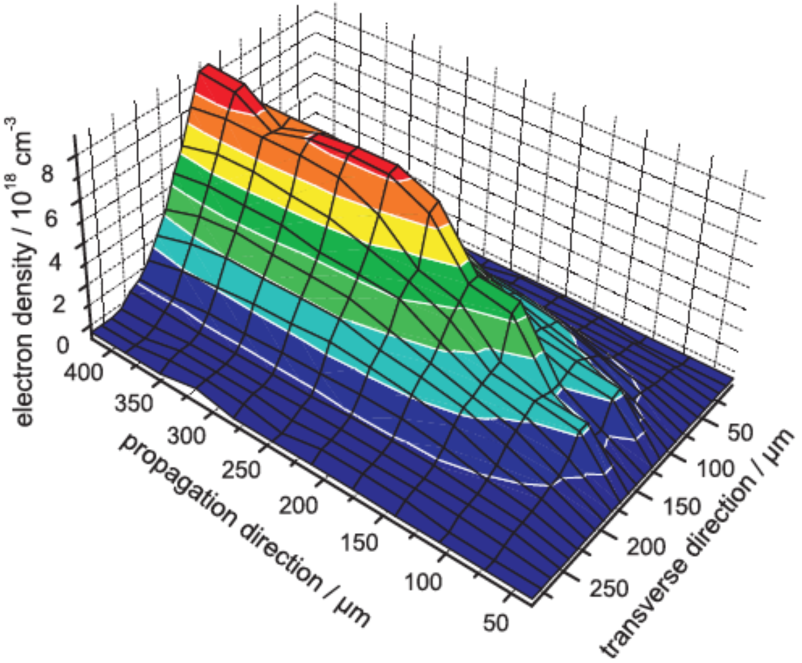
$$n_e(r) = -\frac{n_{cr}\lambda_L}{\pi^2}\int_r^R \frac{\mathrm{d}}{\mathrm{d}y}\Delta\varphi(y)\cdot\frac{\mathrm{d}y}{\sqrt{y^2-r^2}}.$$

Electromagnetic Probe Pulses

Interferometry

- Deduce plasma density distribution by assuming cylindrical symmetry:





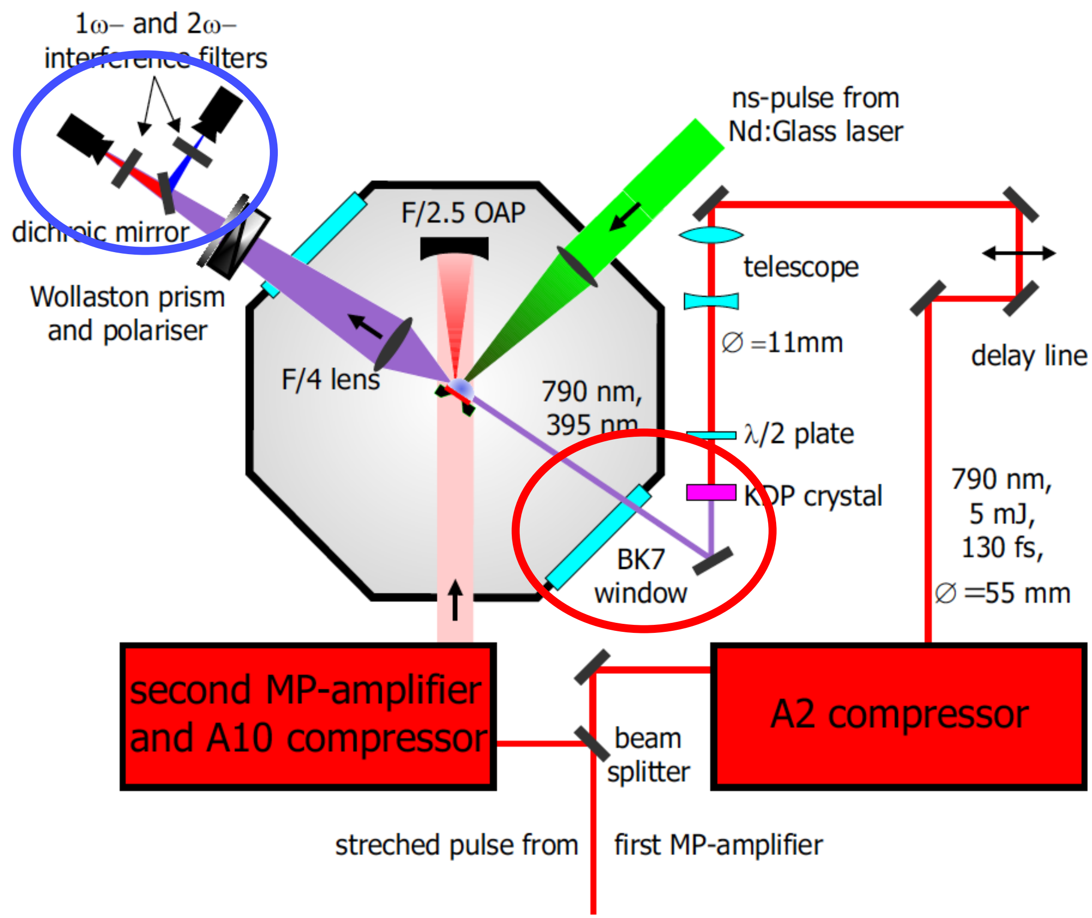
H.-P. Schlenvoigt, PhD thesis, Uni Jena (2009)

Electromagnetic Probe Pulses

Probe-pulse generation

seit 1558
HI Jena
Helmholtz Institute Jena

- 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

Probe-pulse generation

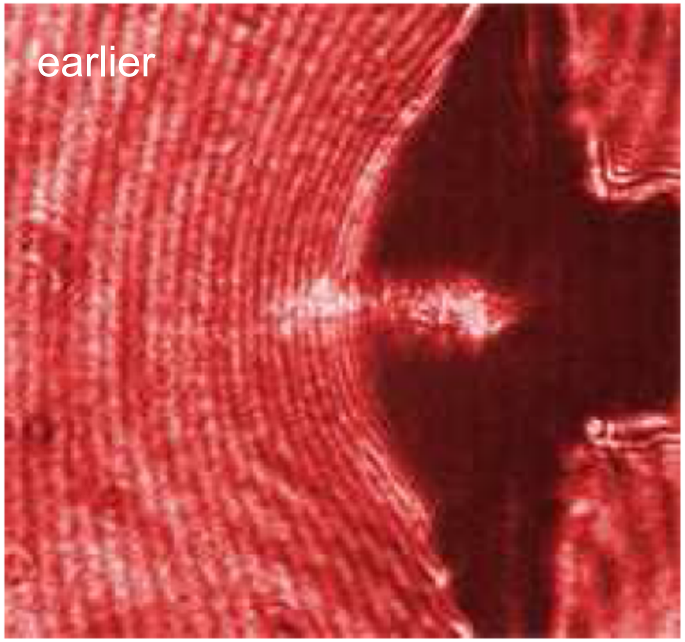
- 2-color probe pulses:

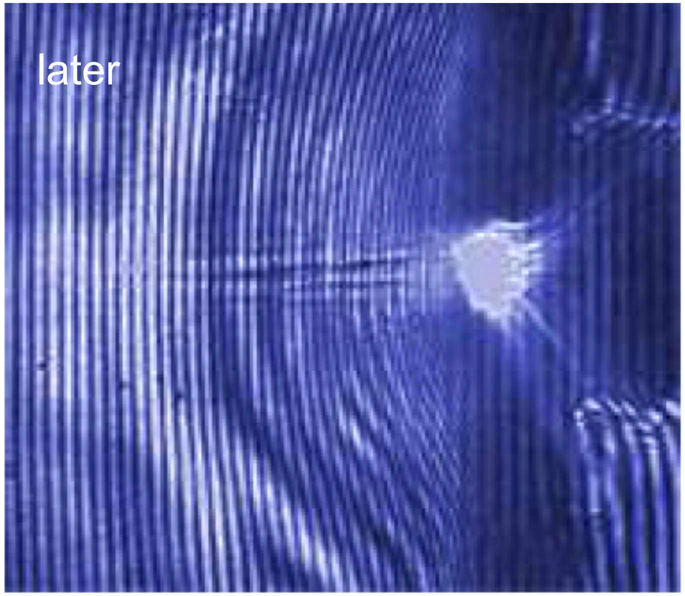
  visualize different time steps of evolution during a single shot by taking 2 images at different times

- 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

Probing of plasma wakefield acceleration process

seit 1558

HI Jena
Helmholtz Institute Jena

- Plasma wave generation (e.g. by laser pulse's ponderomotive potential) $\equiv$ modulation of n_e against ion background ($v_{ph,plasma} = v_{gr,laser}$)

$\Rightarrow$ longitudinal E-fields (~ 0.1 TV/m)

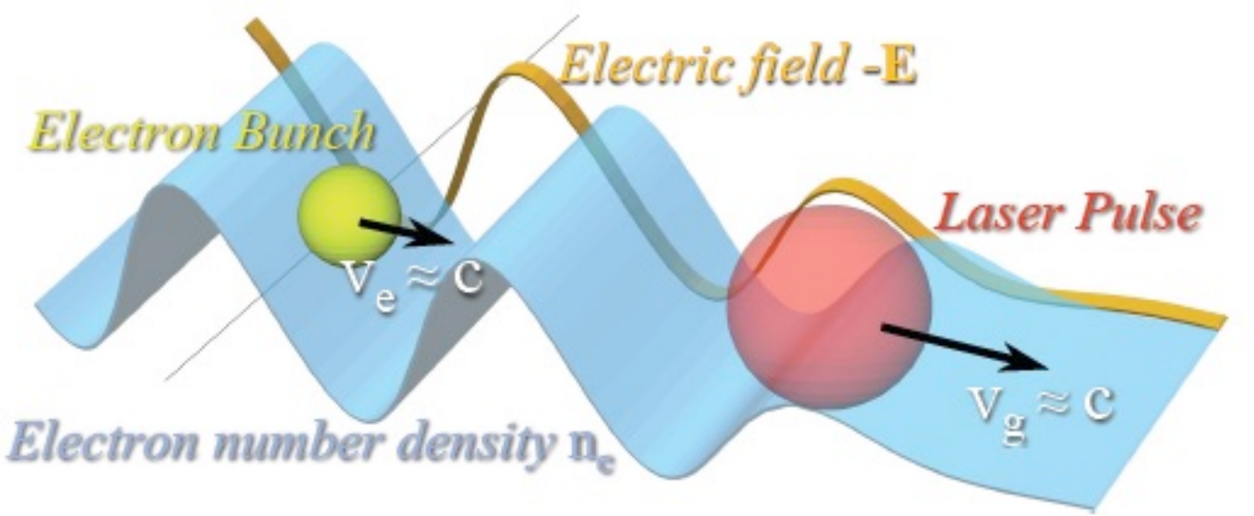


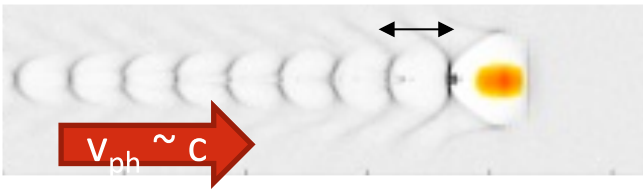
Image courtesy of A.G.R. Thomas

- Injection of electrons into the wave
  $\Rightarrow$ relativsitic electron current $\Leftrightarrow$ azimuthal B-fields

Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

Challenge: Imaging a tiny, fast moving object.

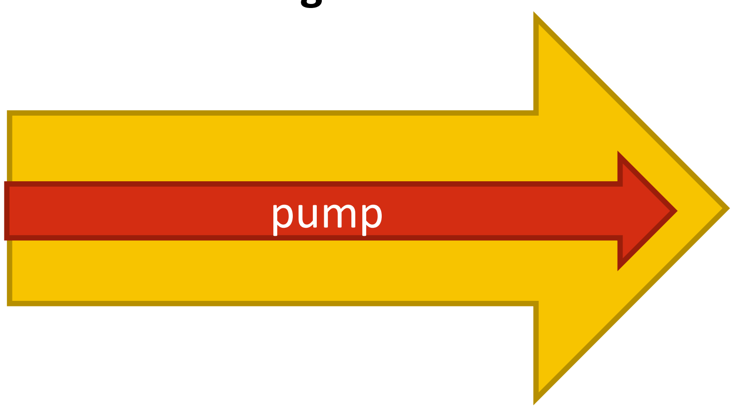


- characteristic length scale: $\lambda_p = \frac{2\pi c}{\omega_p}$

⟶ sufficient resolution

- phase velocity of plasma wave: ~c

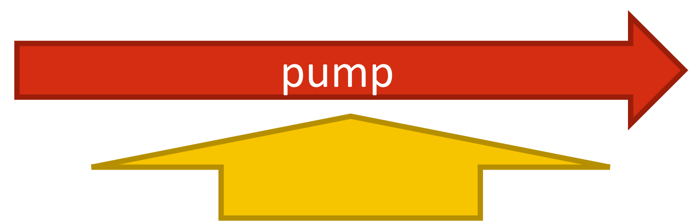
- **longitudinal**



- time integrated
- for slowly evolving plasma features

Fourier Domain Holography, …

- **transversal**



- snap shots: $\tau_{probe} \ll \lambda_p / c$
- for fast evolving plasma features

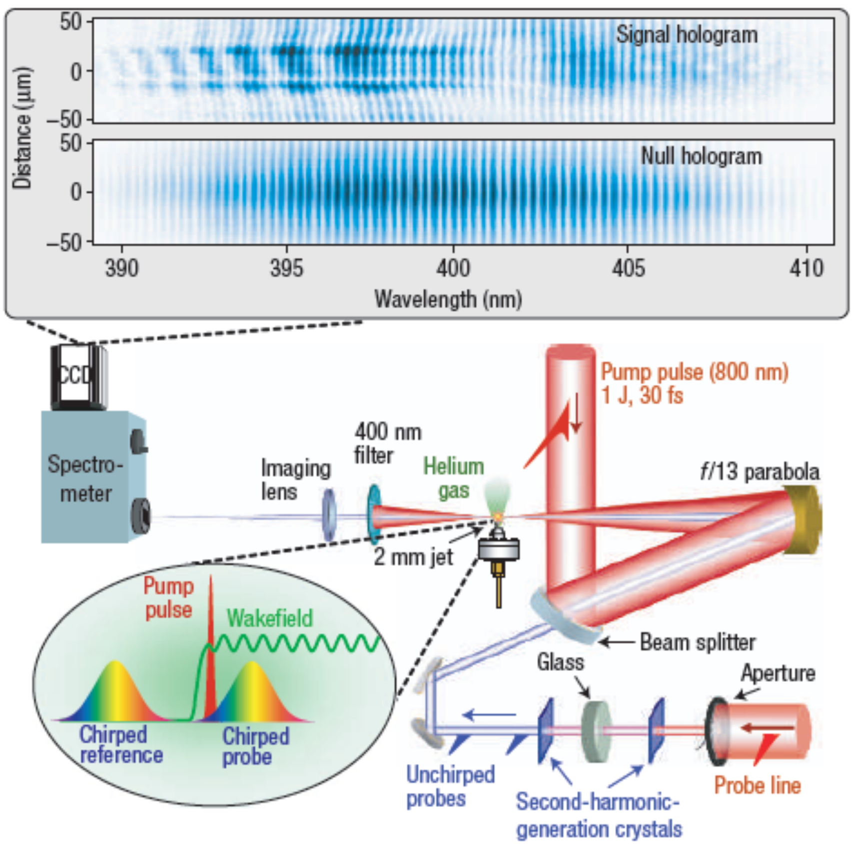
Interferometry, Shadowgraphy, Polarimetry, …

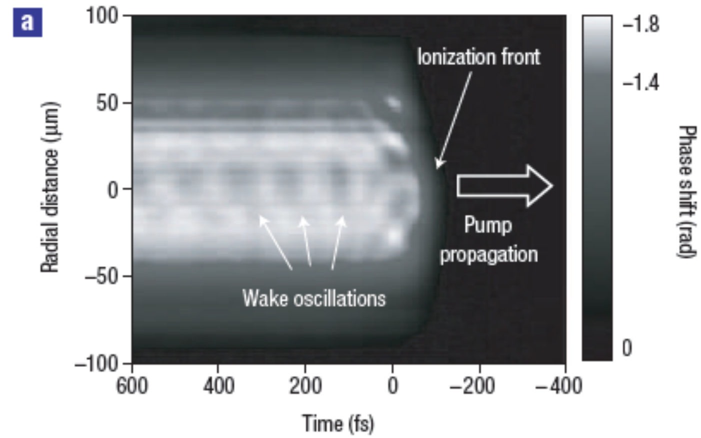
Electromagnetic Probe Pulses

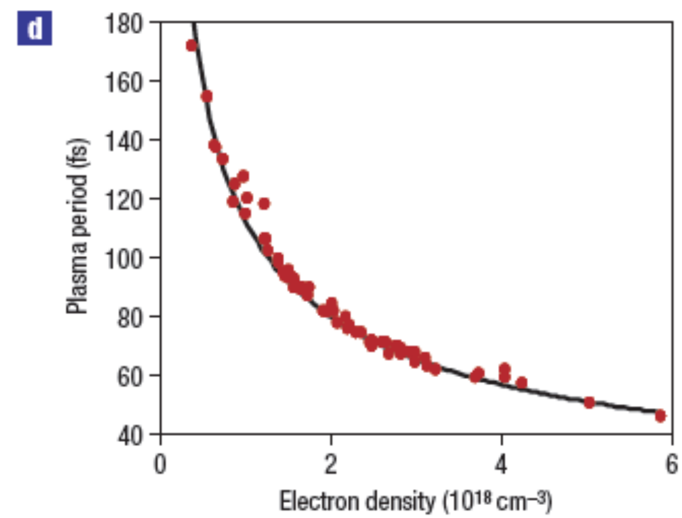
Probing of plasma wakefield acceleration process

„Frequency Domain Holography“

Split off part of the compressed main pulse, chirp it and let it co-propagate







N. Matlis *et al.,* Nature Physics **2,** 749 (2006)

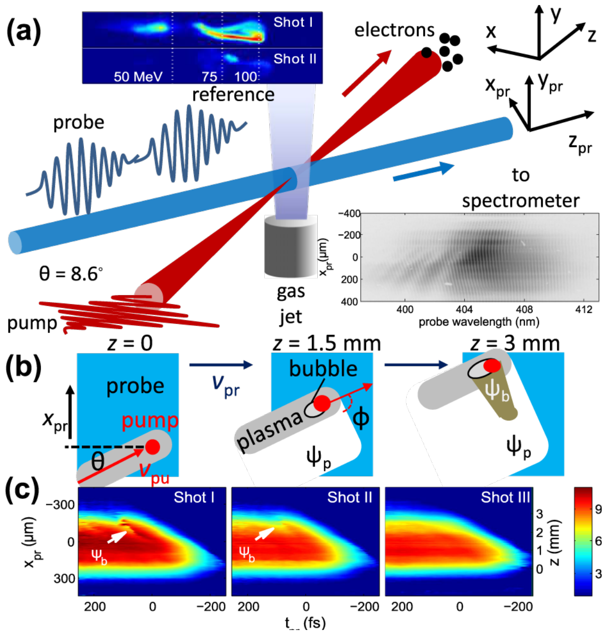
seit 1558

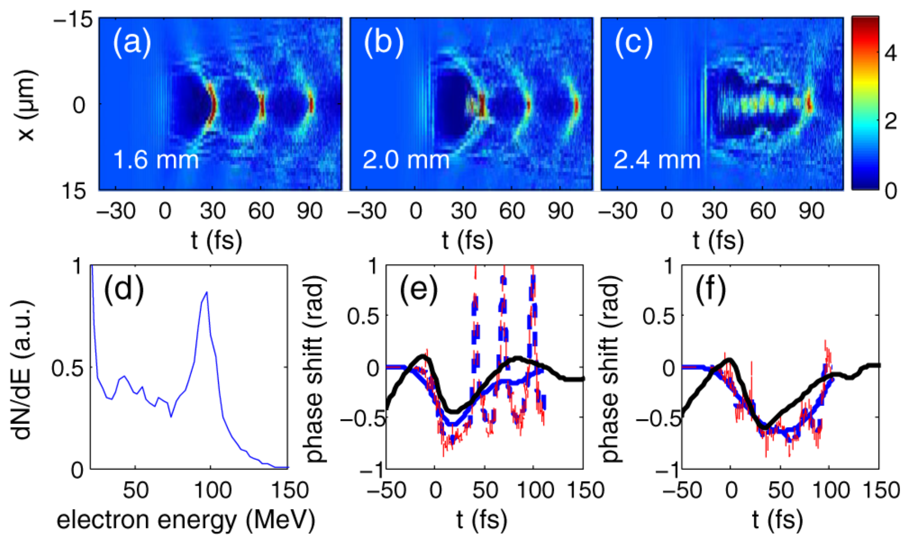
HI Jena
Helmholtz Institute Jena

Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

„Frequency Domain Streak Camera“





Temporal resolution depends on probe pulse bandwidth : $\tau_{probe} \cdot c > \frac{\lambda_p}{2}$

Z. Li *et al.,* Phys. Rev. Lett. **113** 085001 (2014)

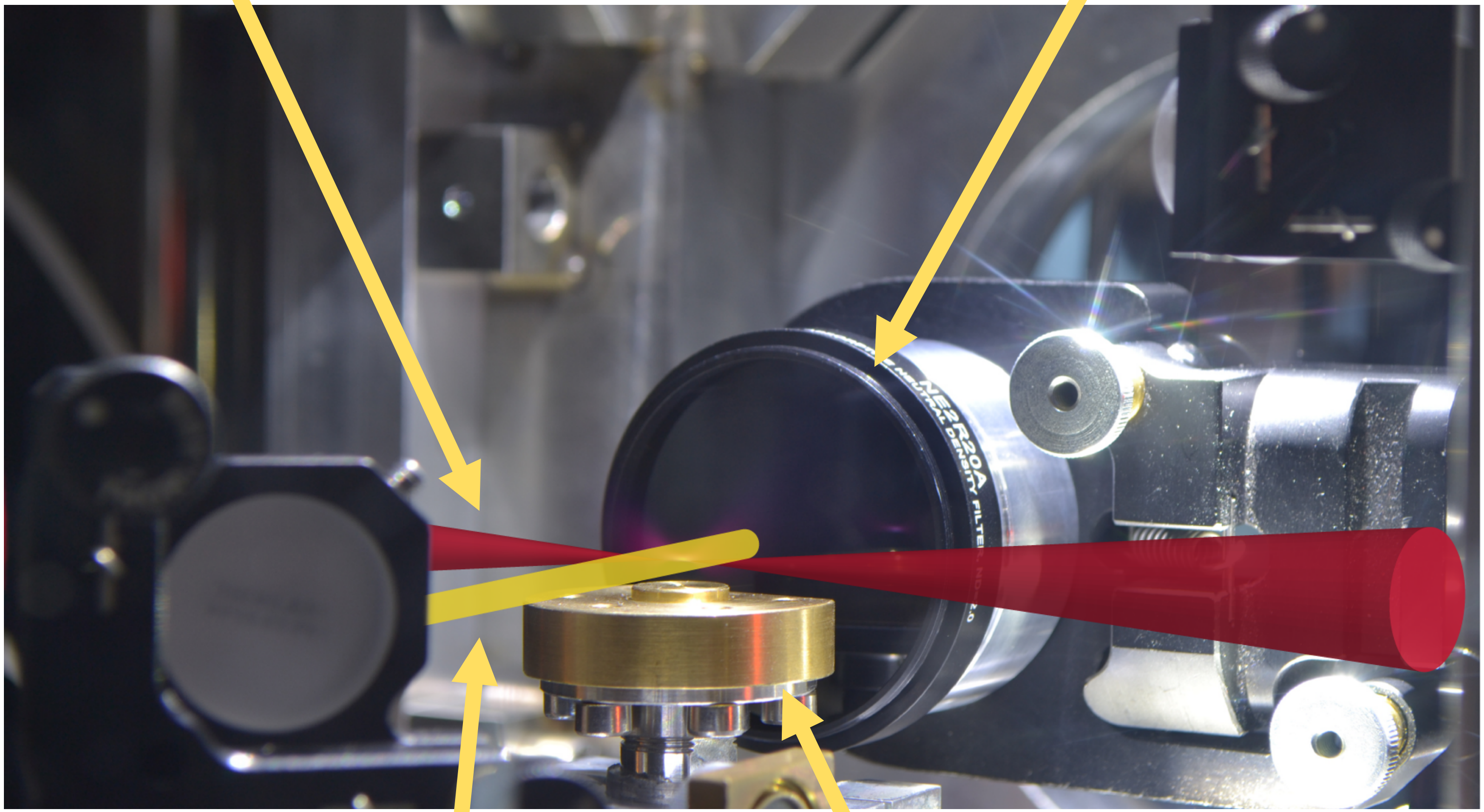
seit 1558

Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

HI Jena
Helmholtz Institute Jena

Transverse probing



seit 1558

Electromagnetic Probe Pulses

Probing of plasma wakefield acceleration process

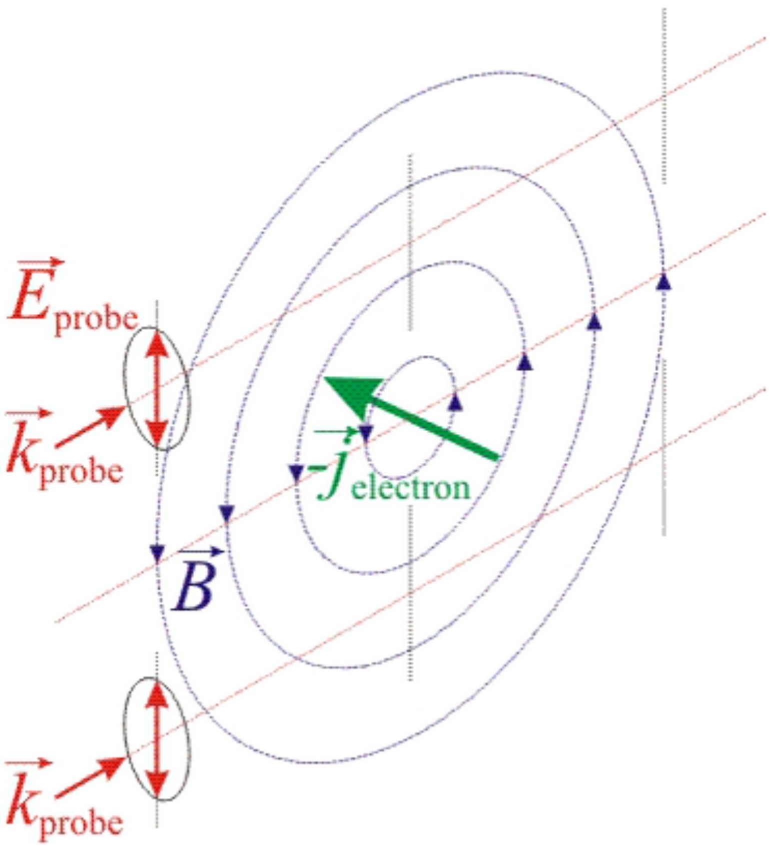
HI Jena
Helmholtz Institute Jena

- 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:

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



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

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