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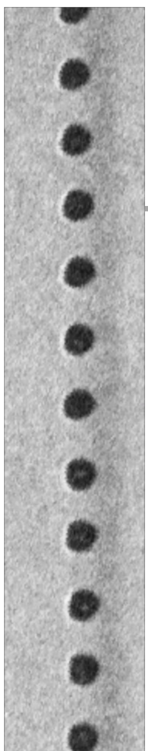
High-Resolution Diagnostics for Plasma-Based Accelerators: a Tool for Detailed Insights into the Interaction



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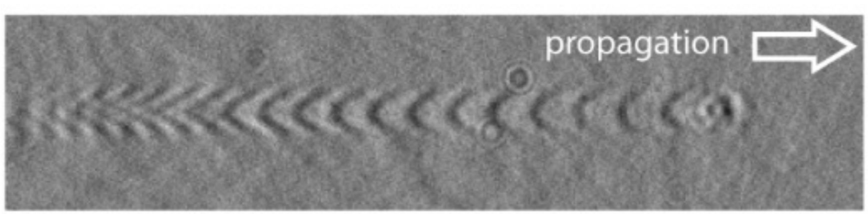

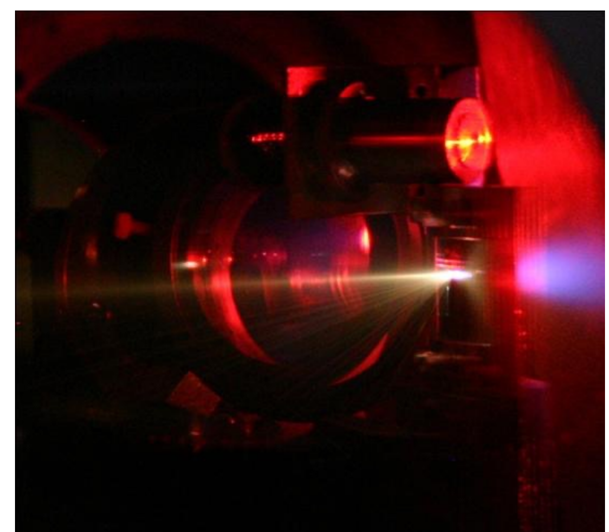

Thanks to all collaborators

A. Sävert, M. B. Schwab, G. A. Becker, D. Klöpfel, A. Seidel, M. Schnell, M. Leier, M. Reuter, D. Hollatz, S. Kuschel, R. Lötsch, S. Tietze, M. Hornung, S. Keppler, A. Kessler, M. Hellwing, F. Karbstein, F. Schorcht, F. Ronneberger, B. Beleites, O. Jäckel, G. G. Paulus, C. Spielmann, M. Yeung, M. Zepf
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Motivation

- Why (and when) is (few-cycle) probing of plasma accelerators useful?
- Which acceleration scenarios can be investigated with a pump-probe configuration?
- Which parameters of the interaction can be diagnosed?
  - plasma parameters (density, temperature,…)
  - acceleration fields (E- and B-fields),
  - laser field?
  - …?
- What are the next steps on our agenda?

Outline

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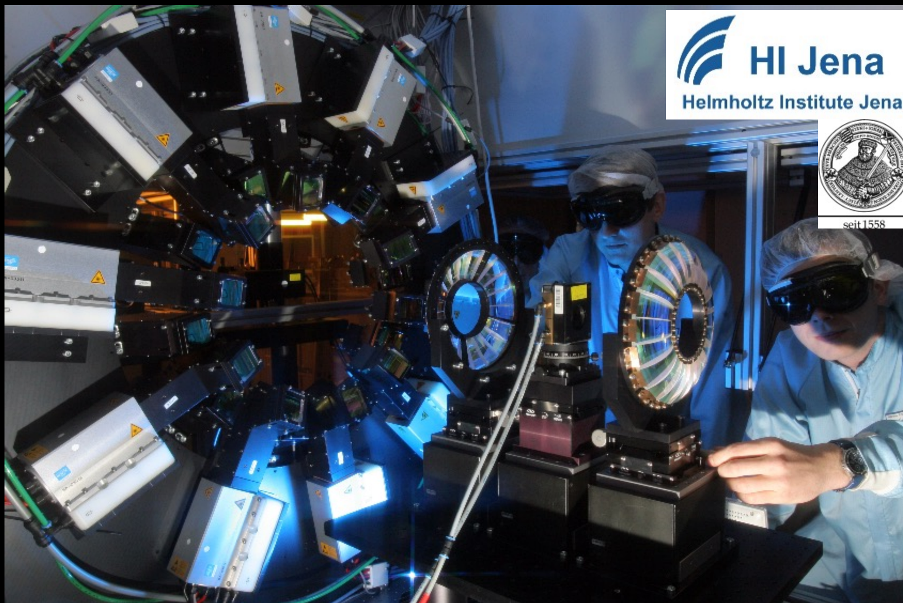
- Motivation
- Jena‘s high-power laser systems used for particle acceleration and probing
- Few-cycle probing of a Laser-Wakefield Electron Accelerator (LWFA)
  - Investigate evolution of plasma wave with transverse shadowgrams
  - Detect signature of laser‘s intensity evolution in the plasma with relativistic electron cyclotron resonances (RECS)
- Optical probing of laser-ion accelerators
- Summary and Outlook

JETI200 and POLARIS @ Jena



300-TW Ti:Sapphire Laser

pulse duration:	17 fs
pulse energy:	> 5 J
focus diameter:	3 µm
max. intensity:	> 10^{21} W/cm^2

40...170-TW Yb:Glass/Yb:CaF$_2$ Laser

pulse duration:	98 fs
pulse energy:	16.7 J
focus diameter:	3 µm
max. intensity:	5×10^{20} W/cm^2

Both equipped with synchronized, ultra-short optical probe pulses.

Transverse few-cycle optical probing

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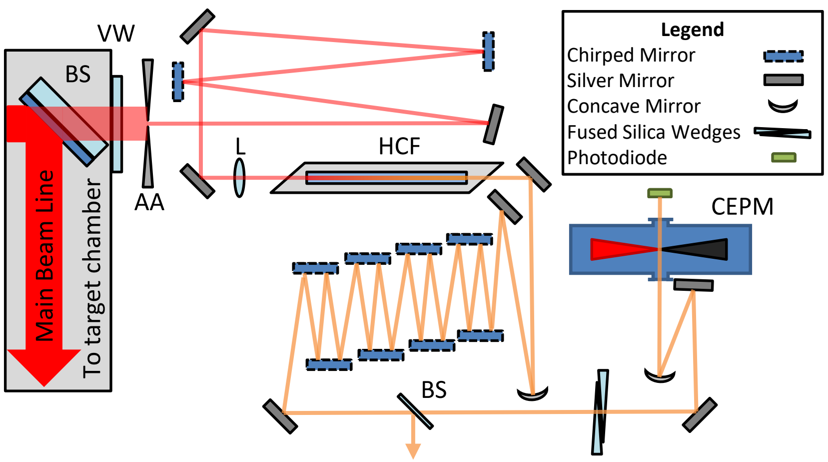
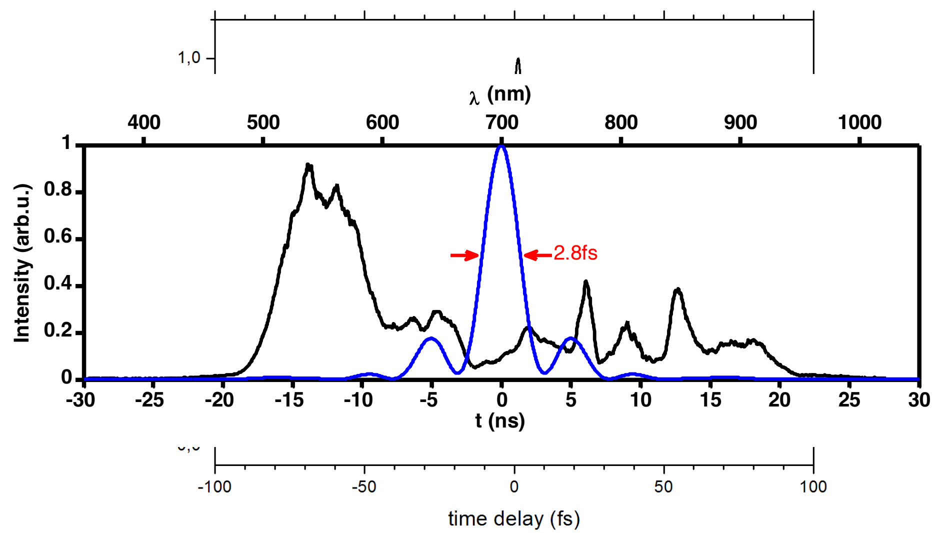
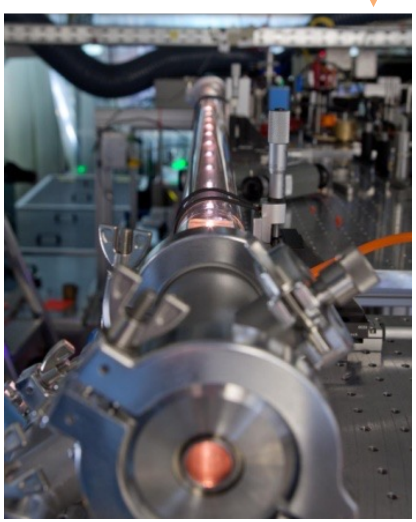
- Few-cycle probe pulse generation at JETI via frequency-broadening







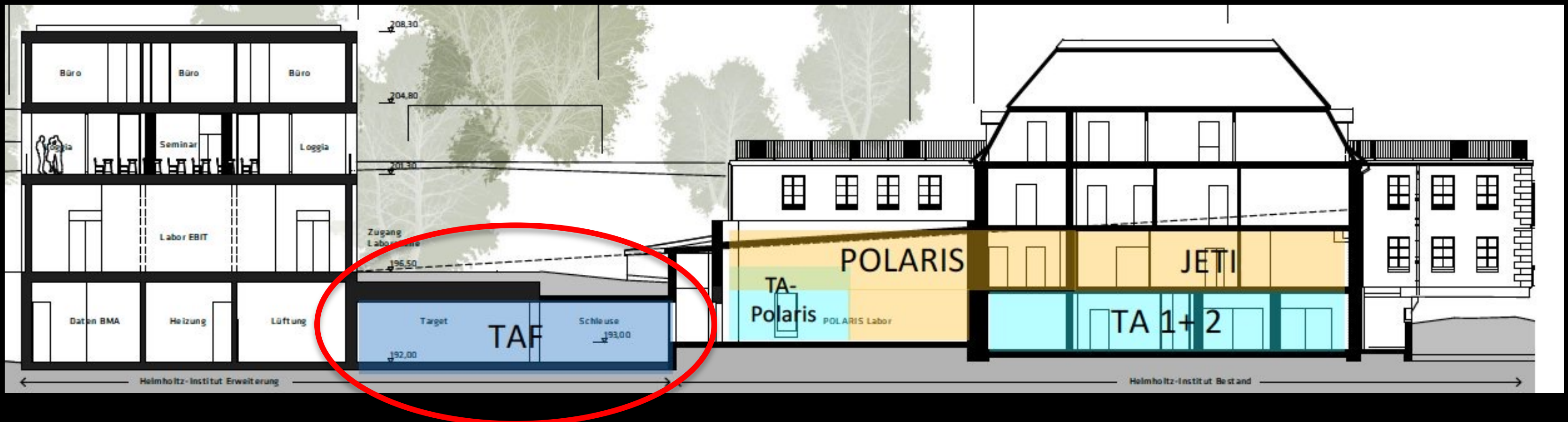
input pulses from JETI: 32 fs, ~1 mJ

⇒ (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)

JETI200 and POLARIS @ Jena



- New target area for experiments with both lasers
- building finished by July/August 2022
- target-area infrastructure finished by summer 2023
- first 2-beam experiments planned for end 2023
- synchronized, independent few-cycle probe pulse (0.8…10 µm)

Laser Wakefield Acceleration of Electrons

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

⇒ longitudinal E-fields (~ 0.1 TV/m)

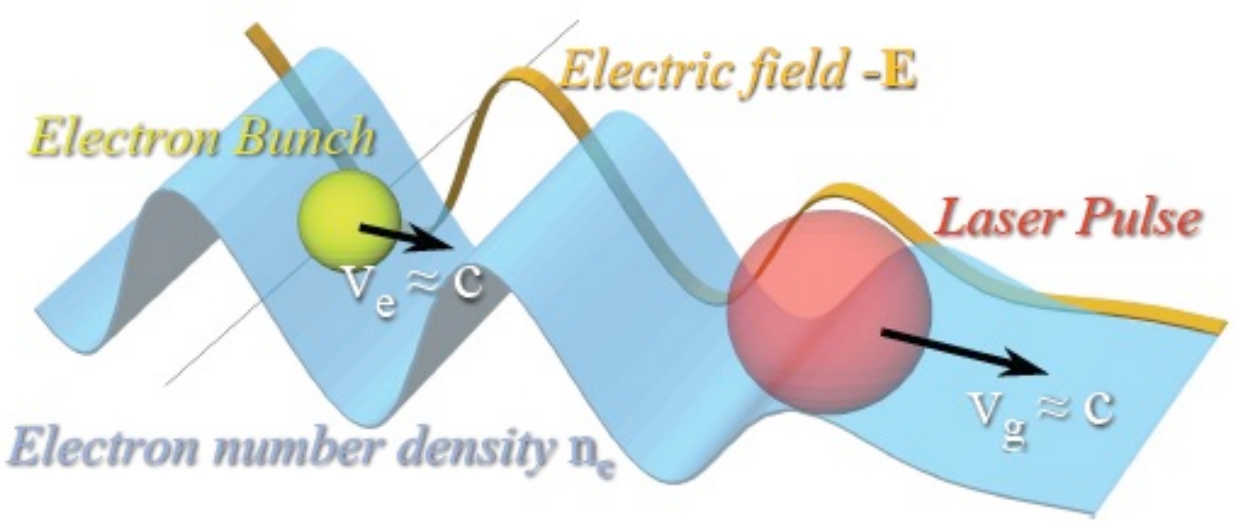


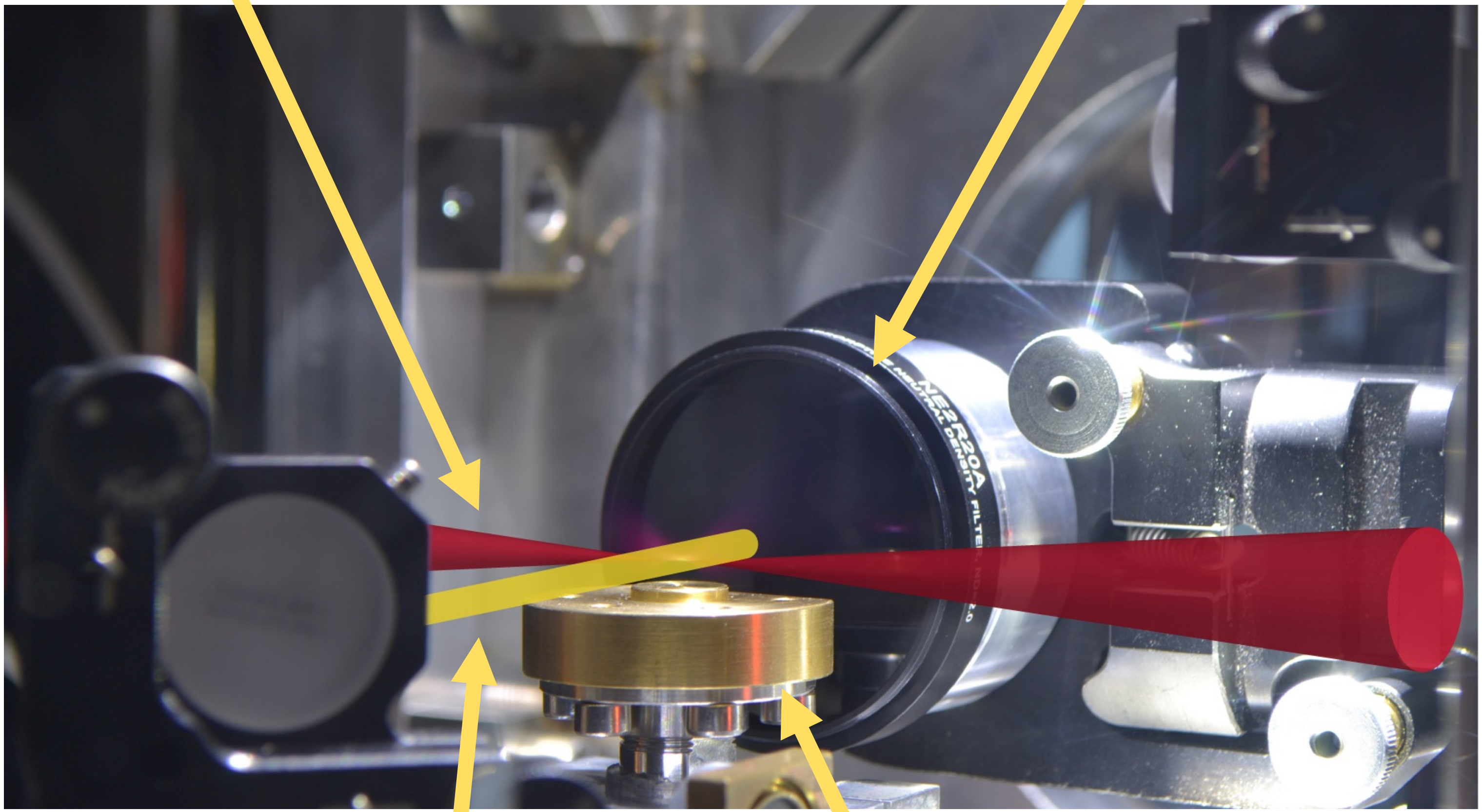
Image courtesy of A.G.R. Thomas

- Injection of electrons into the wave
  ⇒ relativsitic electron current ⇔ azimuthal B-fields

Transverse few-cycle optical probing

pump pulse

imaging lens

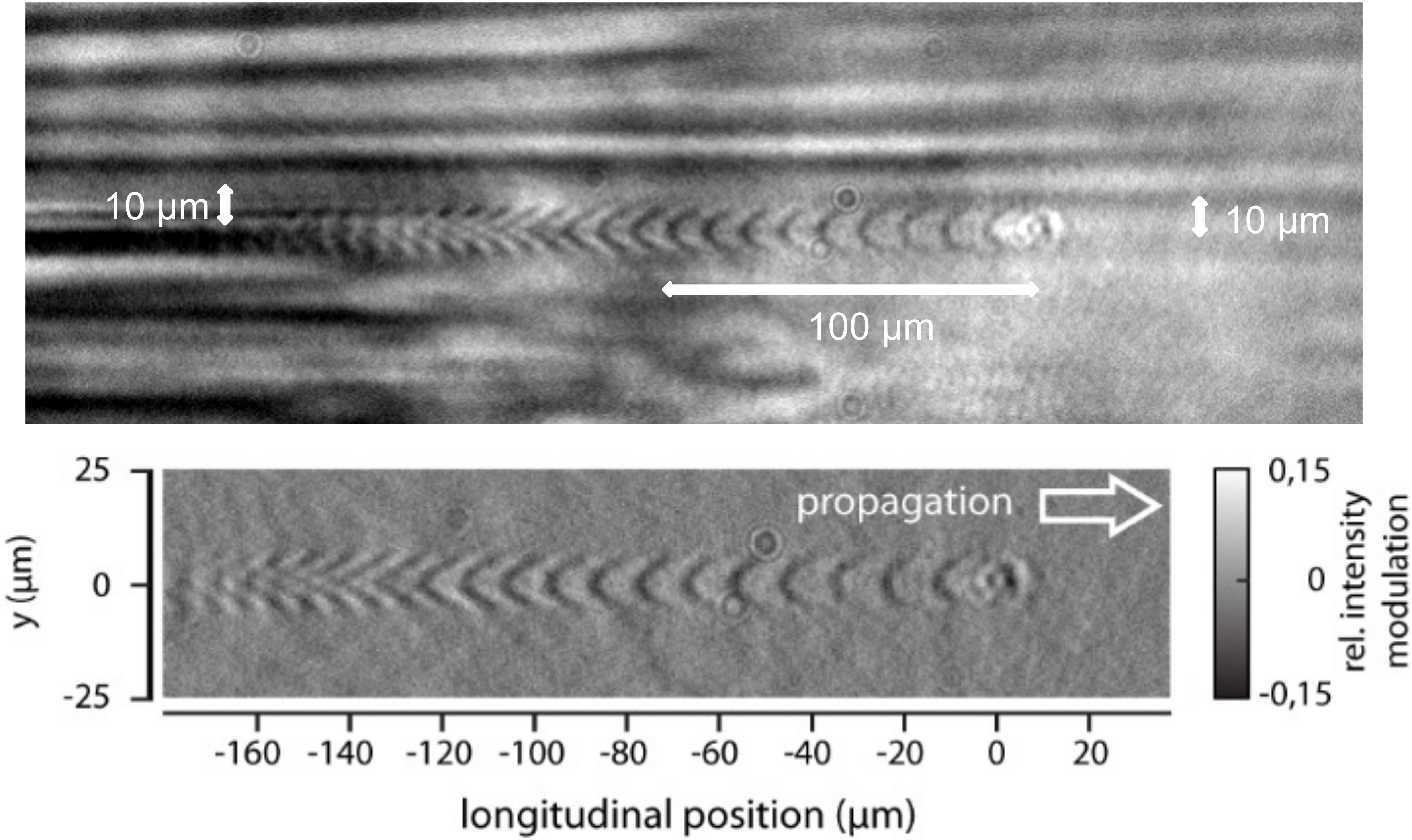


electrons
xrays,…

probe pulse

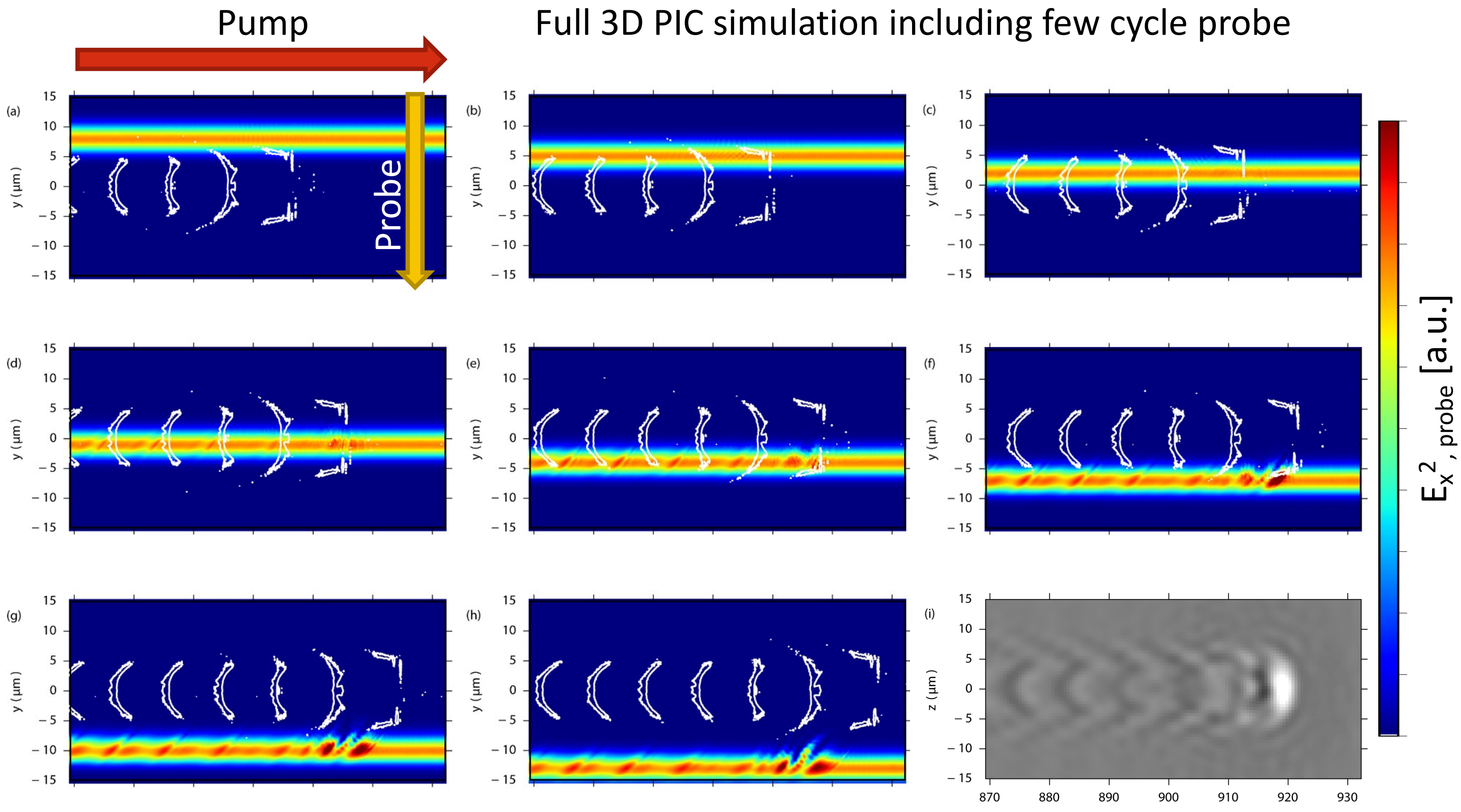
super sonic gas jet

Transverse few-cycle optical probing



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

Transverse few-cycle optical probing



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)

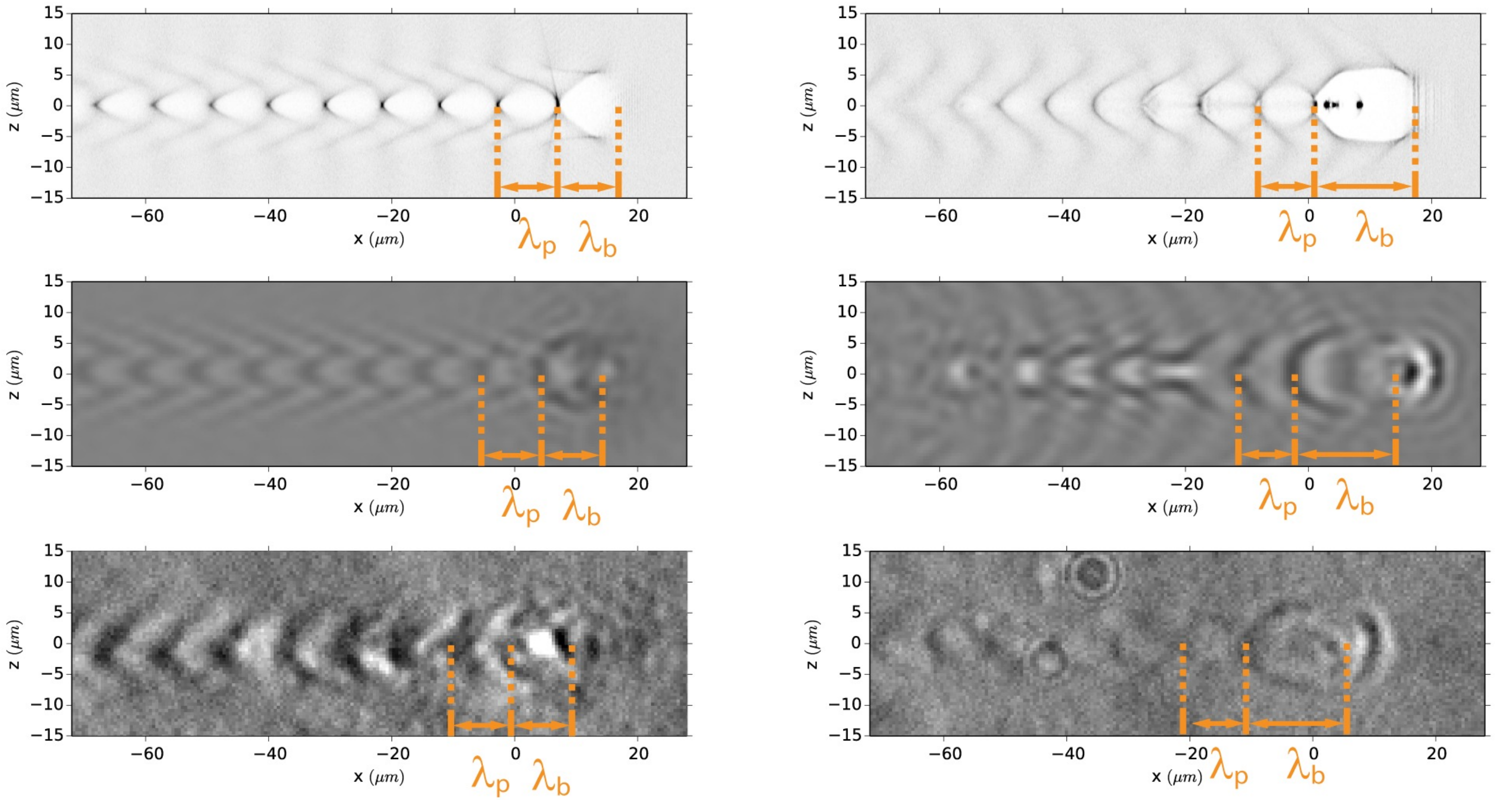
Transverse few-cycle optical probing

$v_g t$=527 µm | **$v_g t$=1214 µm**

electron density:

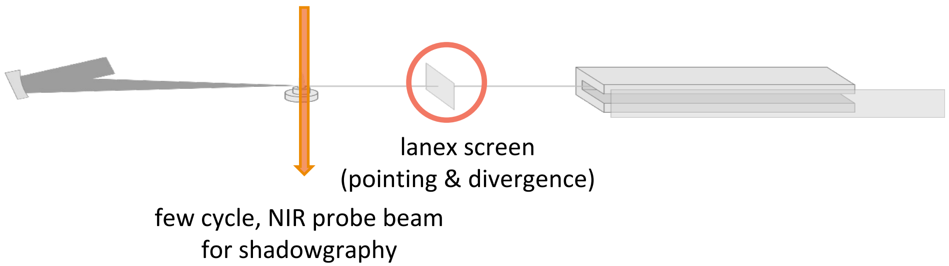
computed shadowgram:

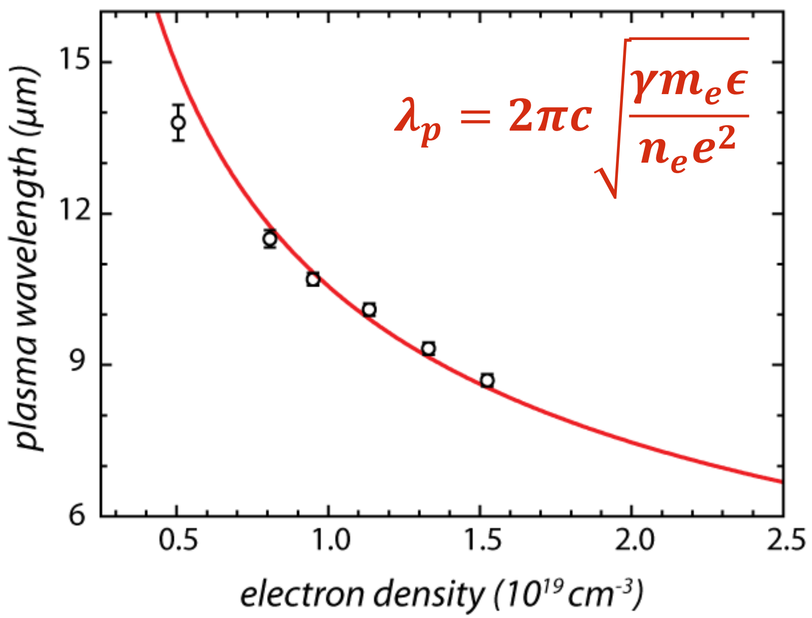
experiment:

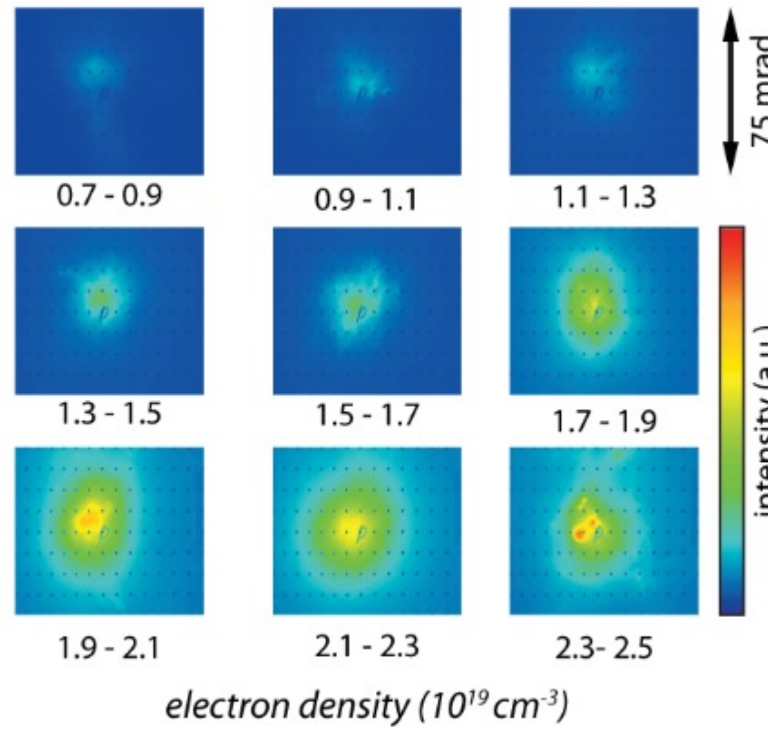


Bubble length and plasma period length are directly accessible!

Transverse few-cycle optical probing







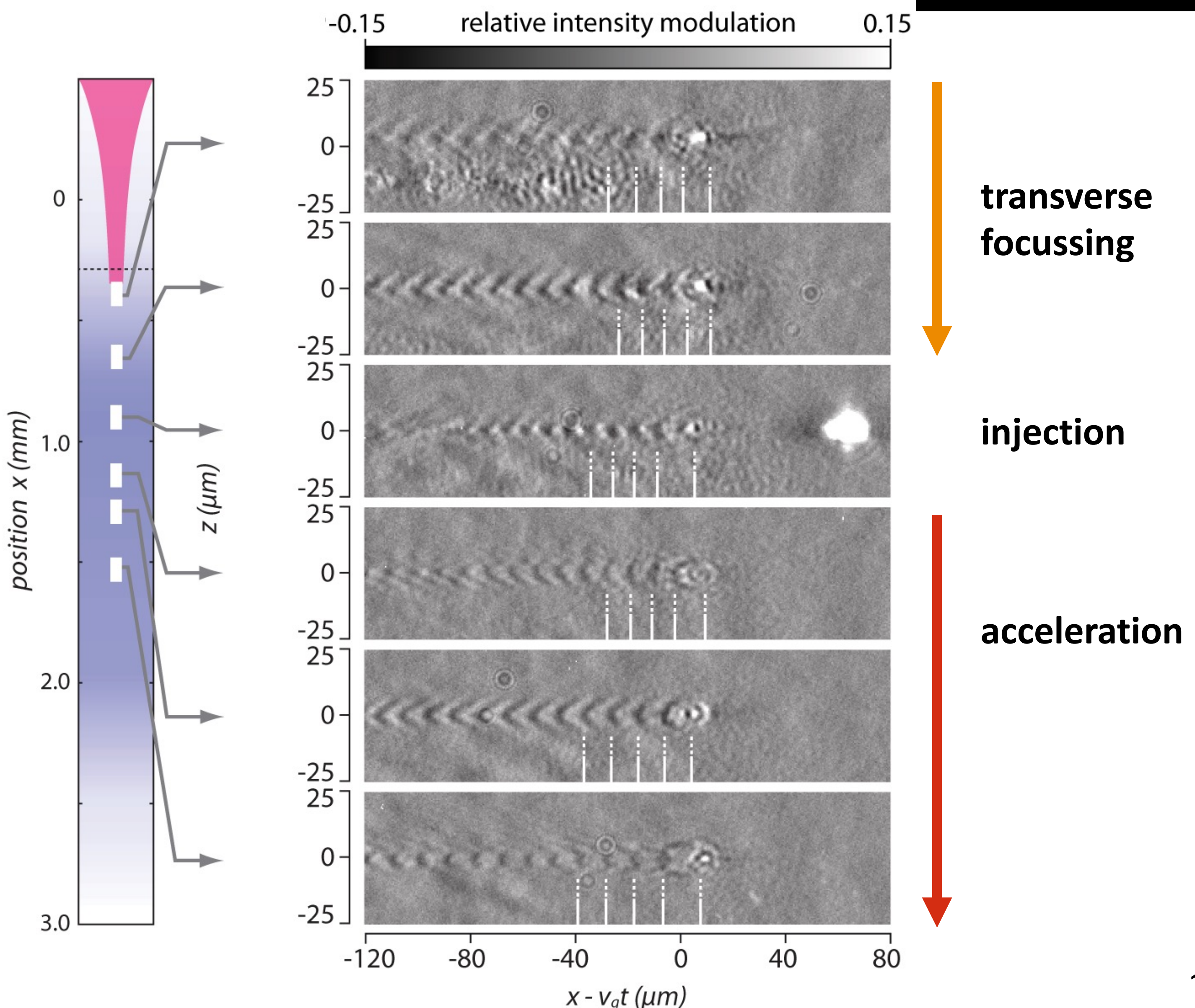
critical power for self trapping:

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

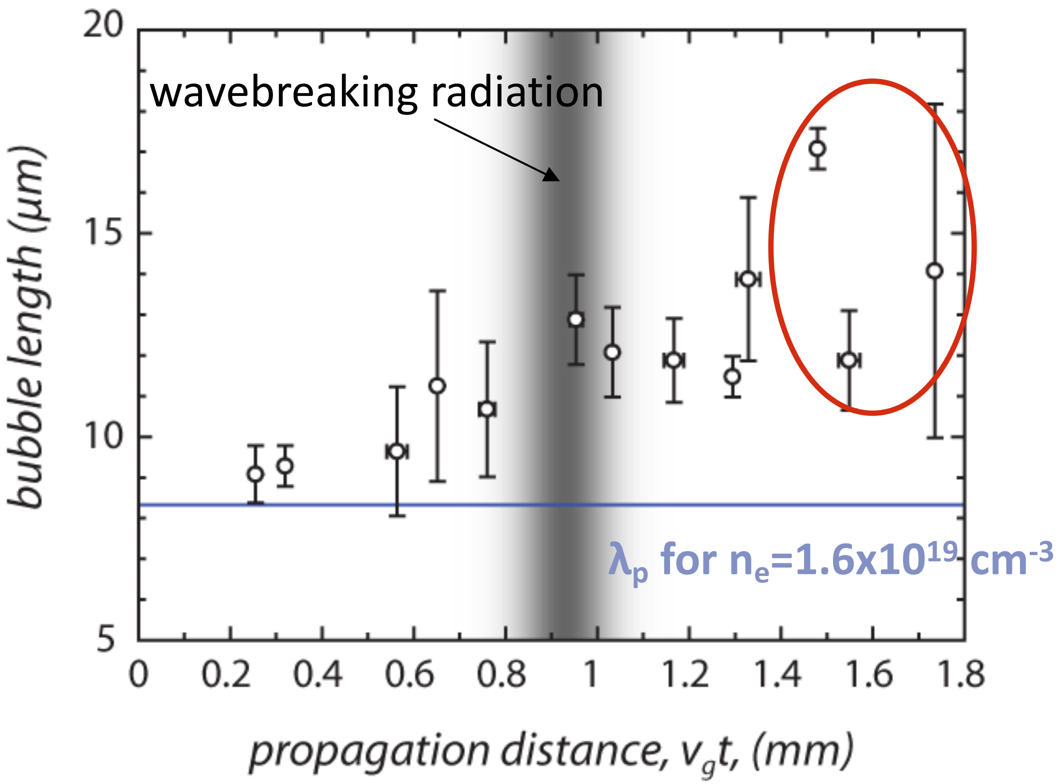
for our parameters: $n_e >$ **1.5×10^{19} cm^{-3}**

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

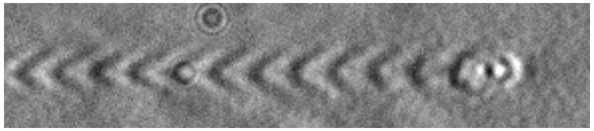
Transverse few-cycle optical probing



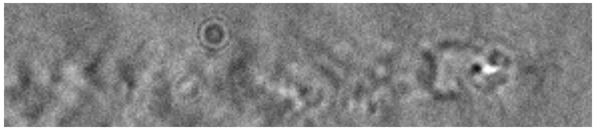
Transverse few-cycle optical probing



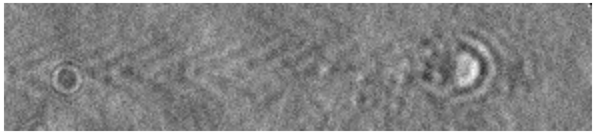
„well behaved“



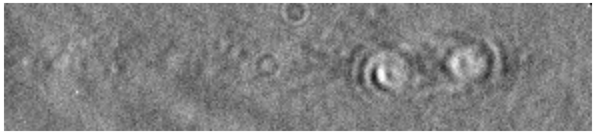
beam loading dominated



single bubble regime



multiple bubble regime



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

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

Transverse few-cycle optical probing

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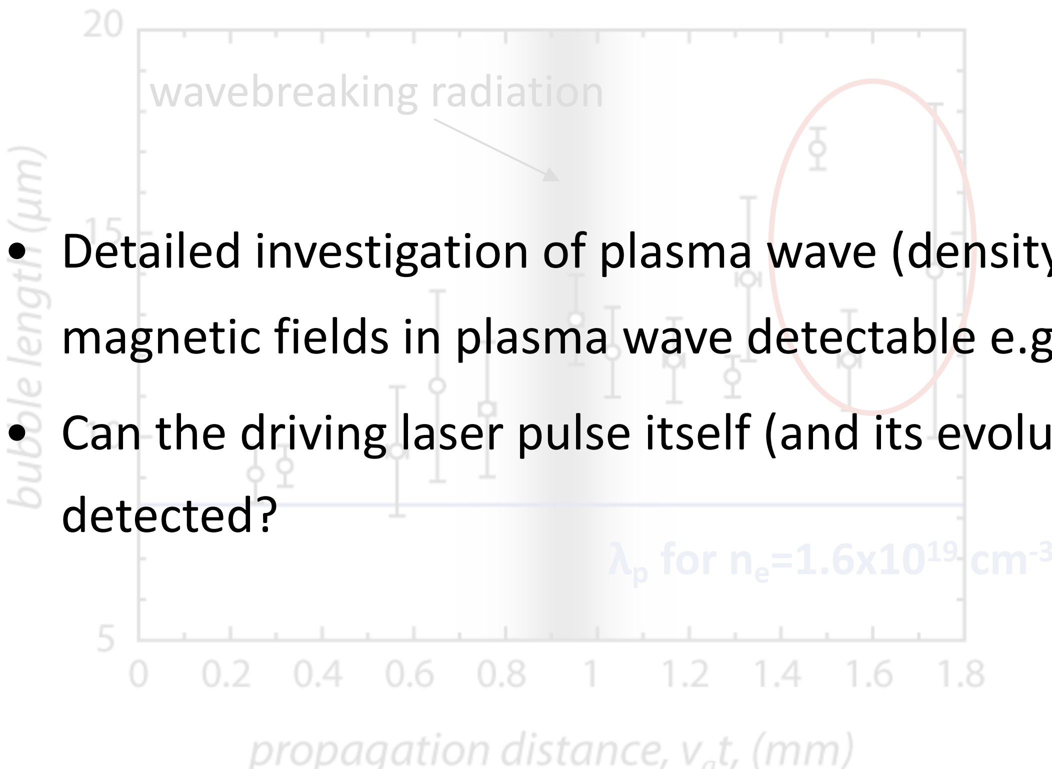
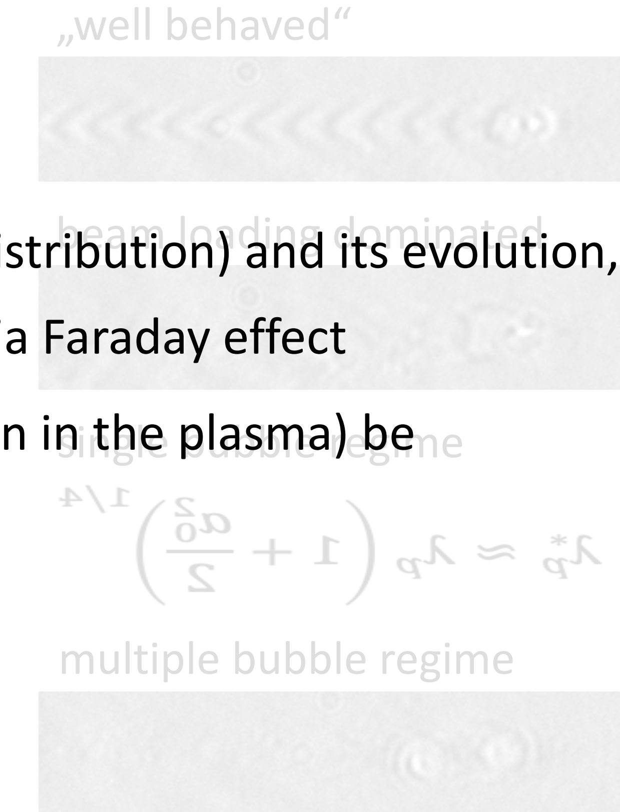


- Detailed investigation of plasma wave (density distribution) and its evolution, magnetic fields in plasma wave detectable e.g. via Faraday effect
- Can the driving laser pulse itself (and its evolution in the plasma) be detected?



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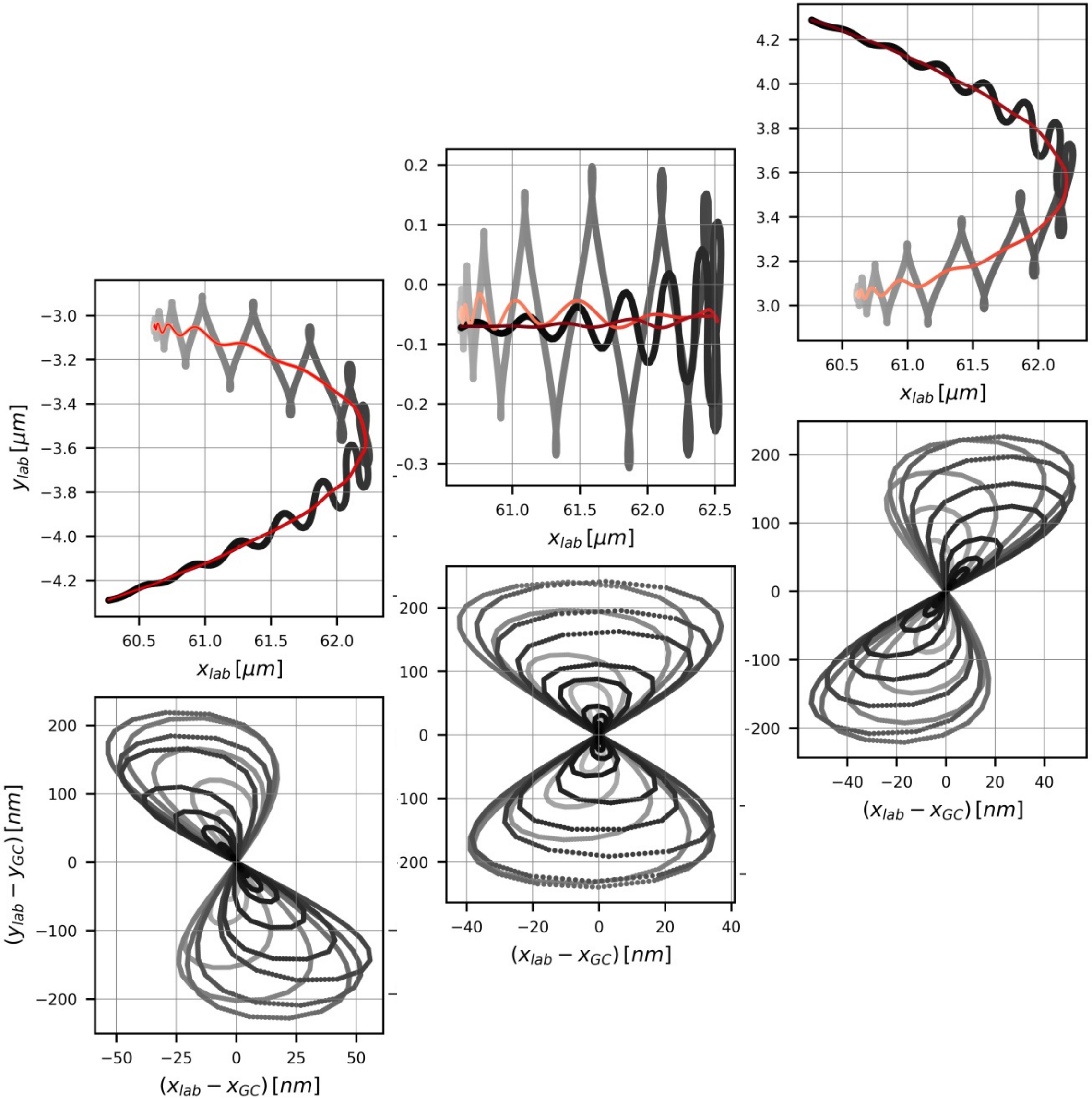
Relativistic Electron Cyclotron Resonance



- Electron trajectory in strong laser fields
- **Top**: motion of electron in lab frame during passage of the pump laser
- **Bottom**: motion of an electron in the drift frame: Figure-of-Eight motion
- **Columns**: different transverse starting positions:
  - -3.05 µm,
  - -0.5 µm,
  - +3.05 µm
- Corresponds to a quasi-cyclotron motion of electron around the pump laser's (oscillating) magnetic field
- Influence on traversing probe pulse?

Relativistic Electron Cyclotron Resonance

$$\Omega_{ce} = \frac{eB}{m_e} \qquad B = a_0 \frac{\omega_L m_e}{e}$$

$$\Omega_{ce} = a_0 \omega_L \qquad \lambda_{ce} = \frac{\lambda_L}{a_0}$$

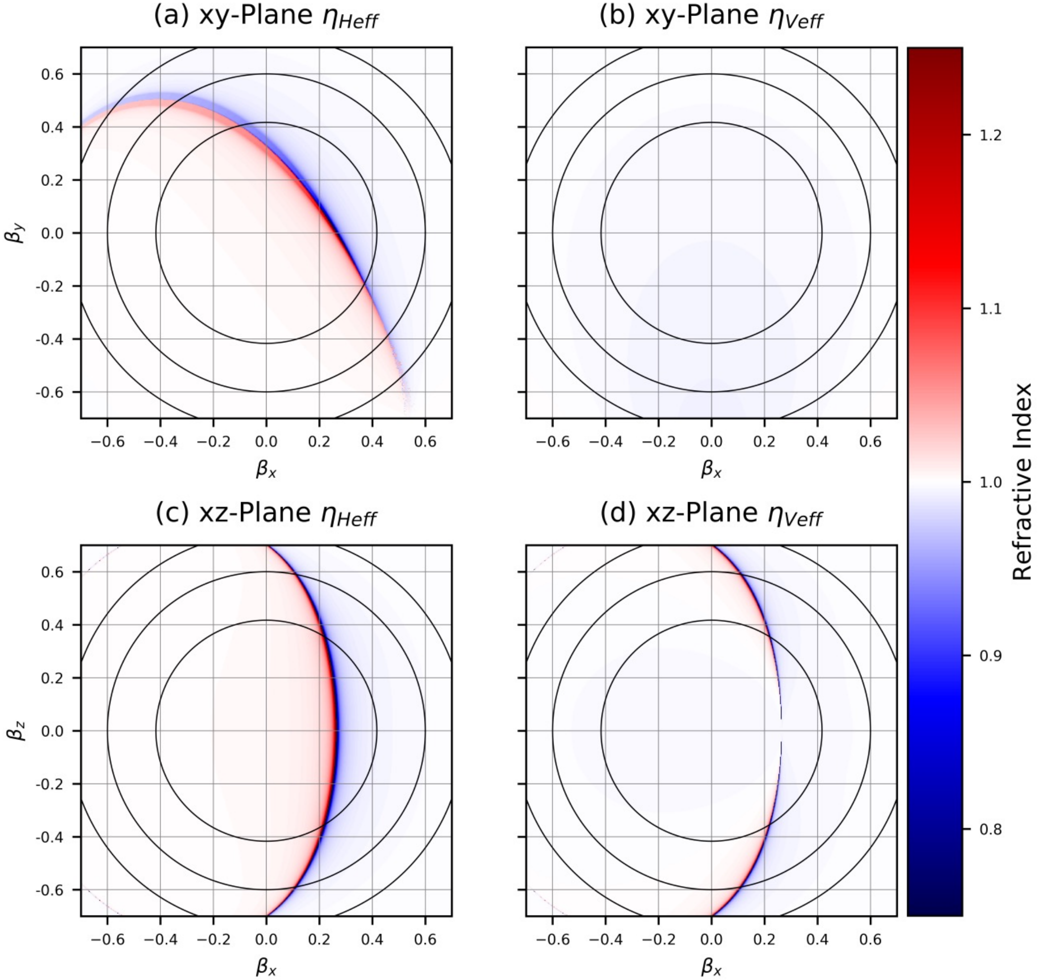
- Example
  - λ_L = 800 nm
  - $a_0 = 1.0$
  - Gives B of 13.4 kT

- Approximation: Classical electron motion and static field
- Cyclotron frequency Ω_{ce} of an electron in a static magnetic field B
- Magnetic field of a laser B with a given normalized vector potential a_0
- **Results**: for relativistic intensity of a pump laser in LWFA, i.e., $a_0 \sim 1$, the electron cyclotron frequency overlaps with the laser's frequency
- **Resonance**: an EM-wave polarized in the plane of electron-cyclotron motion and matching the electron-cyclotron frequency will experience resonance, typically meaning absorption or reflection of the EM-wave
- **Appleton-Hartree-Equation:** plasma's birefringence in presence of strong B

Relativistic Electron Cyclotron Resonance

$$\boldsymbol{E}' = \gamma(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B}) - (\gamma - 1)\frac{\boldsymbol{v}\cdot\boldsymbol{E}}{v^2}\boldsymbol{v}$$

$$\boldsymbol{B}' = \gamma\left(\boldsymbol{B} - \frac{1}{c^2}\boldsymbol{v}\times\boldsymbol{E}\right) - (\gamma - 1)\frac{\boldsymbol{v}\cdot\boldsymbol{B}}{v^2}\boldsymbol{v}$$



- Requires relativistic modifications to the Appleton-Hartree equation
  - Lorentz transform pump and probe fields into frame of the plasma electron's guiding center, i.e., relativistic drift velocity.
  - Changes vector orientations and amplitudes of the fields
  - Cyclotron resonance becomes also dependent on local motion of the plasma electrons
  - Figure: change in refractive index away from 1.0 (white) for plasma electron motion in two orthogonal planes.
  - Concentric rings show electron's gamma value of 1.1, 1.25, and 1.5

Relativistic Electron Cyclotron Resonance

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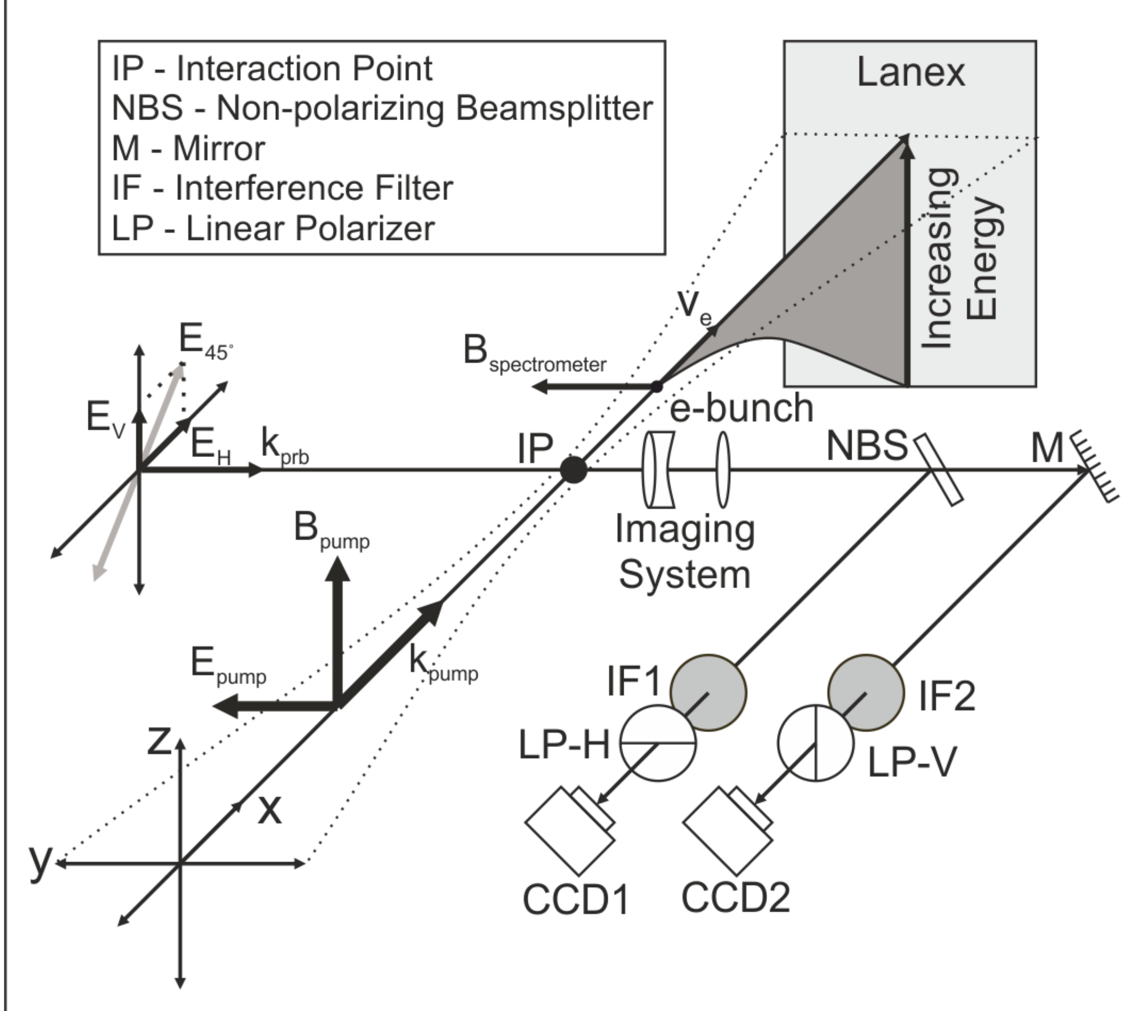
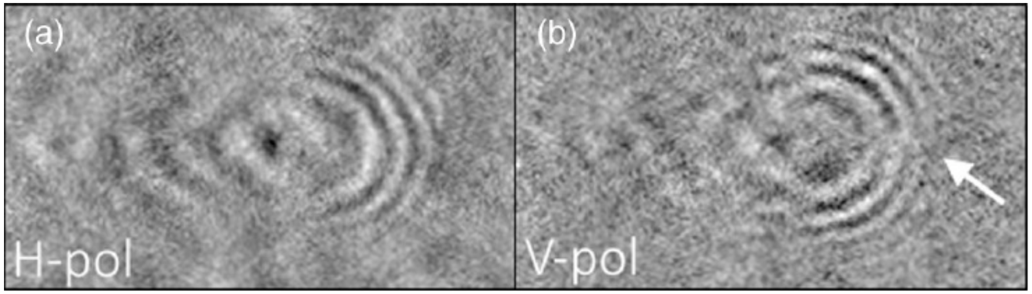
LWFA: General Setup with Few-Cycle Probe

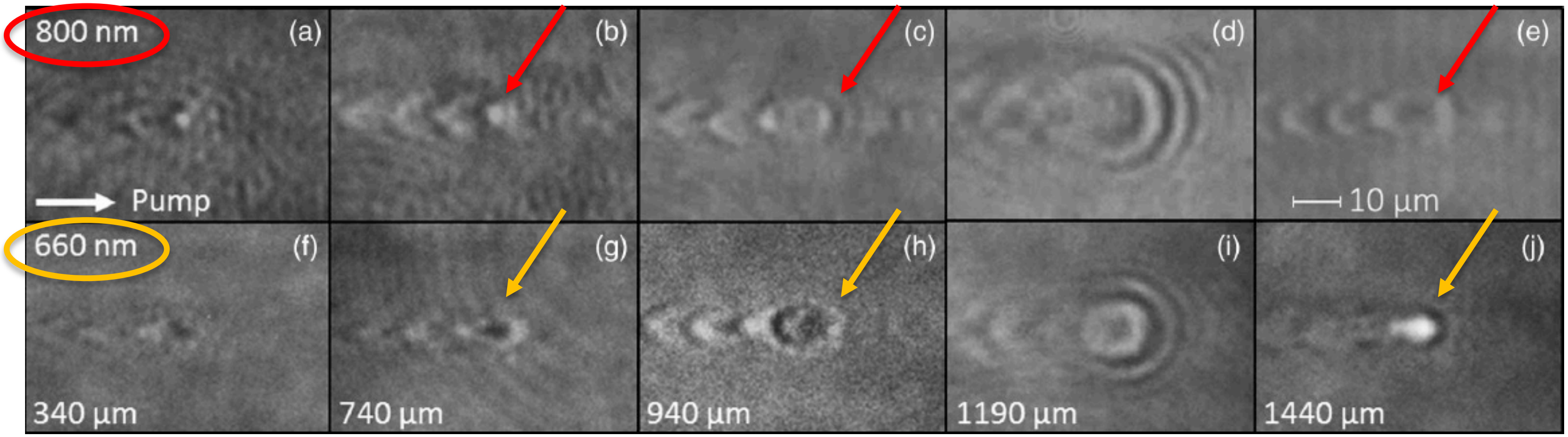


- Pump-probe experiment with N_2 doped He in a gas cell
- Dipole magnet spectrometer with Lanex screen for electron characterization
- Transverse, few-cycle probe imaging system with linear polarizers and spectral bandpass filters
- Probe beam's spectrum should overlap with expected cyclotron frequencies at the pump laser's peak location
- **Goal**: record the propagation of the plasma wave driven by the pump laser using different polarizations and/or spectral bands of the probe

- Two clear phenomena observed:
  - "Half-ring signal":
    diffraction (half) rings, on-axis break in V-pol, no break in H-pol

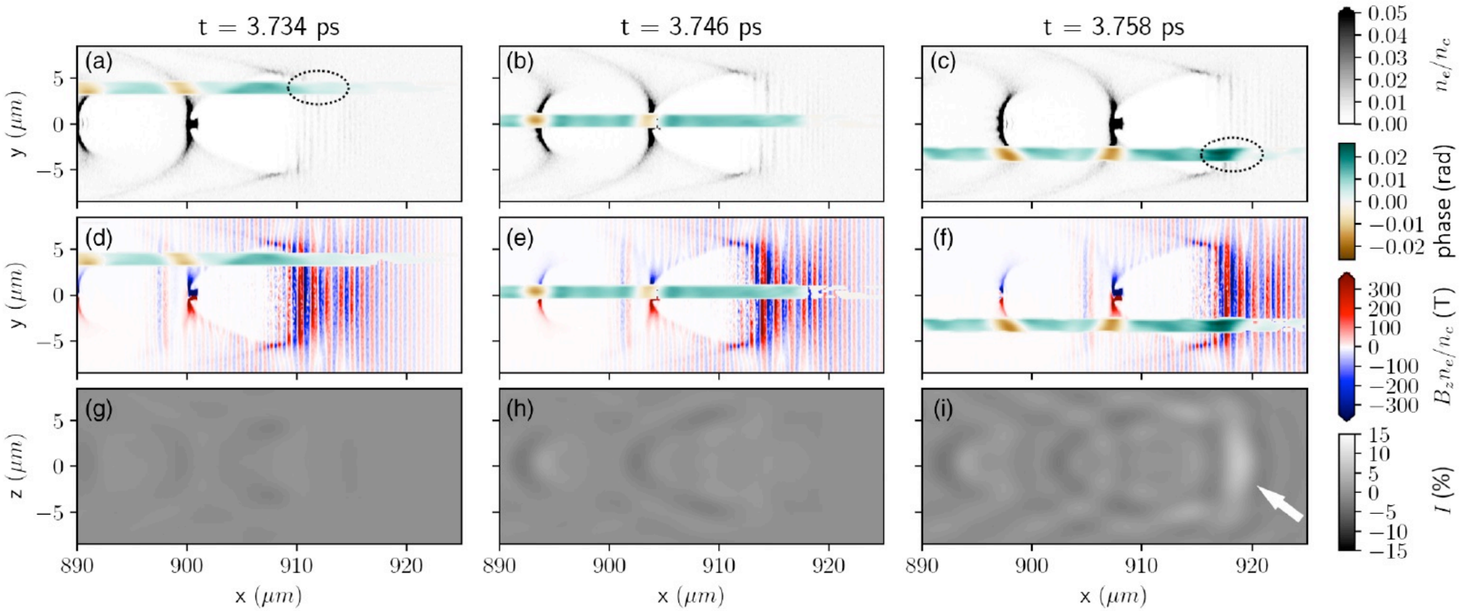


  - "Asymmetric signal":
    wavelength and time dependent probe brightness variation near pump.



Relativistic Electron Cyclotron Resonance

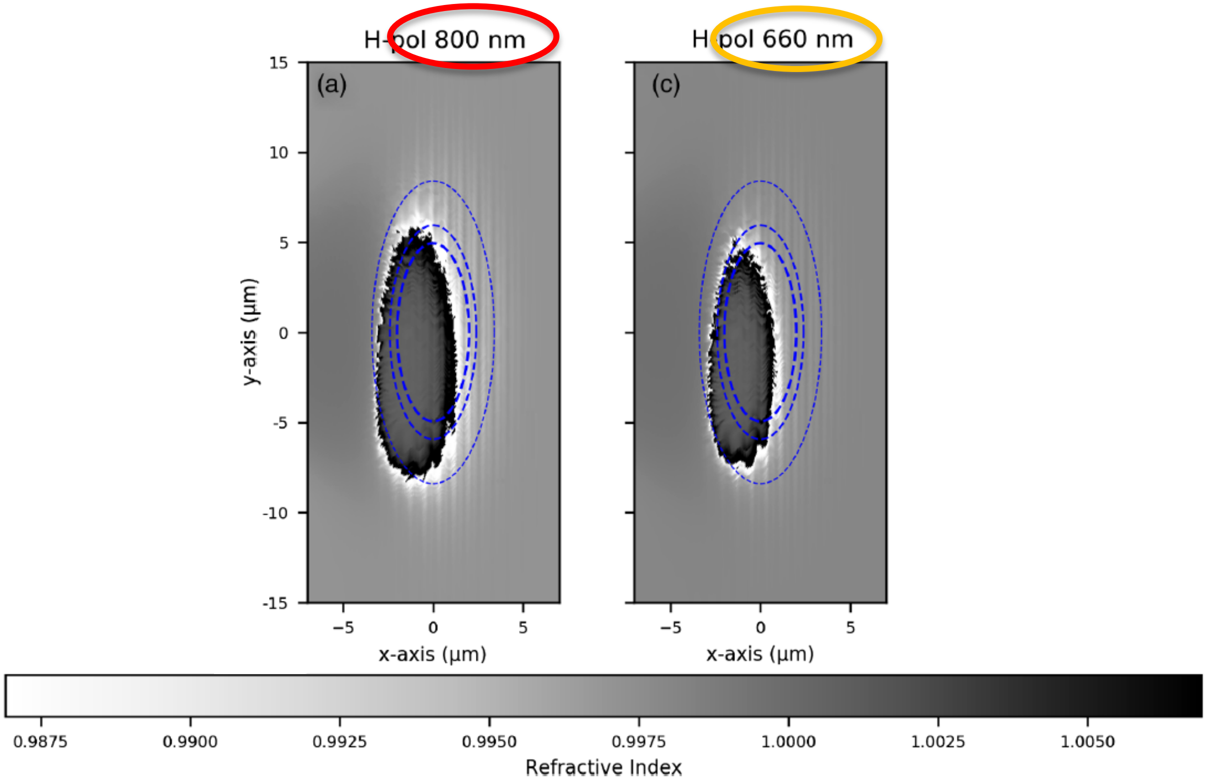
- Asymmetric Signal
  - due to resonance of probe field's oscillation with relativistic plasma electrons
  - 3D PIC simulations: increase in the probe's local phase, i.e. large change in refractive index indicating a resonance, only on the side of the plasma wave facing the imaging system (-> "asymmetric signal")
  - **Figure**: courtesy of E. Siminos
    - Top row: compare dotted ovals in top row (a) and (c) for difference in instantaneous probe phase
    - Middle row is same as top but with added plasma and pump magnetic fields (weighted)
    - Bottom row is a simulated shadowgram, with the white arrow in (i) indicating the asymmetric signal's location

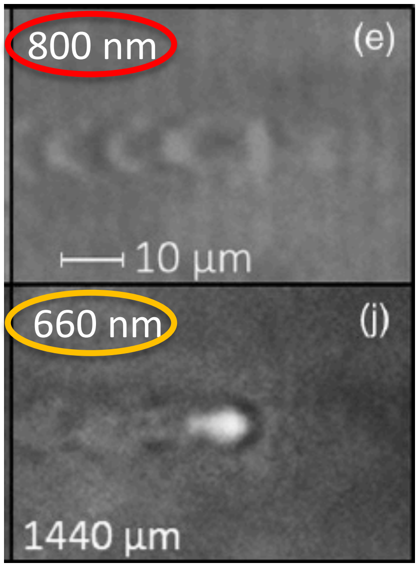


- Asymmetric Signal
  - 2D PIC data -> reconstruct plasma’s refractive index for two probe wavelengths
  - Extent and position of resonance depends on probe’s wavelength

→ Shadowgrams at different wavelength differ at the location of the pump

→ Intensity ratio signature of local pump intensity





Summary I: Few-Cycle Shadowgraphy and Relativistic Electron-Cyclotron Resonances

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- Few-cycle shadowgraphy is a powerful tool to investigate wakefield accelerators, e.g. evolution of the plasma wave.
- Details of the acceleration mechanism can be diagnosed with high spatial and temporal resolution.
- Cyclotron motion of the plasma electrons around the pump's peak magnetic field in LWFA creates a locally anisotropic plasma with a strong spectral dependence
- Relativistic corrections must be considered due to the electrons' relativistic drift and quiver velocities
- This phenomenon can be visualized using transverse, few-cycle shadowgraphy and could be used to help better understand the evolution of the pump's intensity distribution during its propagation in plasma

1. M. B. Schwab *et al.* Visualization of relativistic laser pulses in underdense plasma, Phys. Rev. Accel. Beams 23, 032801 (2020).
2. E. Siminos *et al.* Modeling ultrafast shadowgraphy in laser-plasma interaction experiments, Plasma Phys. Controlled Fusion 58, 065004 (2016).
3. A. Sävert *et al.* Direct Observation of the Injection Dynamics of a Laser Wakefield Accelerator Using Few-Femtosecond Shadowgraphy, Phys. Rev. Lett. 115, 055002 (2015).

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Thank you for your attention!