Monochromatic shadowgraphy and mid-infrared probing of LWFA

Yu Zhao[1], Alexander Sävert[1], Malte C. Kaluza[1]

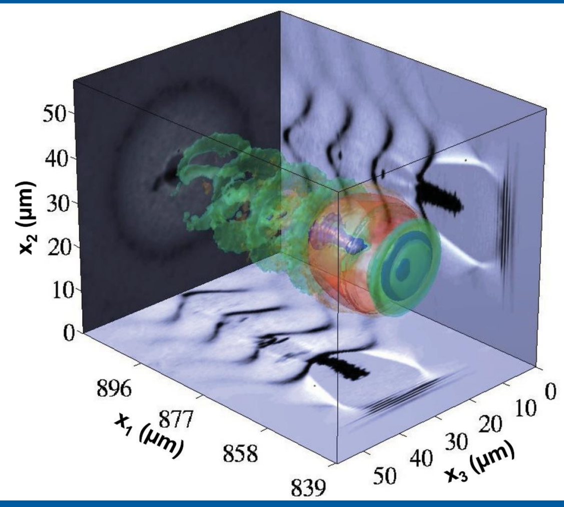
[1] Helmholtz-Institut Jena, Fröbelstieg 3, 07743 Jena, Germany

Motivation

- Laser wakefield accelerator (LWFA): a more compact and less expensive electron accelerator gives shorter electron bunch duration and lower emittance compared to conventional rf accelerators
- Challenges of LWFA: pointing stability, energy and charge spread, etc.
- To overcome these challenges: a better understanding of the injection and acceleration mechanism can be provided by the comparison of **complex simulations** and **direct observations**

Laser Wakefield Acceleration

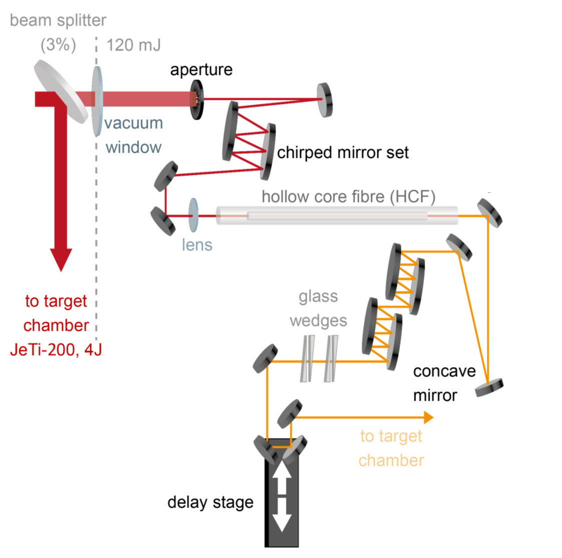
- Proposed by Tajima and Dawson in 1979 [1]
- A high-intensity laser pulse ($> 10^{18}$ W/cm^2) propagates through an underdense plasma, the ponderomotive force of the laser pulse expels electrons from high intensity region, forming periodic charge separation, so-called laser wakefield
- This charge separation gives an extremely high longitudinal electric field (> 100 GV/m @ $n_e \sim 10^{18}$ cm^{-3})
- Background electrons can be injected and accelerated by this longitudinal electric field to very high energy (~GeV) over a short distance



- Illustration of LWFA in the bubble regime [2]:
  $\tau_p = 29$ fs (FWHM),
  $w_0 = 10$ μm,
  $a_0 = 4$,
  $n_e = 0.005 n_c$ (He plasma)
  ~ 8.75×10^{18} cm^{-3} @ 800 nm

Few-cycle femtosecond NIR optical pulse generation

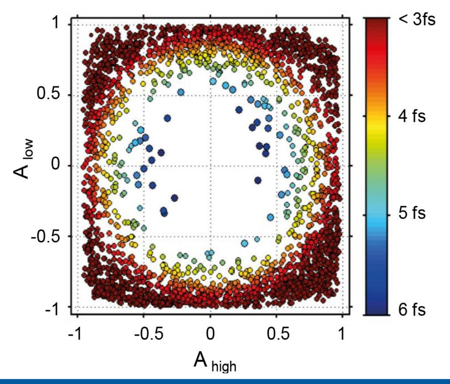
- Schematic of the few-cycle probe setup [3]



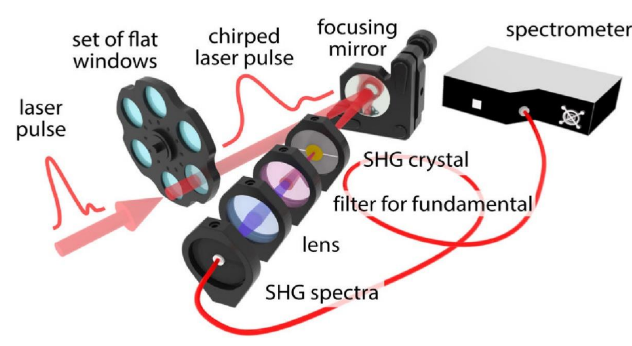
- Split off a fraction from the main pulse, therefore probe pulses are intrinsically synchronized to the main pulse
- Reduce the size by a reverse bull's eye apodizing aperture
- Spectral broadened by self-phase modulation (SPM) inside an Argon or Neon filled hollow core fiber (HCF)
- Group delay dispersion compensated by chirp mirror pairs and glass wedges
- Resulting NIR ultrafast probe laser pulse (central wavelength @ 800 nm) with a duration < 4 fs (FWHM) and an energy ~300 μJ

Few-cycle pulse characterization

- Due to the ultra short pulse duration (< 4 fs, FWHM), conventional fs pulse characterization methods such as FROG, SPIDER, and Wizzler are limited
- Two methods to characterize few-cycle femtosecond pulses:
  - **Stereo ATI Phasemeter**, 3600 pulses are measured, over 86% of pulses are < 4 fs (FWHM) [4]



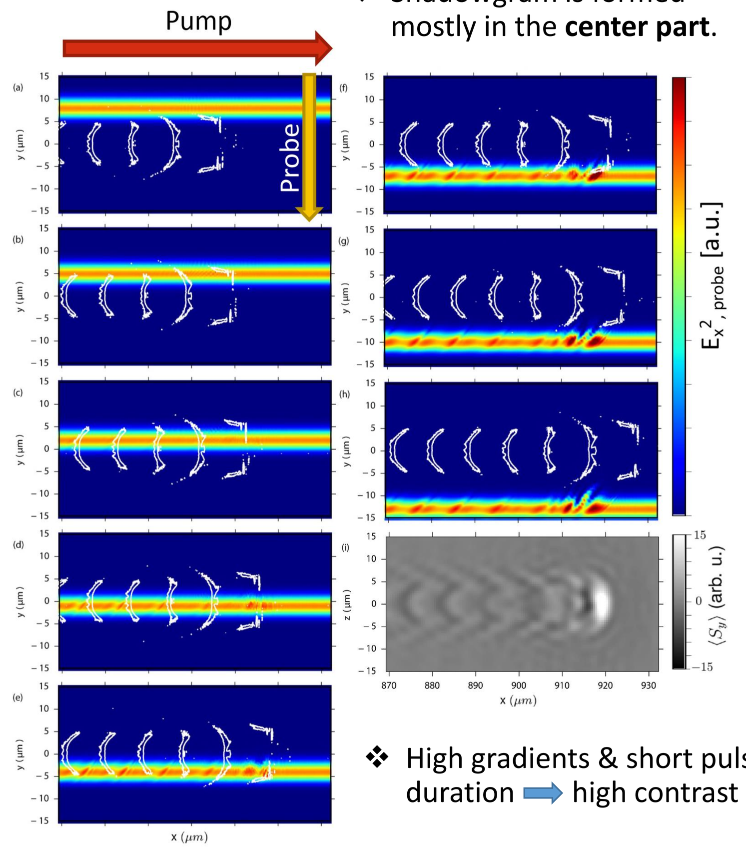
  - Schematic of a **discrete dispersion scan** (d-scan) setup [5]



Ultrafast shadowgraphy of LWFA: previous results

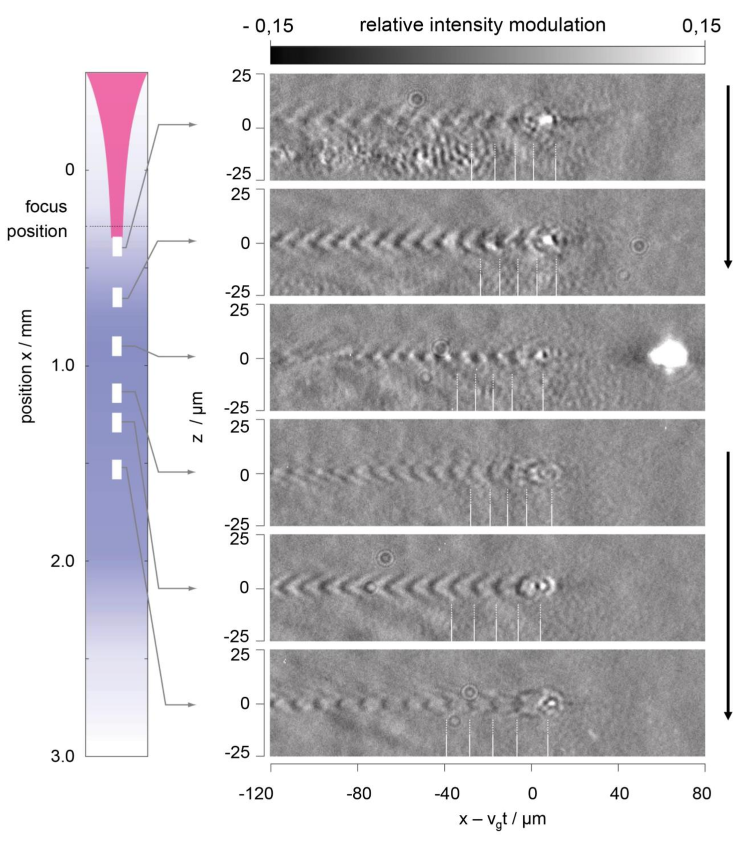
- 3D PIC simulation of LWFA process including a few-cycle probe, imaging optics and detector [6]

❖ Shadowgram is formed mostly in the **center part**.



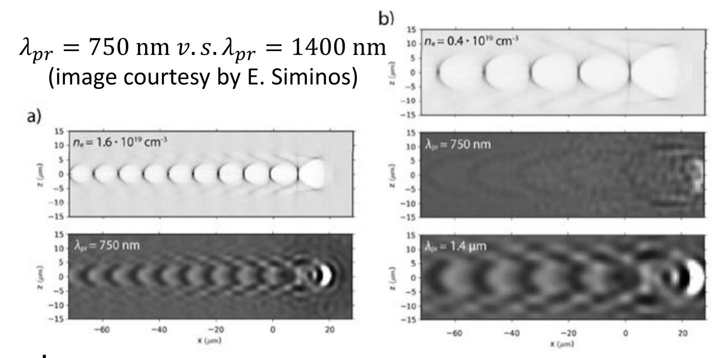
❖ High gradients & short pulse duration ➡ high contrast

- Experimental shadowgrams at various positions in a He plasma: $n_e = 1.65\times 10^{19}$ cm^{-3}, pump pulse $a_0 \approx 1.7$ [7]

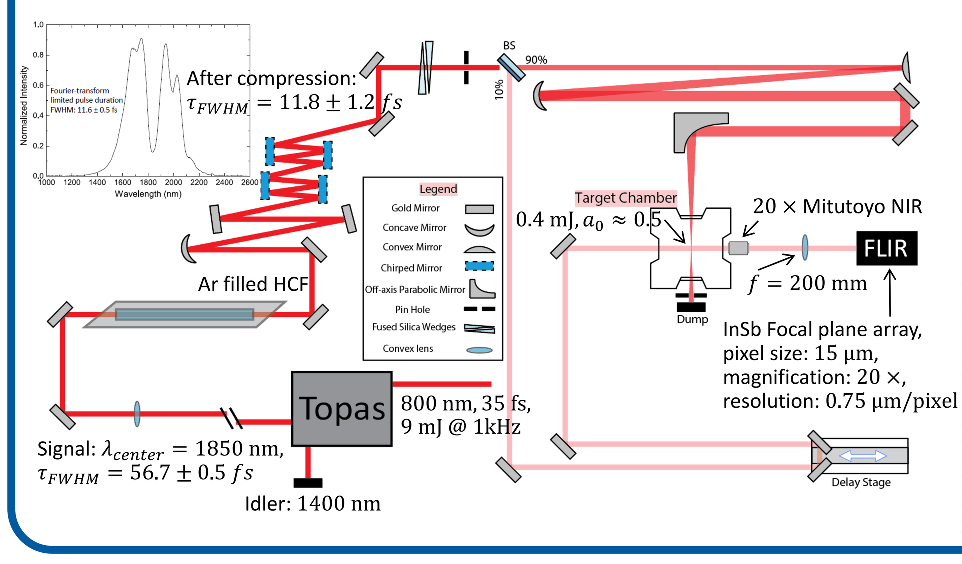


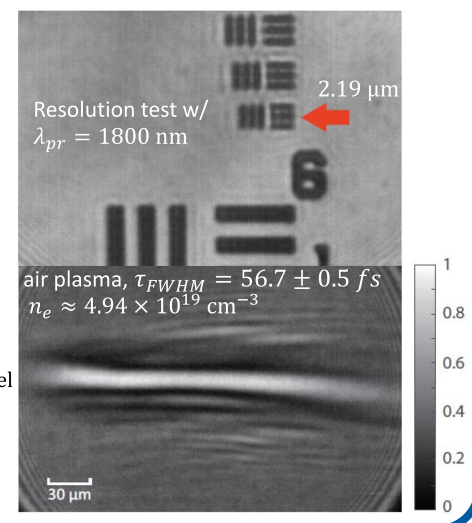
SWIR probing

- Motivation:
  - LWFA energy gain [8]:
    $\Delta E[\mathrm{GeV}] \cong 1.7 \left(\frac{P[\mathrm{TW}]}{100}\right)^{1/3} \left(\frac{10^{18}}{n_e[\mathrm{cm}^{-3}]}\right)^{2/3} \left(\frac{0.8}{\lambda_0[\mu m]}\right)^{4/3}$
    → lower plasma density, higher energy gain
  - Sensitivity of shadowgraphy [9]:
    $\frac{\Delta I_d}{I} = L\left[\frac{d}{dx^2} + \frac{d}{dy^2}\right] \int \eta \, dl$ & refractive index $\eta = \sqrt{1 - \frac{\omega_{plasma}^2}{\gamma \omega_{probe}^2}}$
    → lower plasma density + fixed λ_{probe} → lower sensitivity
  - For a lower plasma density: larger λ_{probe} → more sensitivity
    $\lambda_{pr} = 750$ nm $v.s.$ $\lambda_{pr} = 1400$ nm (image courtesy by E. Siminos)



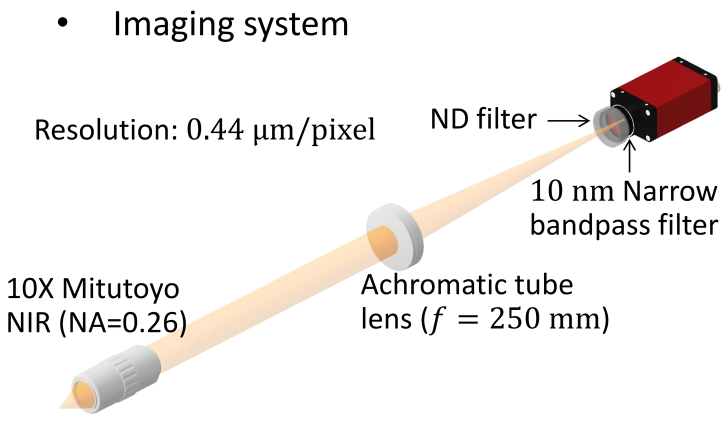
- Preliminary results of SWIR shadowgraphy:



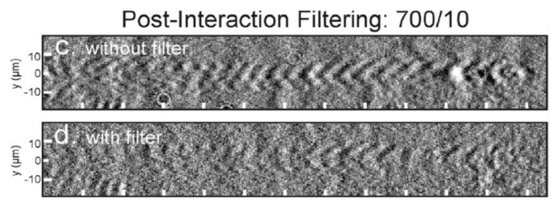


Monochromatic shadowgraphy

- Motivation: avoid chromatic aberration, suppress plasma emission, …
- Imaging system

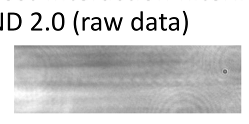


- Previous results @ JETi 40 [3]

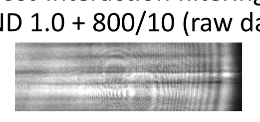


- Ongoing project @ JETi 200

Post-Interaction filtering: ND 2.0 (raw data)



Post-Interaction filtering: ND 1.0 + 800/10 (raw data)

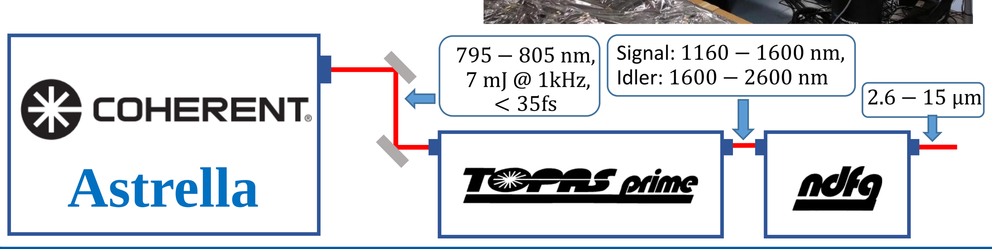


- E_{probe} ↑
  ↳ SNR ↑ (compare to [3])
- Temp. Res.: preserved

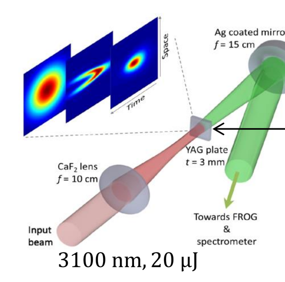
- What's next?
  - The previous study of LWFA shadowgraphy at various delays: assume shot-to-shot fluctuation is negligible [7]
  - In reality: acceleration structures are transient and prone to shot-to-shot variation. Single shot probes are desirable [10]
  - Next step: single shot muti-frame shadowgraphy by a linearly chirped probe pulse and spectral filtering

Outlook: mid-IR probing

- Motivation:
  - SWIR probing of laser-plasma has been proved in principle
  - Previous pump-probe study: probe spectrum is closely related to the pump spectrum (centered ~ 800 nm) [3,7]
  - An independent probe laser w/ a tunability of wavelength is desired
- JETi ONE
  - a probe laser with a tunable wavelength range from 1160 nm to 15 μm
  - will be synchronized with JETi 200 and POLARIS in the future, with a relative timing jitter of < 20 fs (RMS)



- A way towards few-cycle mid-IR pulse: self-compression in bulk material [11]



- Spatial and temporal resolution [10]:
  - plasma wavelength: $\lambda_p \uparrow = \frac{2\pi c}{\omega_p} = 2\pi c\sqrt{\frac{\varepsilon_0 m_e}{e^2 n_e \downarrow}}$
  - Spatial resolution: lower plasma density → larger acceleration structure
  - single-cycle limit of a few-cycle mid-IR pulse: $\tau = 10$ fs @ $\lambda_{pr} = 3$ μm
  - Temporal resolution: for a low-density plasma, $\tau_{pr} \le \frac{\lambda_p}{2c}$ is still valid

Reference

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