Burst shot of the self-injection dynamics of a laser wakefield accelerator in bubble regime

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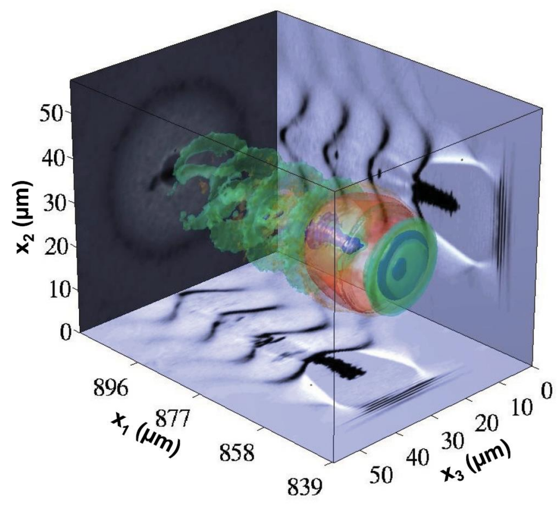
Motivation

- 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
- Self-injection: perhaps the most basic and simplest mechanism of electron injection into wakefield
- Previous study: only one snapshot can be taken from one interaction process → affected by shot-to-shot fluctuations of a high-power laser system
- To have a better understanding of the self-injection dynamics in bubble regime: a burst shot imaging technique which can catch **multiple frames** from **one single interaction process** with **preserved temporal and spatial resolution** is desired
- LWFA in bubble regime: a drastically change of the weakfield amplitude can happen before and after the injection, which is a good scenario to test our new burst shot imaging technique

Laser Wakefield Acceleration

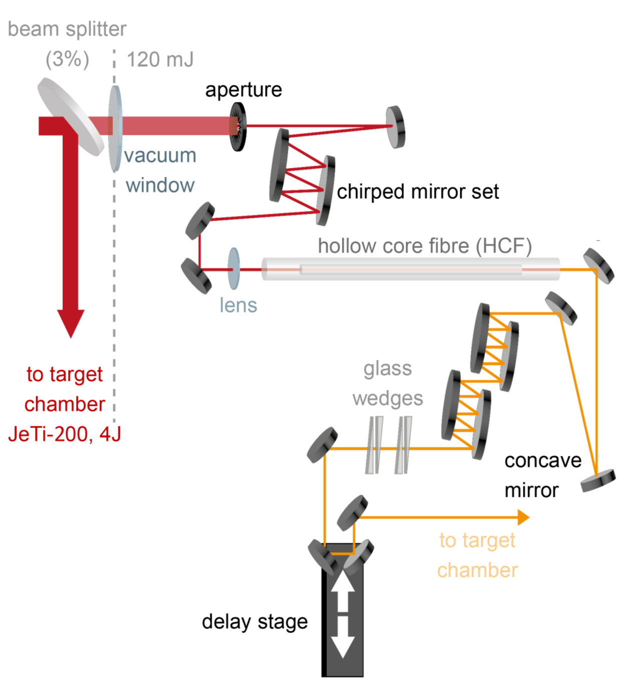
- Proposed by Tajima and Dawson in 1979 [1]
- A high-intensity laser pulse ($> 10^{18}$ W/cm^2) propagates through an underdense plasma, the ponderomotive force of the laser pulse expels electrons from high intensity region, forming periodic charge separation, so-called laser wakefield
- This charge 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

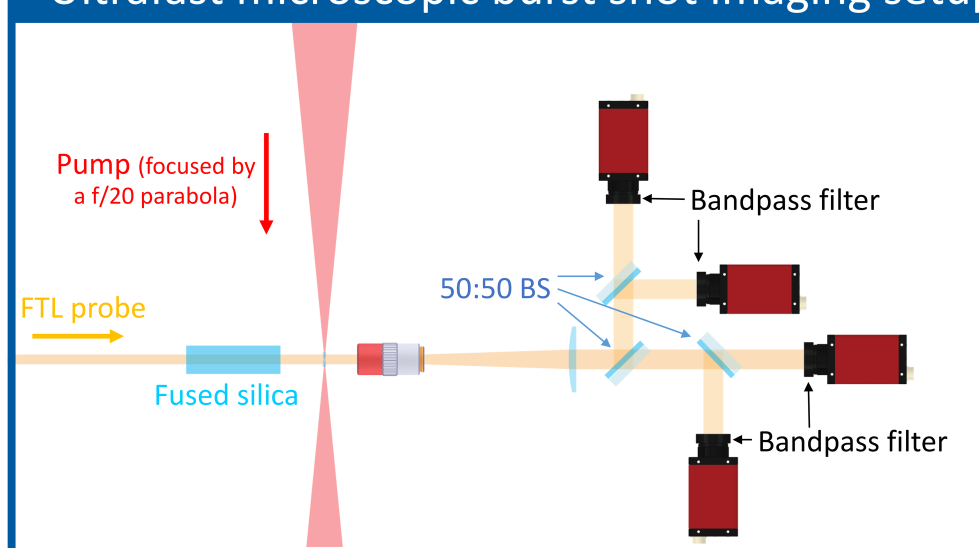
Few-cycle femtosecond NIR optical pulse generation

- Schematic of the setup for few-cycle probe generation [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

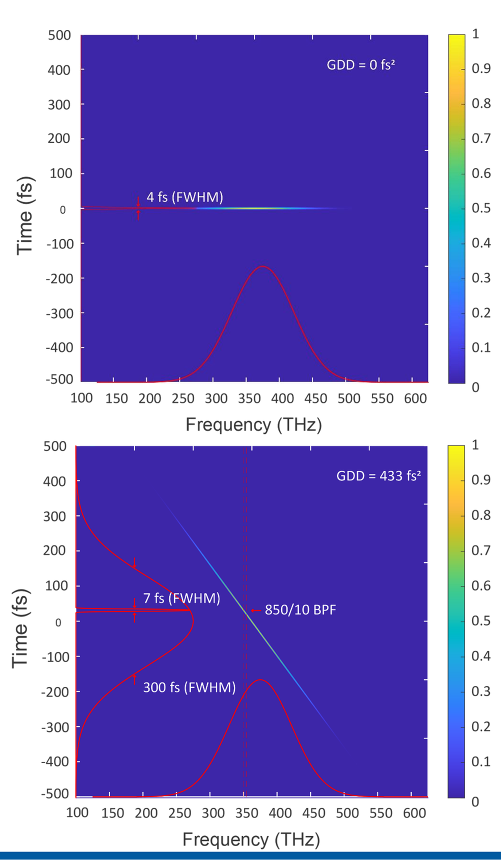
Ultrafast microscopic burst shot imaging setup



- Pump pulse:
  - $\lambda_c = 800$ nm
  - $\tau = 24$ fs
  - $E = 1.4$ J
  - d_{focus} = (FWHM): 22 μm
- Fourier transform limited (FTL) probe pulse:
  - $\tau \approx 4$ fs
- Fused silica:
  - Add GDD to stretch the FTL probe pulse
- Bandpass filters:
  - Spectral filtering to recover the temporal resolution

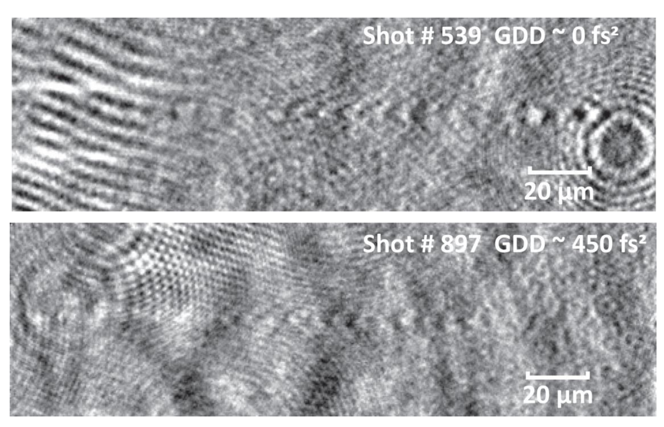
Preliminary results: temporal resolution

- Effective temporal resolution of a linearly chirped probe pulse after filtering [6]

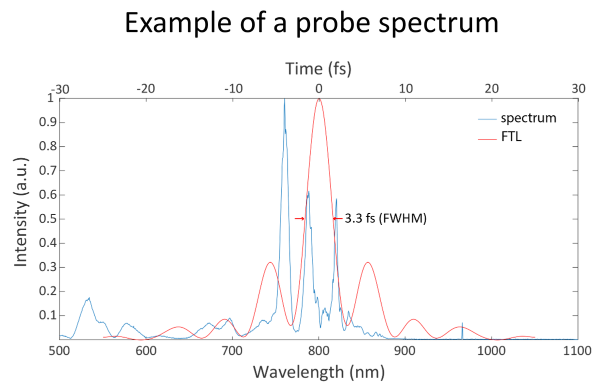


- Wakefield images from JETi 200

FTL probe v.s. linearly chirped probe

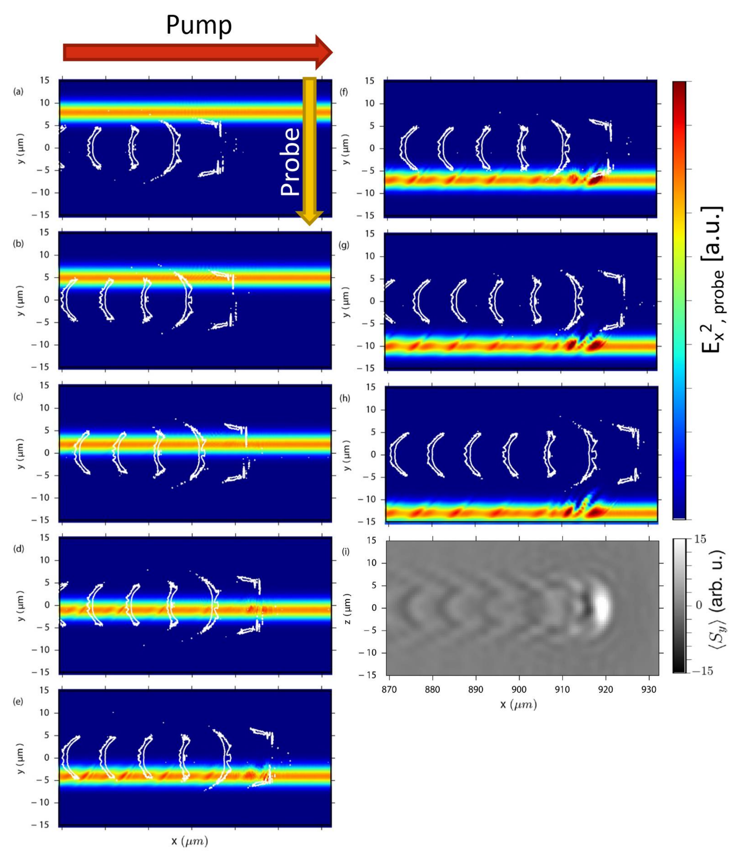


Example of a probe spectrum



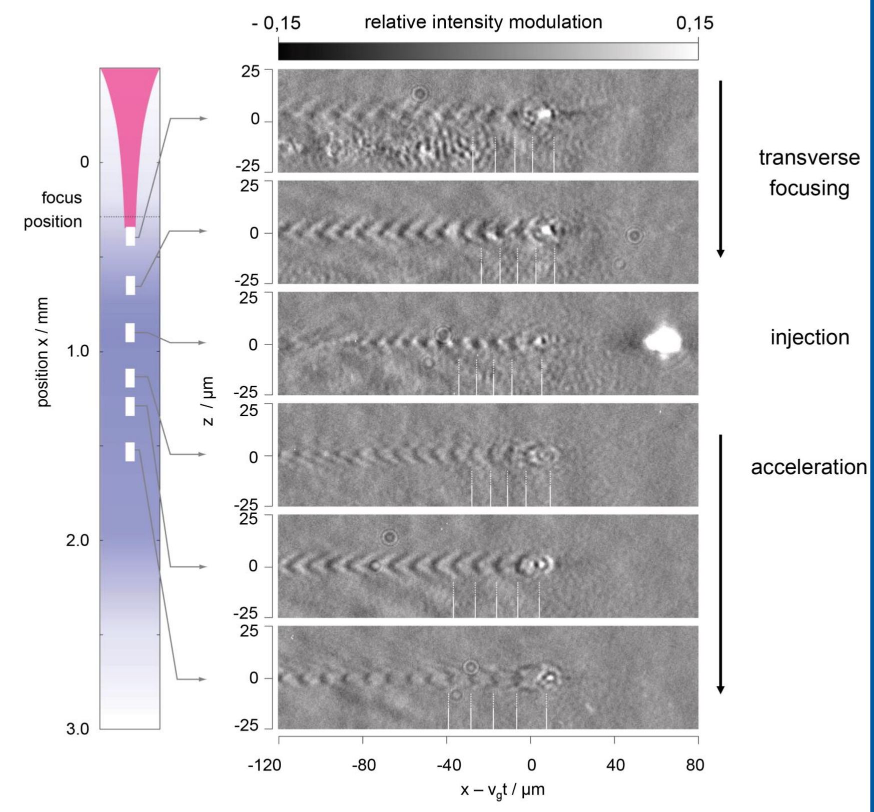
Ultrafast shadowgraphy of LWFA: previous results

- 3D PIC simulation of LWFA process including a few-cycle probe, imaging optics and detector [4]



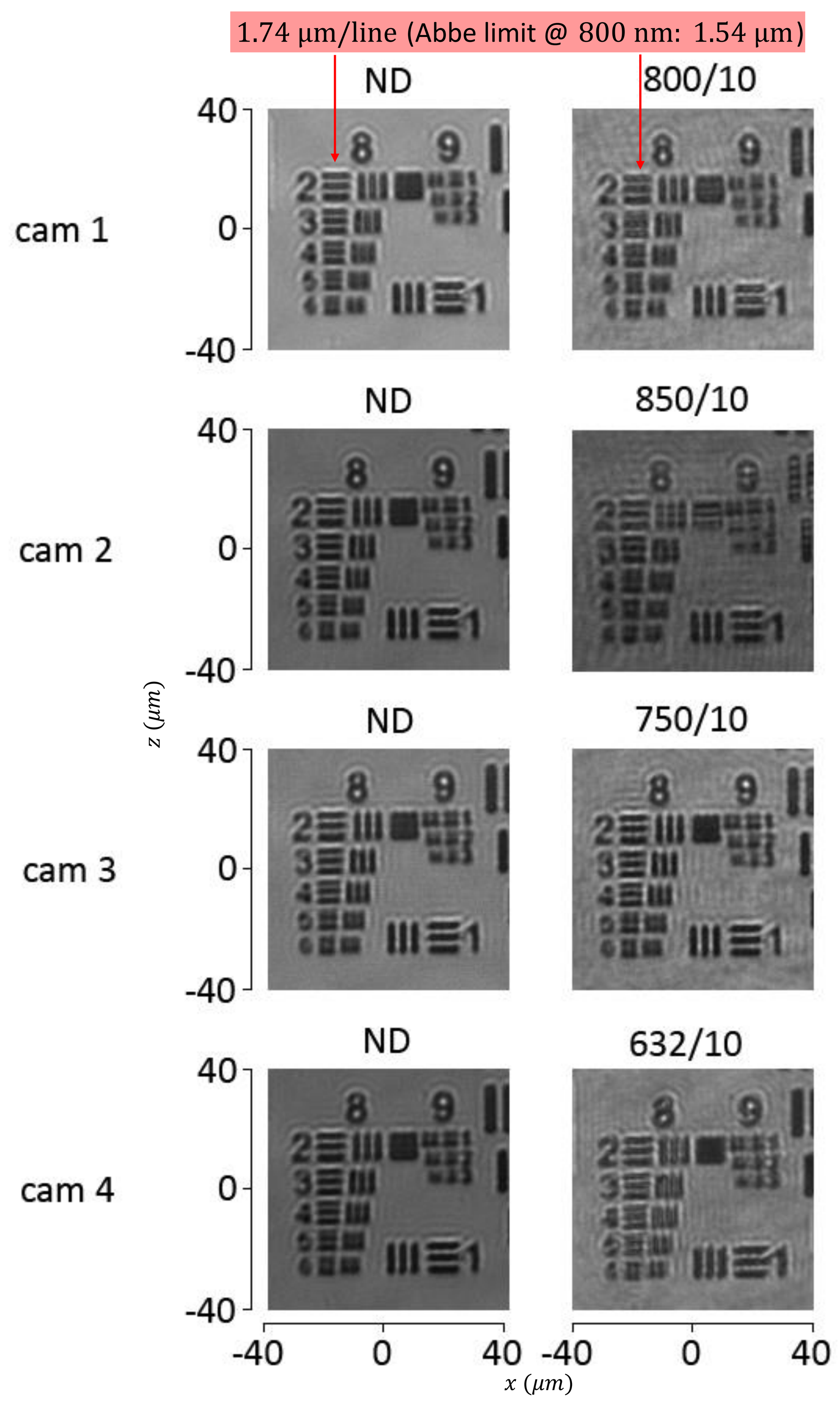
- Shadowgram is formed mostly in the center part.
- High plasma density gradients & short pulse duration → high contrast of the probe image

- Experimental shadowgrams at various positions in a He plasma: $n_e = 1.65 \times 10^{19}$ cm^{-3}, pump pulse $a_0 \approx 1.7$ [5]

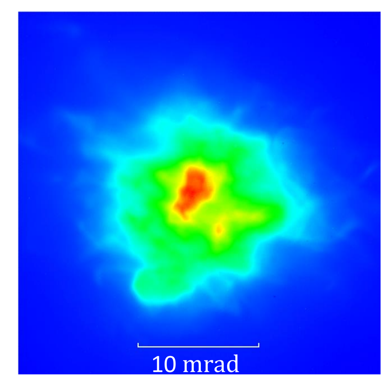


Preliminary results

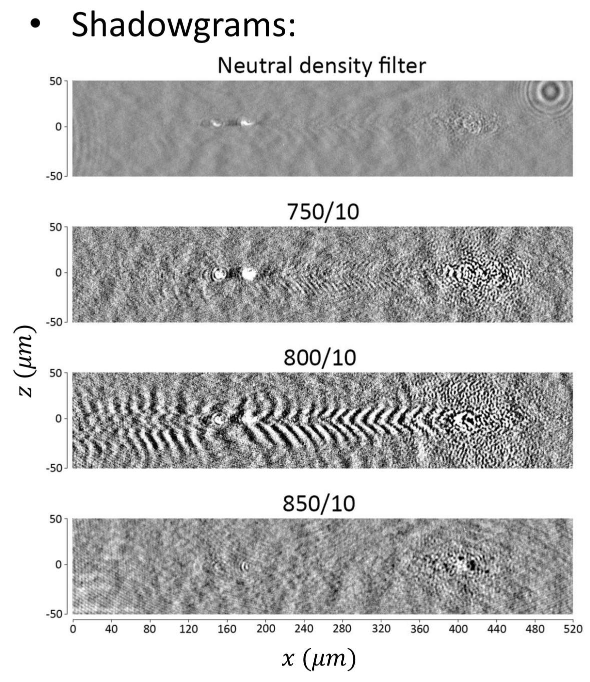
- Spatial resolution test of 4-cam (Mag.: 12.4 ×):



- Electron beam pointing:



  - Averaged over 30 shots
  - Plasma density: ~7×10^{18} cm^{-3}
- Shadowgrams:



- Temporal resolution only preserved @ 800 nm
- Possible reason: higher order spectral phase caused the temporal resolution loss
- Further optimization will be needed

Reference

[1] T. Tajima and J.M. Dawson, Phys. Rev. Lett. 43; 267 (1979)

[2] Félicie Albert et al., Plasma Phys. Control. Fusion 58 103001 (2016)

[3] M. B. Schwab et al., Appl. Phys. Lett. 103, 19118 (2013)

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[5] A. Sävert et al., Phys. Rev. Lett. 115, 055002 (2015)

[6] K.-H. Hong et al., Appl. Phys. B 74, S231 (2002)

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