Latest trends in Laser Wakefield Acceleration

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Contents

An ultrashort review (on order) of recent experimental results on Laser WakeField Acceleration (LWFA) - from the perspective of a reader/reviewer rather than of a specialist in the topic.
The focus is on the electron source and not on applications.

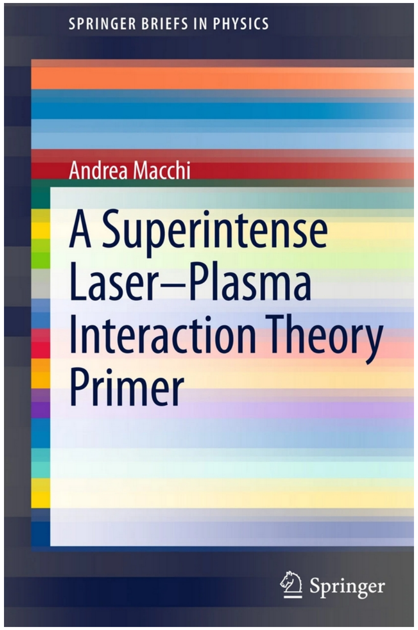
Disclaimer: The selection of papers is entirely based on a personal choice (and available time for preparation and presentation) without any claim to be exhaustive and really representative of the progress in the field and/or of the contributions of all groups active on LWFA.

Acknowledgment: Thanks to Carlo Benedetti (Lawrence Berkeley National Laboratory) for useful discussions

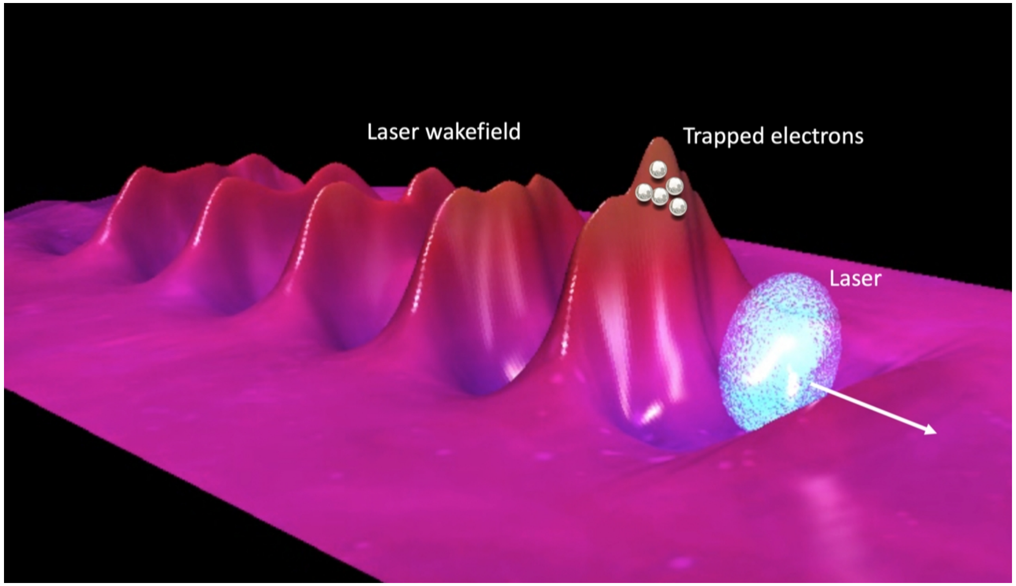
Laser Wakefield Acceleration

Electrons surfing plasma waves created in the wake of a laser pulse

For basic tutorials: AM, "Plasma waves in a different frame", Am. J. Phys. **88**, 723 (2020)



coming soon:
2^{nd} edition



Figures from:
- Daderot, Wikipedia, public domain
- T.Katsouleas, Nature **444** (2006) 688
- PRX, special collection on laser-plasma particle acceleration (2020)

From Cover to Cover (Twenty Years After)

← Nature **431**, n.7008 (2004)

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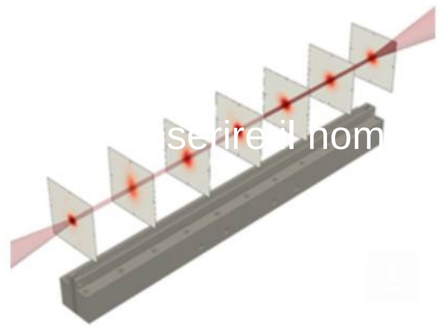


On the Cover

Frame-by-frame demonstration of optical guiding through a 30-cm-long laser-plasma accelerator. Selected for a Viewpoint in *Physics Magazine* and for an Editors' Suggestion, and featured in a podcast episode of *This is Physics*.

From the article

Matched Guiding and Controlled Injection in Dark-Current-Free, 10-GeV-Class, Channel-Guided Laser-Plasma Accelerators

A. Picksley, J. Stackhouse, C. Benedetti, K. Nakamura, H. E. Tsai, R. Li, B. Miao, J. E. Shrock, E. Rockafellow, H. M. Milchberg, C. B. Schroeder, J. van Tilborg, E. Esarey, C. G. R. Geddes, and A. J. Gonsalves

Phys. Rev. Lett. **133**, 255001 (2024)

PRL **133** n.125 (2024) →

(also covered in APS Physics and in Physics Today)

Near-10 GeV Electrons at LBNL

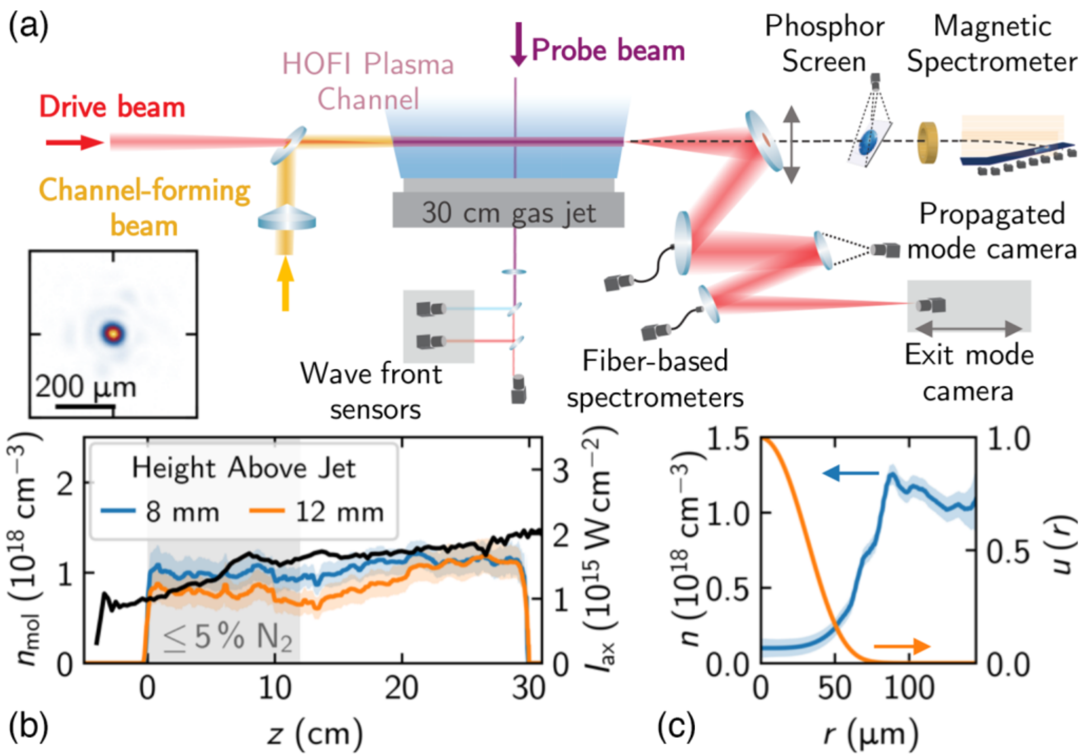
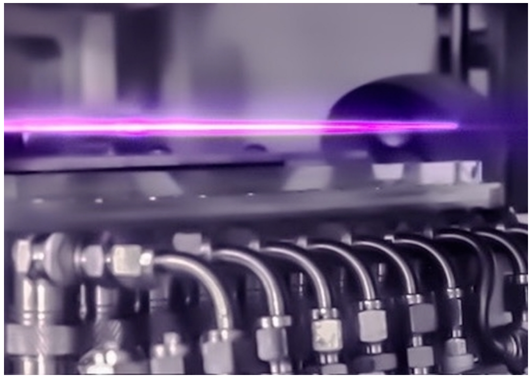


FIG. 1. (a) Schematic of the experimental setup. Inset: measured vacuum mode of the drive laser pulse. (b) Measured molecular density of the gas jet (blue and orange lines) and peak intensity of the channel-forming pulse along the length of the gas (black line). (c) Measured electron and neutral density $n = n_e + n_n$ of the HOFI plasma channel at $\Delta\tau = 6$ ns (blue) and calculated fundamental mode of the measured plasma channel (orange line).

A. Picksley et al,
PRL **133**, 255001 (2024)

- Matched guiding in a preformed density channel
- Localized ionization injection

BELLA laser, 21 J, 40 fs, w_0=53 μm , a_0=2.2



Near-10 GeV Electrons at LBNL

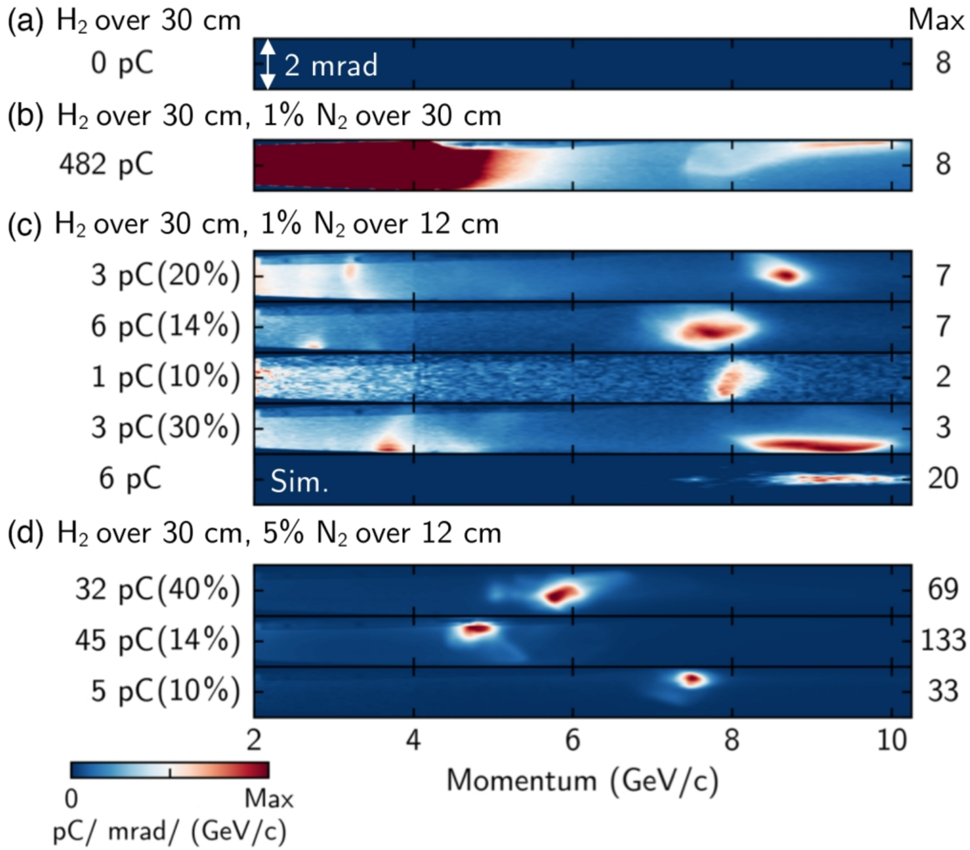
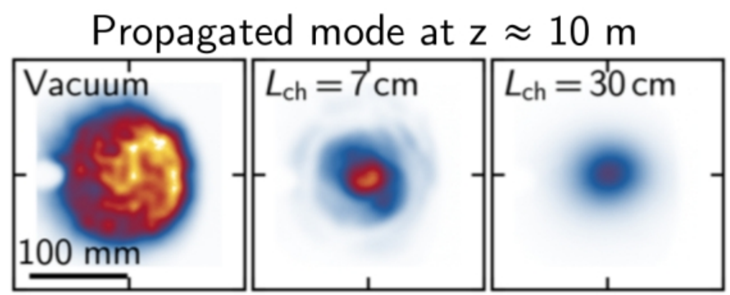


FIG. 4. Example electron beams generated in 30-cm-long HOFI channels with $\mathcal{E}_0 = (21.3 \pm 0.3)$ J. For each row, the charge measured by the spectrometer within the quasimonoenergetic bunch and percent captured by the spectrometer is given. (a) $\Delta\tau = 6$ ns, no nitrogen, (b) $\Delta\tau = 7$ ns, 1% nitrogen, $L_{dop} \approx 30$ cm, (c) $\Delta\tau = 5$ ns, 1% nitrogen, $L_{dop} \approx 12$ cm, (d) $\Delta\tau = 6$ ns, 5% nitrogen, $L_{dop} \approx 12$ cm.

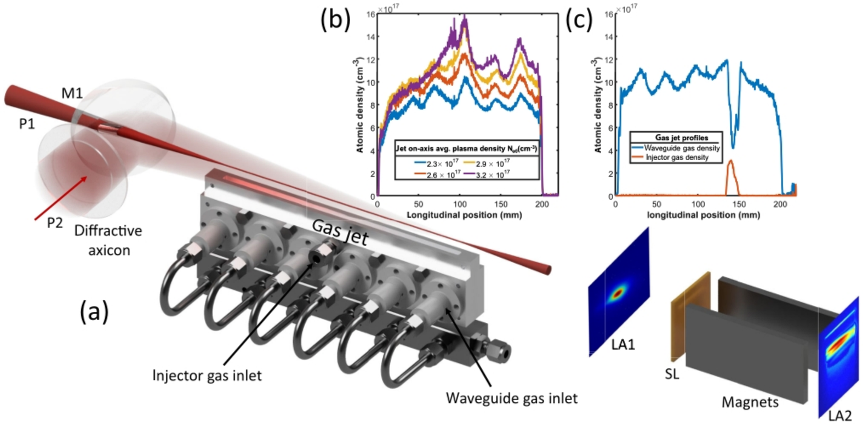
A. Picksley et al,
PRL **133**, 255001 (2024)

- Undesired high order modes are filtered along the density channel



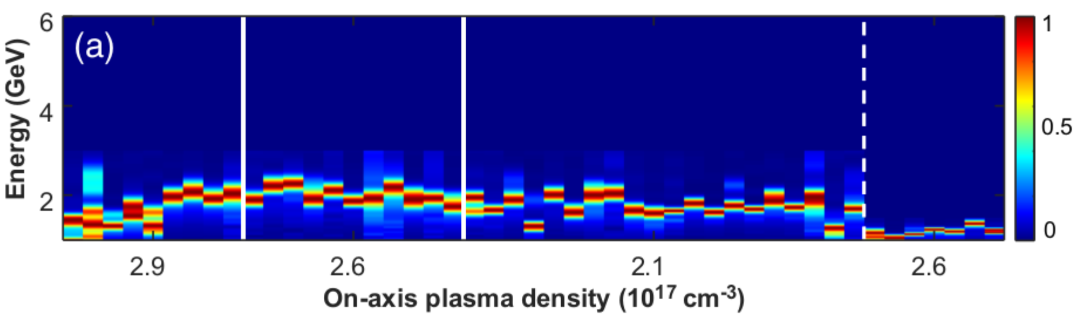
- Shot stability affected by laser pointing
- No electron beam without injection

Guiding + Ionization Injection: Best LWFA Recipe?

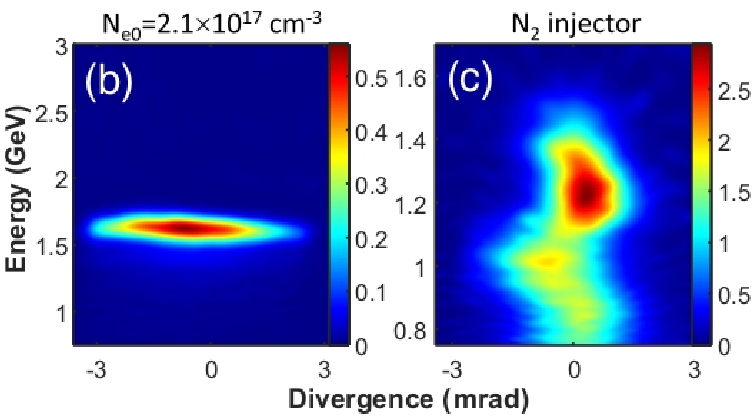


A. Shrock et al,
PRL **133**, 045002 (2024)

- "New nonlinear propagation regime" in preformed plasma channels
- Study of modulated vs localized injection

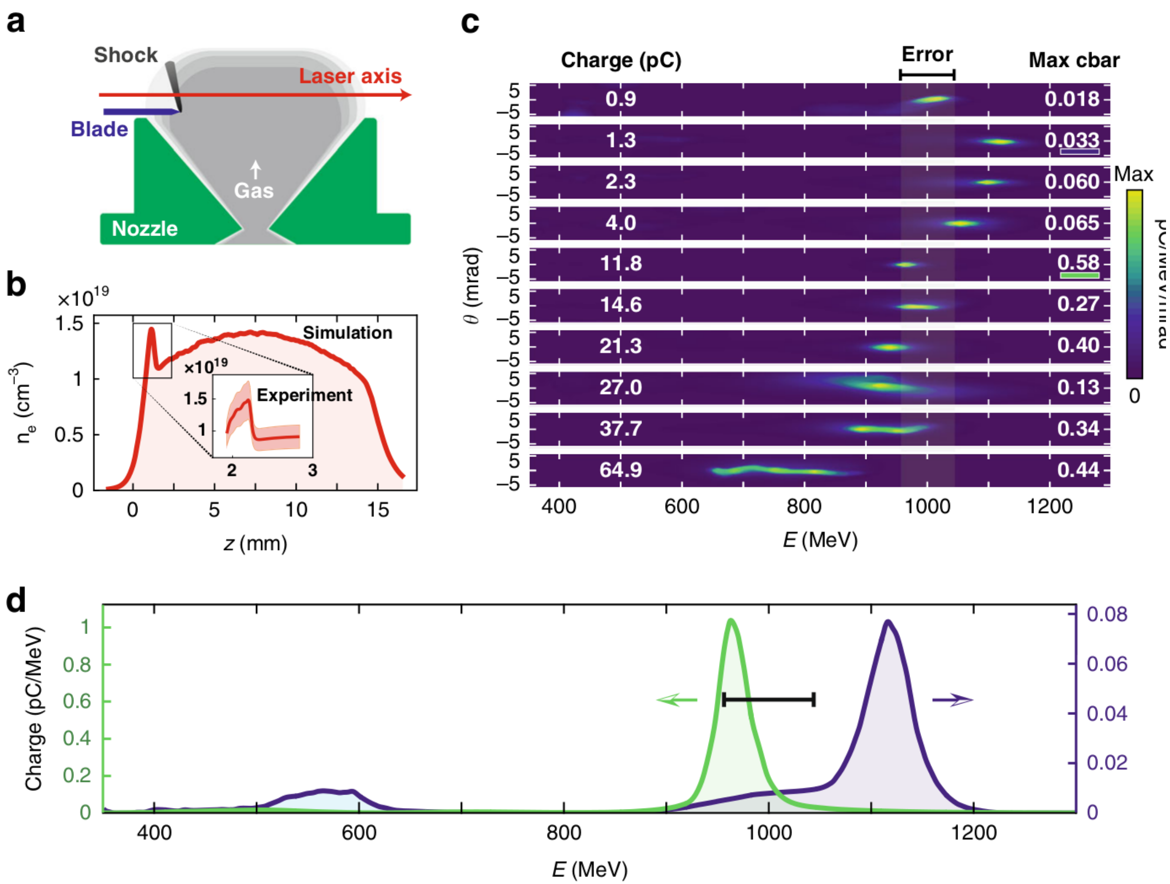


Narrow spectral peaks up to ~2.5 GeV energy



ALEPH laser, Colorado State University
10-15 J, 45-65 fs, w_0=30 μm , a_0=1.5-2

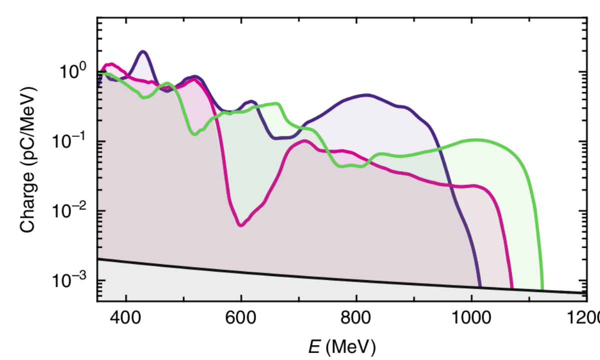
Guiding + Density Transition Injection



K. Oubrerie et al, Light: Science & Applic. **11**, 180 (2022)

- Density transition in channel (produced by an hydrodynamic shock) yields peak at ~1.1 GeV

- Ionization injection produced broad spectra



LOA laser, Colorado State University

1.7 J, 30 fs, w_0=13.5 μm , a_0=3

~10 GeV Electrons at Texas University

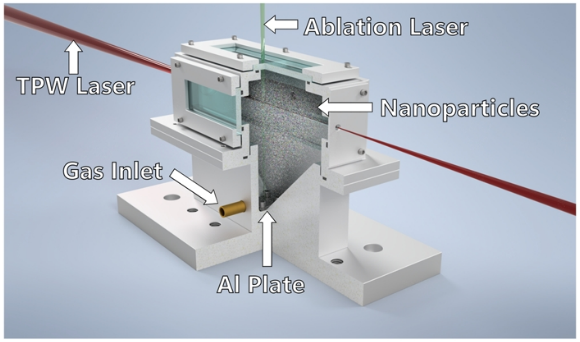
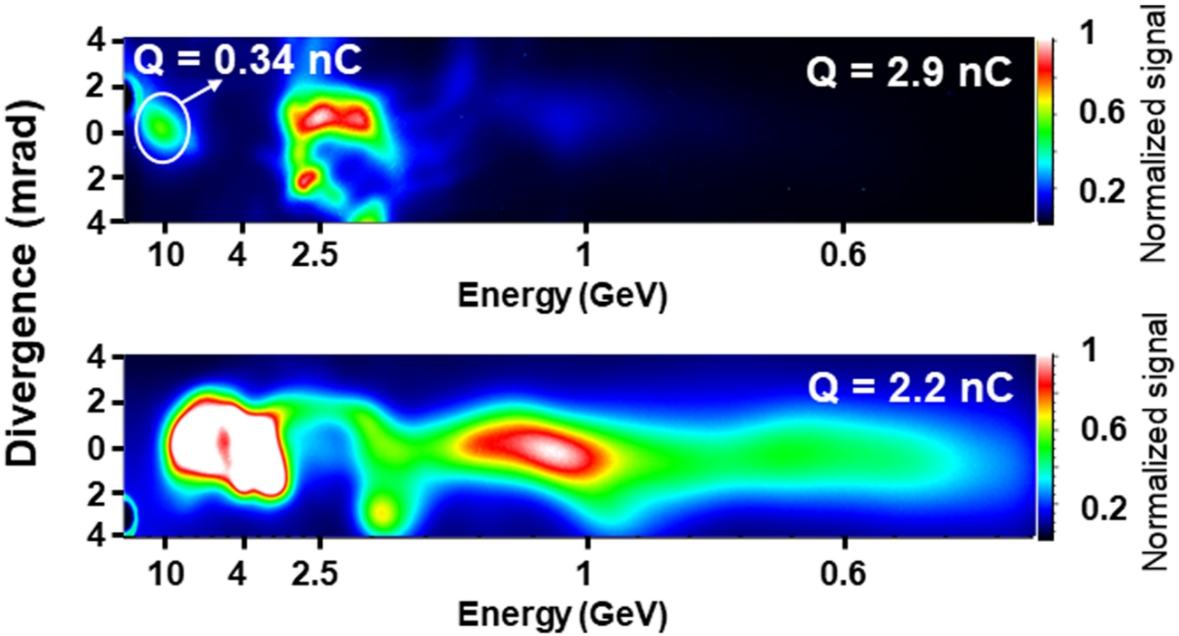


FIG. 2. A drawing of the gas cell. A 532-nm laser is focused through the top window onto the surface of a metal plate and generates the nanoparticles through laser ablation. The nanoparticles mix with the helium gas and fill the volume of the gas cell uniformly. The Texas Petawatt Laser enters the gas cell through a 3-mm-diameter pinhole and generates electrons that exit the gas cell through another 3-mm pinhole.

C. Aniculaesei et al, Matter Radiat. Extremes **9**, 014001 (2024)

- gas target with addition of Al nanoparticles



Texas Petawatt laser, 130 J, 135 fs, w_0=55 μm , a_0=2.9

FIG. 8. Electron energy spectra of the two most energetic shots recorded by DRZ2. The energy spectra were recorded simultaneously on two consecutive screens to correct any off-axis electron beam pointing. The top spectrum shows a high energy bunch with the centroid at 10.4 ± 1.93 GeV, a 3.4 GeV rms energy spread, a 340 pC electric charge (2.9 nC total charge), and a 0.9 mrad rms divergence. The bottom energy spectrum shows a 4.9 ± 0.39 GeV centroid electron bunch with a tail energy that extends beyond 10.4 GeV and has a 2.2 nC total charge with a 1.4 mrad rms divergence. The energy spread from the electron beam divergence has not been deconvolved, and its value could be lower than estimated.

~10 GeV Electrons at Texas University

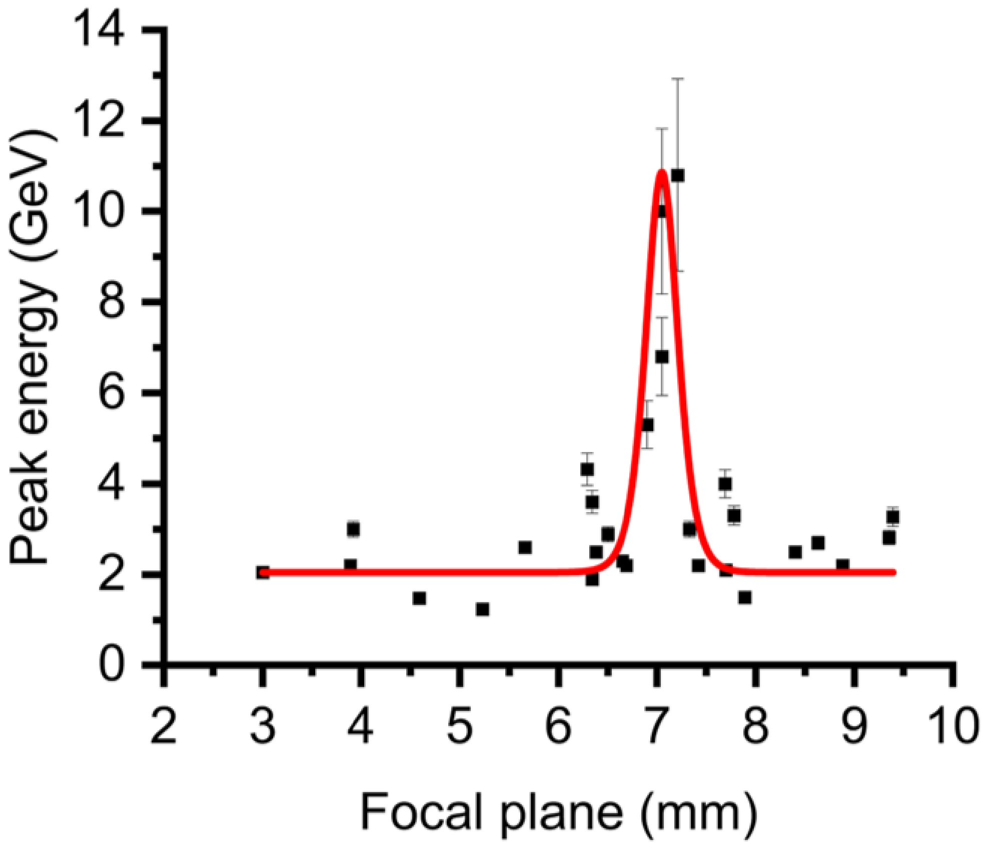


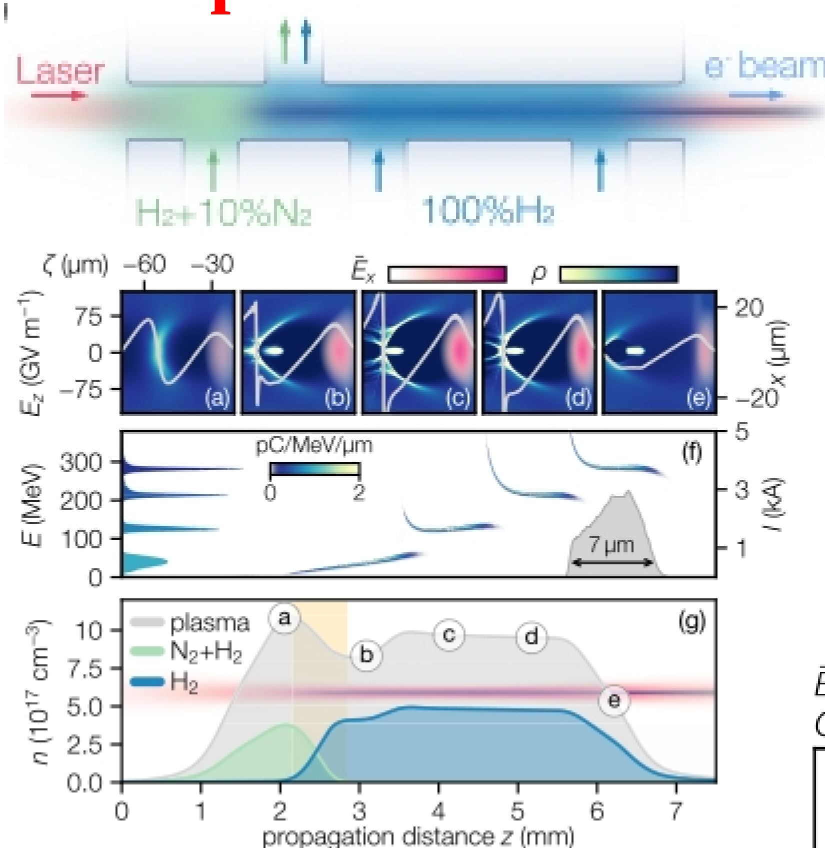
FIG. 11. The dependence of the maximum (or cut-off) electron energy on the position of the laser focal plane in the gas cell. It can be observed that all the shots with electron energies above 3.5 GeV are grouped around 7 ± 1 mm. The red curve is drawn to guide the eye, and the entrance pinhole is at 0 mm where the laser with a vacuum Rayleigh length of ~1.5 cm is focused.

C. Aniculaesei et al, Matter Radiat. Extremes **9**, 014001 (2024)

- gas target with addition of Al nanoparticles

Texas Petawatt laser, 130 J, 135 fs, w_0=55 μm , a_0=2.9

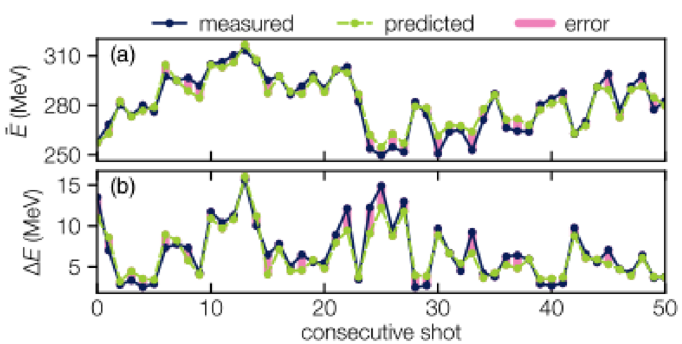
Optimization of Beam Loading

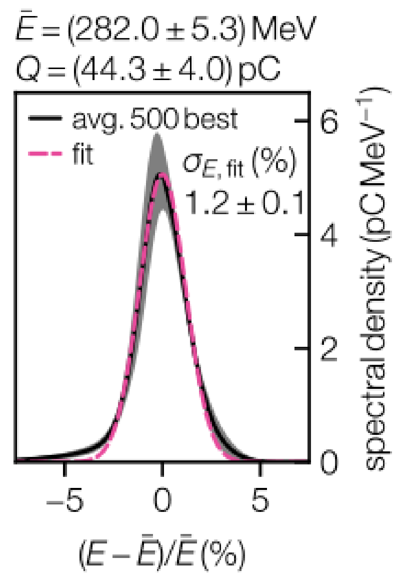


M. Kirchen et al,
PRL **126**, 174801 (2021)

ANGUS laser at DESY, 2.6 J, 34 fs, w_0=25 μm , a_0=2.1

Controlled Beam loading flattens accelerating fields to reduce energy spread

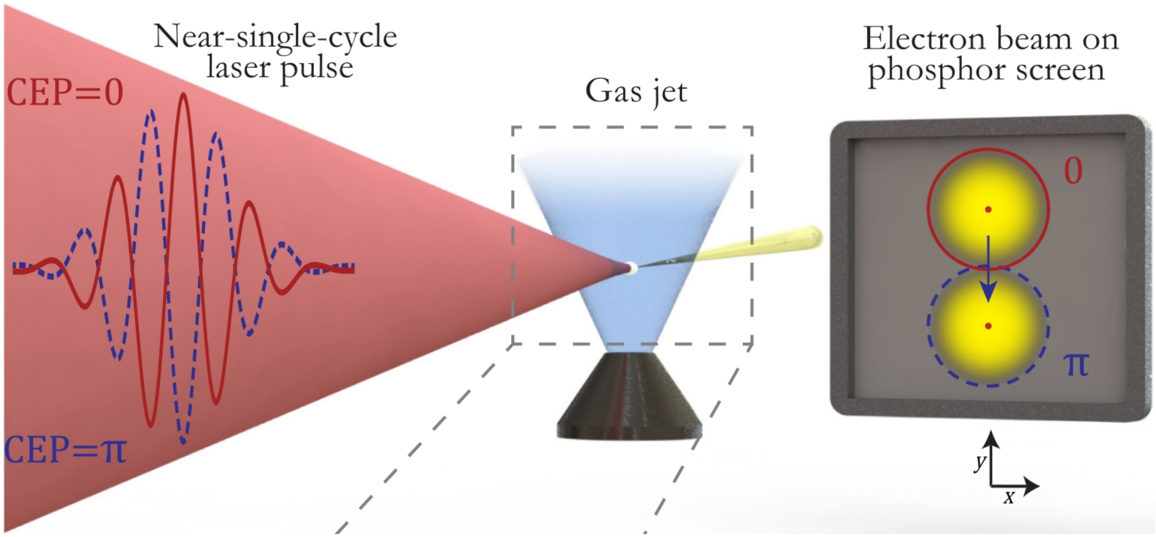


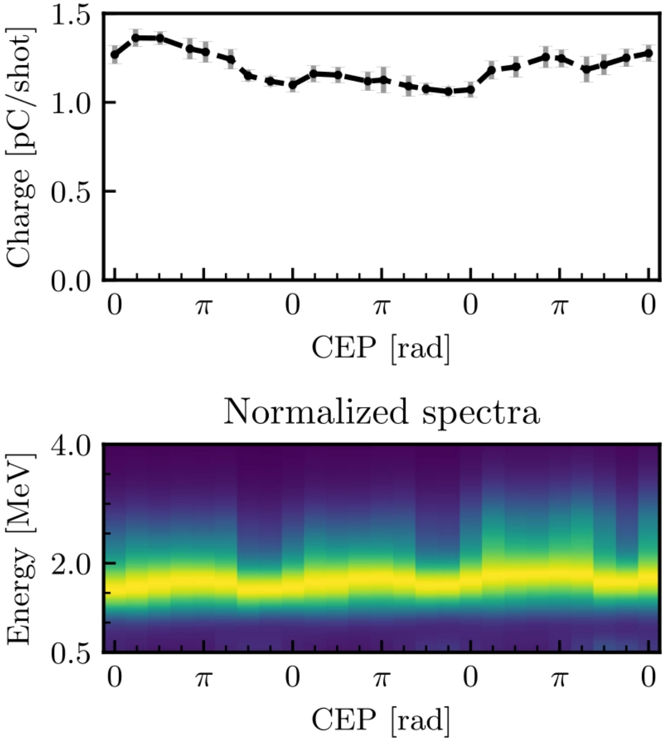


Plasma stability enables to train a neural network for beam quality prediction
(see also S. Jalas et al, PRL **126**, 104801 (2021) - same laser & group)

High Rate LWFA with Few-Cycle Pulses

- Carrier-envelope phase (CEP) affects pointing, energy and charge





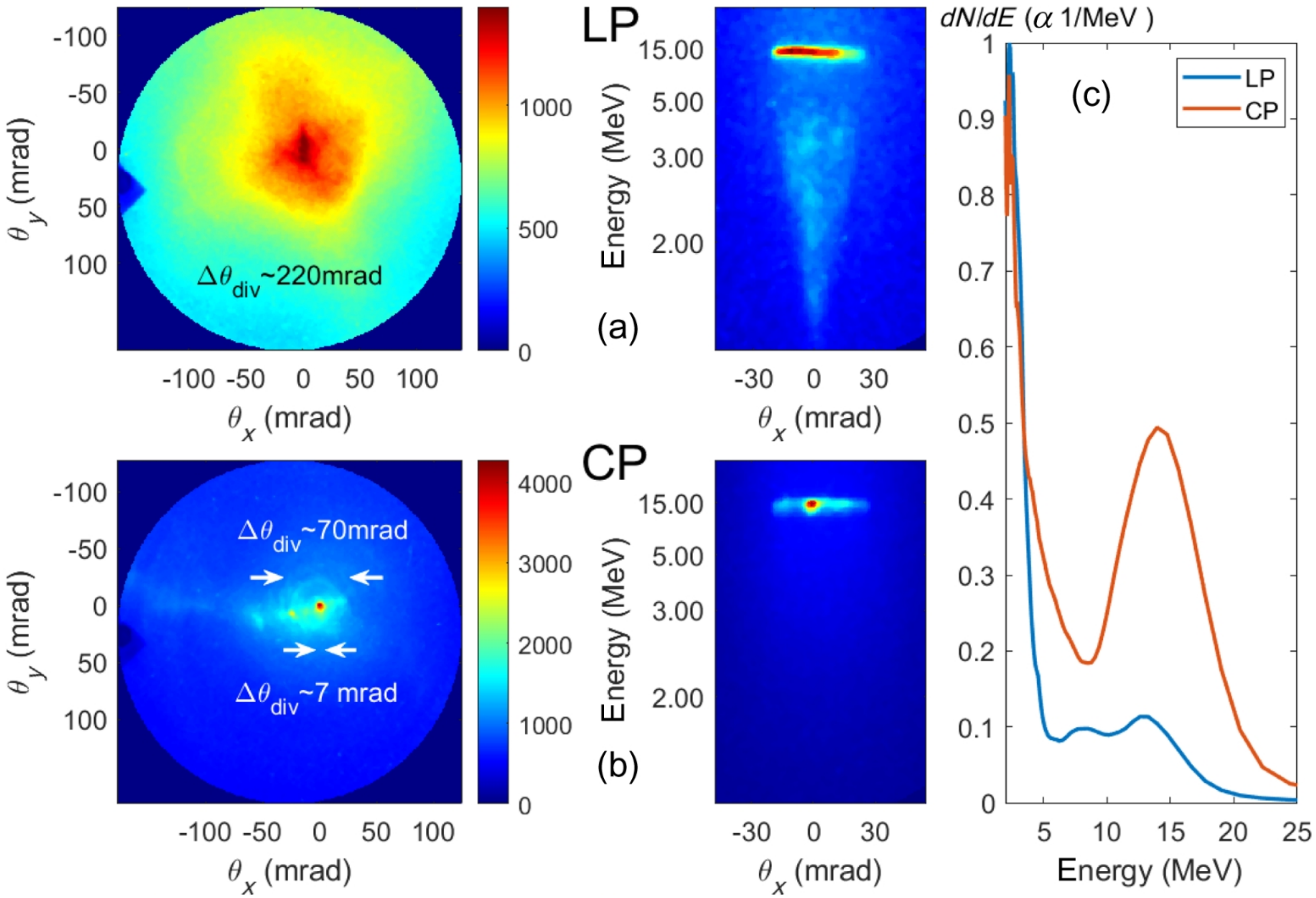
LOA, France

few cycle pulse at 1 kHz operation rate:
2.5 mJ, 3.5 fs, w_0=2.7 μm , a_0=1.5

J. Huijts et al, PRX **12**, 011036 (2022)

High Rate LWFA with Few-Cycle Pulses

- CEP effect reduction by using circular polarization
- Injection by density downramp



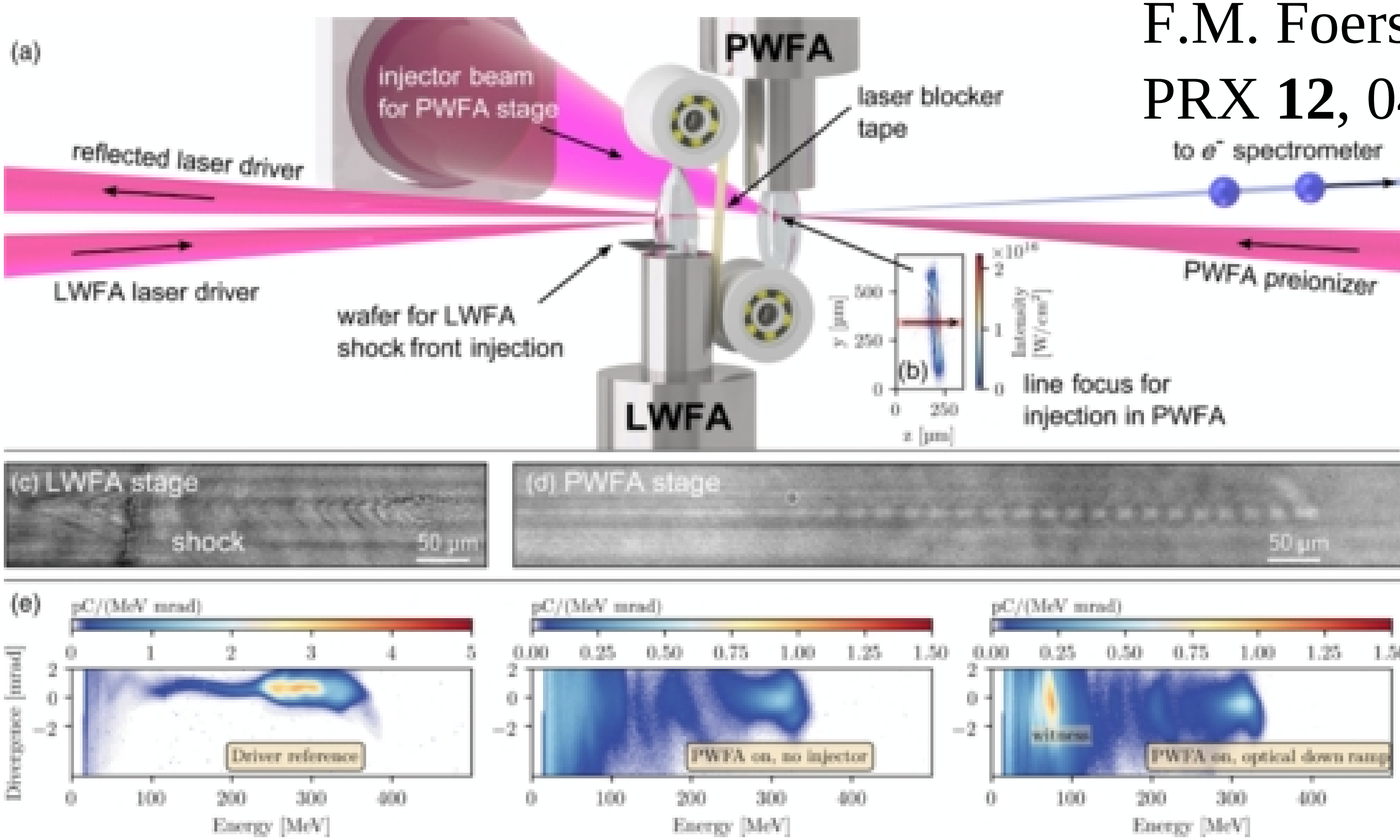
F. Salehi et al, PRX **11**, 021055 (2021)

LILMI, University of Maryland

few cycle pulse: 2.6 mJ, 5 fs, w_0=4.5 μm , a_0=0.9

Hybrid Laser/Plasma Wakefield Acceleration

F.M. Foerster et al,
PRX **12**, 041016 (2022)



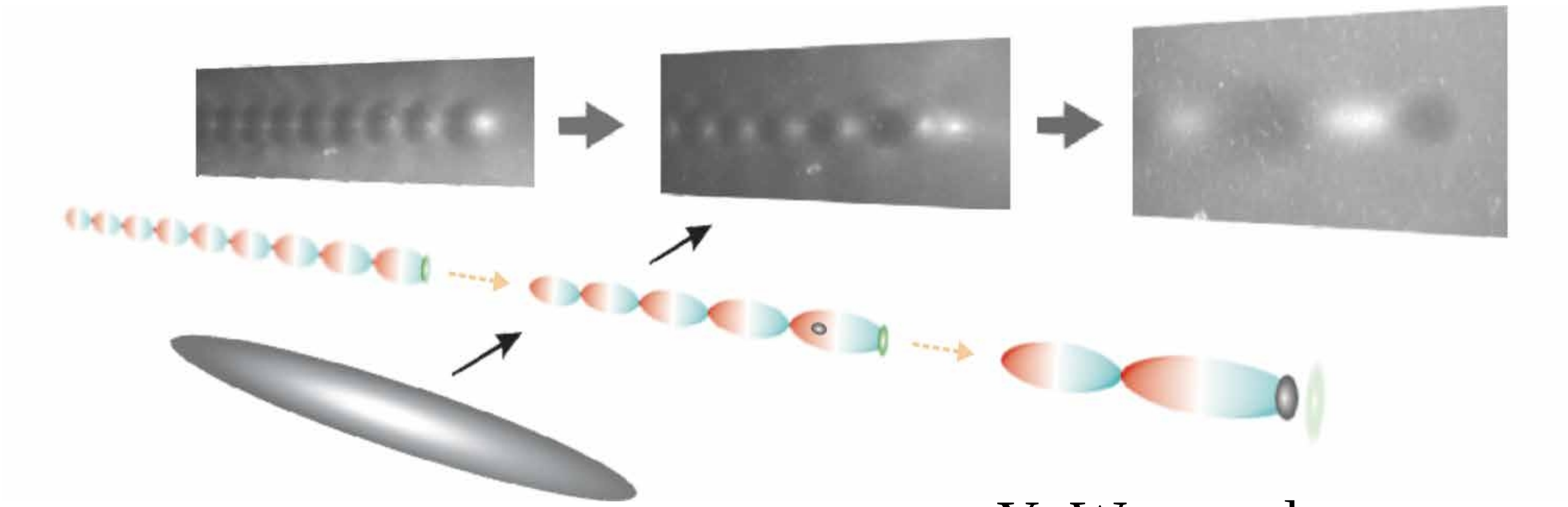
(also covered
in APS Physics)

Sequential LWFA and PWFA to enhance beam quality

~10% efficiency from LWFA to PWFA stage

ATLAS laser at CALA Garching, 5 J, 30 fs, a_0=2.5

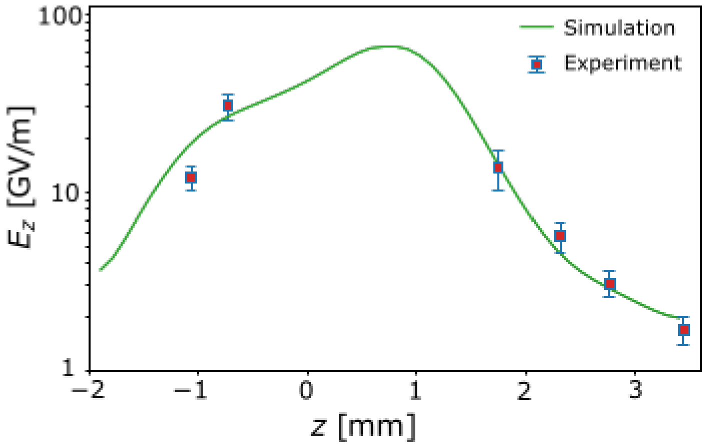
Visualizing the Wakefield in Real Time



Y. Wan et al,
Sci. Adv. **10**, eadj3595 (2024)

- Transverse probing of the wakefield with a femtosecond electron bunch from a "twin" LWFA
(estimated bunch duration: 2 fs)

HIGGINS laser at Weizmann Inst.



Comments: Still Looking for the Perfect Wave?

- Remarkable success (LBNL experiment) in putting together at work elements which have been tested independently before (laser guiding, ionization injection, ...)
- High level of control over plasma profile and injection
- Laser source development necessary for both better stability/reproducibility and for going beyond 10 GeV
e.g. k-Bella at LBNL
(multiple staging necessary for TeV energies)
- Still new ideas (e.g. hybrid laser-plasma wakefield) are proposed and tested ...
- Real-time visualization and machine learning-aided feedback improve beam control and help the understanding of the physics (and will contribute to the extinction of laser-plasma theorists ...)

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