Experimental Progress of PWFA in a Laser-Ionized Plasma Source FACET-II

EAAC 2025

Sep. 24, 2025

Elba, Italy

Authors: Michael Litos (speaker, CU Boulder),
Valentina Lee (CU Boulder), Robert Ariniello (SLAC Nat'l Lab)

On behalf of E-301 and E-333 collaborations

Co-Authors

University of Colorado Boulder

Alexander Knetsch (SLAC National Accelerator Laboratory) Brendan O'Shea (SLAC National Accelerator Laboratory) Chandrashekhar Joshi (UCLA) Dr Chaojie Zhang (University of California Los Angeles) Christine Clarke (SLAC National Accelerator Laboratory) Dr Christopher Doss (Lawrence Berkeley National Laboratory) Ms Claire Hansel (University of Colorado Boulder) Claudio Emma (SLAC National Accelerator Laboratory) Doug Storey (SLAC National Accelerator Laboratory) Ms Elena Ros (University of Colorado Boulder) Elias Gerstmayr (Queen's University Belfast) Erik Adli (University of Oslo, Norway) Fei Li (Tsinghua University) Jiawei Cao (UiO) Dr Kenneth Marsh (University of California Los Angeles) Mark Hogan (SLAC National Accelerator Laboratory) Nathan Majernik (SLAC National Accelerator Laboratory) Pablo San Miguel (Ecole Polytechnique) Prof. Sebastien Corde (Laboratoire d'Optique Appliquée) Mr Shutang Meng (University of Colorado Boulder) Spencer Gessner (SLAC) Thamine Dalichaouch (University of California Los Angeles) Viktoriia Zakharova Warren Mori (Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA) Weiming An (Beijing Normal University)

(Apologies if incomplete!)

Research Funding and Facility Credit

University of Colorado Boulder

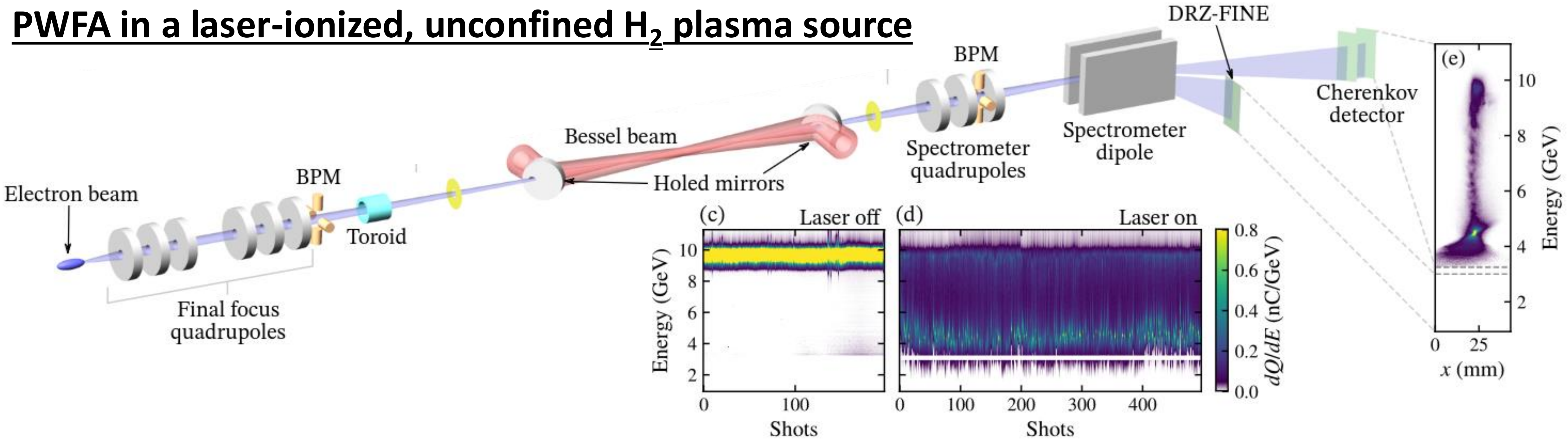
U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC001796.

This research used resources of the Facility for Advanced Accelerator Experimental Tests II (FACET-II), which is a DOE Office of Science User Facility.

E-301 Experiment at FACET-II

University of Colorado Boulder

PWFA in a laser-ionized, unconfined H_2 plasma source



Unique features:

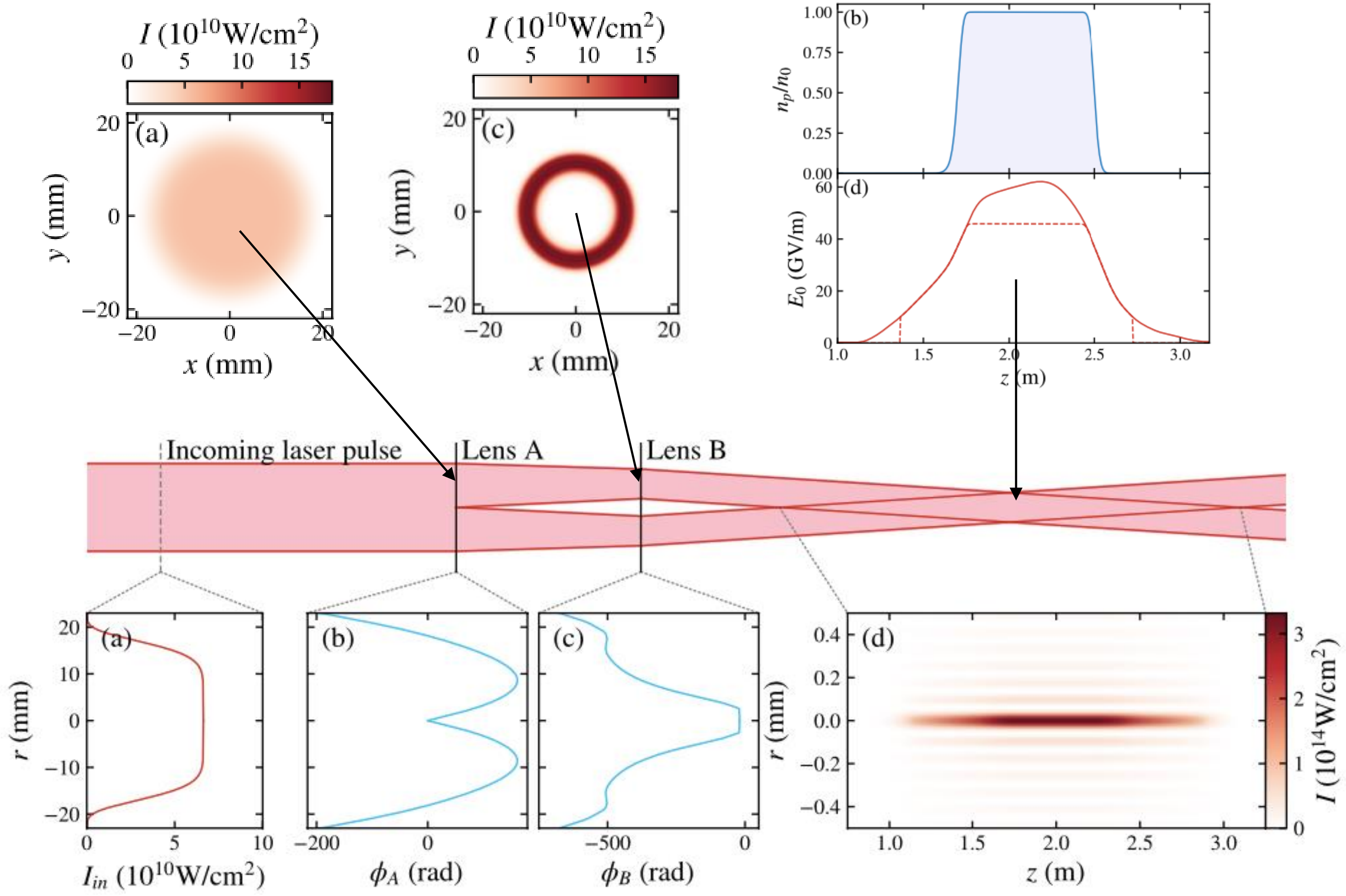
- Semi-arbitrary density profile controlled by laser focusing
- Rapid tunability of plasma density and length
- Permits localized gas jets of different species along main filament
- Highly accessible to diagnostics

Science Goals:

- Optimal performance PWFA stage at 10 GeV scale
  - High energy gain, efficiency, and low energy spread
  - Full charge transmission and emittance preservation
- Platform for other experiments
  - High brightness beam injection (E304, E307, E31X)
  - Narrow channel electron and positron PWFA (E333)
  - Ion channel laser (E306)

Tandem Lens Focusing of Ionization Laser

University of Colorado Boulder



A pair of diffractive optics acts in tandem to shape the laser intensity profile.

Lens A controls initial intensity profile at Lens B.

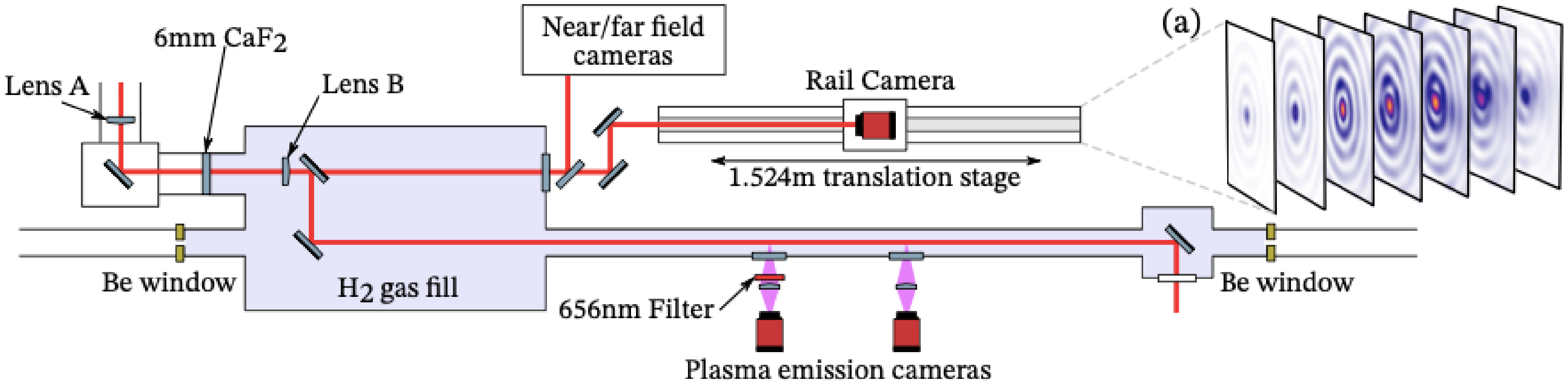
Lens B produces axicon-like Bessel focusing.

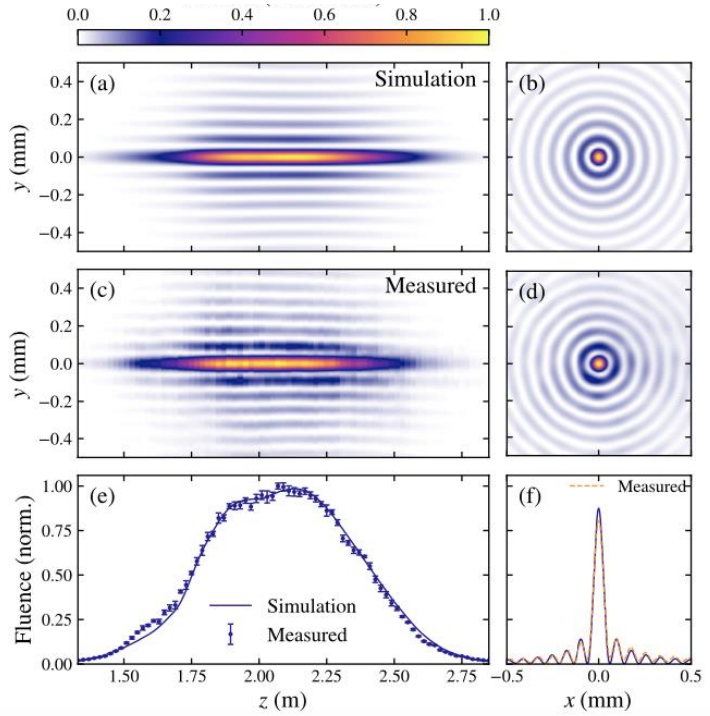
Shape of donut profile at Lens B determines axial intensity profile downstream.

Plasma refraction helps to broaden plasma filament.

R. Ariniello, V. Lee, M. Litos, "Demonstration of a tandem lens for producing shaped laser-ionized plasmas for plasma wakefield acceleration", arXiv:2509.01747 (2025)

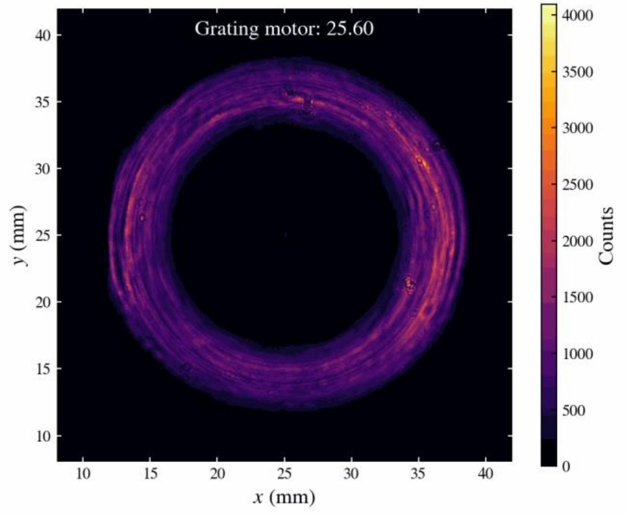
Axial Intensity Profile



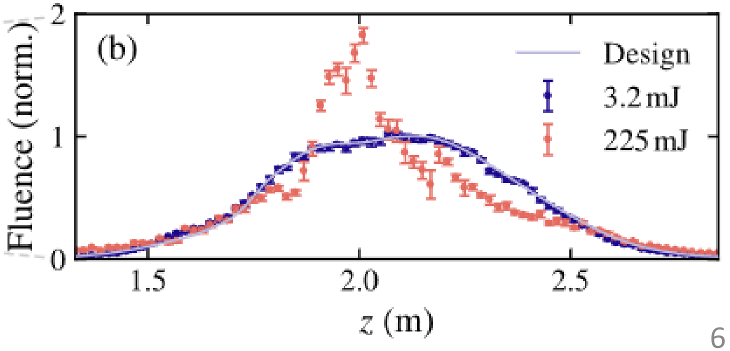


Left: At low intensity, laser profile matches prediction with excellent accuracy.

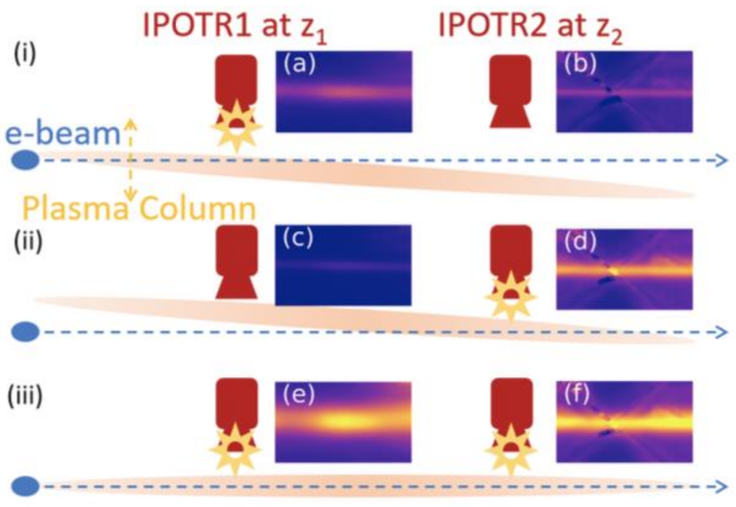
Right: At high intensity, nonlinear effects in a window between Lens A and Lens B produce aberrations in the wave front leading to distortion of the axial intensity profile.

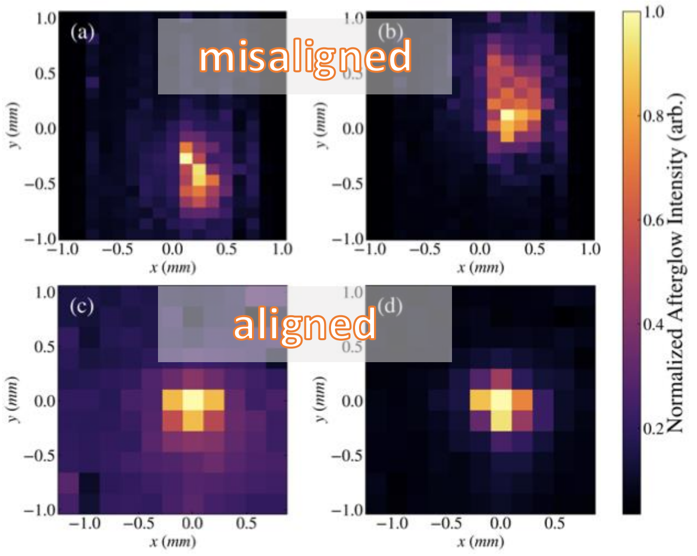


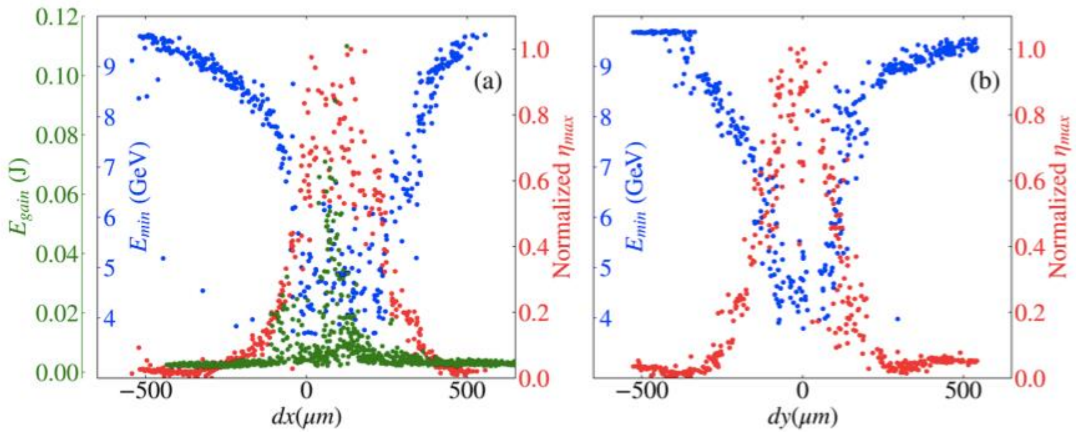
~85 cm x 250 µm, 4x10^{16} cm^{-3} plasma filament.
Not ideal, but useable.
Window has been removed for upcoming run.



Alignment of Plasma Source to e-Beam







A method was developed for rapid alignment of plasma source to e-beam.

Initial coarse alignment achieved using OTR foils.

Fine alignment achieved using plasma glow after interaction with e-beam. Brighter light = better alignment.

Measurement of drive and witness beam interaction confirmed simple geometric alignment constraint:

$$\Delta r + L\sin(\Delta\theta) \leq 2(R_p - R_b)$$

Δr: radial offset, Δθ: angular offset
L: length of plasma, R_p: radius of plasma, R_b radius of blowout

V. Lee, et al., "Precision alignment and tolerance of a plasma wakefield accelerator in a laser-ionized plasma source", arXiv:2508.16864 (2025)

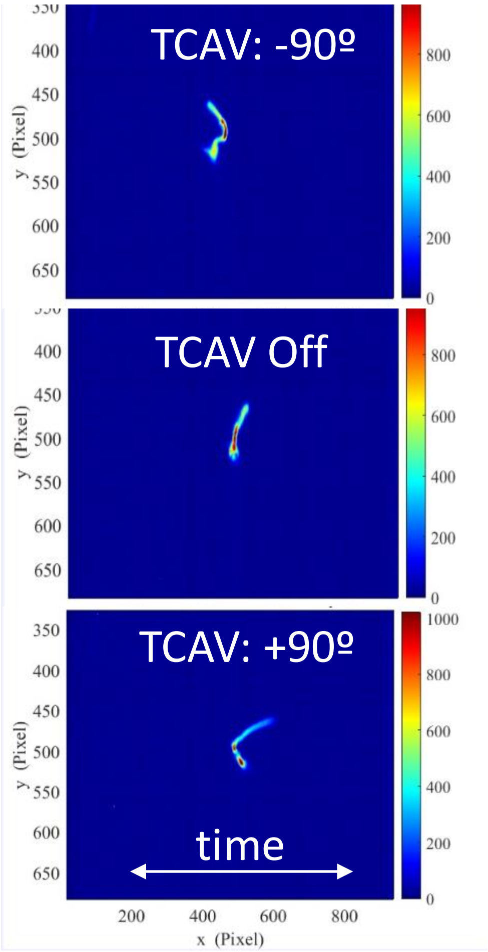
Plasma Interaction Optimization Process

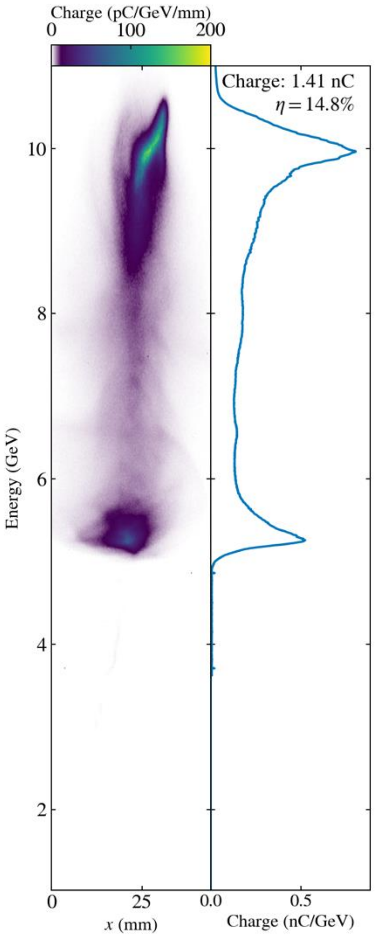
Step 1: Overlap drive and witness in time – both will lose energy driving wake

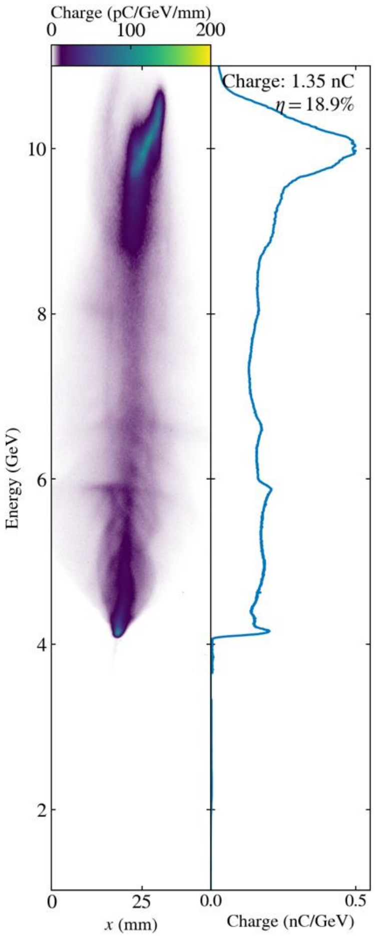
Step 2: Send into plasma and observe energy loss

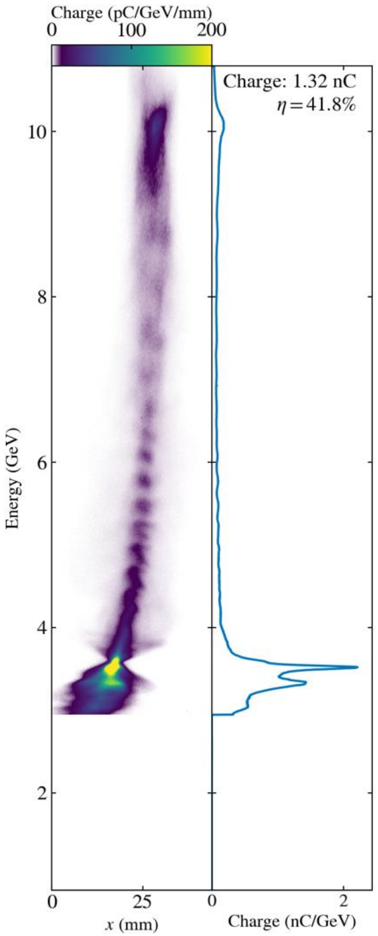
Step 3: optimize longitudinal waist location

Step 4: Optimize sextupole tuning to minimize dispersion









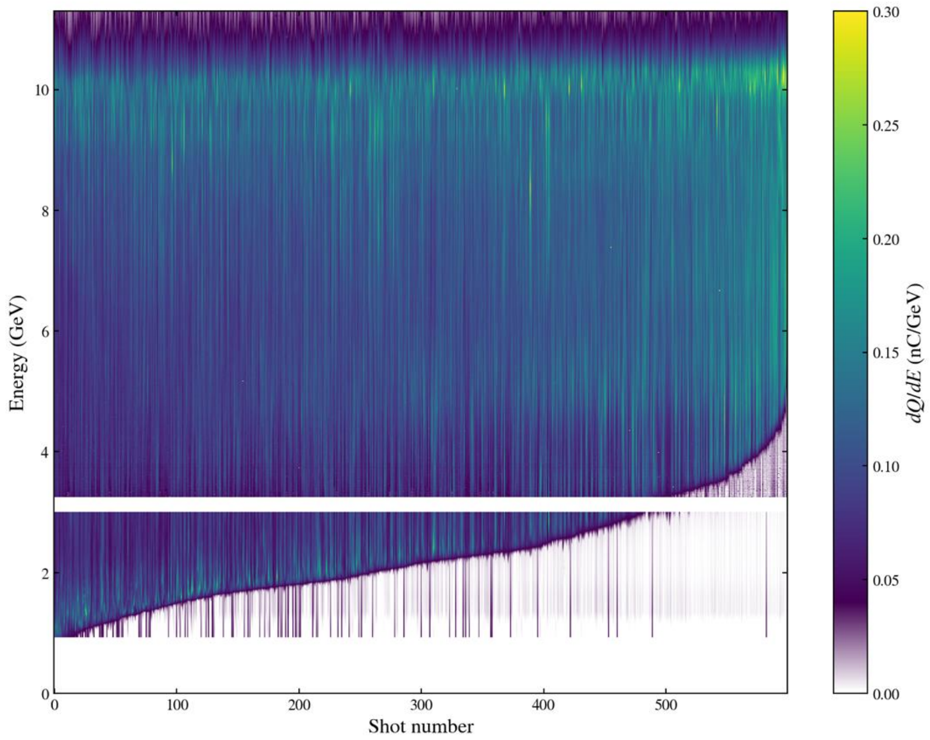
Drive Bunch Depletion and High Efficiency

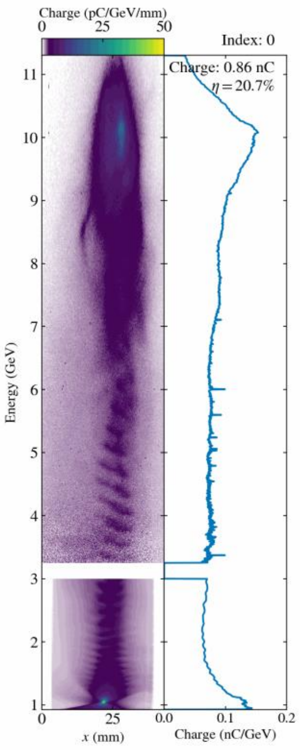
Drive Beam Depletion

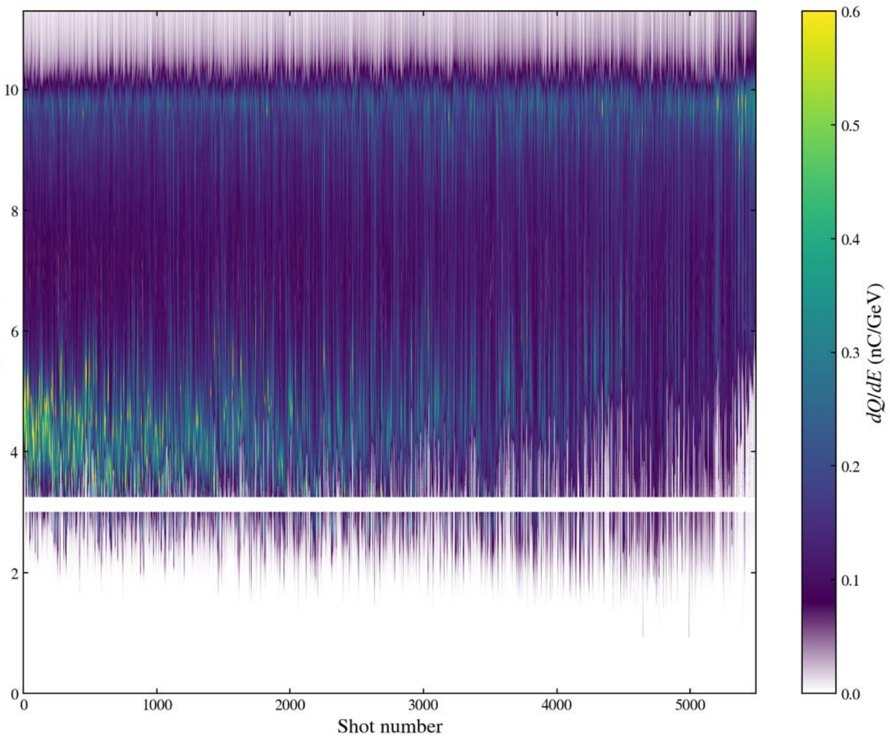
- Spectrometer was set to image charge at ≤1 GeV
- Many shots show deceleration below 1 GeV
- In this data, >200 pC did not participate strongly in the beam-plasma interaction.

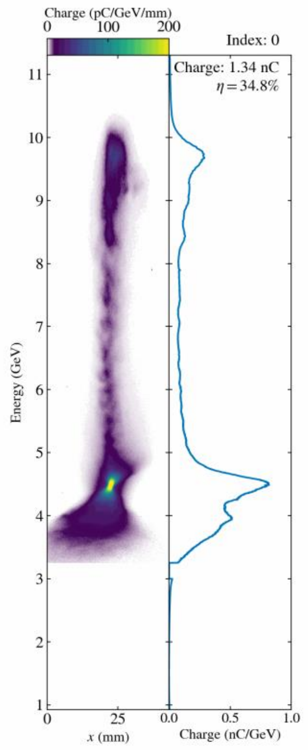
High Drive-to-Wake Efficiency

- Spectrometer set to image charge at 3.5 GeV
- >30% of drive beam energy transferred plasma wake
- Best shot achieving 37% → 5.6 Joules of energy deposited in the plasma.







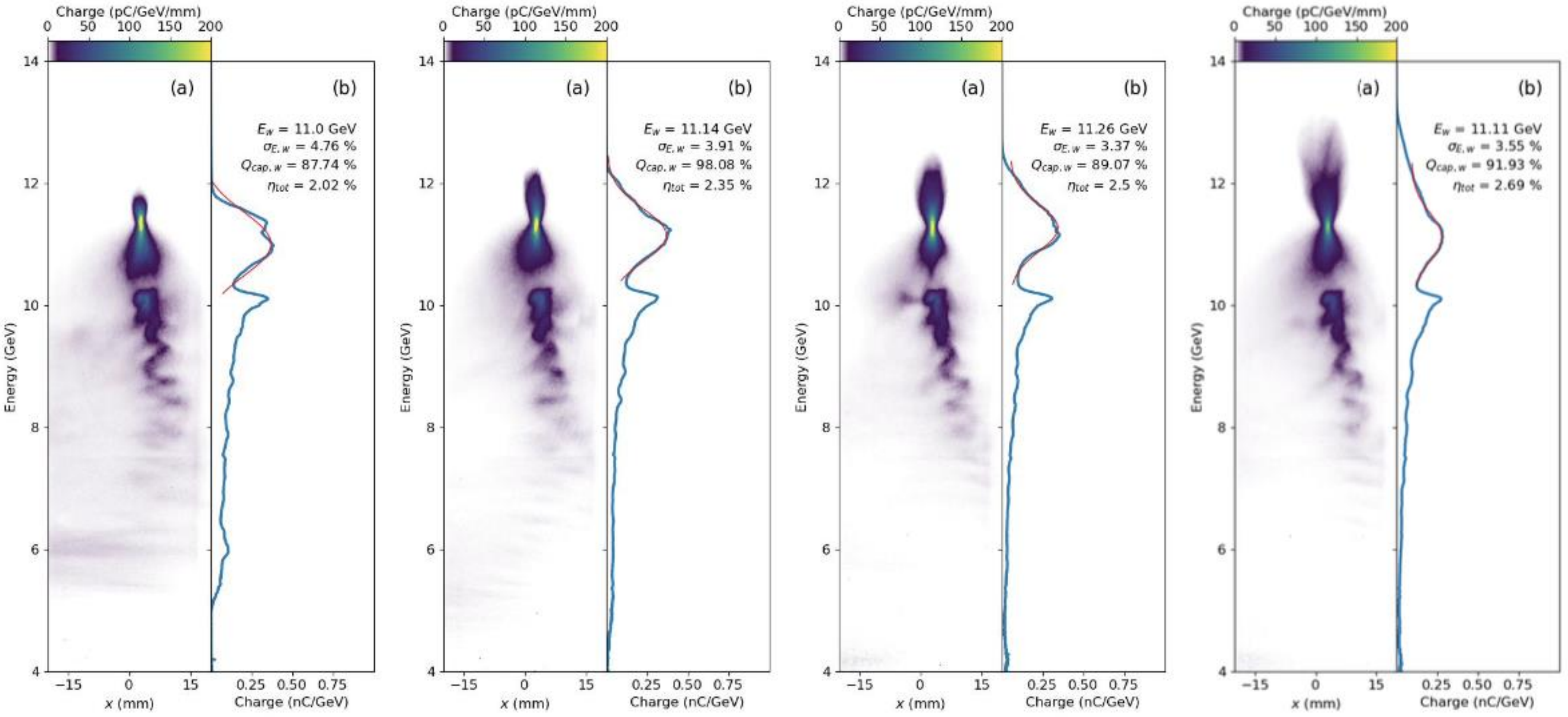


High Charge Capture and Transmission

98% charge capture

Total Charge Capture

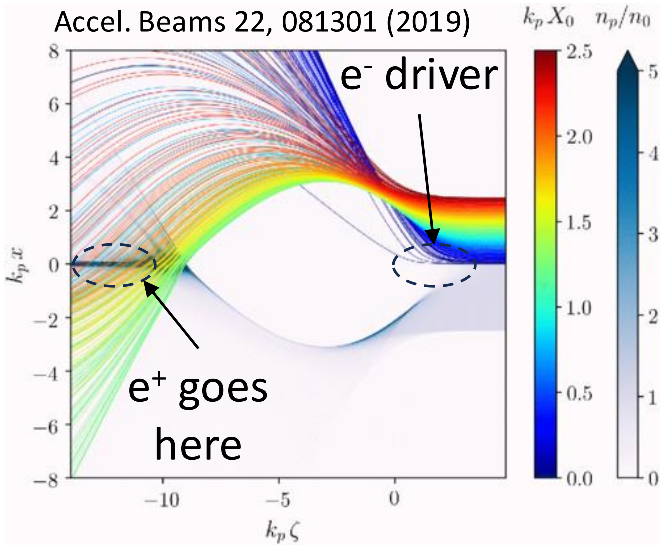
- Two-bunch data from FACET-II
- ~1 GeV gain, ~3.5% spread
- >90% charge capture of the witness bunch with multi-GeV energy gain
- ~2.5% total efficiency: energy gained / init. drive energy
- High charge capture enabled by long plasma density ramps
- At start of ramp, density is low, and wake bubble is large
- Density then increases adiabatically, gradually focusing down beam with wake bubble

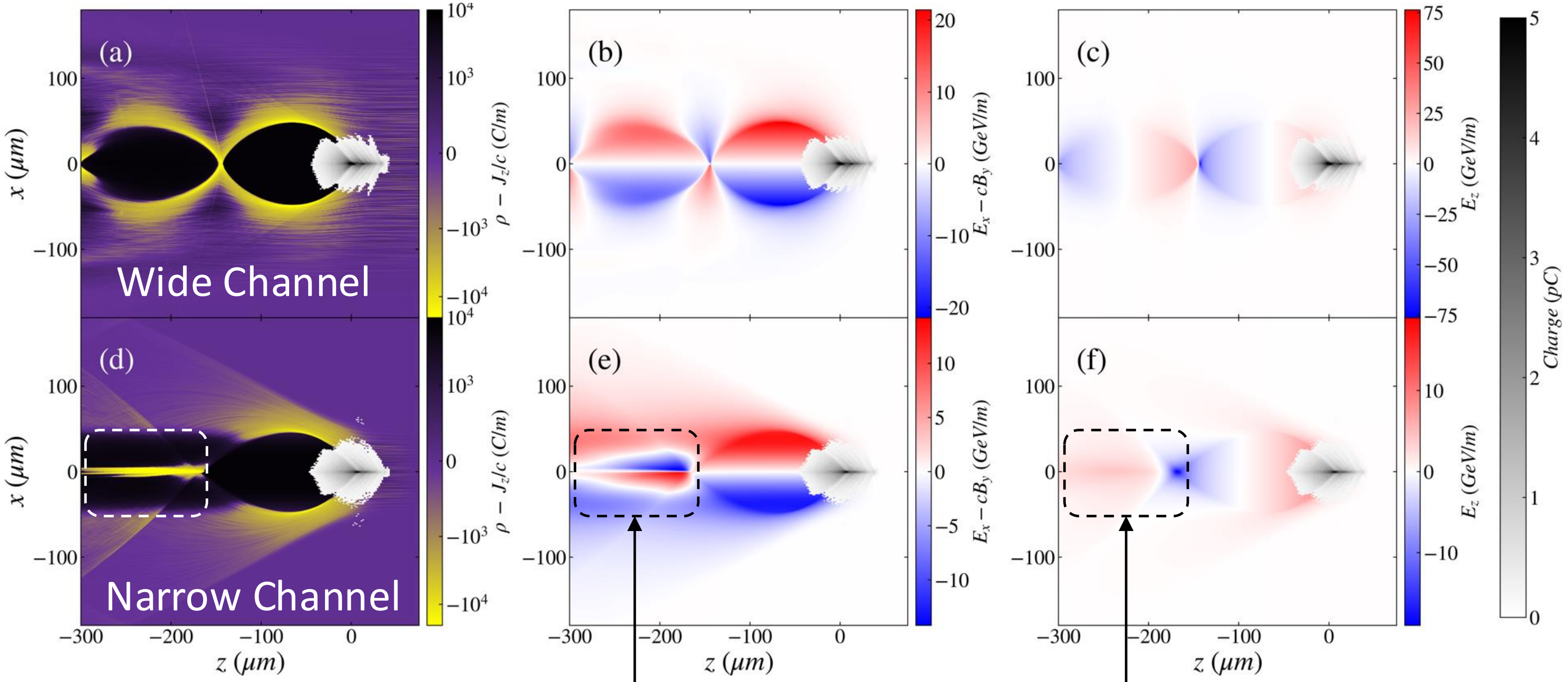


University of Colorado Boulder

PWFA in a narrow plasma channel → toward positron PWFA

S. Diederichs, et al., Phys. Rev. Accel. Beams 22, 081301 (2019)





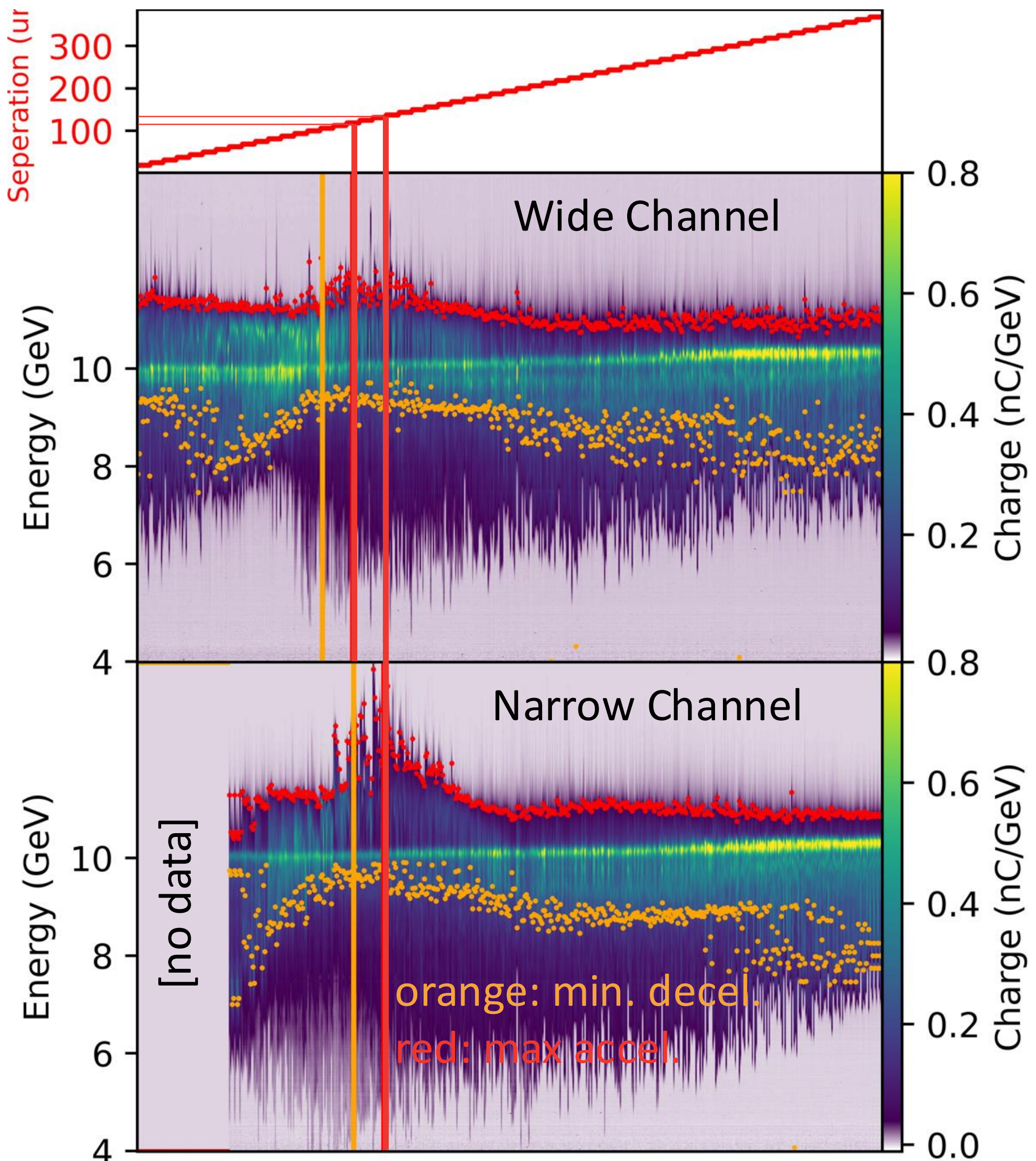
Focusing for **Positrons** Accelerating for **Positrons**

Science Goals:

- Demonstrate ability to control plasma channel radius
- Measure PWFA response to narrowing of plasma channel
  - Guiding of e-beams along channel
  - Elongation of plasma wake bubble

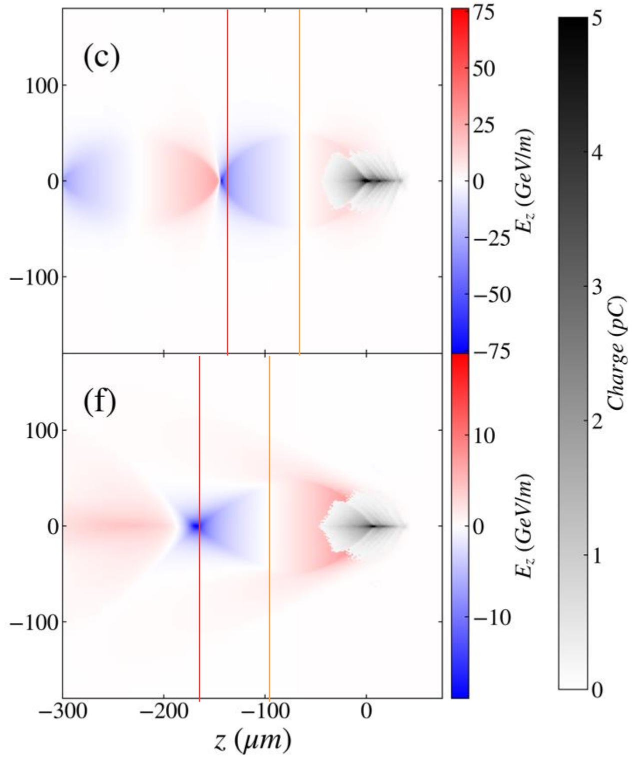
Elongated Wake Measurement

University of Colorado Boulder



Drive-Witness Separation Scan

- Reduced plasma width by reducing laser energy
- Scanned drive/witness separation from 0 to 400 µm
- Observed shift of max acceleration and min deceleration location by ~20 µm in narrow plasma
- Qualitative agreement with expectations
- Detailed simulation campaign ongoing



Summary

University of Colorado Boulder

E-301: PWFA in laser-ionized gas plasma

- Performed PWFA in meter-scale laser-ionized unconfined H_2 plasma source
- Achieved drive beam depletion: ~35% drive-to-wake efficiency, ~5 J energy deposition
- Achieved total charge capture: >90% charge capture, 1 GeV gain, 2.5% total efficiency
- Demonstrated importance of long plasma ramps for charge capture

E-333: PWFA in narrow-channel plasma

- Generated plasma channel with width smaller than blowout radius
- Compared wide channel and narrow channel PWFA
- Observed expected elongation of wake in narrow channel

Publications

University of Colorado Boulder

1. R. Ariniello, V. Lee, M. Litos, “Demonstration of a tandem lens for producing shaped laser-ionized plasmas for plasma wakefield acceleration”, arXiv:2509.01747 (2025) [*submitted for publication*]

2. R. Ariniello, et al., [*PWFA in a laser-ionized gas, in preparation*]

3. V. Lee, et al., “Precision alignment and tolerance of a plasma wakefield accelerator in a laser-ionized plasma source”, arXiv:2508.16864 (2025) [*submitted for publication*]

4. V. Lee, et al., [*PWFA in a narrow plasma channel, in preparation*]