Multi-GeV Electron Combs from a Plasma Wakefield Accelerator

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(on behalf of the E300 Collaboration)

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See arXiv:2607.08069 for more details

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Simulations done using OSIRIS and QPAD on Perlmutter@NERSC

What to expect

We show the experimental generation of multi-GeV electron combs:

- a multi-GeV electron beam consisting of more than 10 microbunches
- microbunch charge: several pC; energy spread down to 0.5% rms
- up to 0.26 GeV (7%) energy spacing between adjacent spectral peaks

measured

- microbunches should be sub-fs in duration and separated in time

inferred

- **mechanism: beam-induced ionization injection of helium electrons into a lithium plasma wake, with longitudinal mapping due to gentle density gradients**

Plasma accelerators keep improving: energy, brightness, stability

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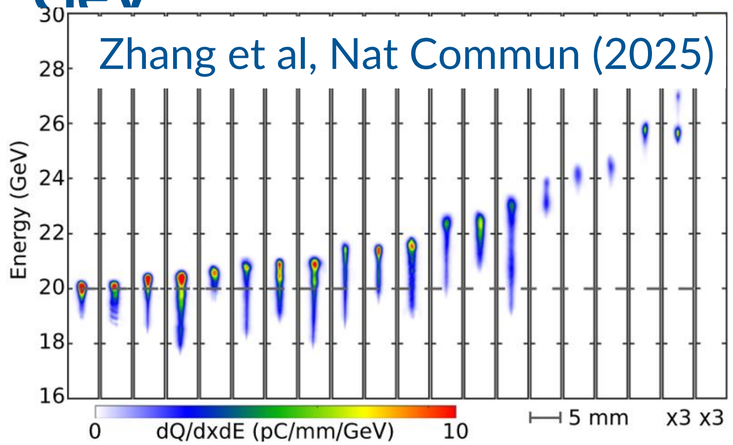
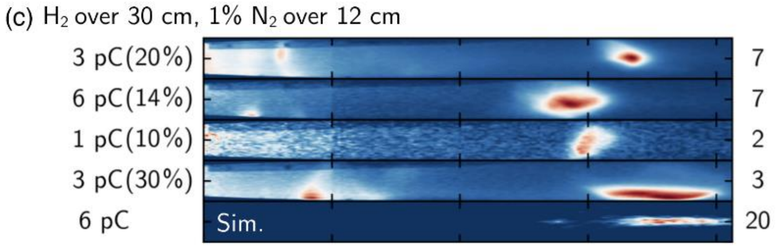
Energy reached O(10) GeV

Zhang et al, Nat Commun (2025)

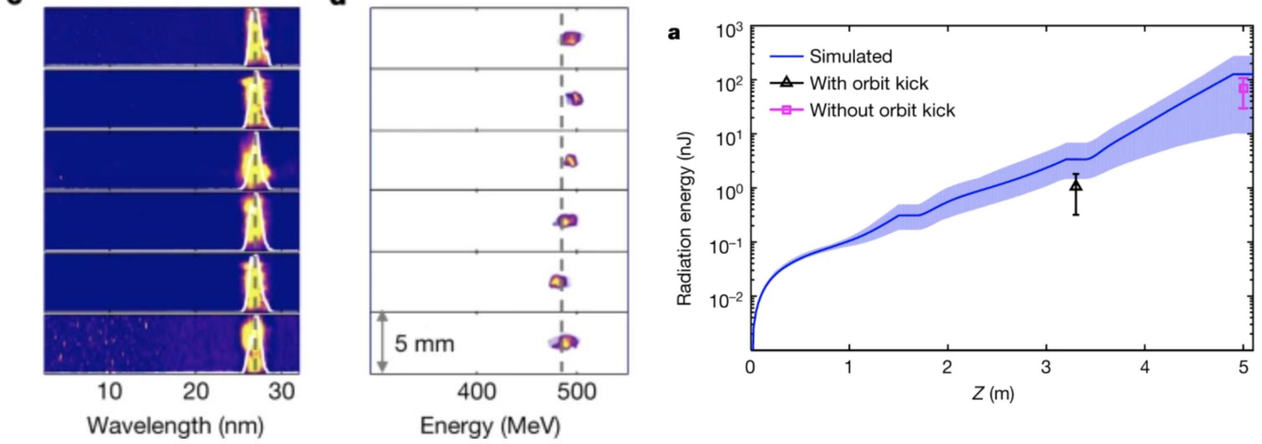




Picksley et al, PRL (2024)

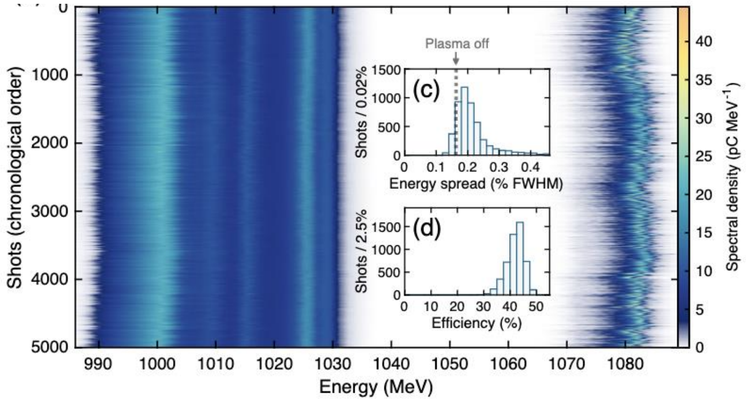
Beams bright enough to drive an EUV FEL

Wang et al, Nature (2021)



Stability and reproducibility

Lindstrøm et al, PRL (2021)



A less-explored feature of plasma accelerators: in-situ beam shaping

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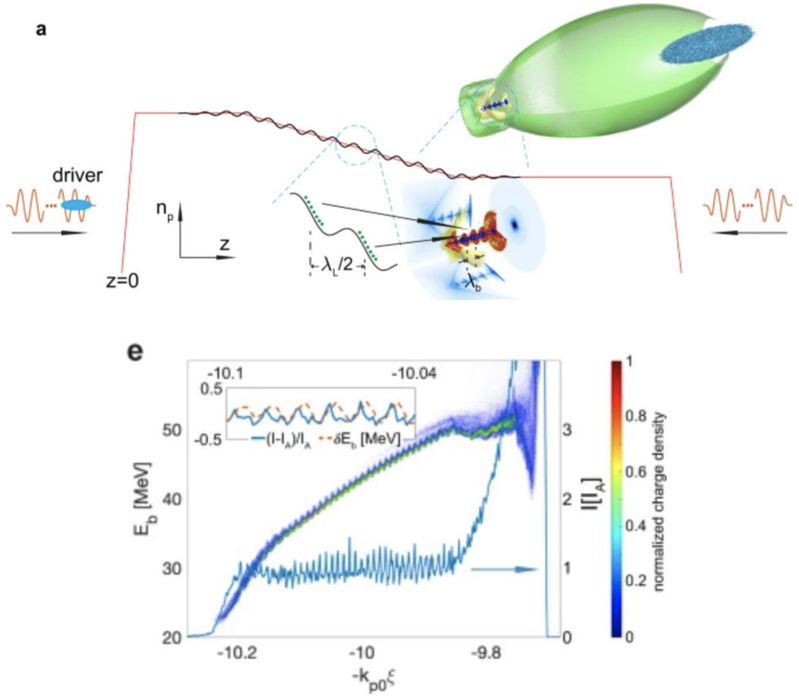
Internally injected electrons in a plasma accelerator can be tailored in situ, on fs timescales, by manipulating the injection process.

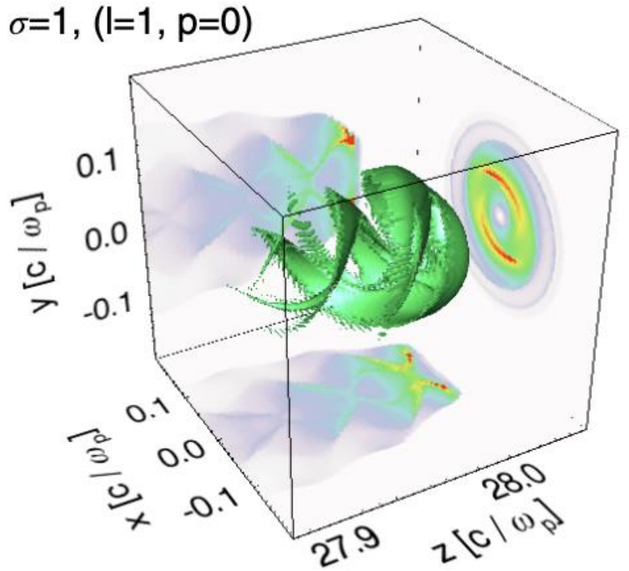
Examples:

nm pre-bunched beams from modulated downramp injection



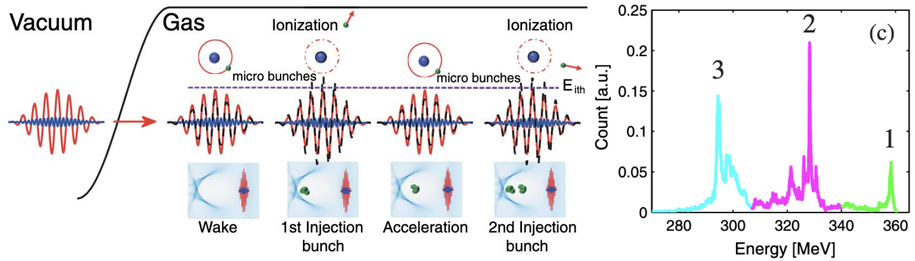
Xu et al, Nat Commun (2022)

spiral e- bunch from ionization injection using LG lasers



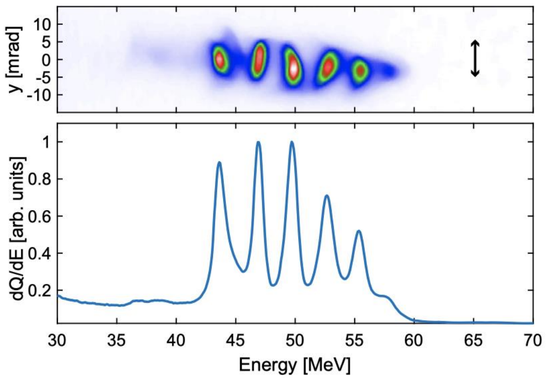
Xu et al, PRAB (2022)

multi-color beam from two-color ionization injection



Zeng et al, PRL (2015)

recently demonstrated in experiment



Angella et al, PRL (2026)

Multi-color beam generated in a PWFA (the FACET E217 experiment)

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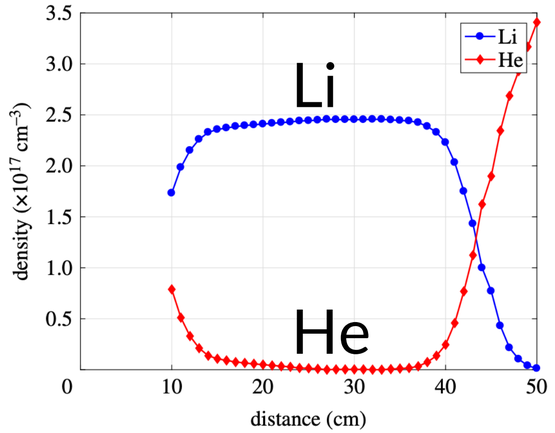
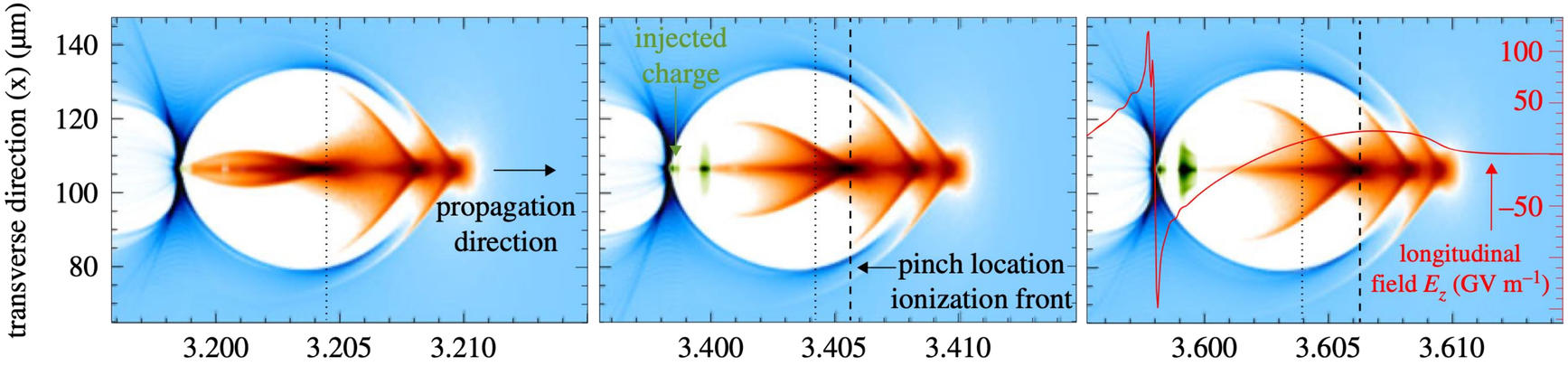
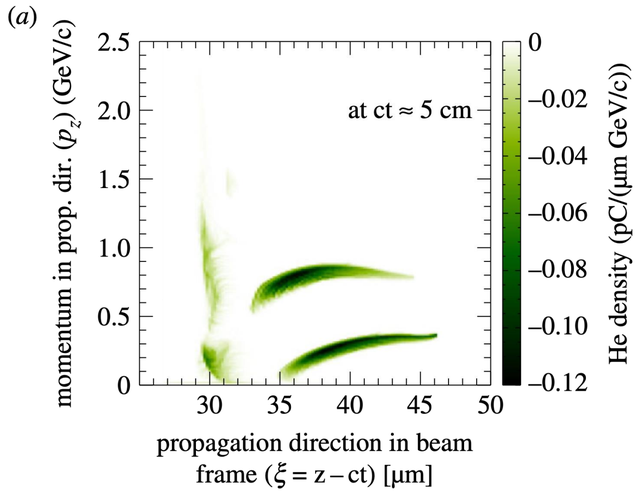
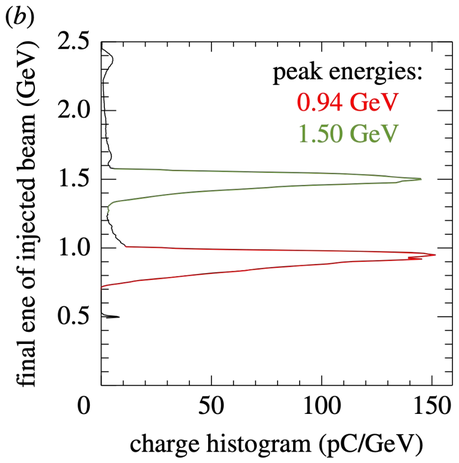
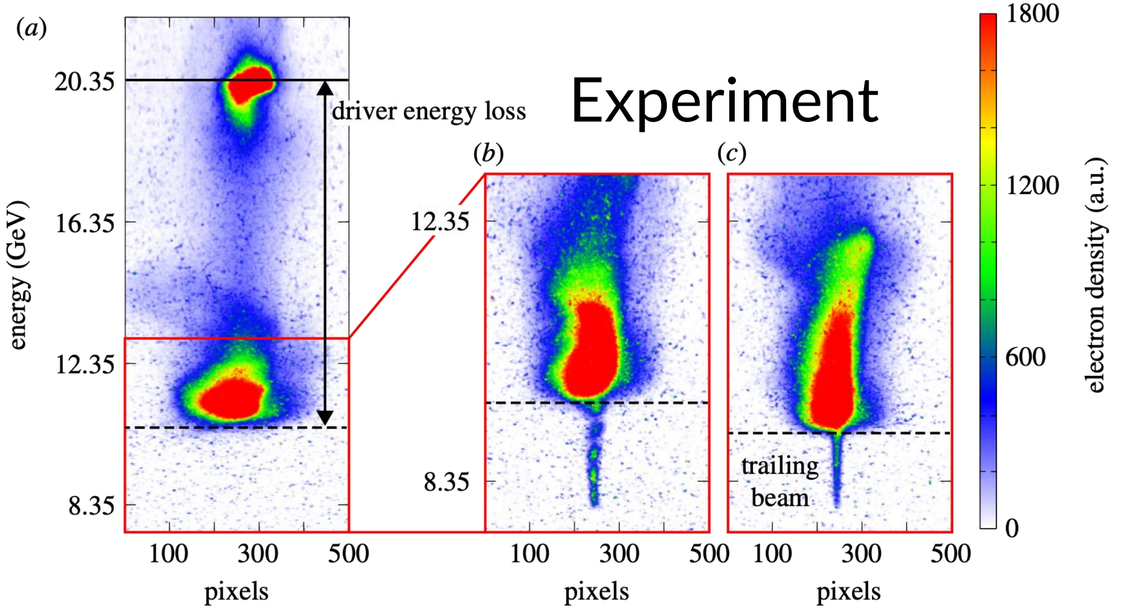
- Periodic pinching of the drive bunch ionizes the helium dopant gas in a lithium plasma
- Injection happens every half betatron wavelength









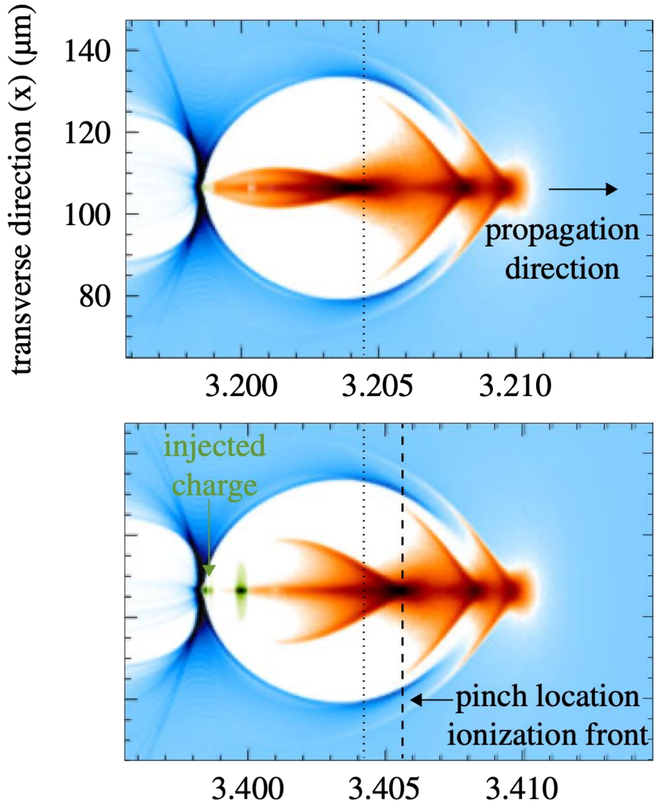


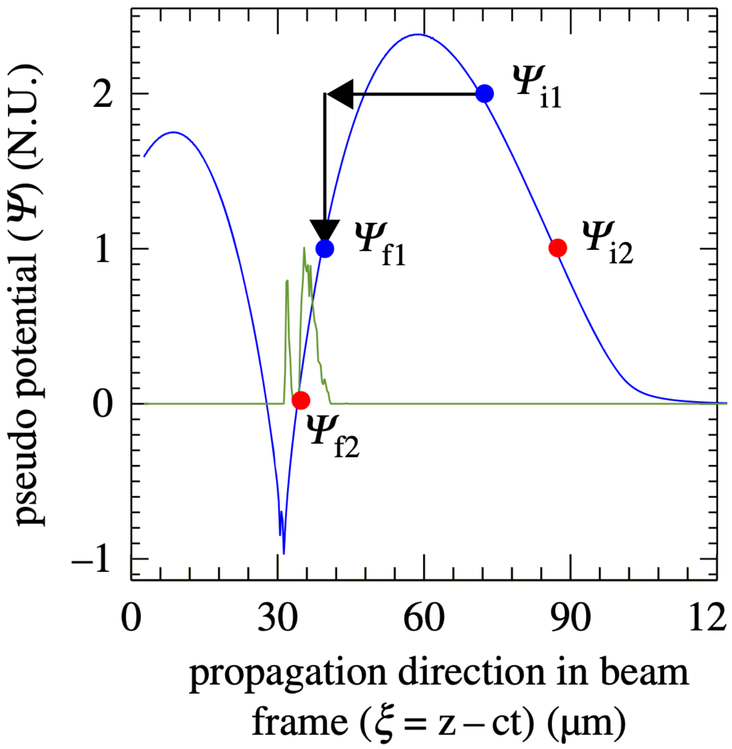
N. Vafaei-Najafabadi et al, Phil. Trans. R. Soc. A (2019)

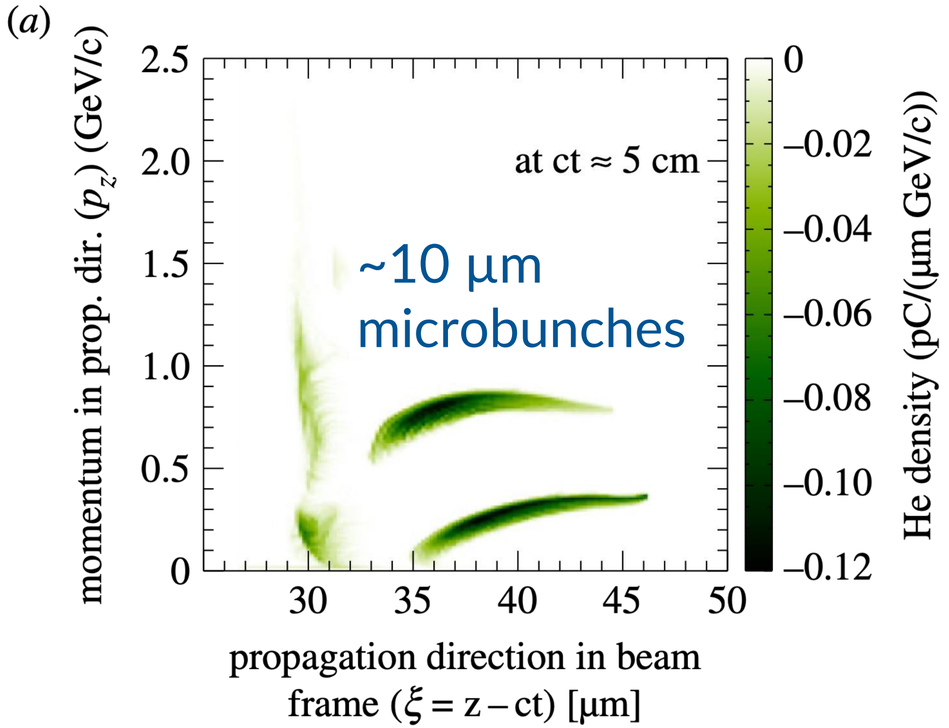
A long driver means a long injection phase

- Long Gaussian driver
  - pinching slice moves along the beam —>
  - changes ionization phases —>
  - injects long, overlapping bunches

Microbunches are separated in energy, but not necessarily in time.



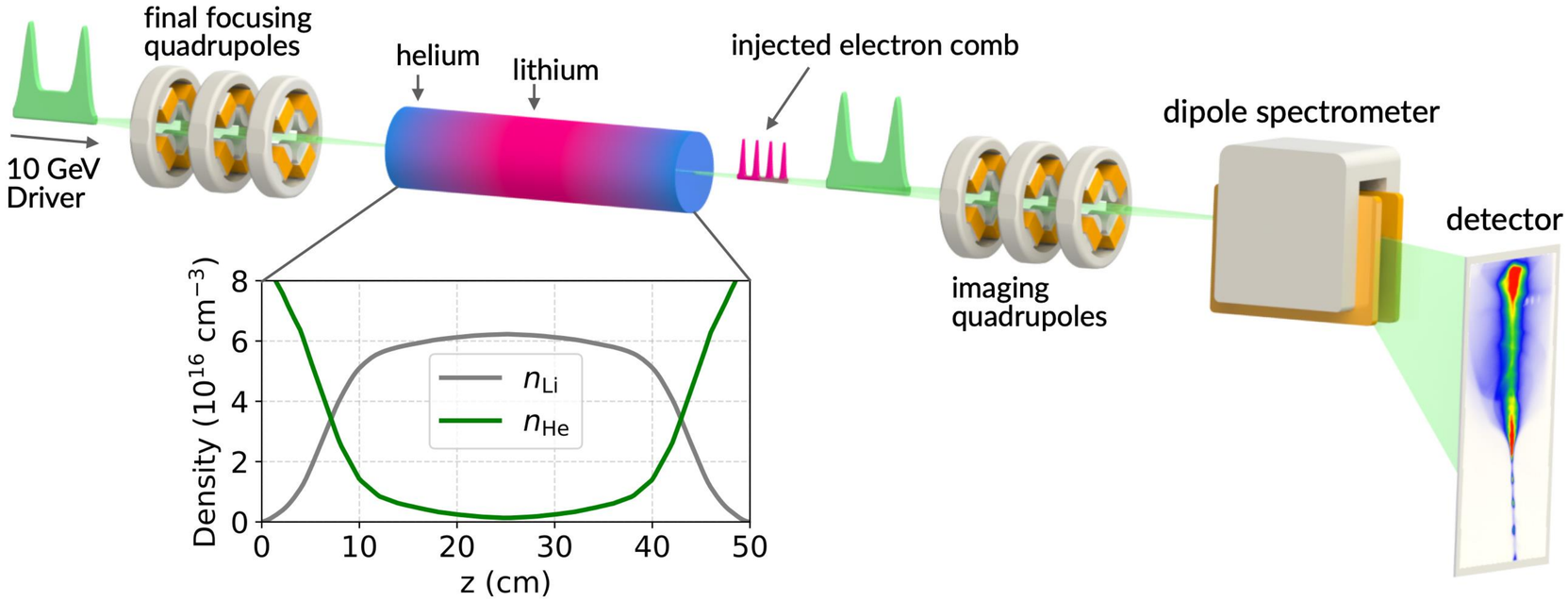




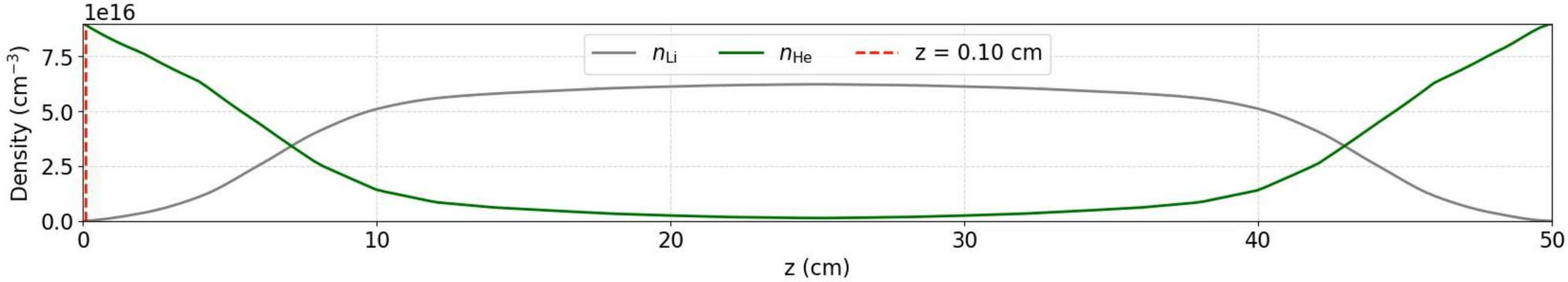
N. Vafaei-Najafabadi et al, Phil. Trans. R. Soc. A (2019)

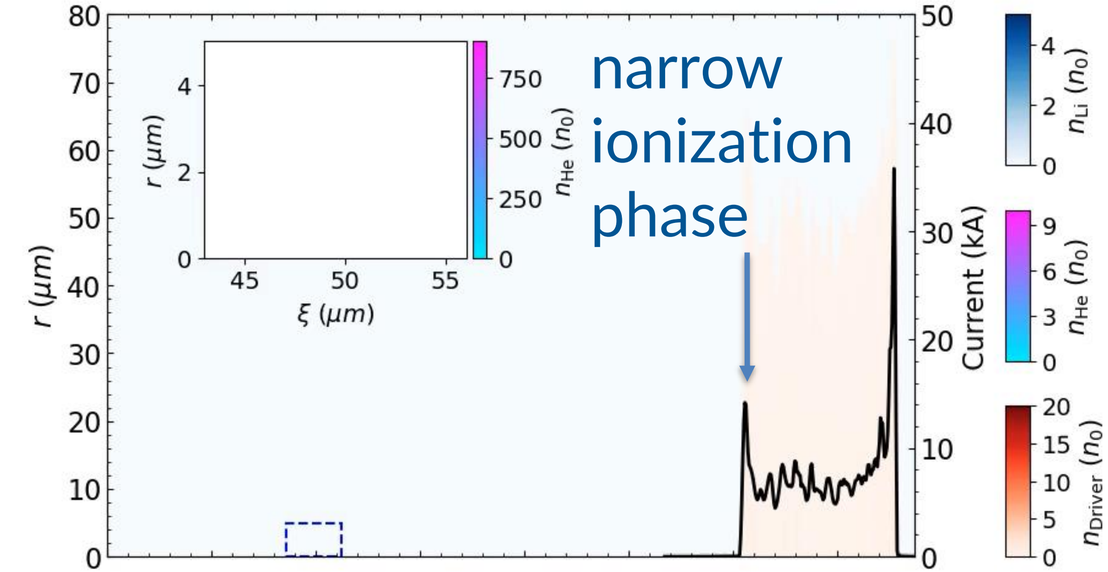
Revisiting E217 at FACET-II: two changes uncover new physics

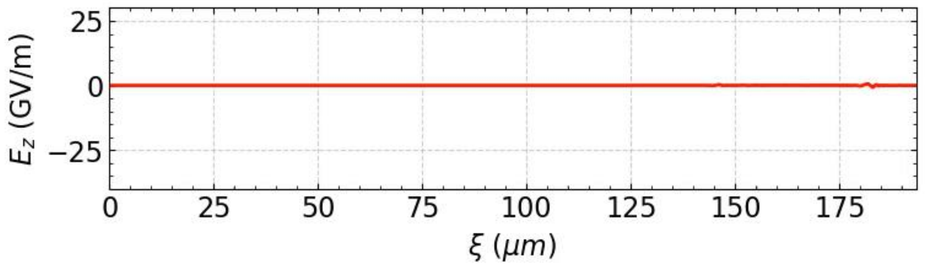
- The experiment was performed at FACET-II using the 1.5 nC, 10 GeV beam (March 2024)
- **The drive beam is over-compressed to generate a double-spike structure**
  - Leading spike ionizes lithium; subsequent charge drives the wake; trailing spike ionizes helium
  - **The narrow current spike limits the ionization/injection phase —> ultrashort bunches**
- **Non-uniform plasma**
  - 40-cm lithium vapor, bounded (and doped) by helium gas
  - **Longitudinal mapping during injection places microbunches at different phases**

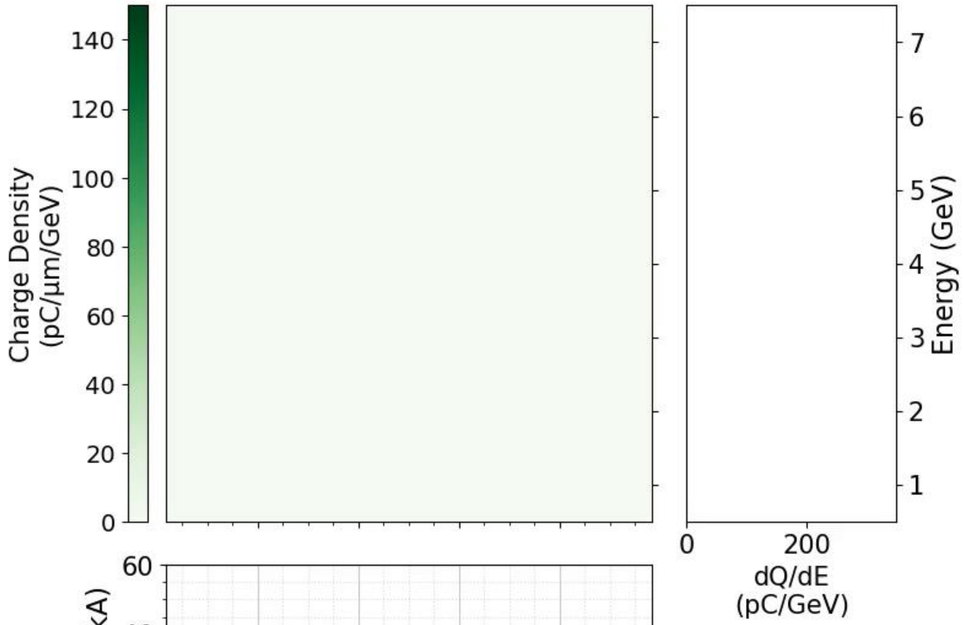


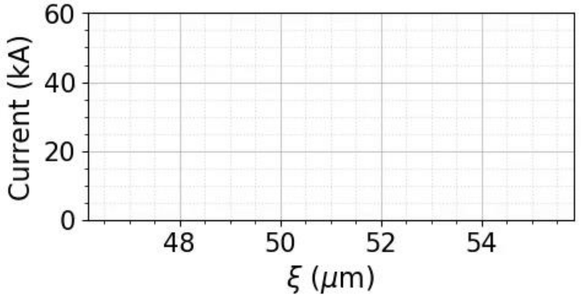
The physics explained by PIC simulations











Ionization-injected beams show distinct energy peaks

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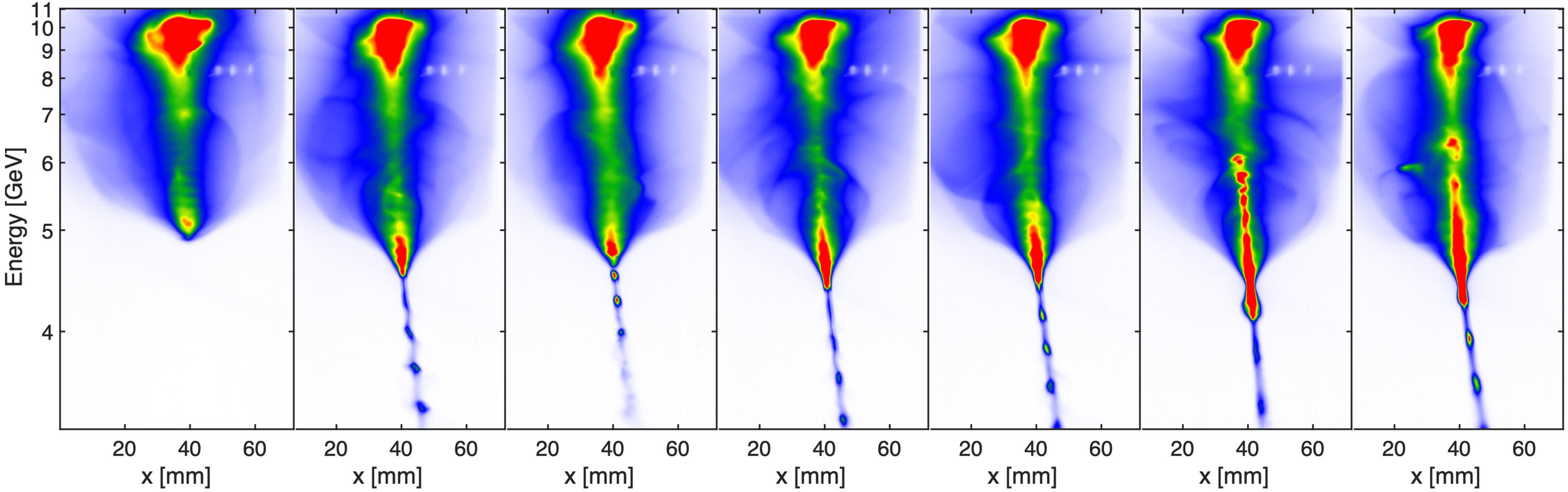
no injection with injection (drive beam waist at optimal location, z=10 cm)



A beam consisting of more than 10 microbunches

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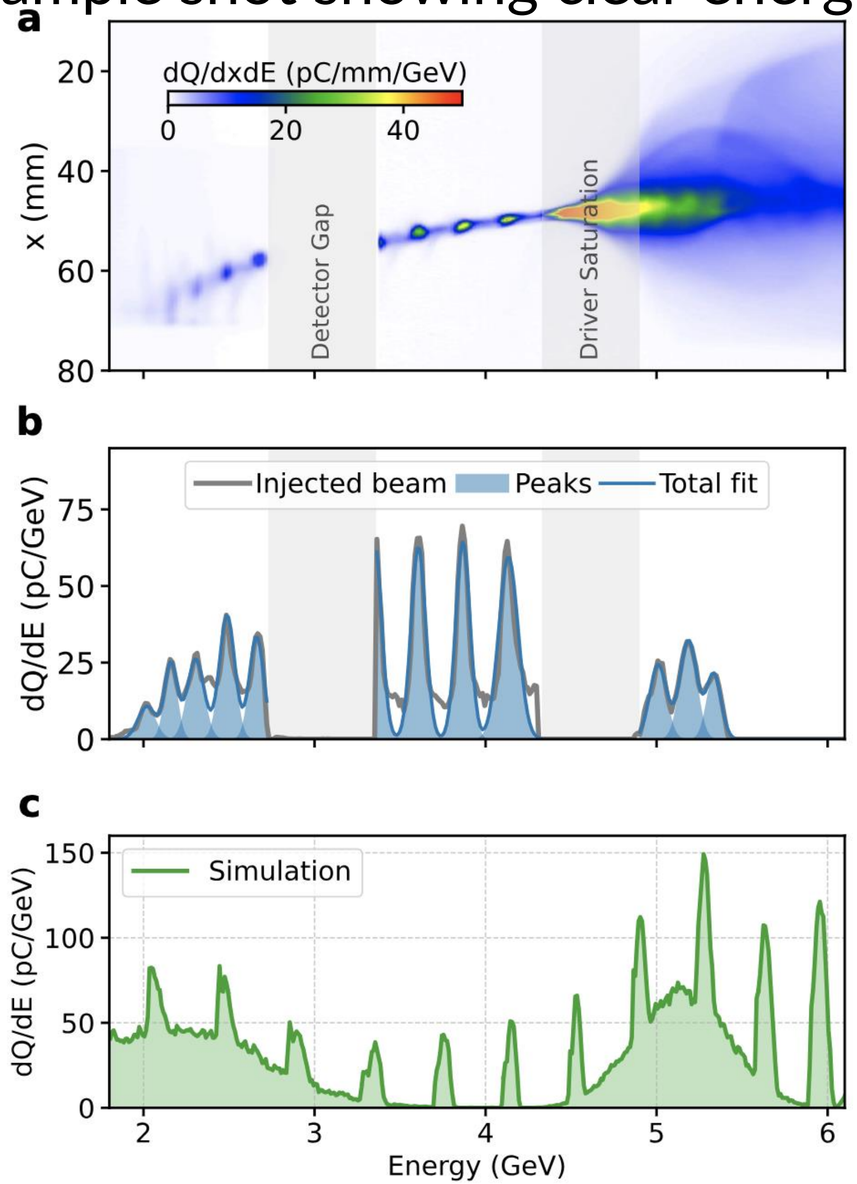
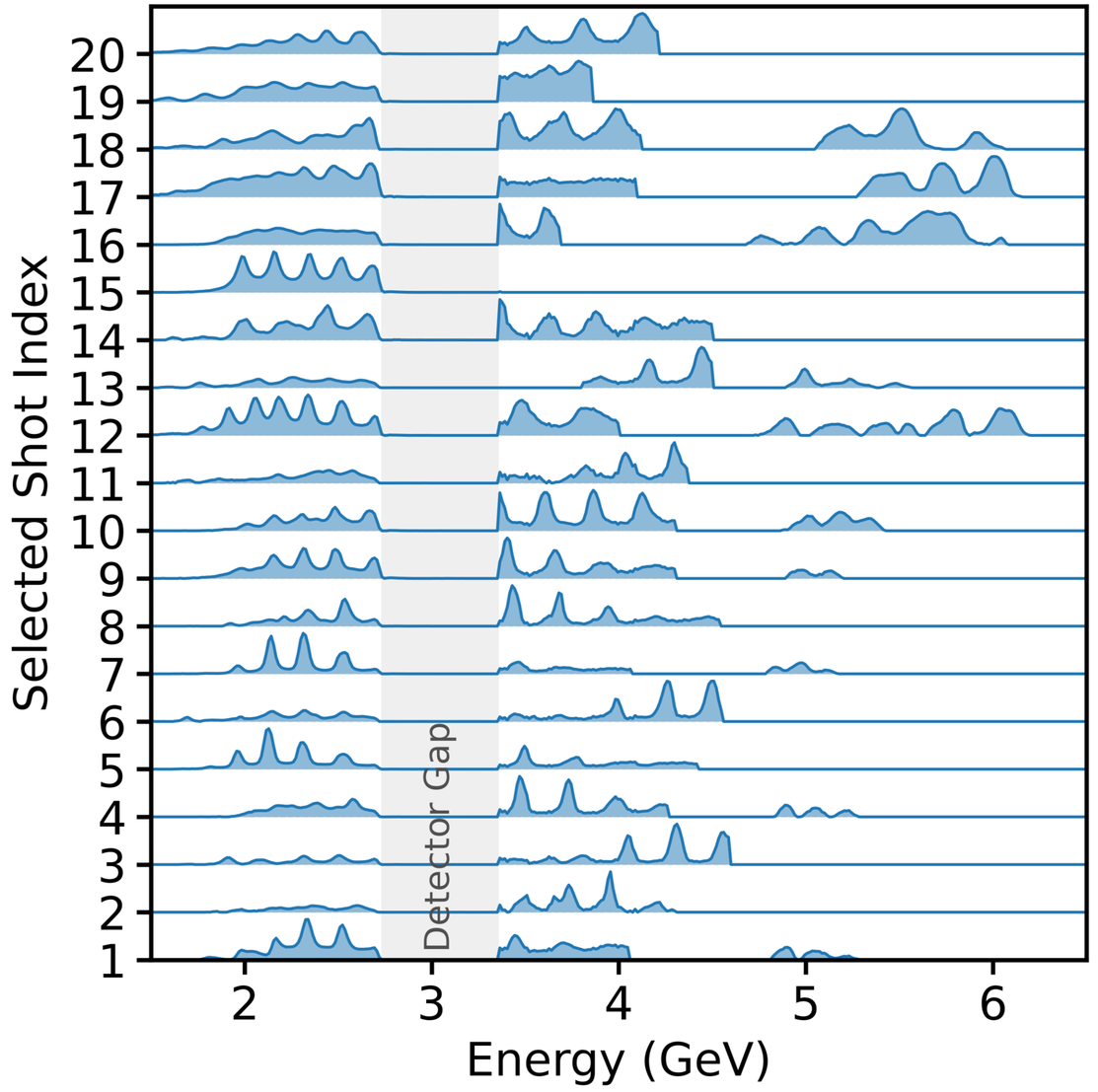
An example shot showing clear energy bunching



20 shots (out of 100 consecutive shots)



Spacing between adjacent peaks turns over at the highest energies

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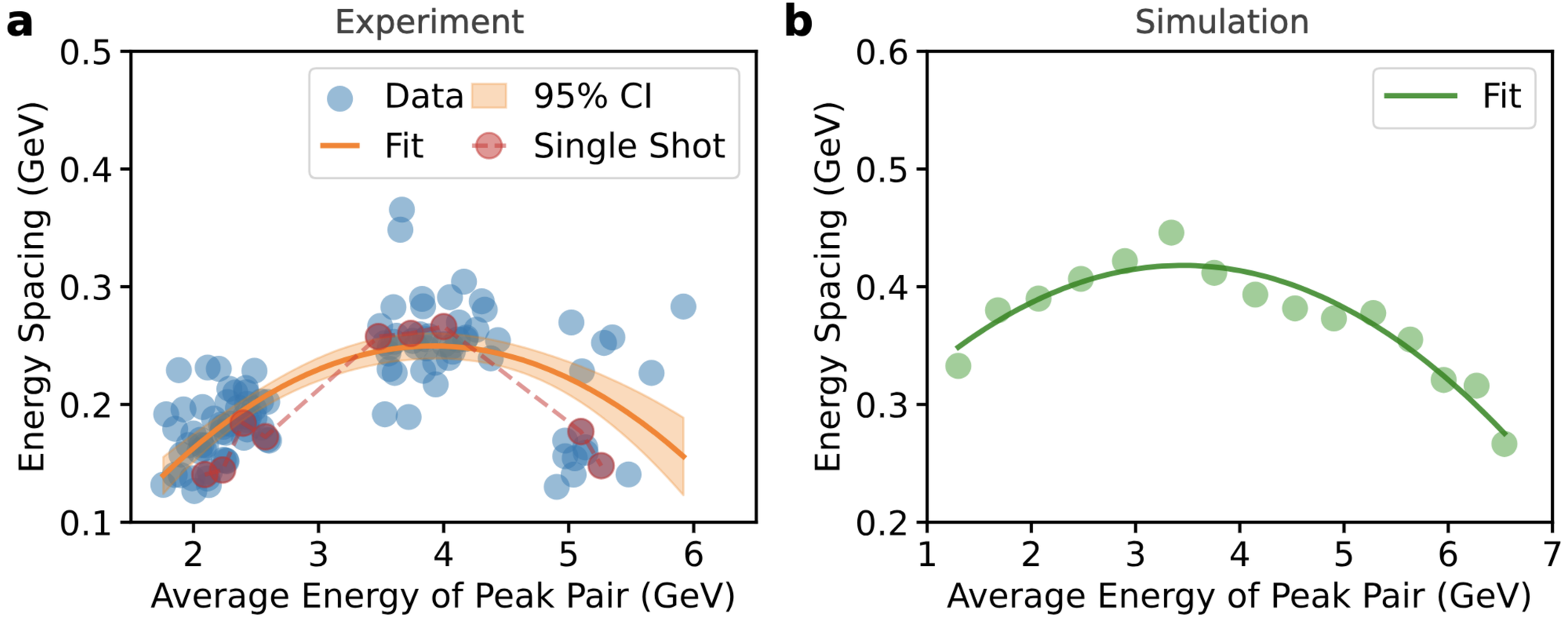
- **We observe the spacing turning over above ~4 GeV**
- **Expected: highest-energy peaks = earliest injected = largest spacing, monotonic**
- The turnover means those bunches are loading the wake and reducing the local field
- **Significant loading requires multi-kA currents → sub-fs bunch lengths at O(10) pC → they cannot fully overlap in time**



Without strong loading, the spacing rises monotonically — as expected

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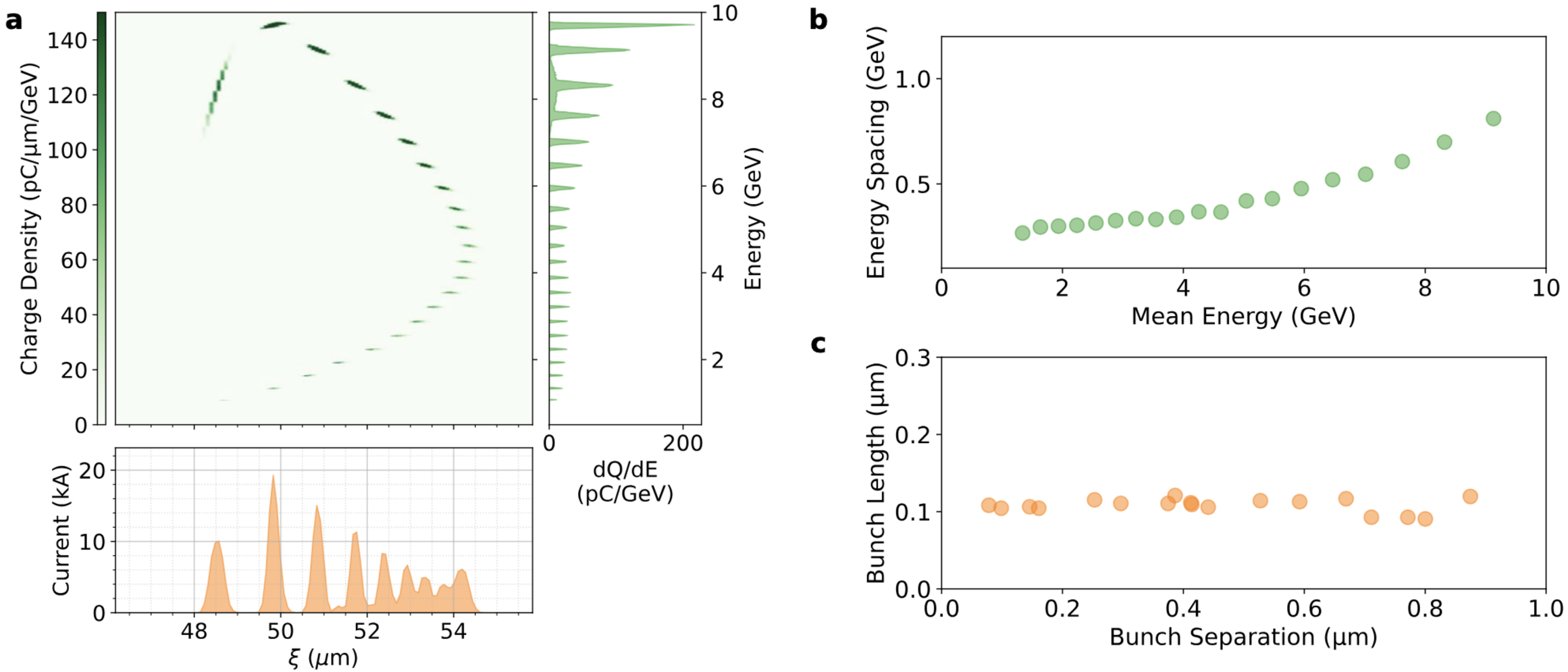
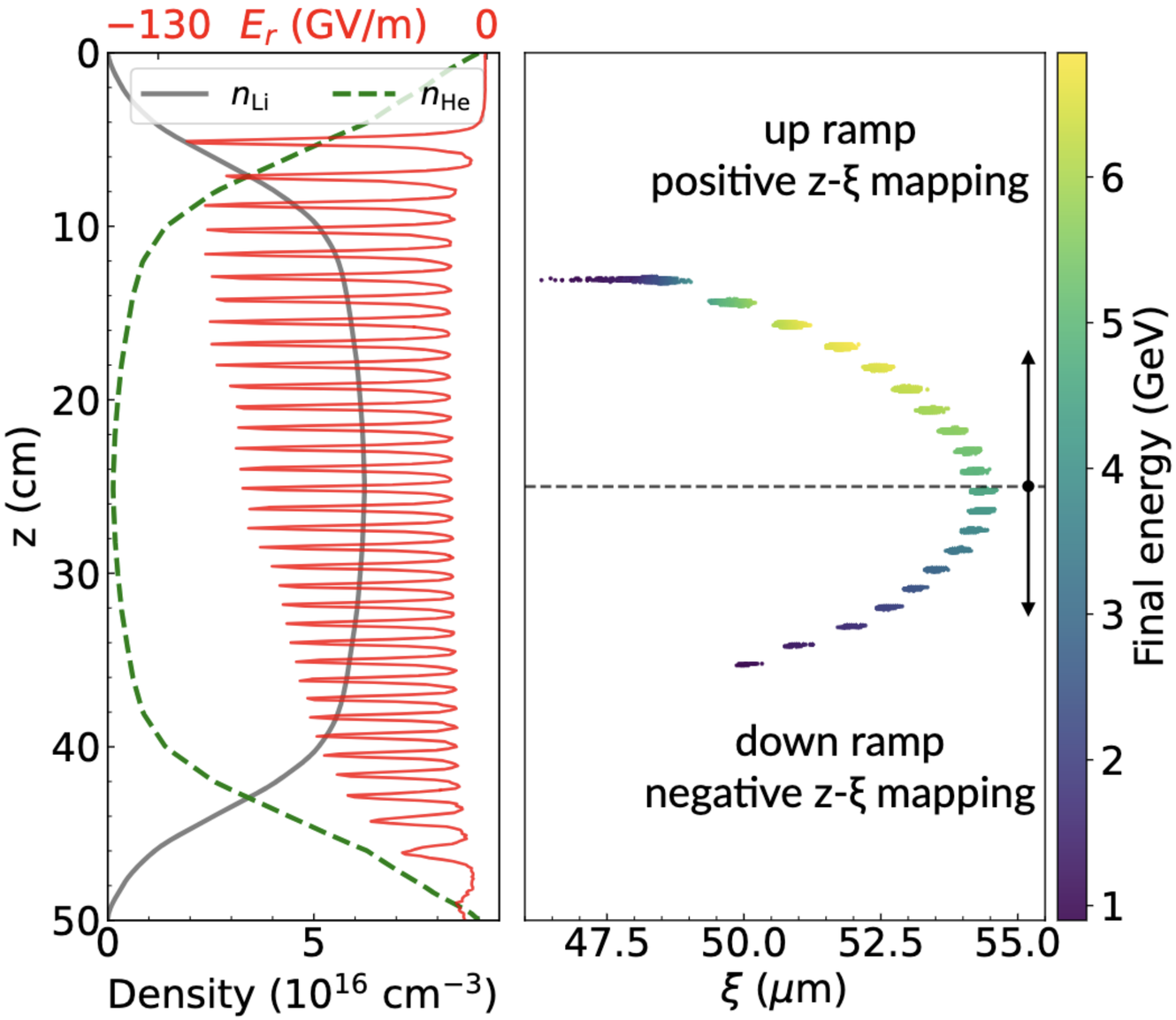


Simulation with reduced injected charge; bunch length ~0.1 μm, separation up to ~0.9 μm

Longitudinal phase space (LPS) mapping during injection



- Helium electrons selectively ionized over a ~21 cm region are mapped into a ~6 μm-long beam **(~35,000x mapping factor)**
- The LPS mapping order is controlled by the density gradient

What does this mean?

We can manipulate the LPS of the injected beam on fs scales by tailoring the plasma on cm scales.

Summary

We show the experimental generation of multi-GeV electron combs:

- a multi-GeV electron beam consisting of more than 10 microbunches
- microbunch charge: several pC; energy spread down to 0.5% rms
- up to 0.26 GeV (7%) energy spacing between adjacent spectral peaks

measured

- microbunches should be sub-fs in duration and separated in time

inferred

- mechanism: beam-induced ionization injection of helium electrons into a lithium plasma wake, with longitudinal mapping due to gentle density gradients
- **enables fs in-situ beam shaping by tailoring the plasma on cm scales**

Backup: Drive beam waist scan

- The amount of charge injected depends on the driver's waist location (betatron oscillation envelope)
- Energy peak contrast increases with injected charge, indicating beam loading effects