E304 (and E300) PWFA self-injection experiments: status and plans

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(E300 collaboration)

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UCLA SLAC

Goals and status of E304

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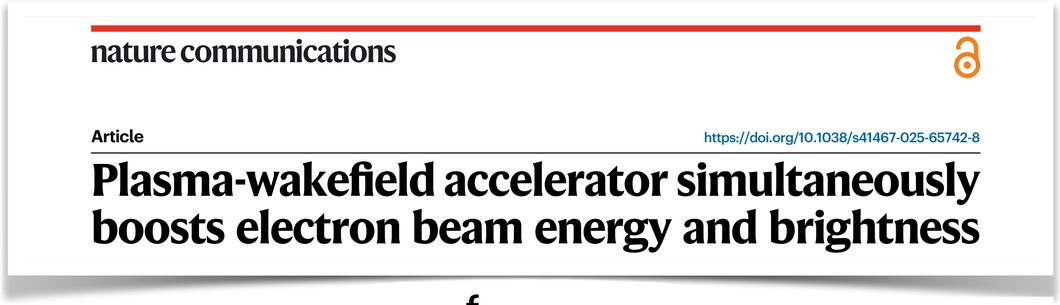
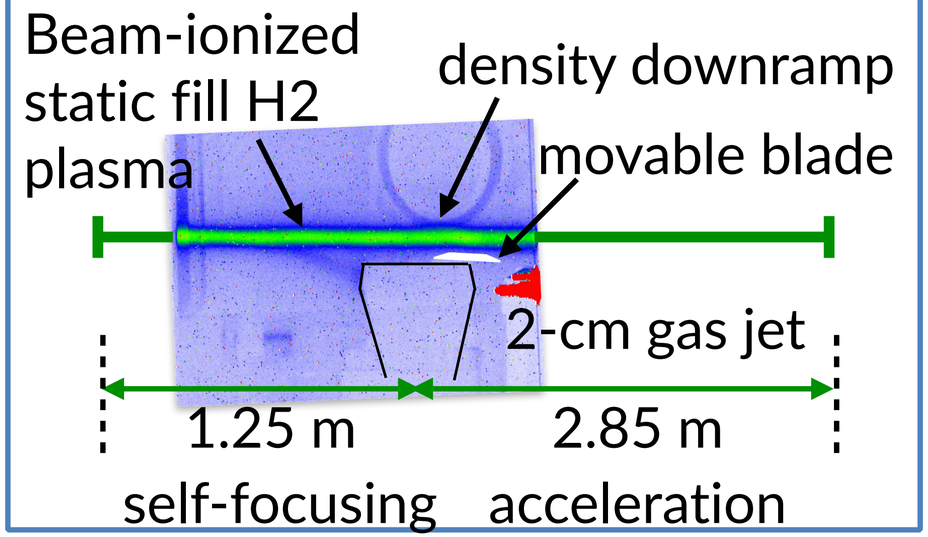
Goal: Generating low-emittance beams using downramp trapping in a plasma wakefield accelerator

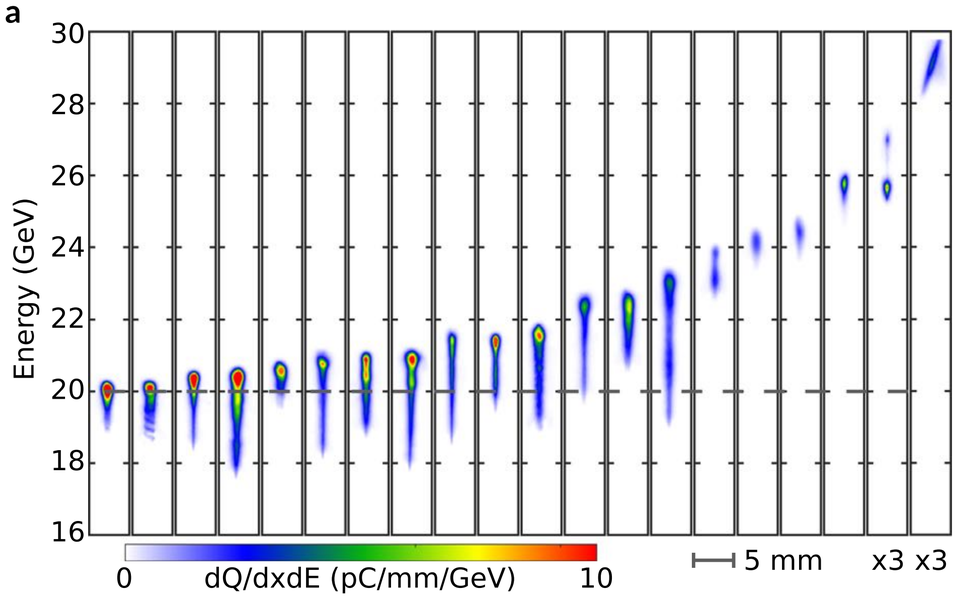
What's been done:

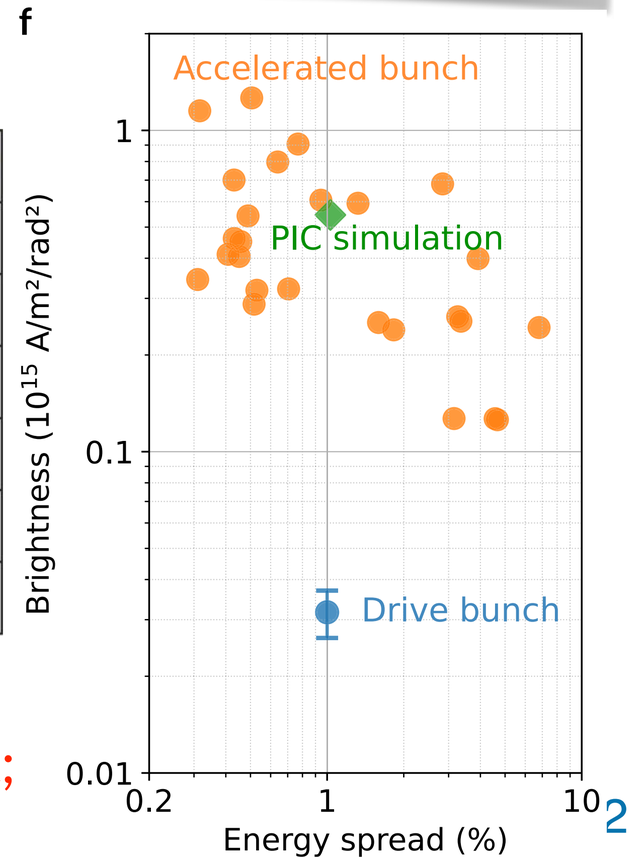
- **FY 2024-2025:** multiple campaigns and publication of the "Plasma Wakefield Dual-Transformer" paper



Gas jet in static fill configuration







Issues: Plasma was beam-ionized and its length varied a lot from shot to shot; injection happened in ~15% of the shots.

Goals and status of E304

Updated goal: Generating stable, lower-emittance, pre-bunched beams in a plasma wakefield accelerator

What we are working on:

- **FY 2026:**
  - **Experiment:** a new plasma source, two shifts, trying to get more stable multi-GeV beams
  - **Publication:** Multi-GeV electron combs, under review. (E300 data, the 2nd part of this talk)
  - **Simulation:** Plasma Acceleration via Regenerative Cascading, TeV beams in two regenerative stages totaling less than 1 km. Under review at PRL. (arXiv:2607.07979)

Mid-term evolution (as stated in the 24 PAC review):

- Modulated downramp injection for generating pre-bunched beams
- Post compression of the injected bunch (in collaboration with E338)

A 15-cm nozzle was built, tested, installed and used in the experiment

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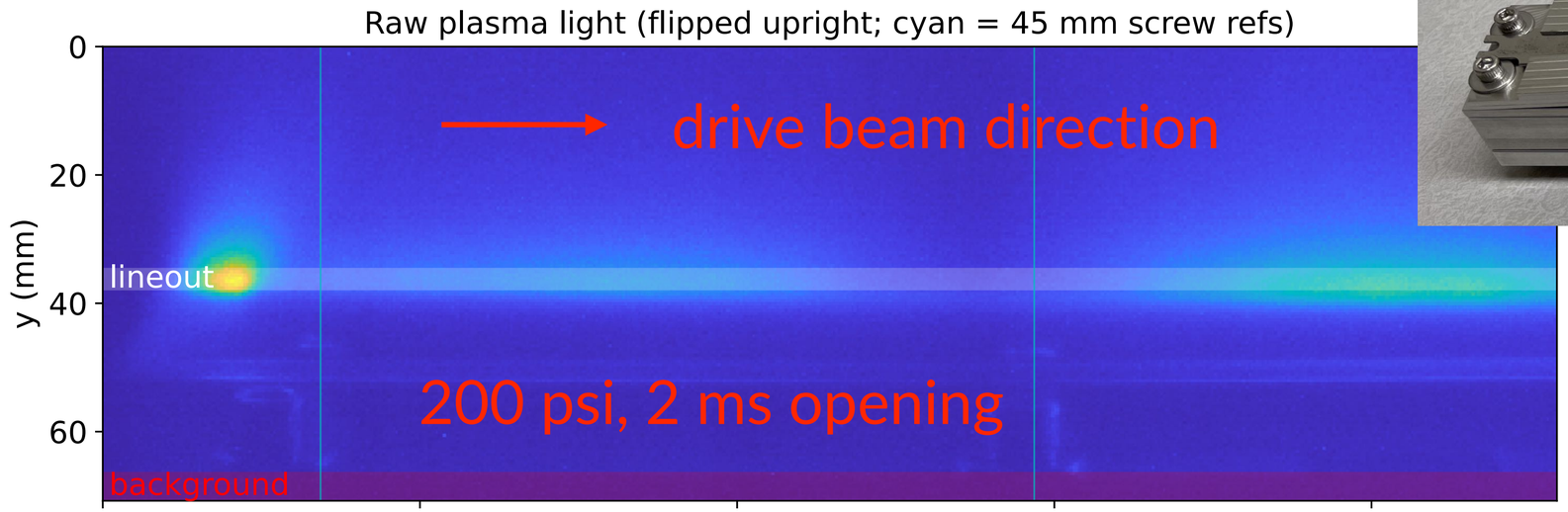
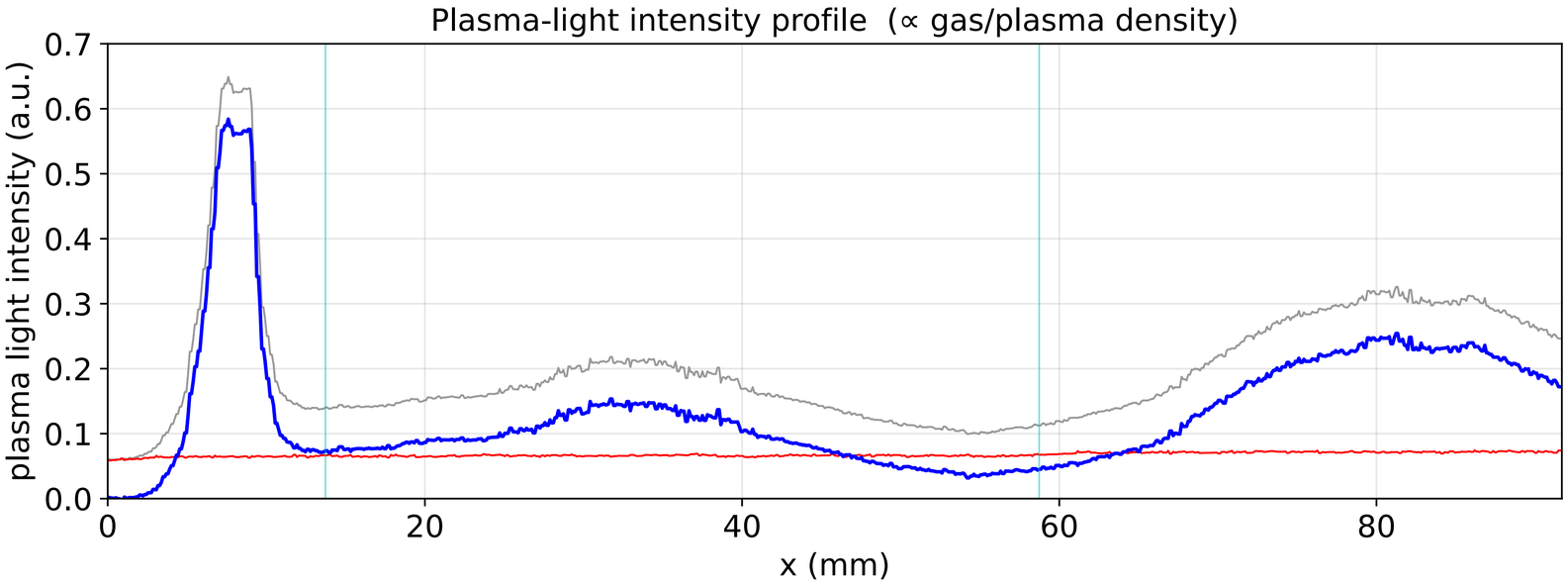




Note:

1) obvious shock structure (density downramp exists)

2) plasma light ratio ~ 5:1, but the actual density ratio could be smaller

Downramp injection did not happen this time

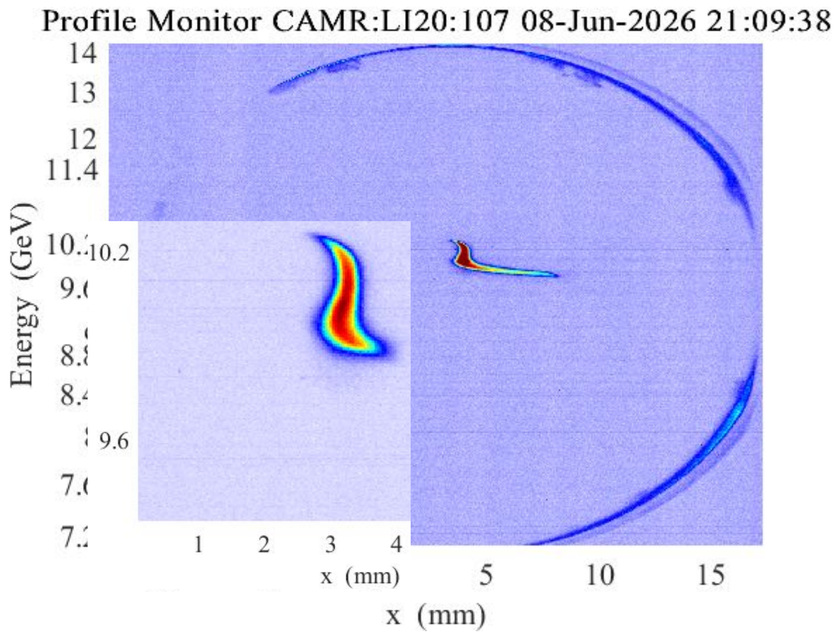
charge: 1.6 nC

sigma_x/y: 29/35 μm

sigma_z: ~30 μm

beta: 25 cm

Beam did not ionize Helium



March 2024:

sigma_x/y: 48/70 μm

sigma_z: ~19 μm

beta: 50 cm

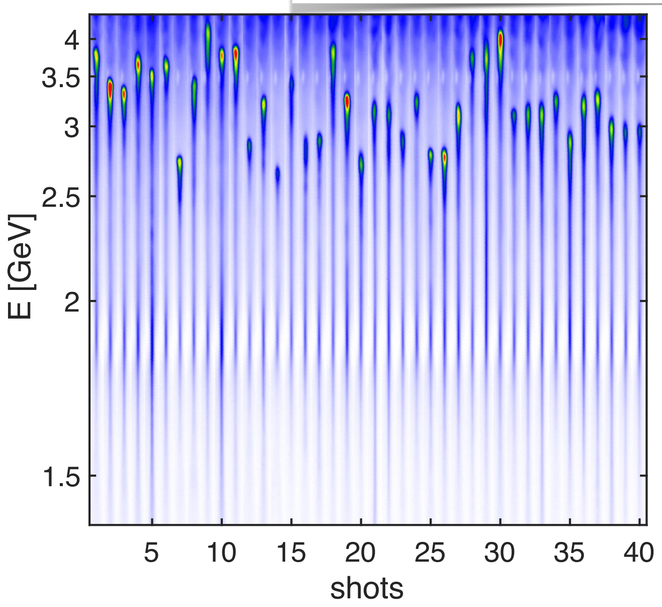
June 2024:

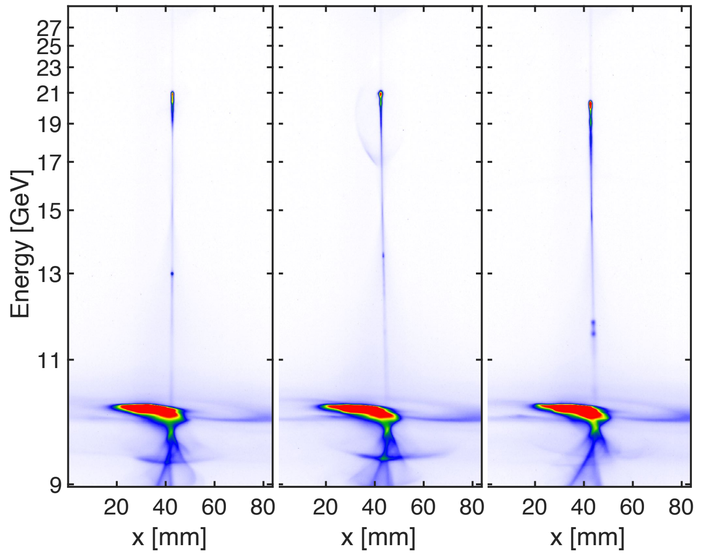
sigma_x/y: 30/19 μm

sigma_z: 21 μm

beta: 50 cm

Beam could ionize Helium

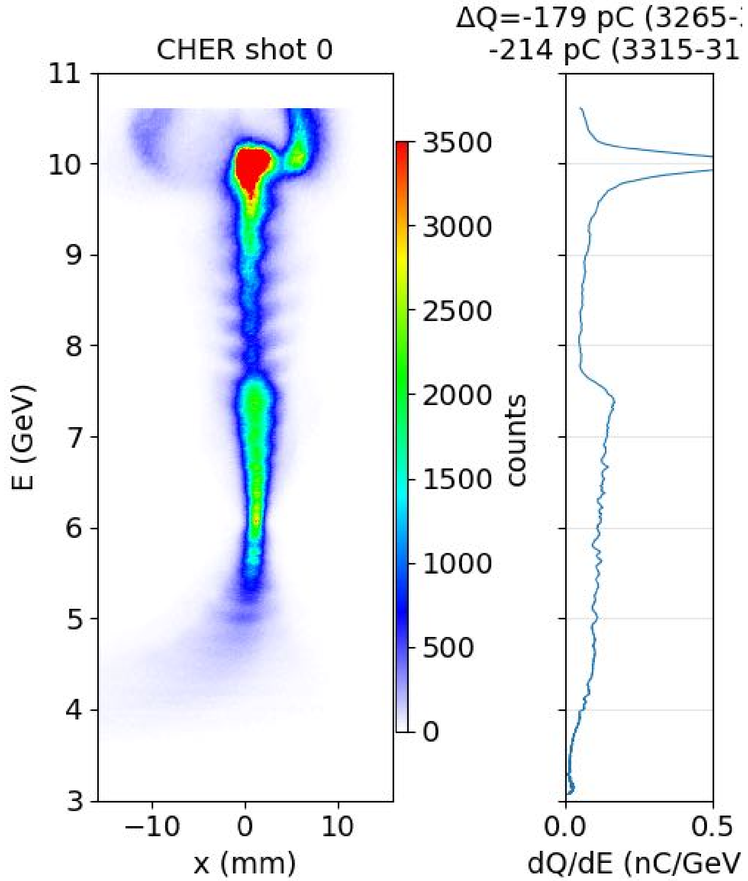


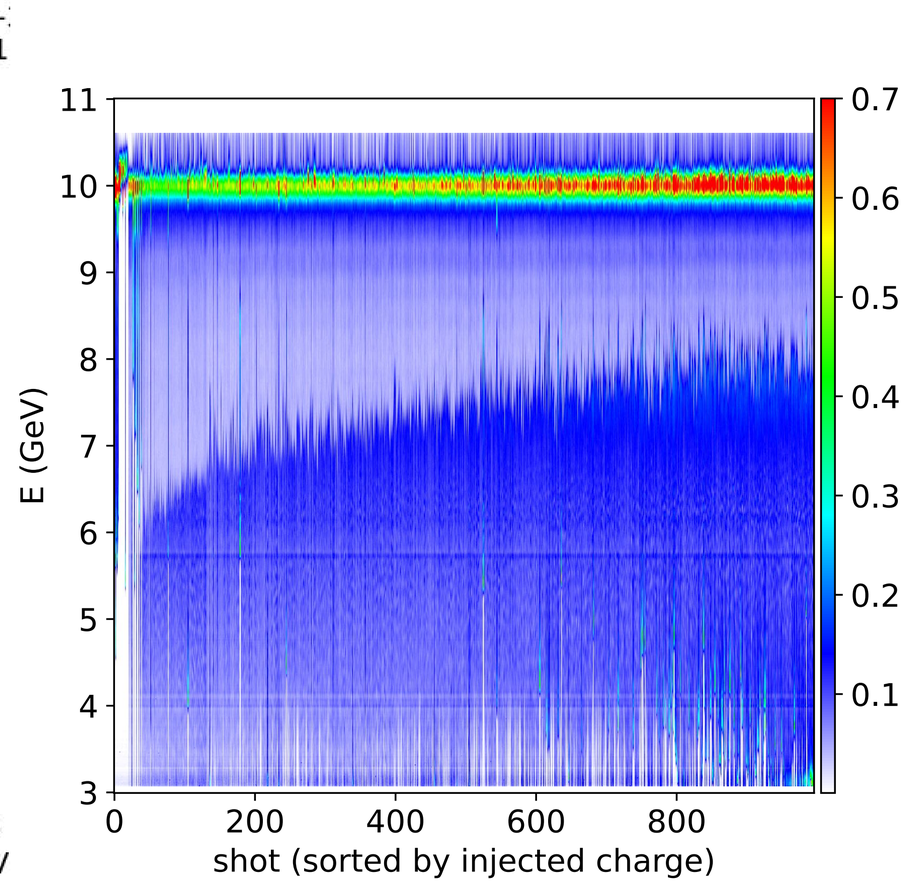


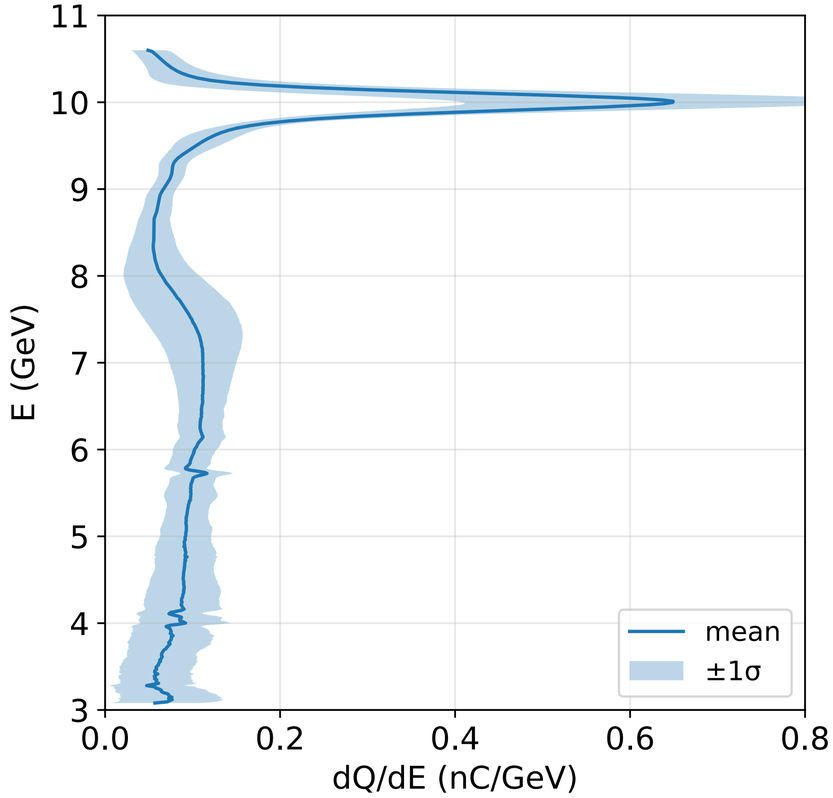
- No built-in plasma lens to accommodate large initial beam size.
- The beam has to do good ionization/wake excitation right at the start of the gas jet.

Tried ionization injection using a H2/He (90/10) gas mixture

- We then switched to He/H2 and tried ionization injection.
- Saw some interesting spectral features looked like injected beam.
- But they are the less decelerated tail of the drive bunch (double-value decelerating field).







1 Torr H2/He; Laser OFF; Quad 12 GeV, Dipole 12 GeV; with collimator.

What looks like injection is the drive bunch's decelerated tail

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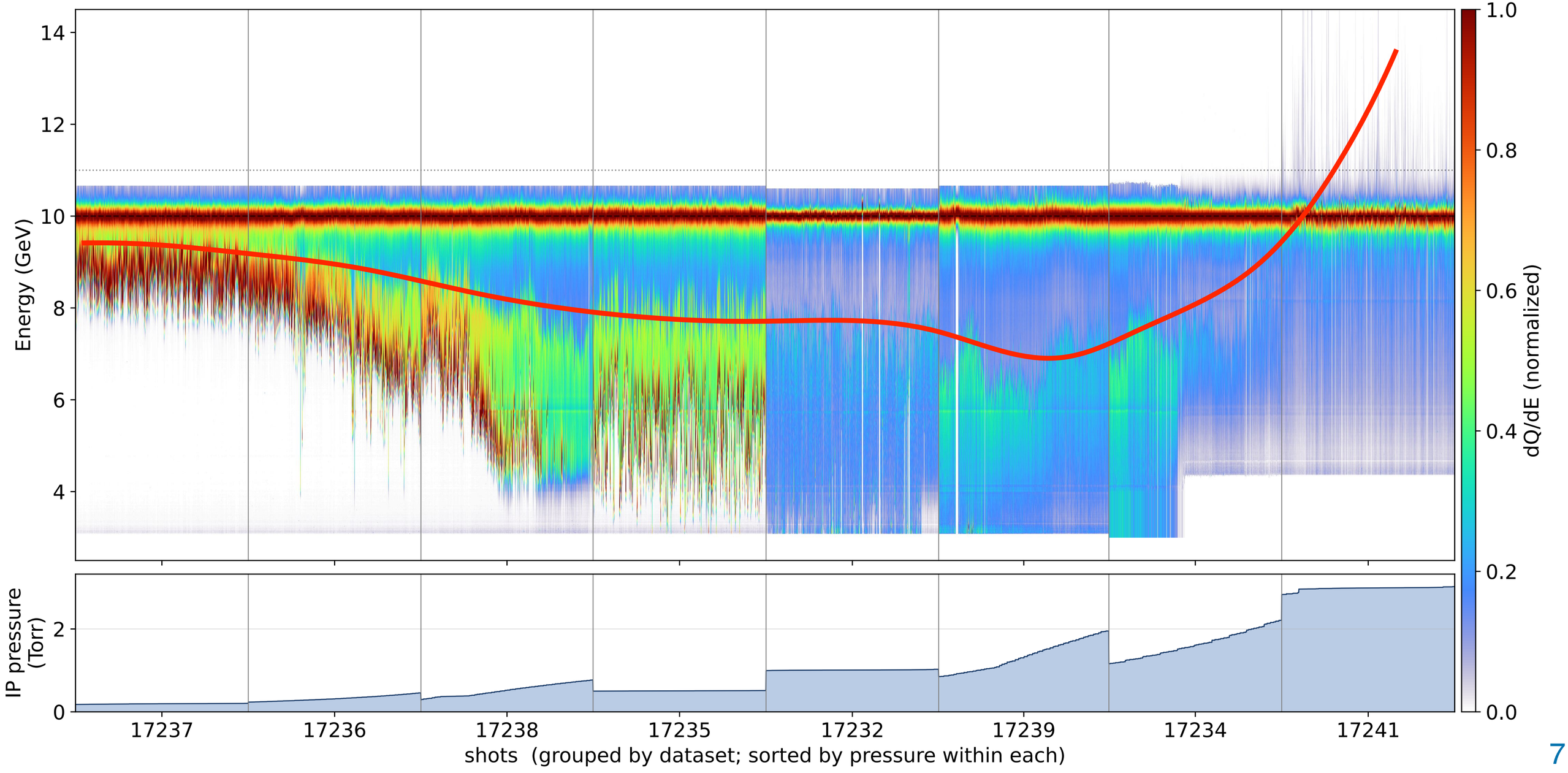
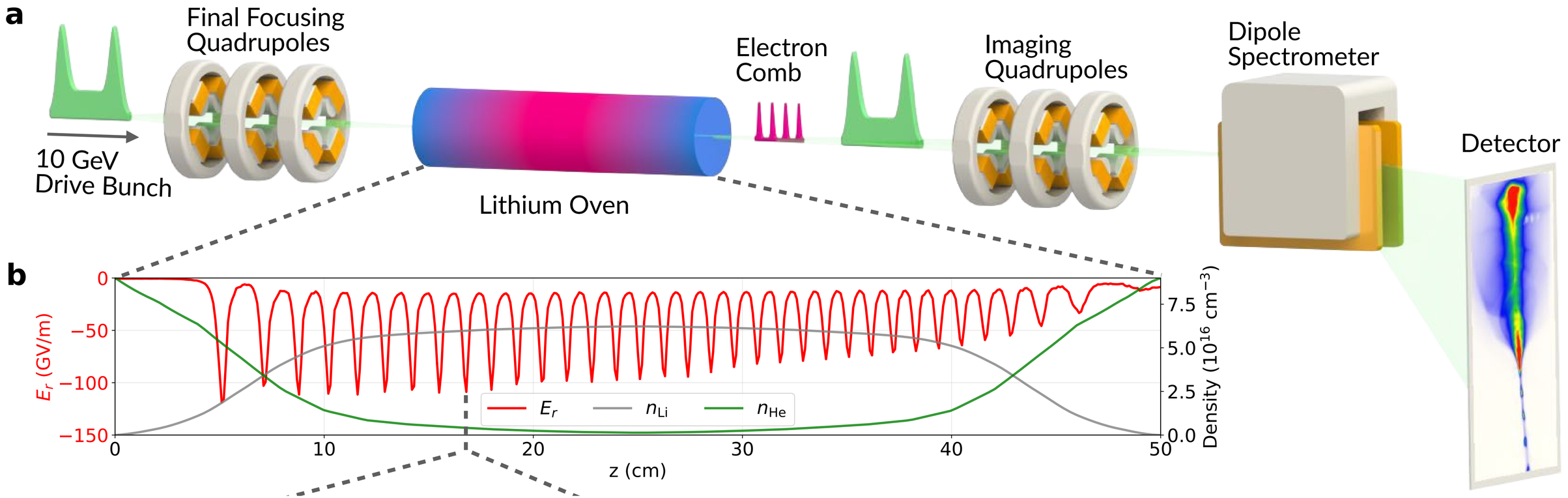


Multi-GeV Electron Combs from a Plasma Wakefield Accelerator

In a 2024 single-bunch E300 shift aimed at maximizing beam-to-plasma energy transfer efficiency, we observed injected electrons.

The experimental setup:



Multi-GeV Electron Combs from a Plasma Wakefield Accelerator

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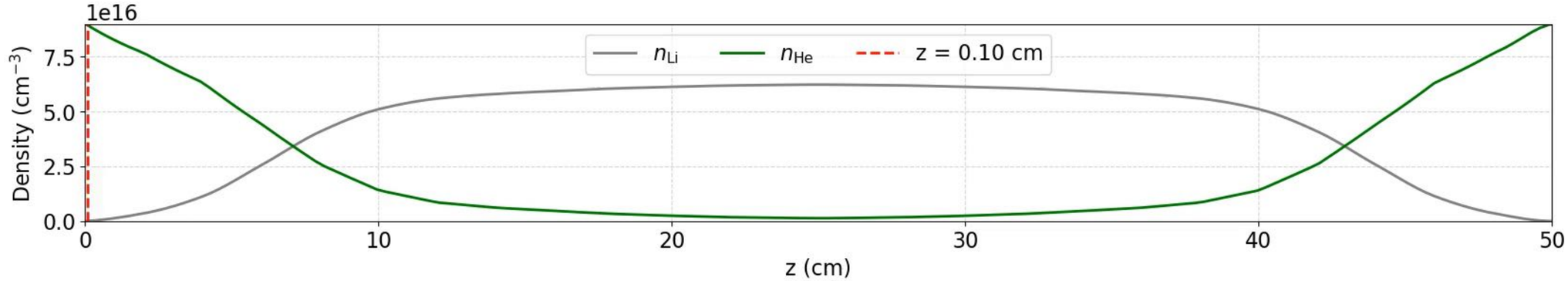

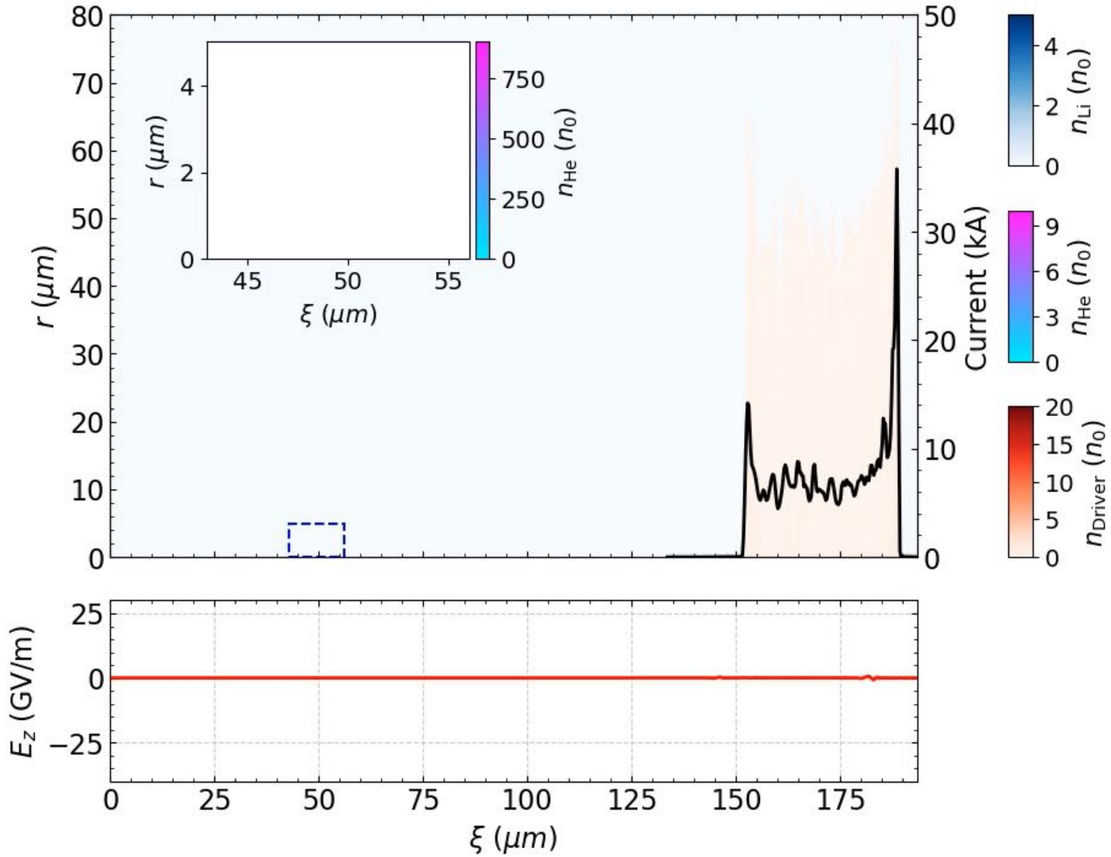

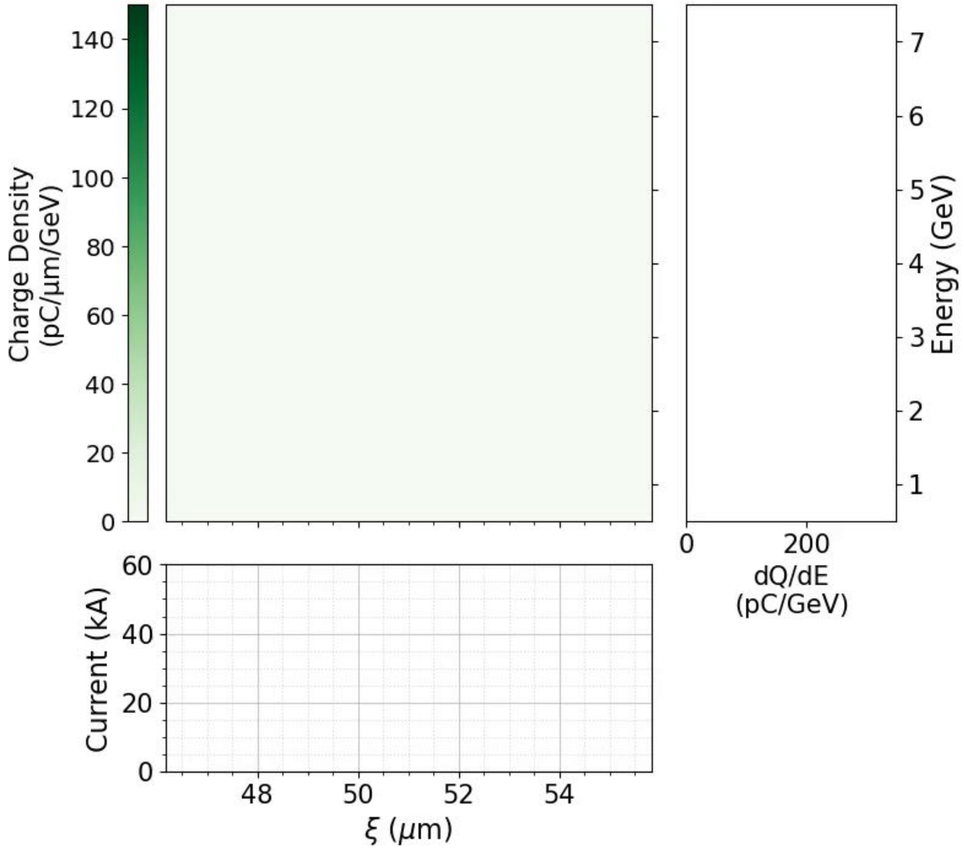

Waist scan

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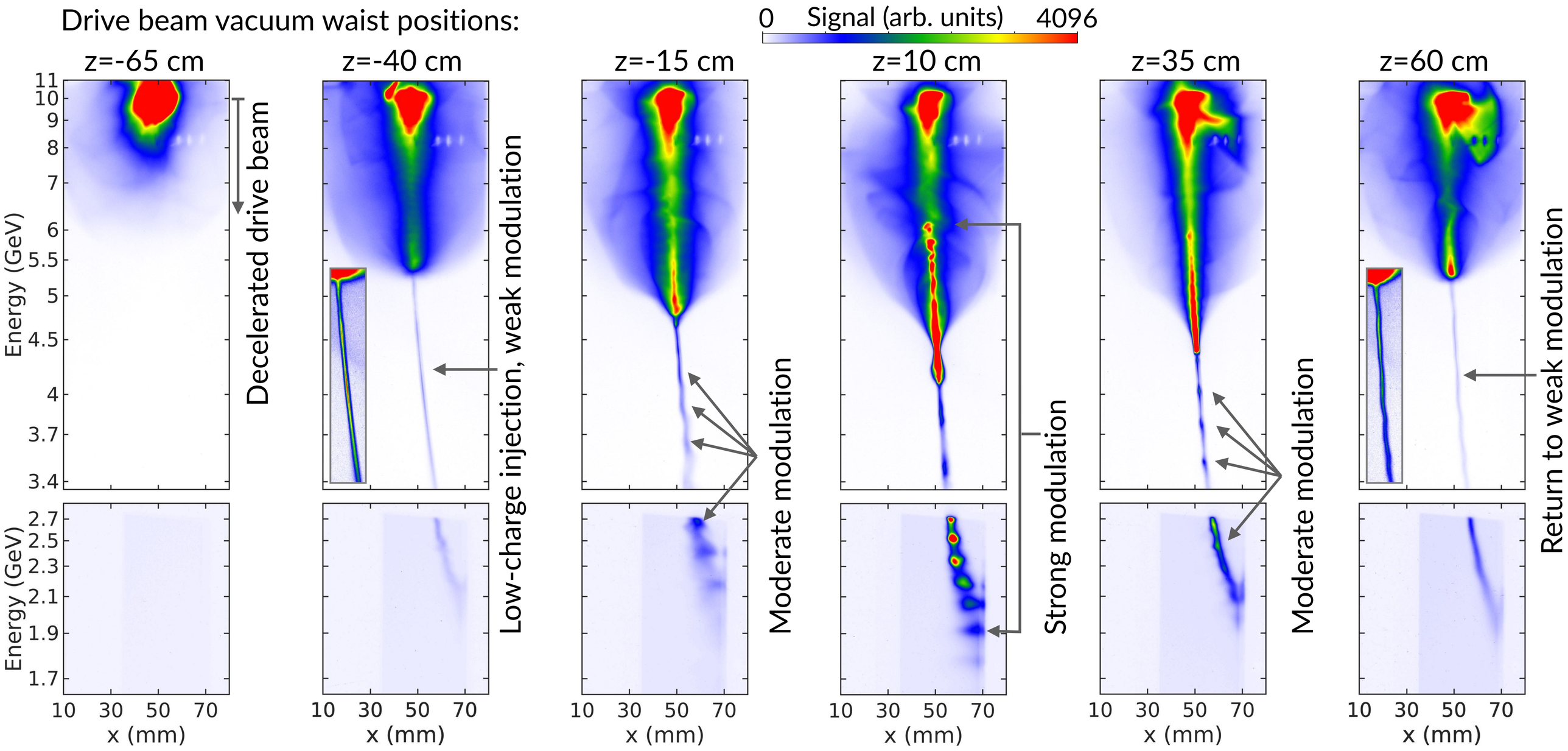
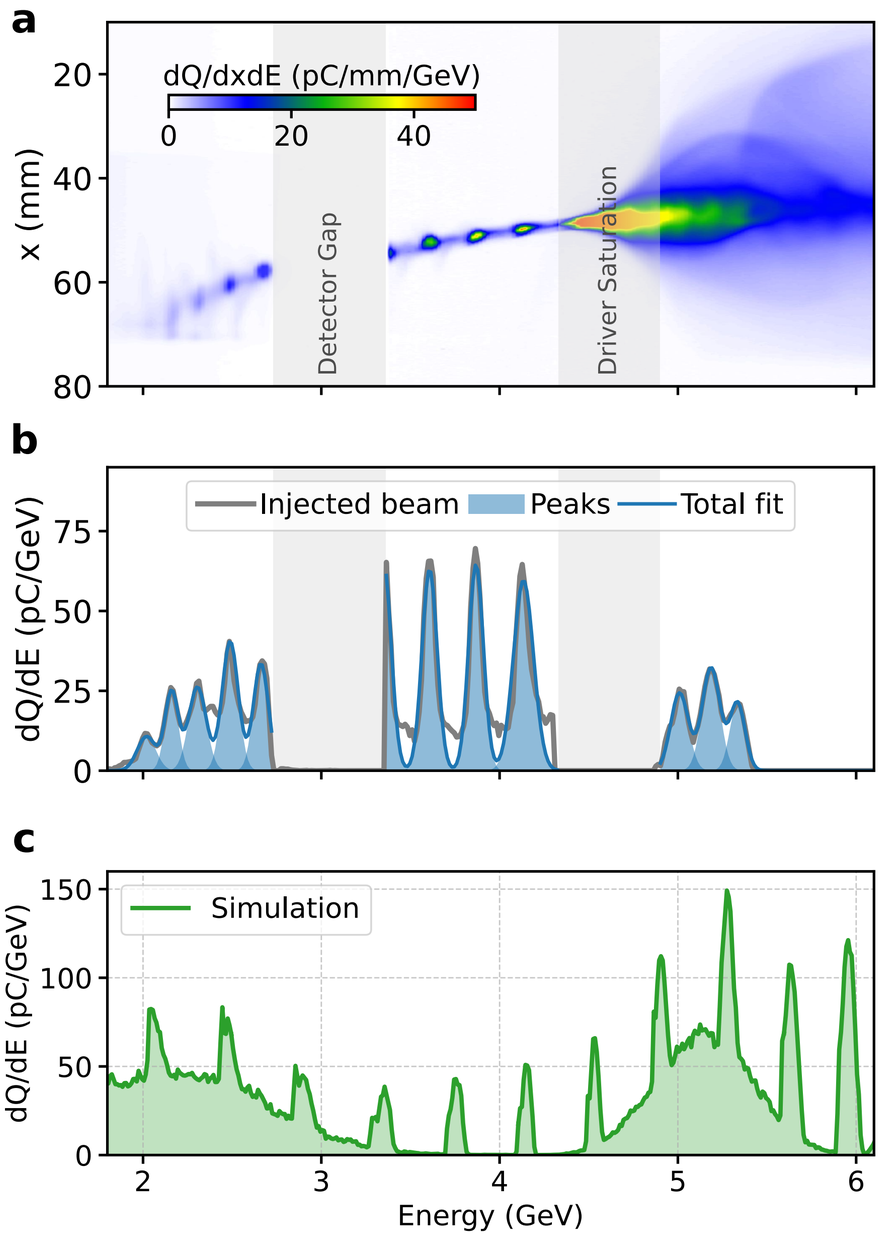
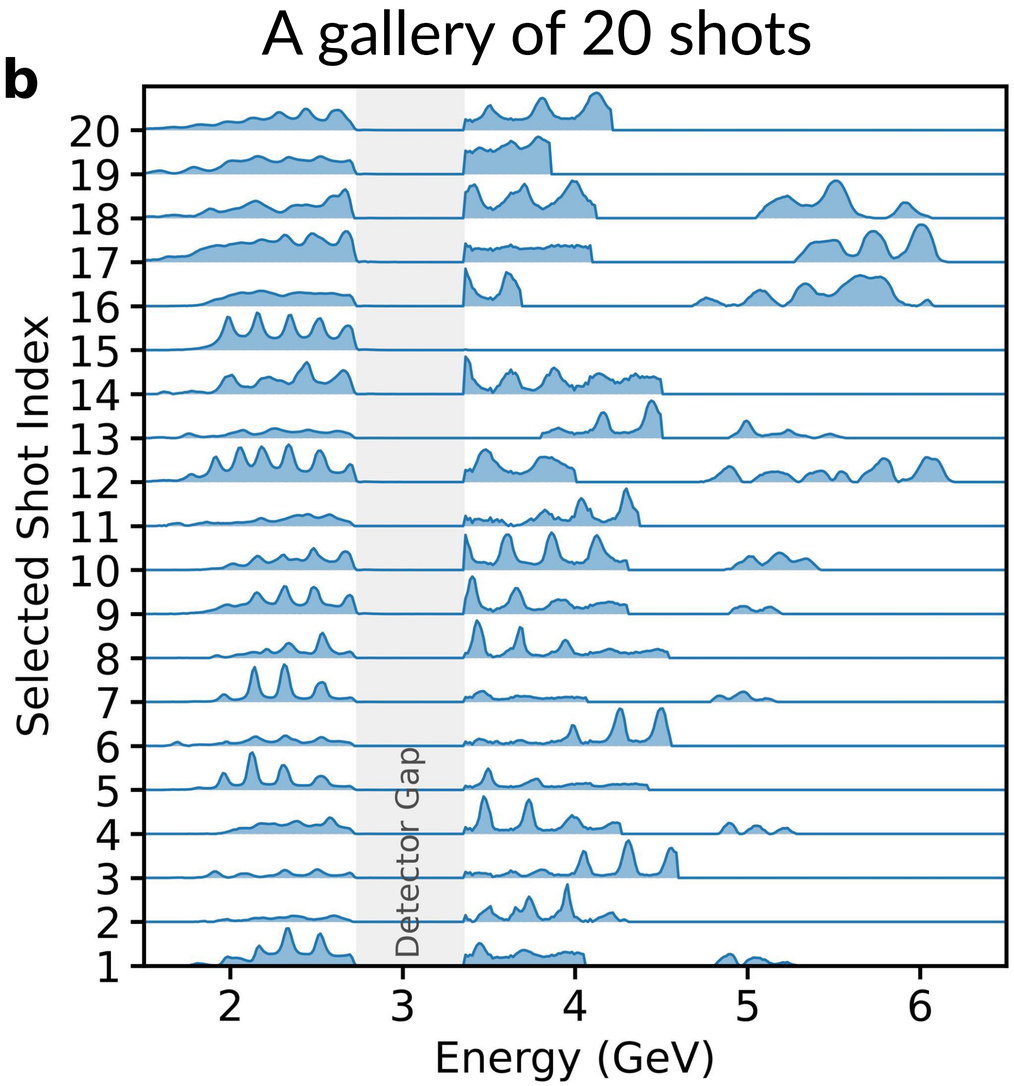


Combs at optimal waist location





Indirect evidence of microbunching from energy spectrum analysis

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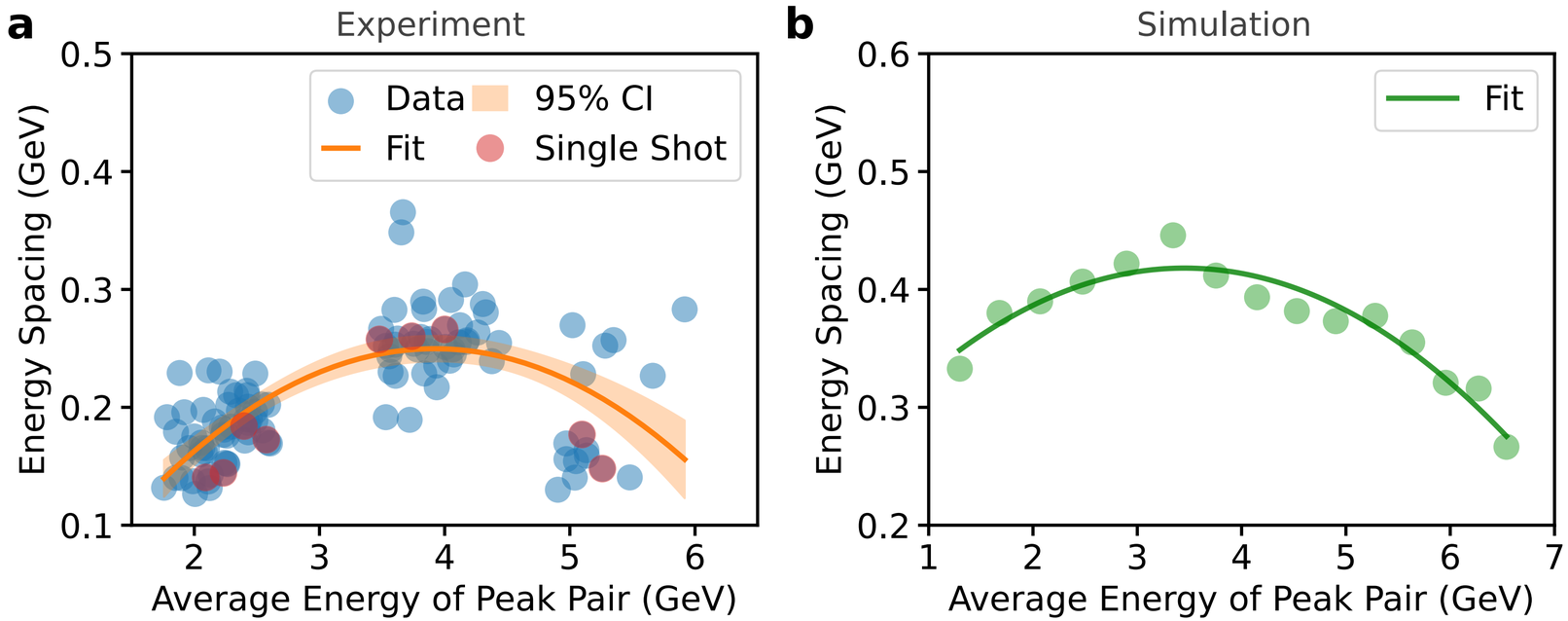
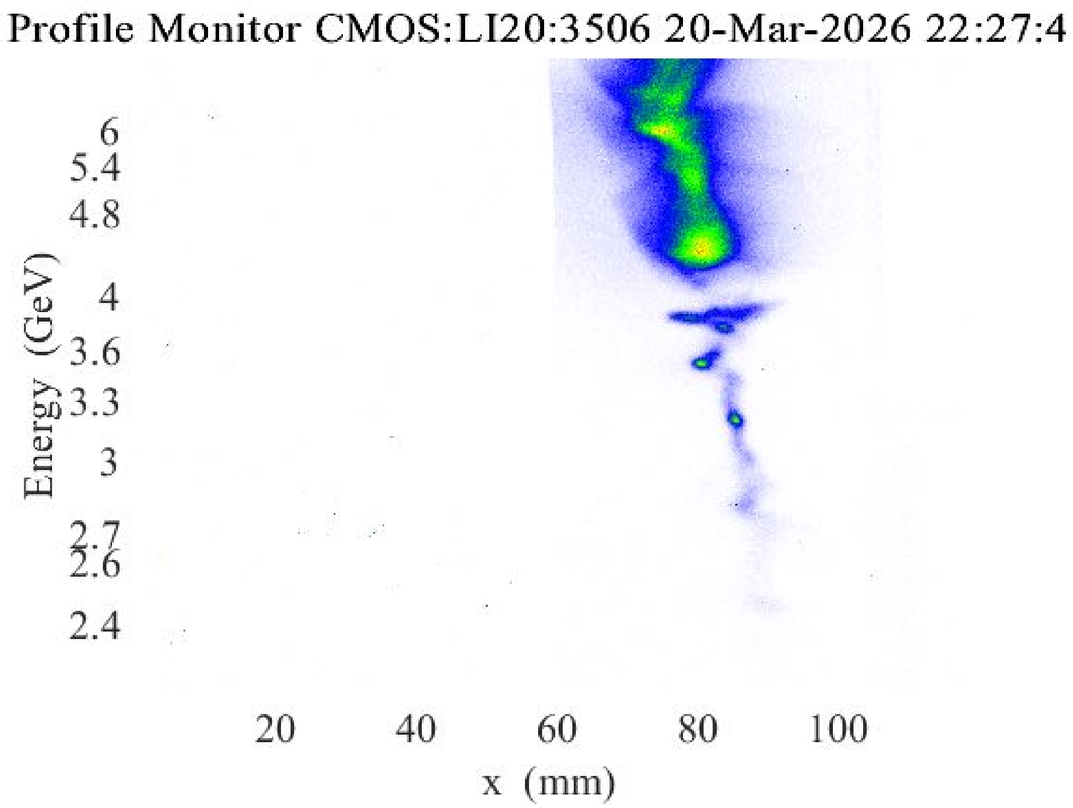
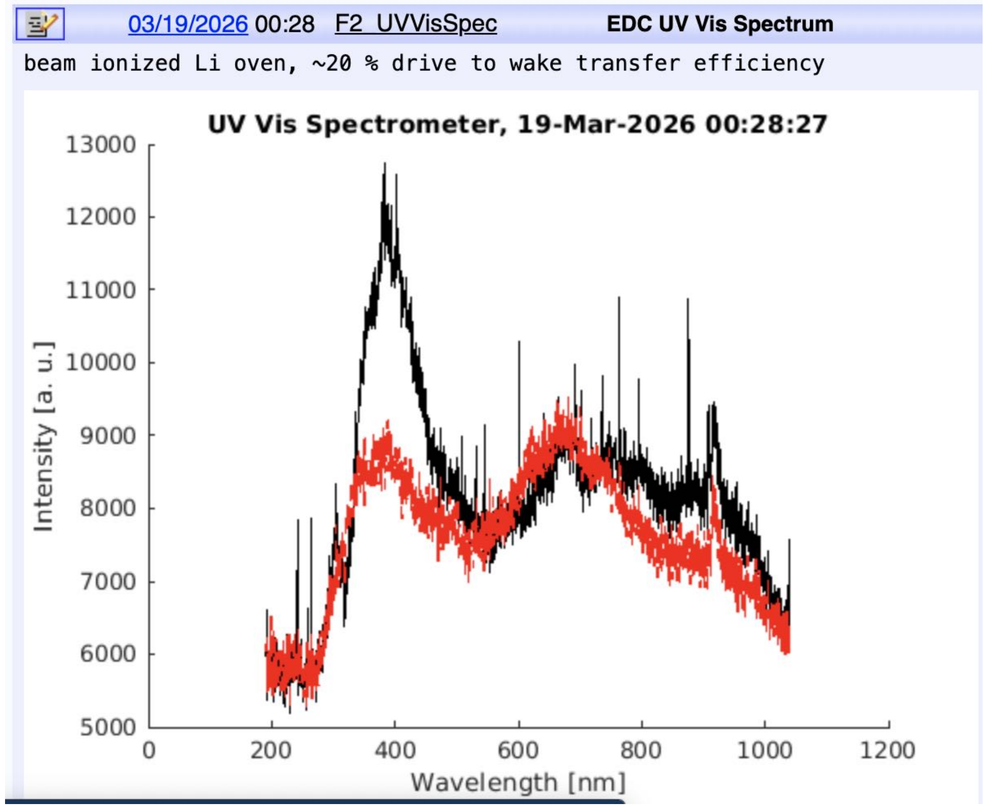


- Microbunches are short (sub-fs)
  - Data: spacing falls at high energy → early injected microbunches load the wake hard → several-kA current → pC ÷ kA = sub-fs
  - Sim: short trailing spike ionizes He in a narrow wake phase → born short
- Separated in time (few fs)
  - Data: all teeth share percent-level spread → overlap would broaden most → separated
  - Sim: density gradient maps injections to distinct positions → separated

The status of the multi-GeV electron comb paper

- It has finished review
- Two reviewers questioned the temporal structure of the comb
- Do we have new data for this?





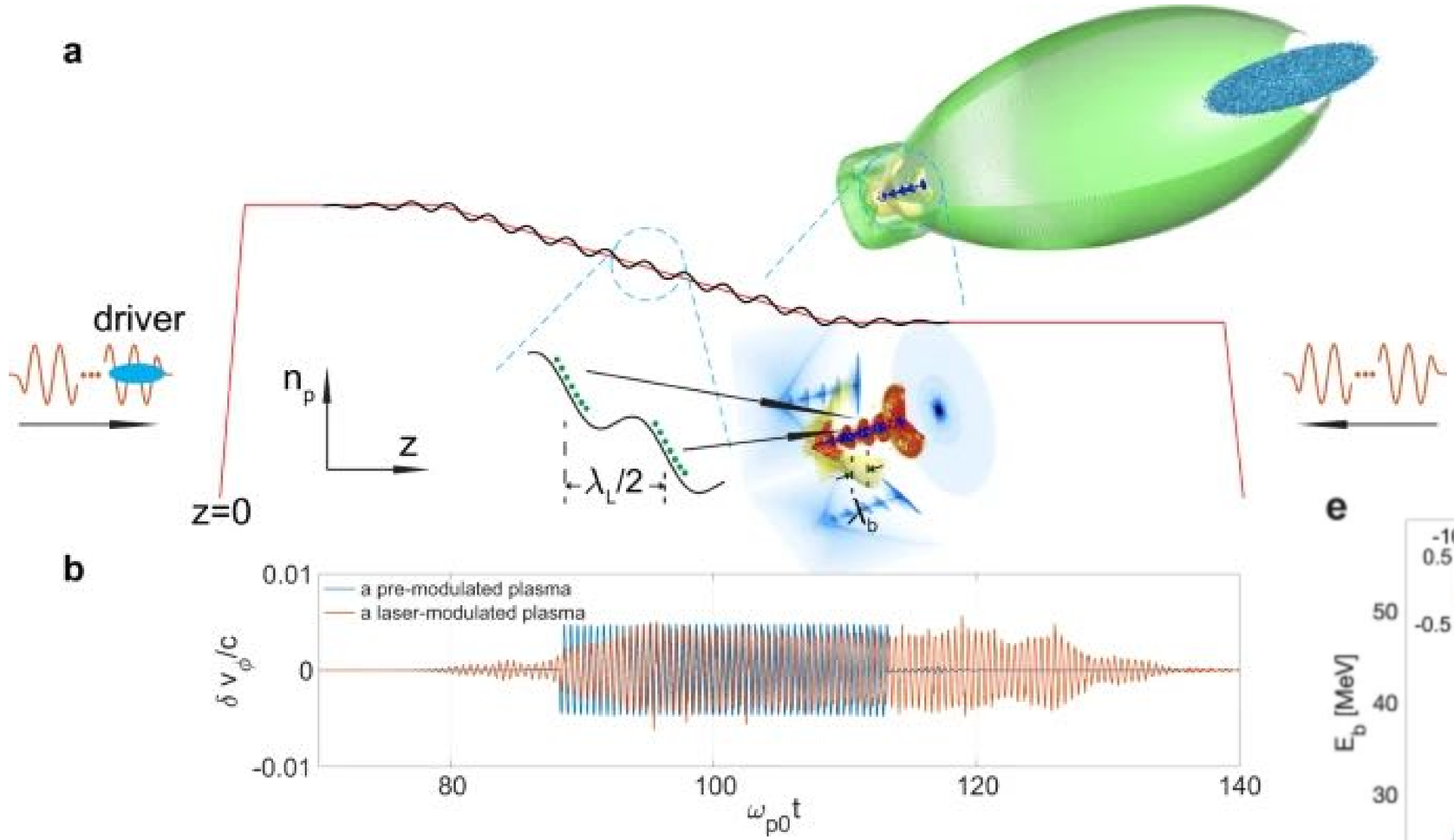
Next steps

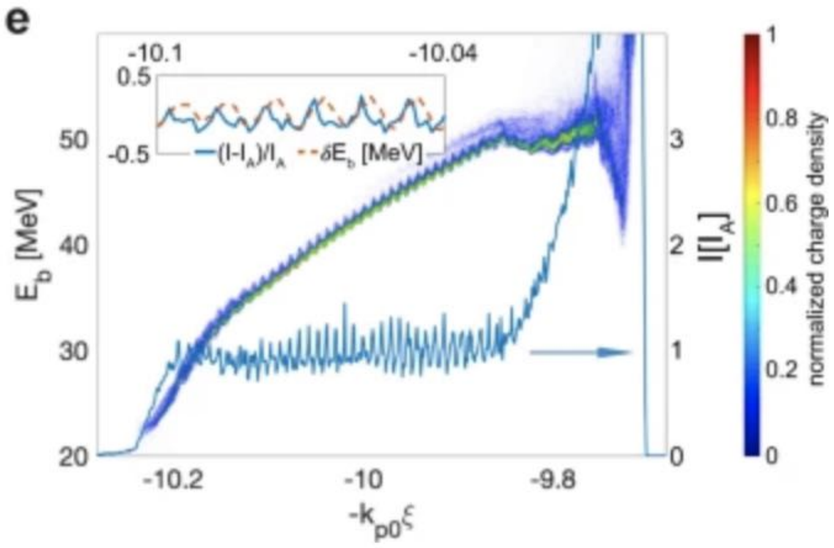
Updated goal: Generating stable, low-emittance, pre-bunched beams in a plasma wakefield accelerator

Plan:

- **FY 2026-27:**
  - **Experiment:**
    - laser pre-ionize the 15-cm jet and try the downramp injection experiment again
    - modulated downramp injection
    - post-compression
  - **Publications:**
    - finish the Multi-GeV electron comb and the PARC paper;
    - more if we have new data

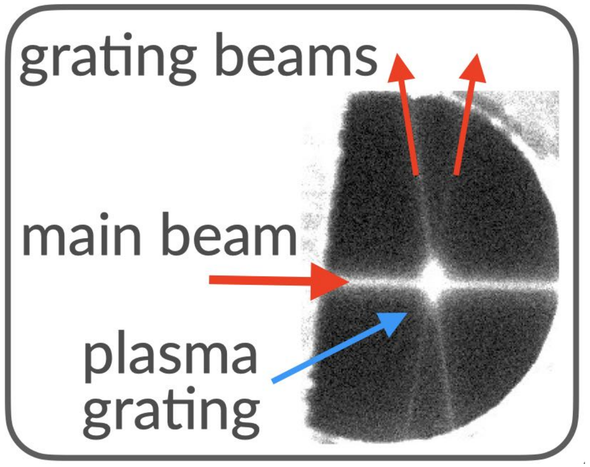
Modulated downramp injection: the concept



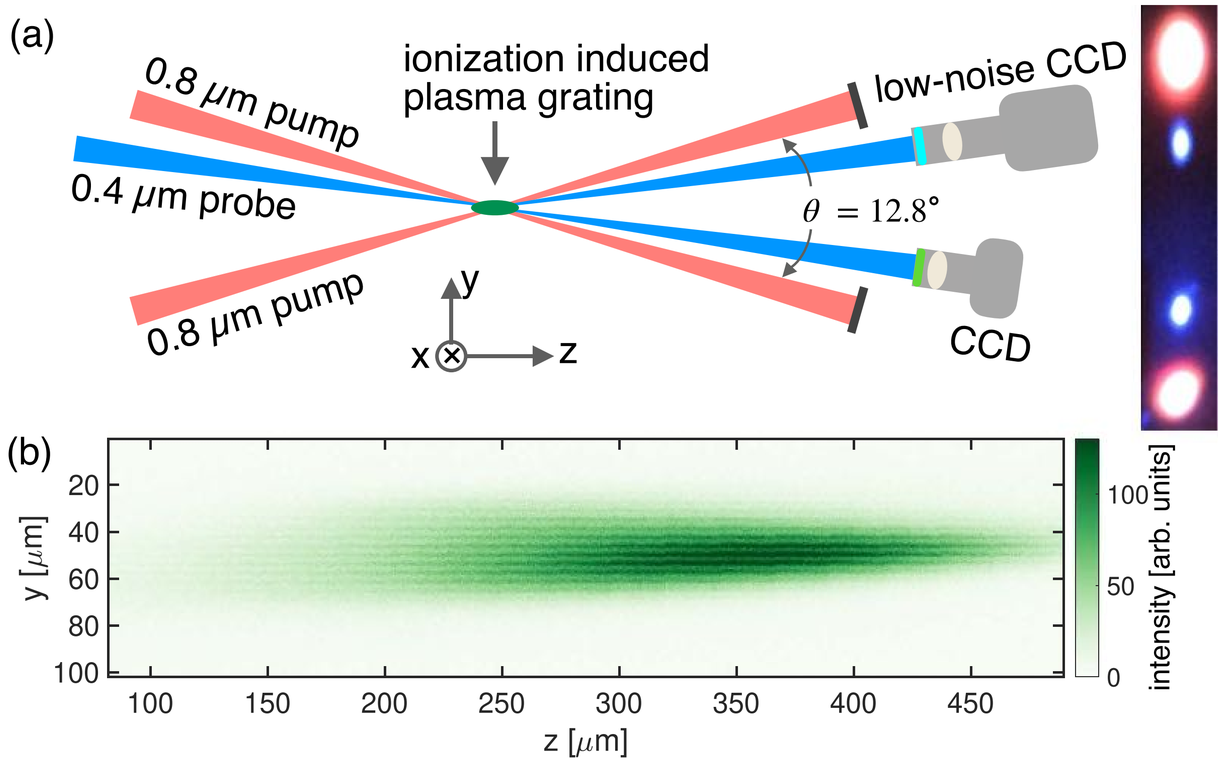


Xu, Xinlu, et al. "Generation of ultrahigh-brightness pre-bunched beams from a plasma cathode for X-ray free-electron lasers." *Nature communications* 13.1 (2022): 3364.

How to create a modulated downramp



- Use a plasma grating to modulate the downramp
- Tested at UCLA
- Self-scattering can serve as an indicator of the grating, does not need an external probe



Modulated downramp to generate bunched beams

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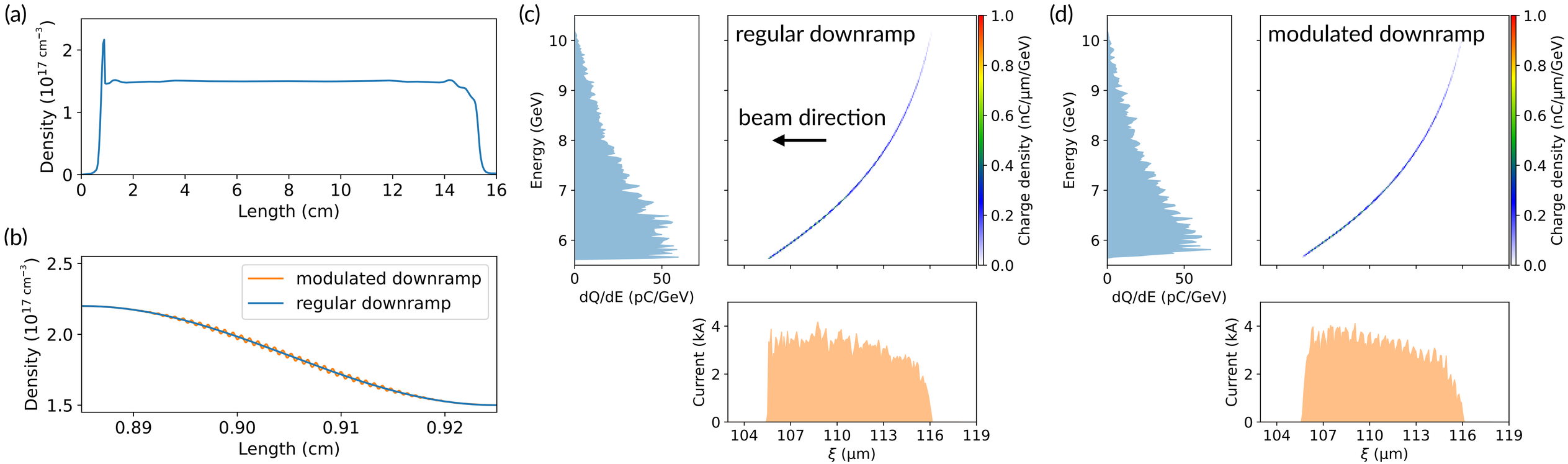
- laser beams intersecting angle: 0.1 rad
- downramp modulation period: 8 μm
- injected beam bunches at ~500 nm (makes diagnostic easier)



Post-compression

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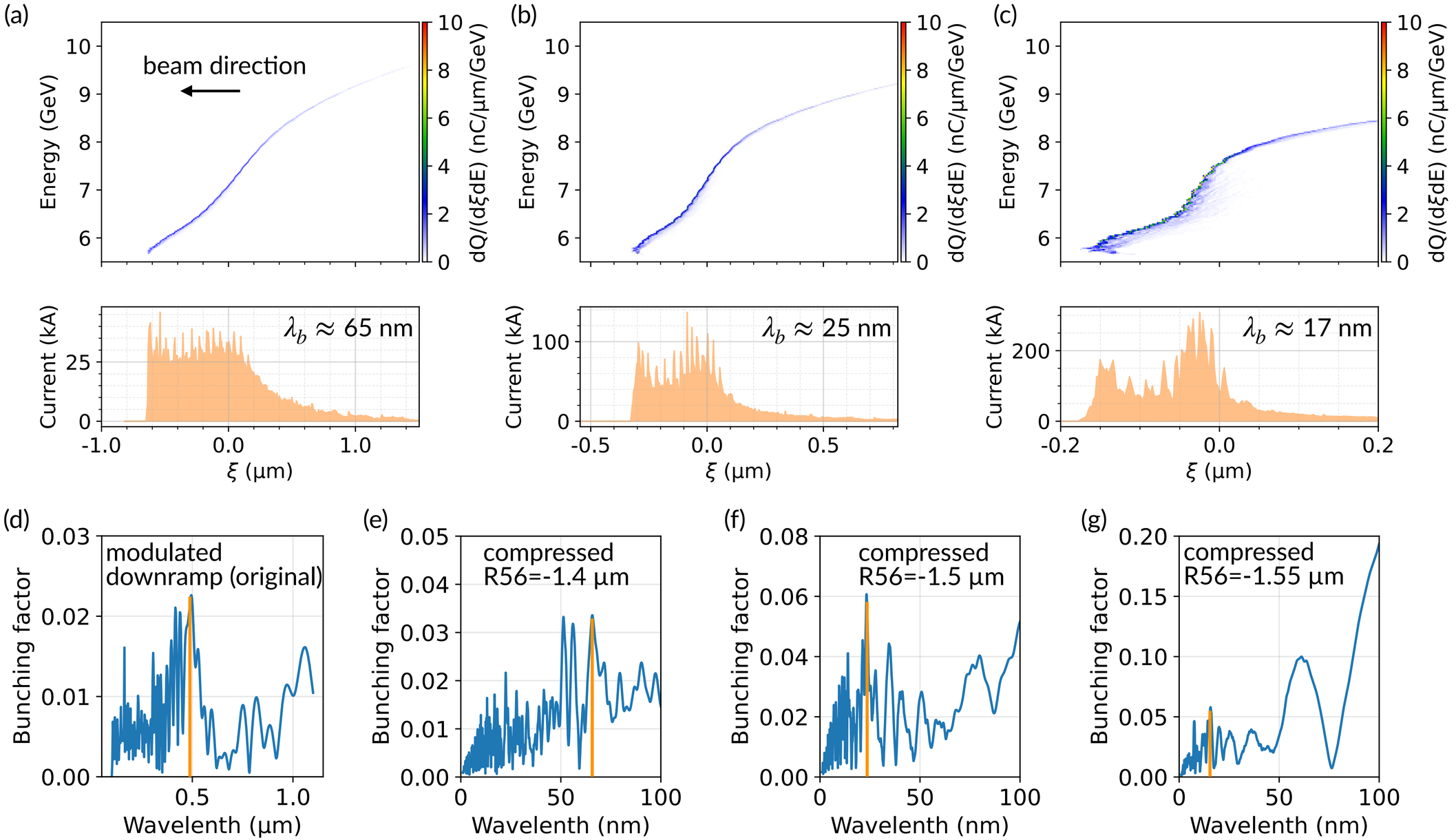
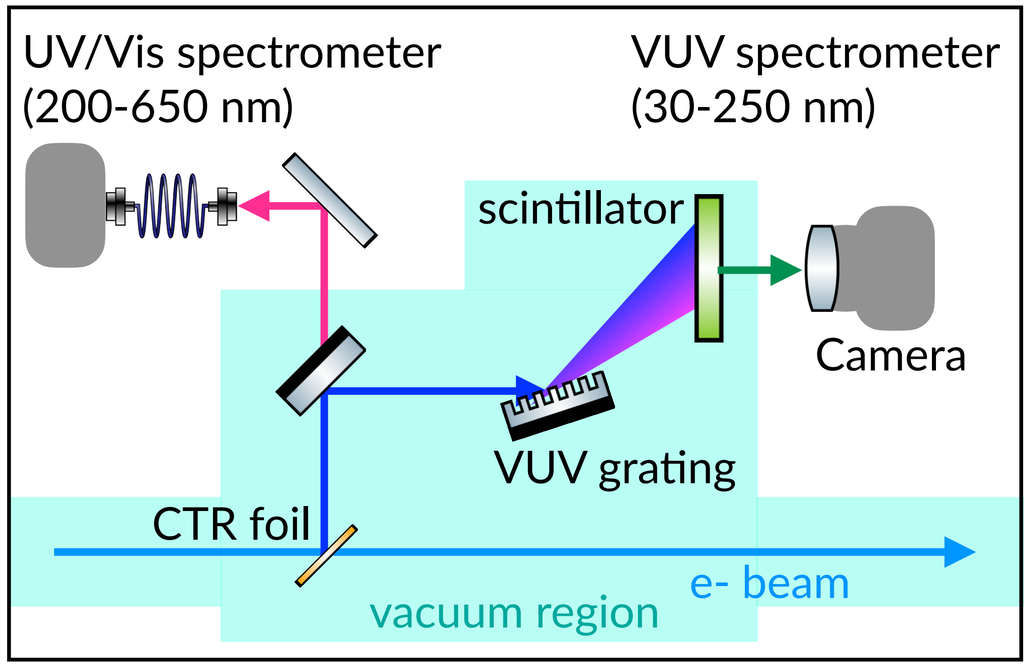


Diagnostics

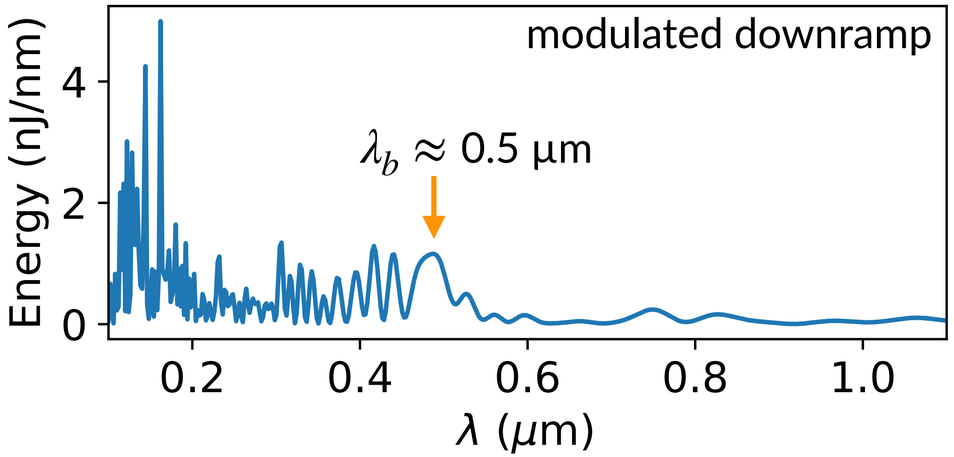
Modulated energy spectrum directly

CTR spectrum

(a)



(b)



(c)