

# E304 Downramp Injection: Results and Analysis Insights

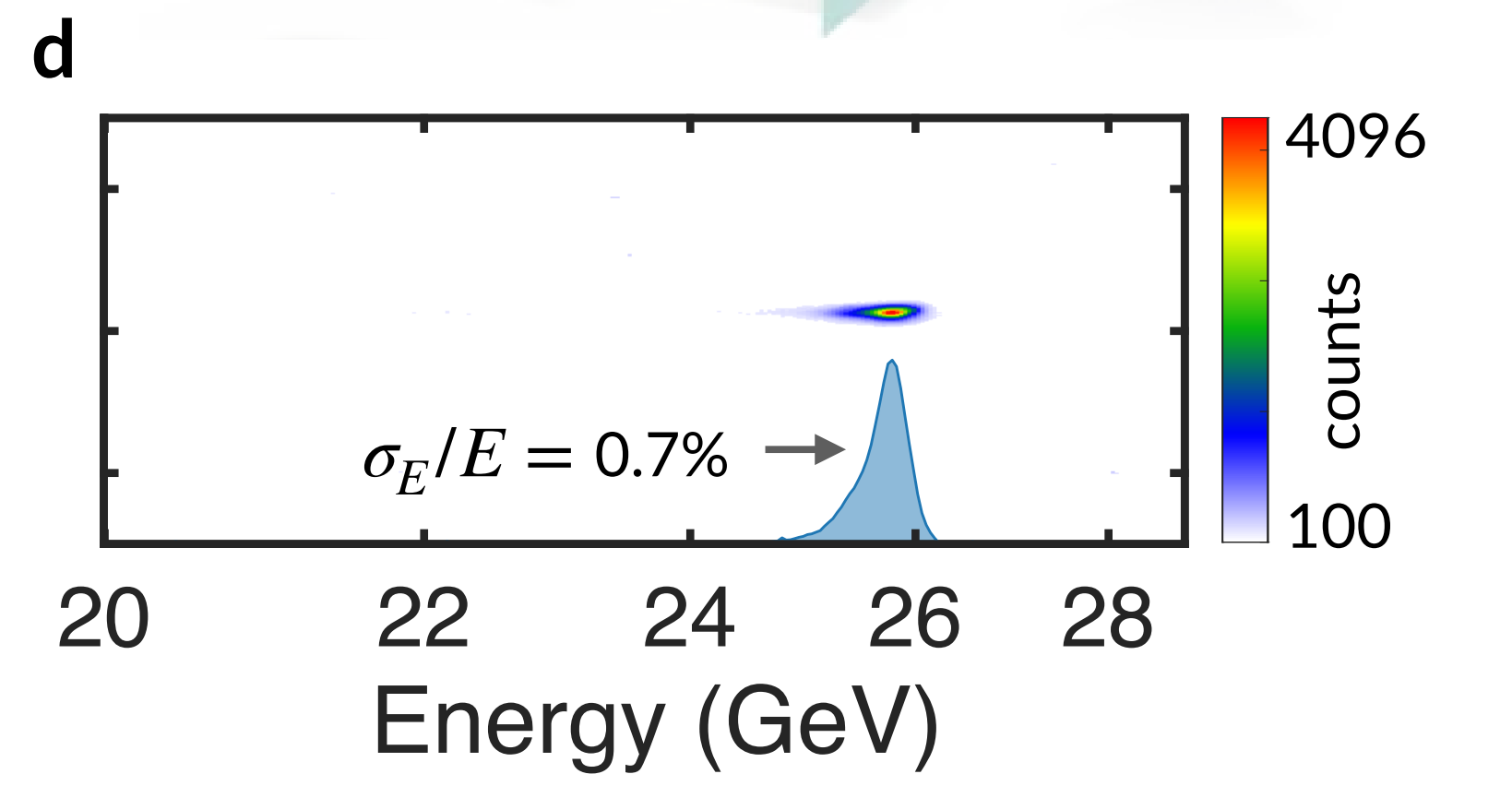
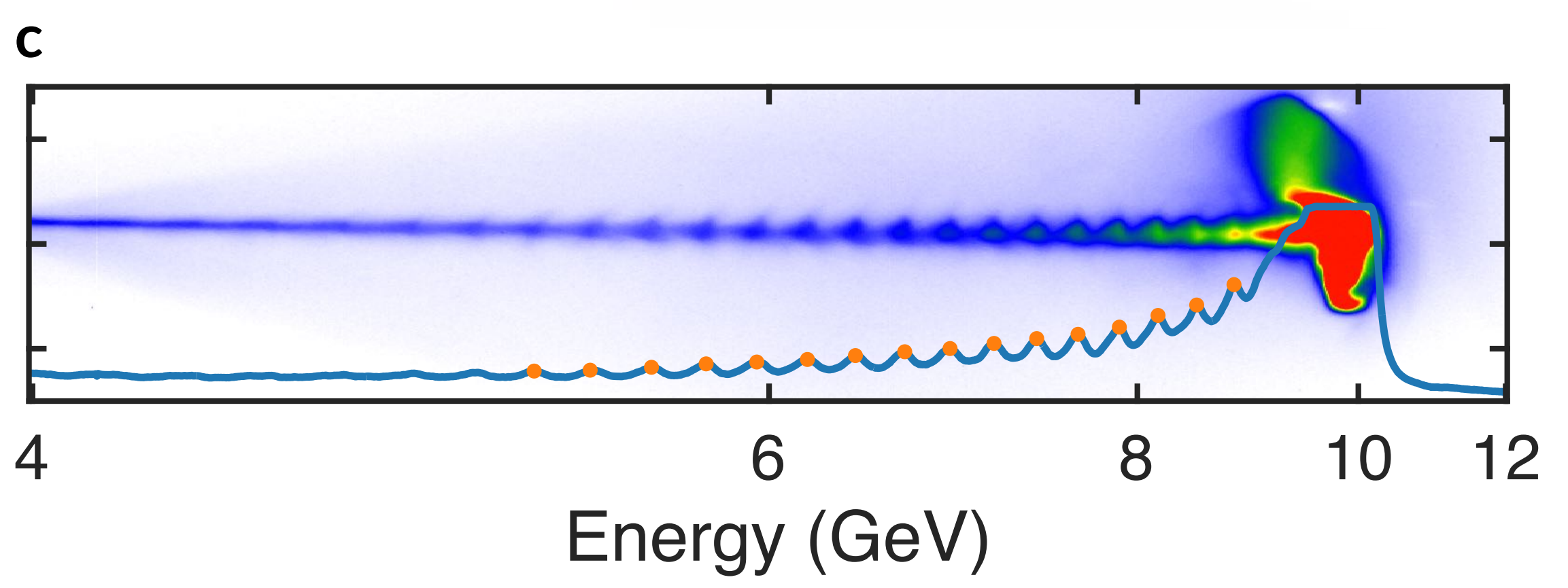
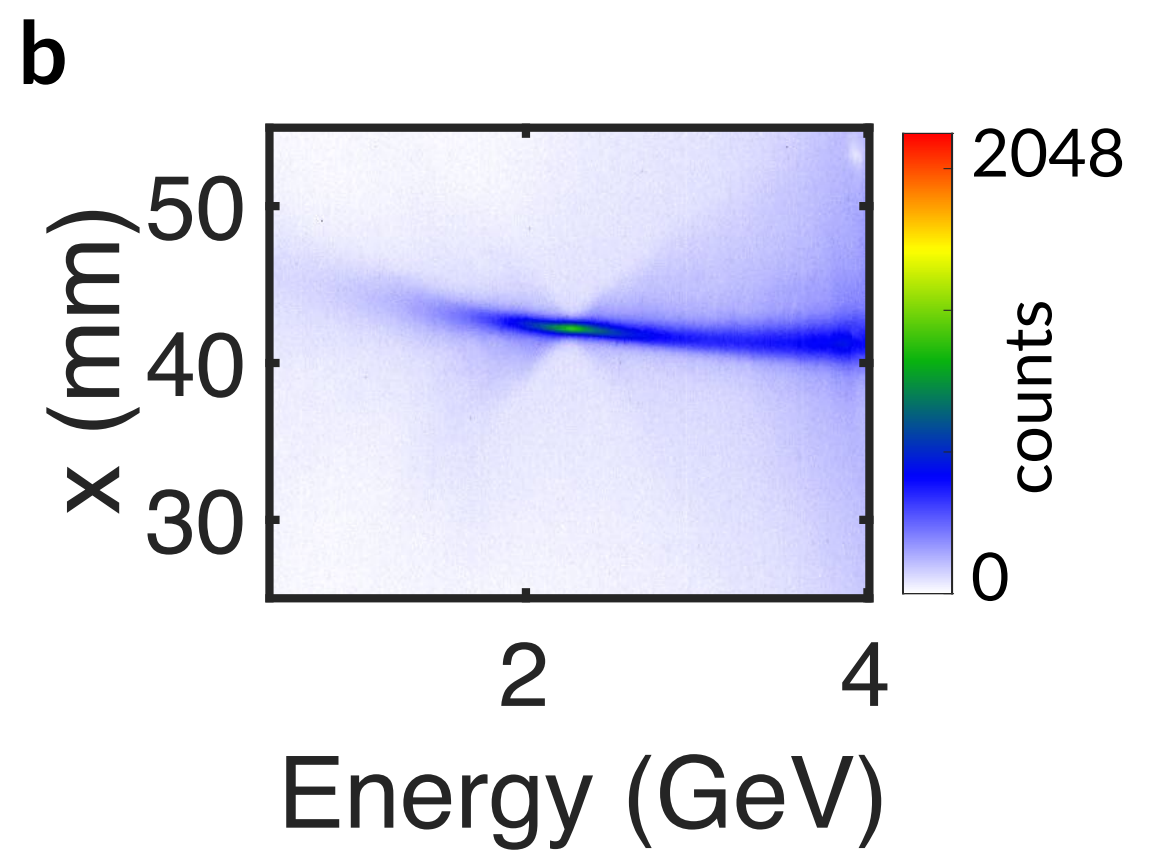
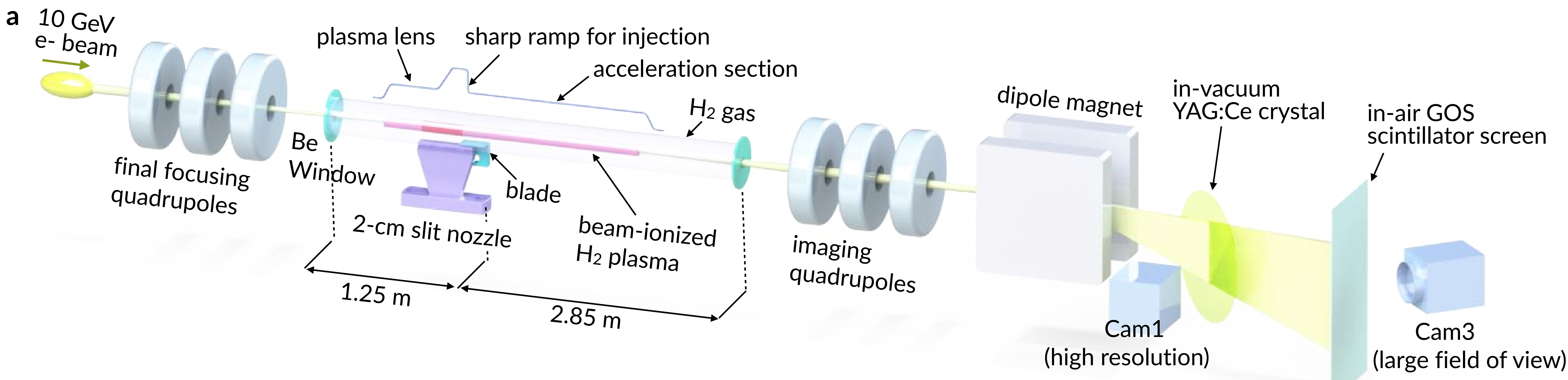
Chaojie Zhang, Chan Joshi  
(E300 collaboration)

*July 23, 2025*

- We collected good data from FY24- high energy, low-emittance downramp injected beams
- So we decided to focus on thorough data analysis instead of rushing to get more data
- We have analyzed some of the most interesting data and written up a paper
- In this paper, we show that a PWFA can act as a transformer to simultaneously boost electron beam energy and brightness
- **The paper is under review by Nat. Communications**
  
- Today I will show you what we found and what might be helpful to other experiments too
- I will go through the NC figures to discuss the physics and methods

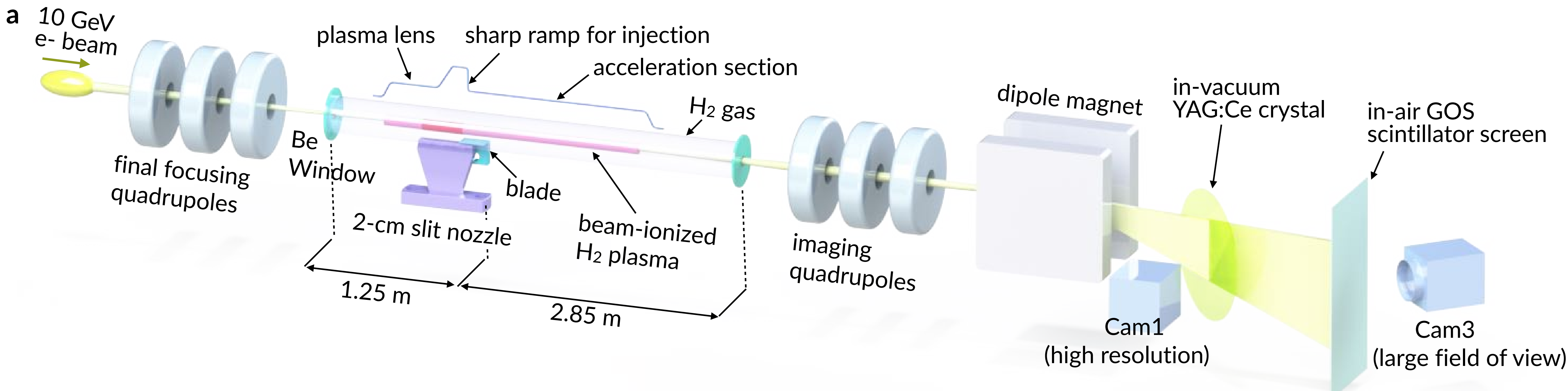
We have demonstrated that a Plasma Wakefield Accelerator can act as a transformer to simultaneously boost energy and brightness of a self-injected trailing beam, with remarkable beam qualities (20+ GeV energy, <1% energy spread,  $\mu\text{m}$  level emittance, 10s pC charge, kA peak current), over meter-scale distances with pump depletion of the drive beam.

# E304 experimental setup, pump depletion and injection



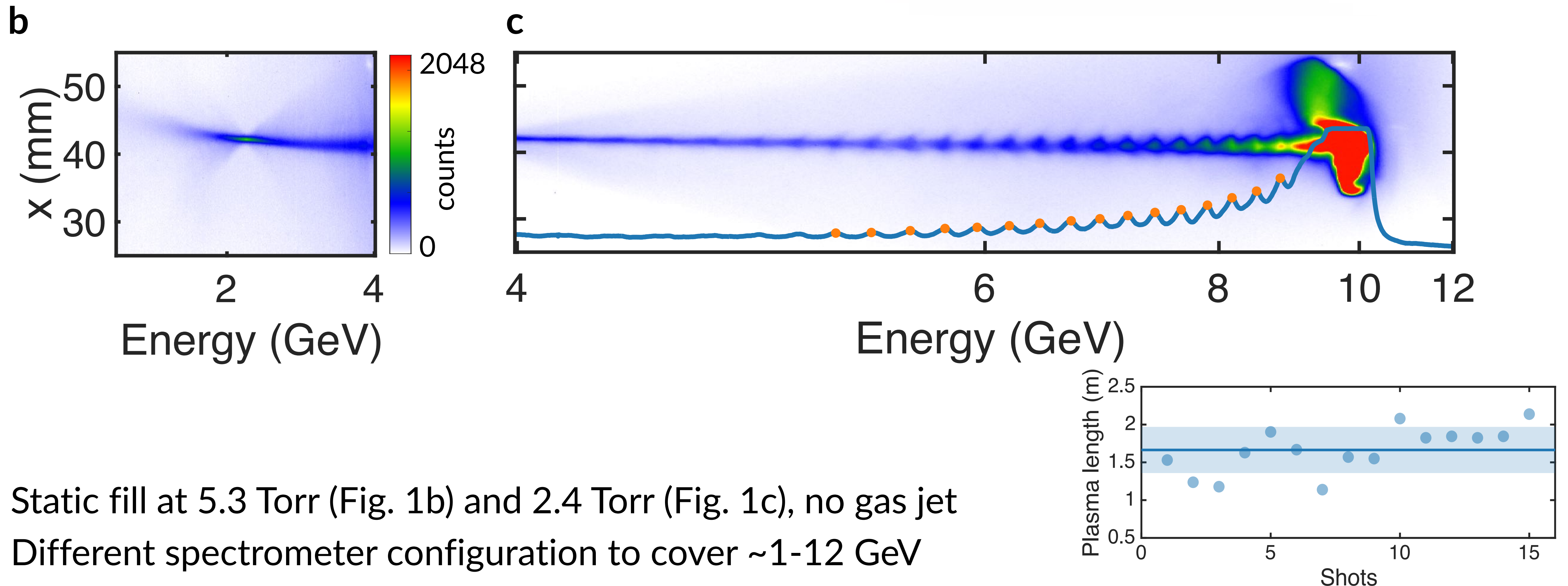
# Figure 1a: Experimental setup

- The novel plasma source consists of three sections:
  - a thick plasma lens to further focus the drive bunch to enable the generation of nonlinear wake
  - a sharp downramp for injection
  - a meter-scale accelerating section
- injector-accelerator setup allows self-matching of the injected bunch into the accelerator
- beam-ionized plasma within the 4-meter-long gas region



# Figure 1b and c: Pump depletion

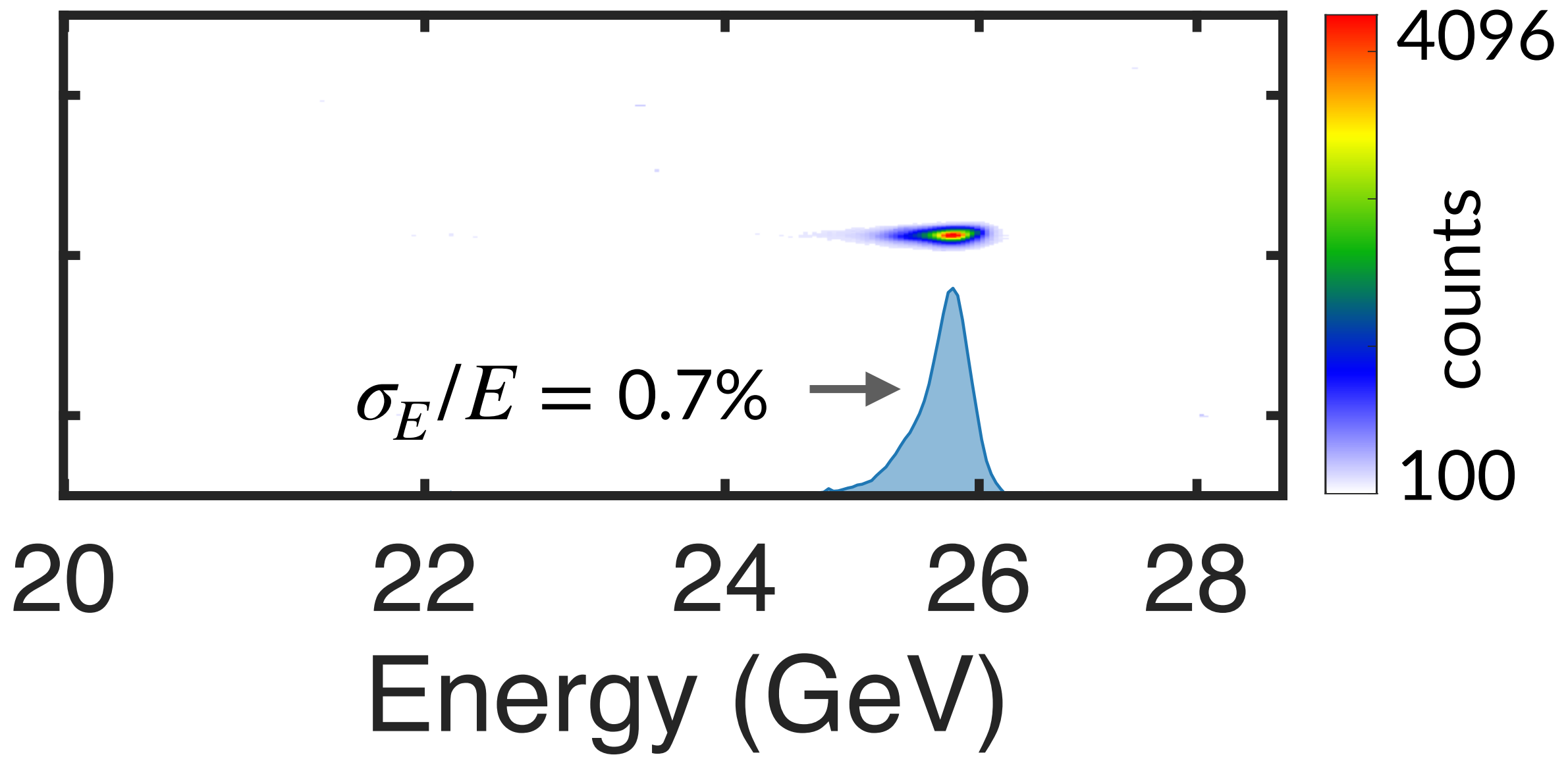
- Visual evidence of pump energy depletion (down to  $\sim 1$  GeV)
- Betatron oscillation (modulation in the energy loss spectrum, 1c)
- deduced emittance of the drive bunch:  $73 \mu\text{m}$  (3.7 times growth from the initial  $20 \mu\text{m}$  emittance)
- deduced plasma length:  $1.37$  m for this shot,  $1.7 \pm 0.3$  m for many other shots in this dataset



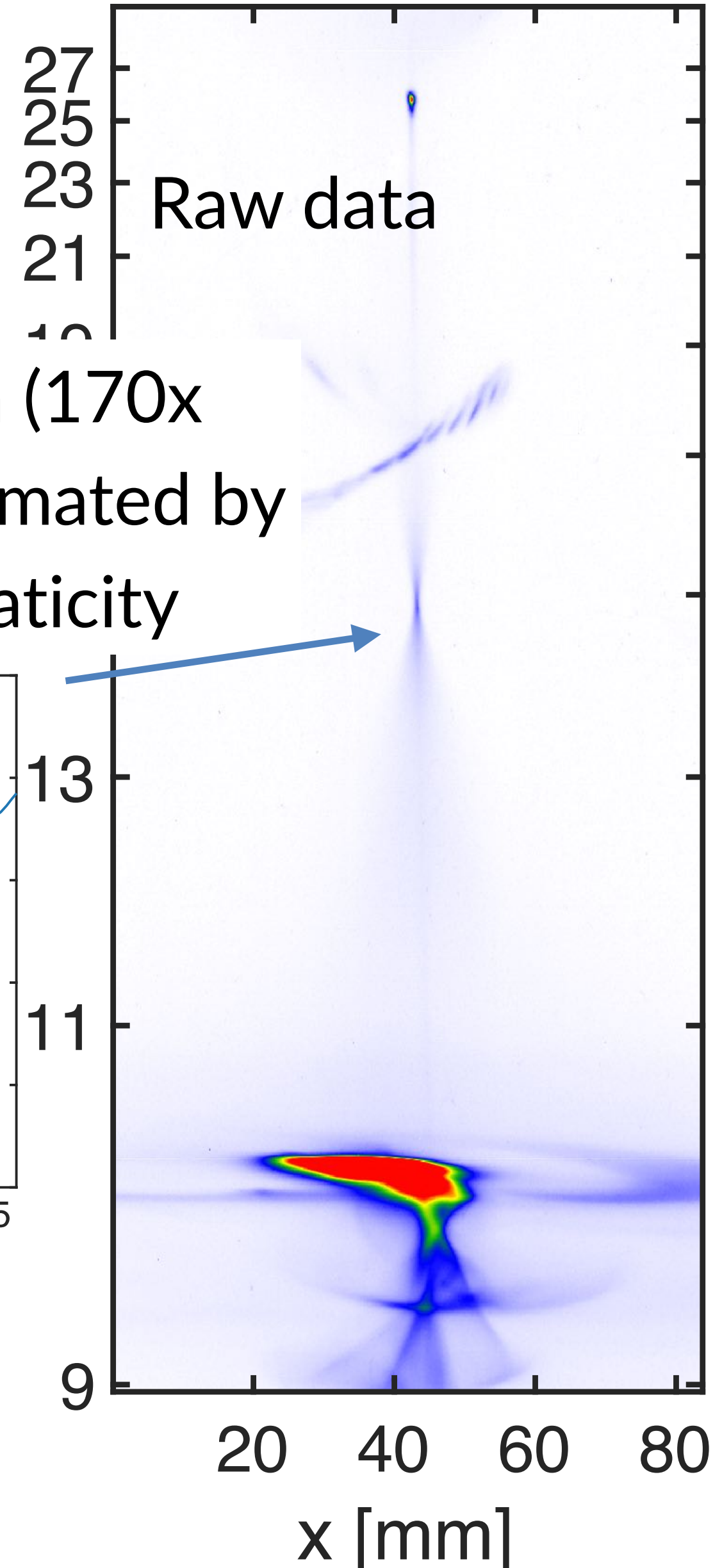
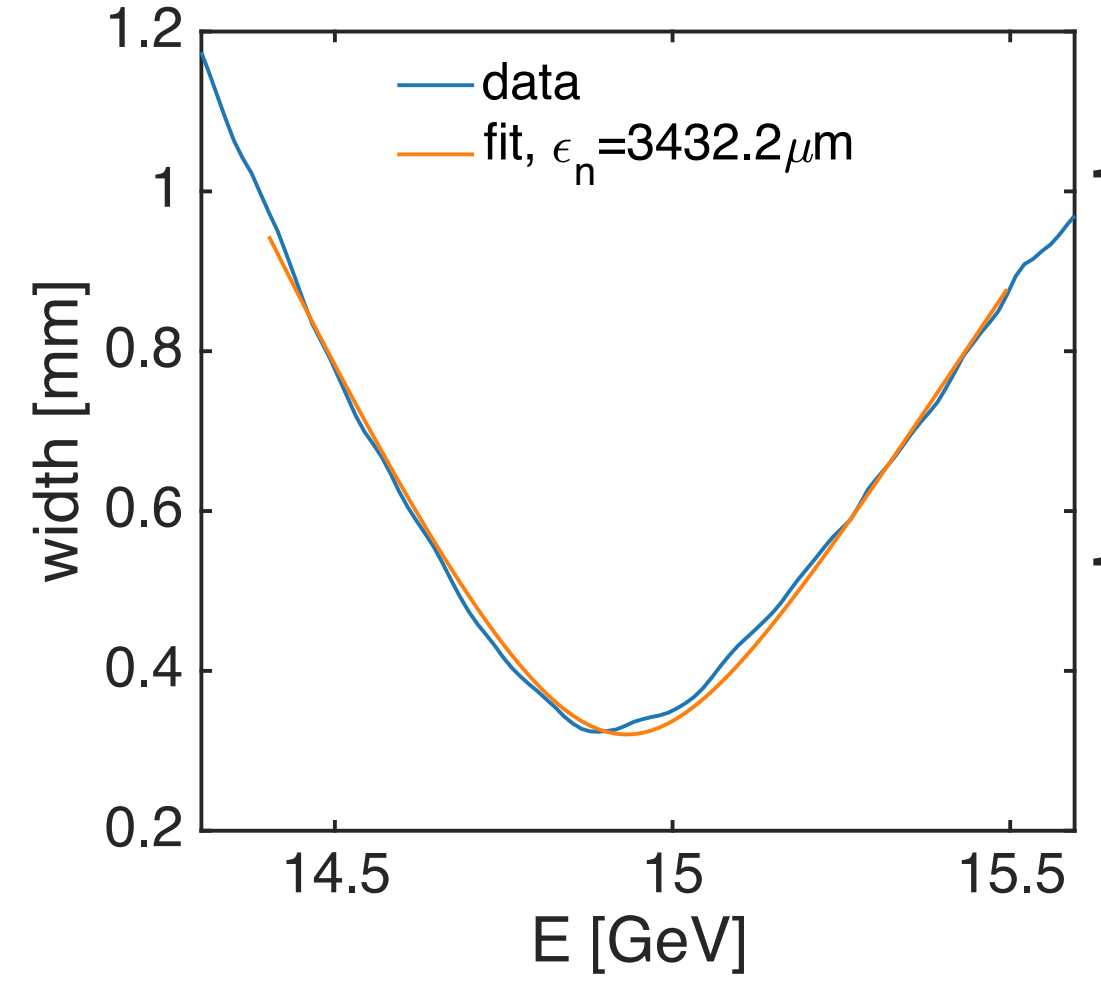
- Static fill at 5.3 Torr (Fig. 1b) and 2.4 Torr (Fig. 1c), no gas jet
- Different spectrometer configuration to cover  $\sim 1$ -12 GeV

# Figure 1d: Injected bunch

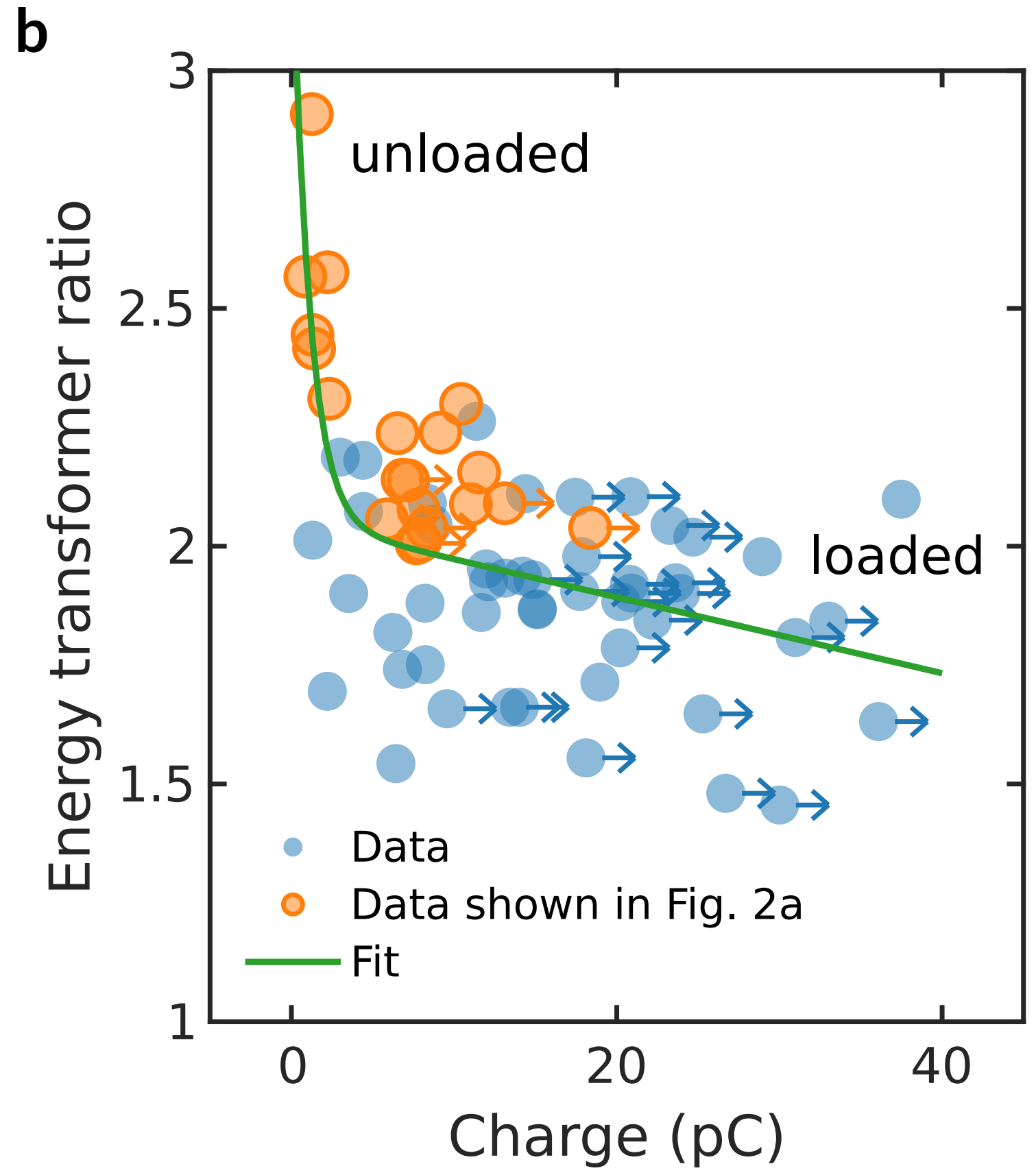
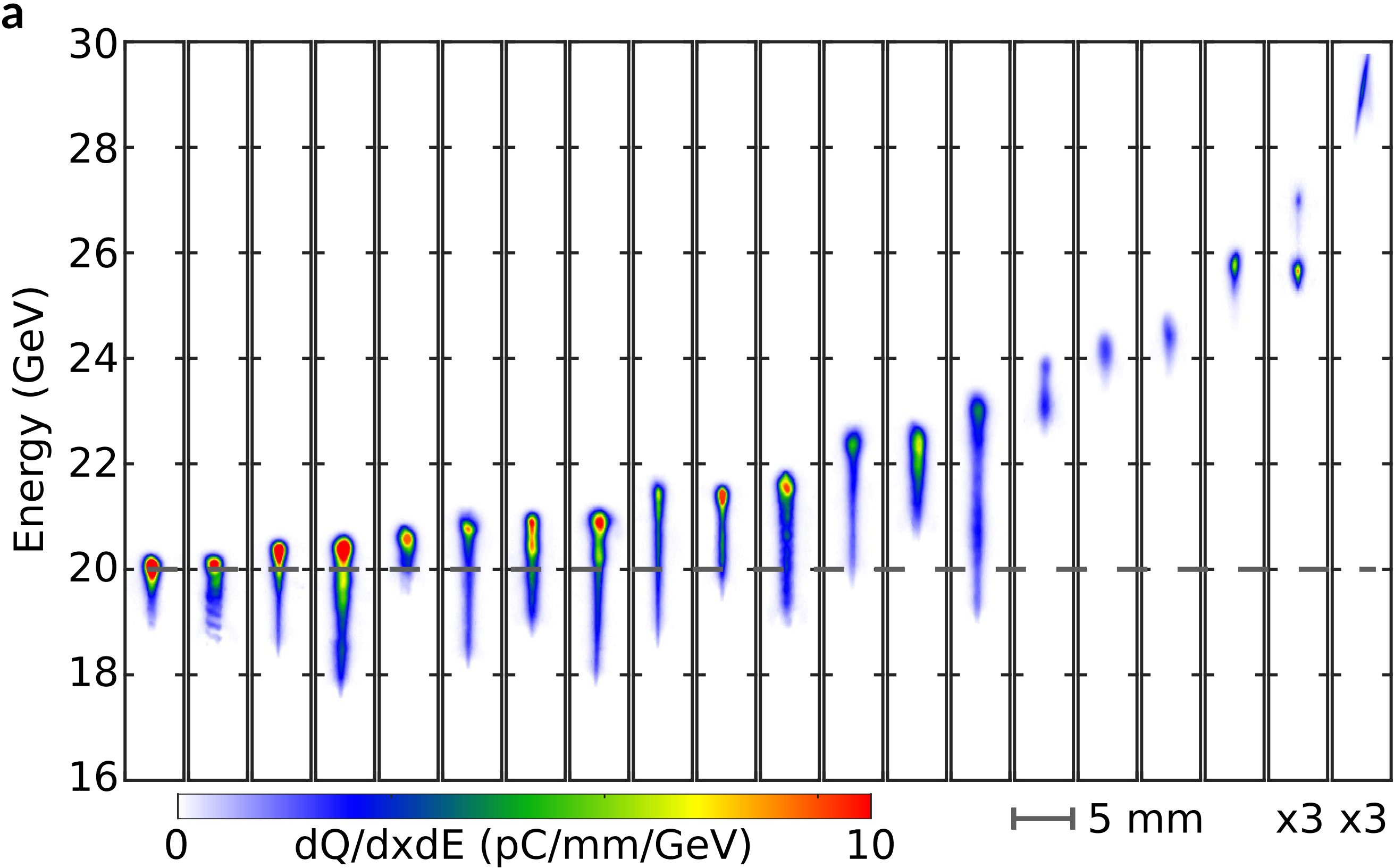
- An example of the injected bunch with good quality:
  - 26 GeV energy gain, 0.7% rms energy spread, 2.3 pC of charge
  - Small divergence even far off the quadrupole focusing energy (15 GeV)

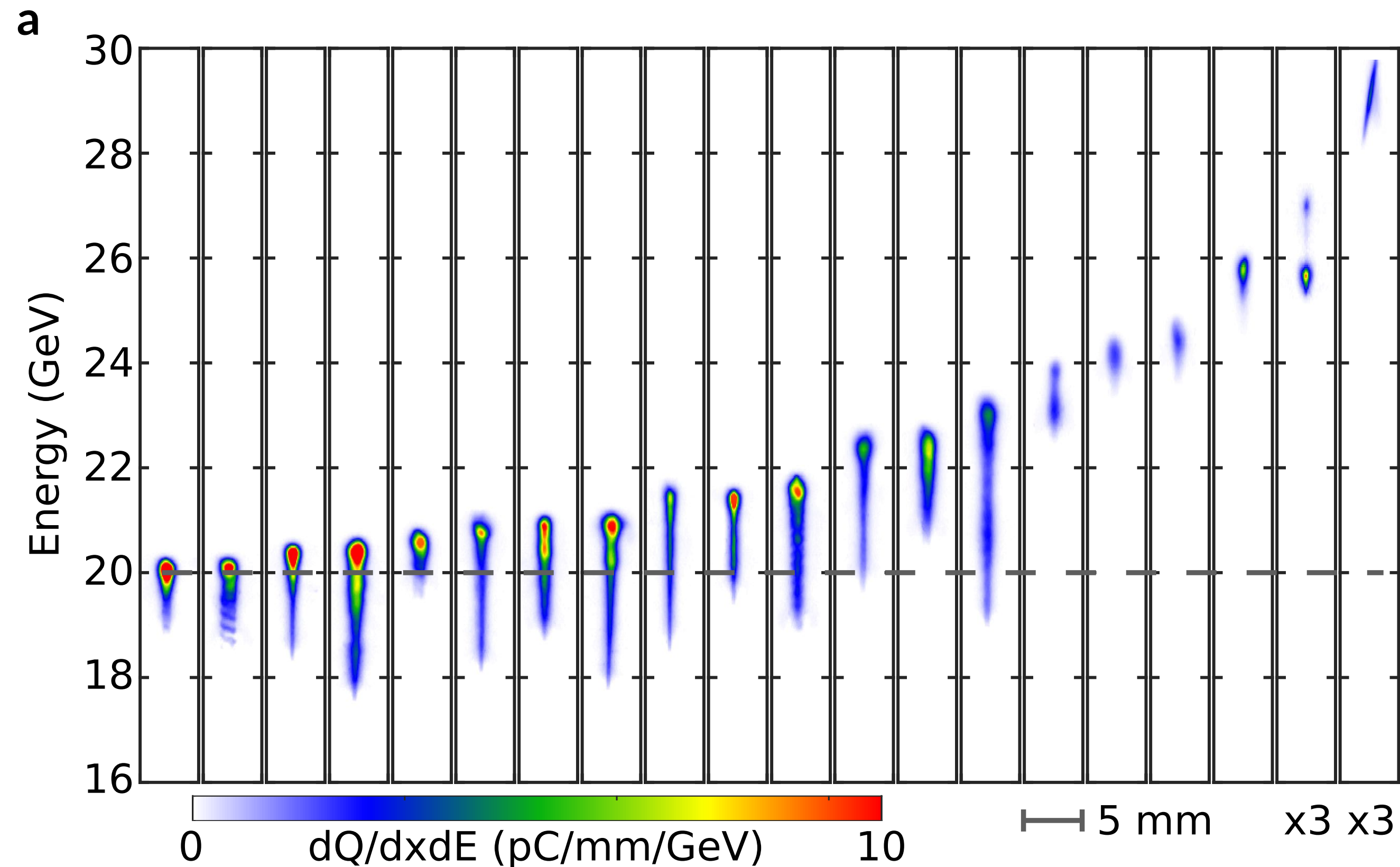


drive emittance: 3400  $\mu\text{m}$  (170x increase), may be overestimated by a few times due to chromaticity

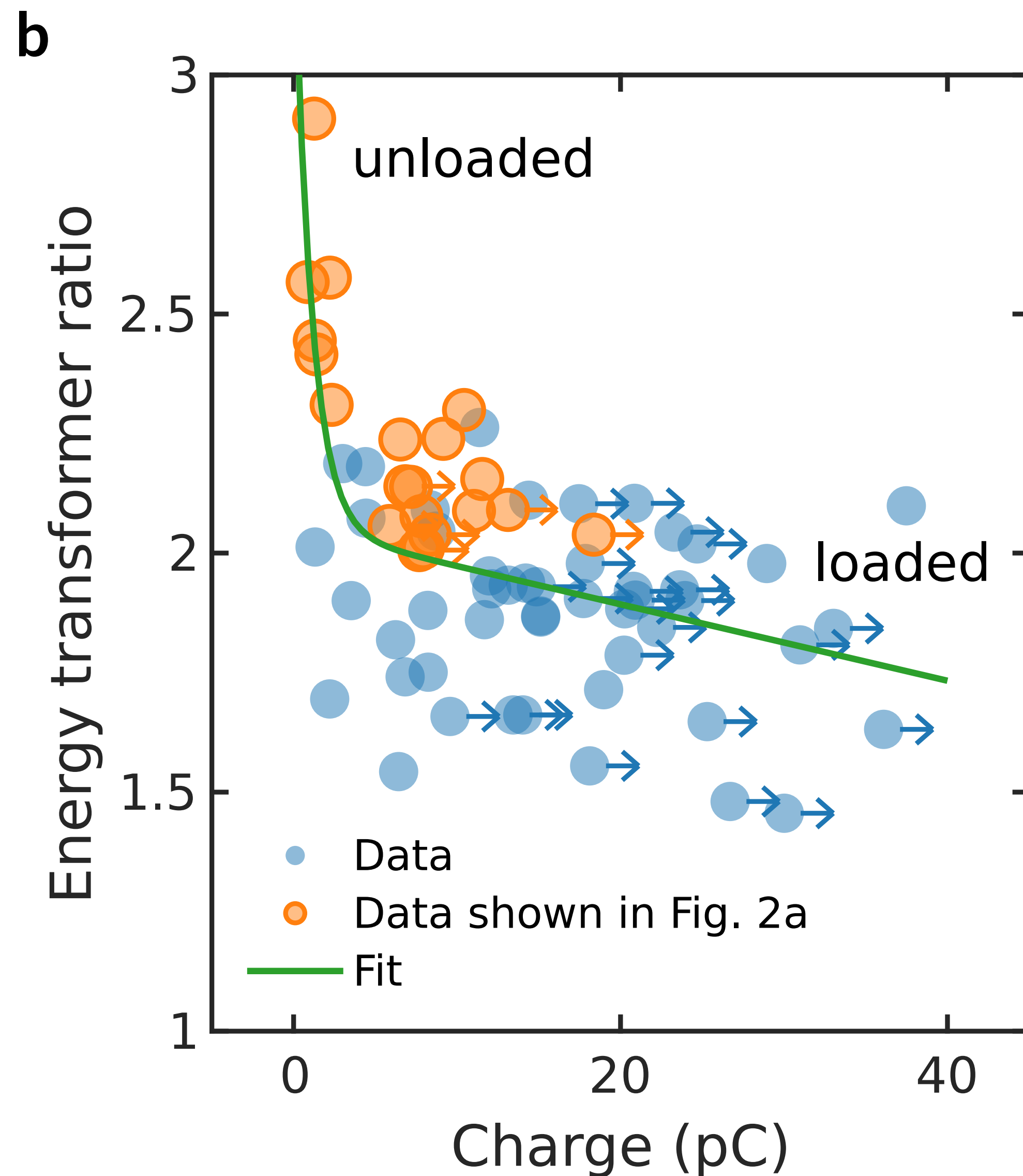


# Energy transformer ratio exceeding two



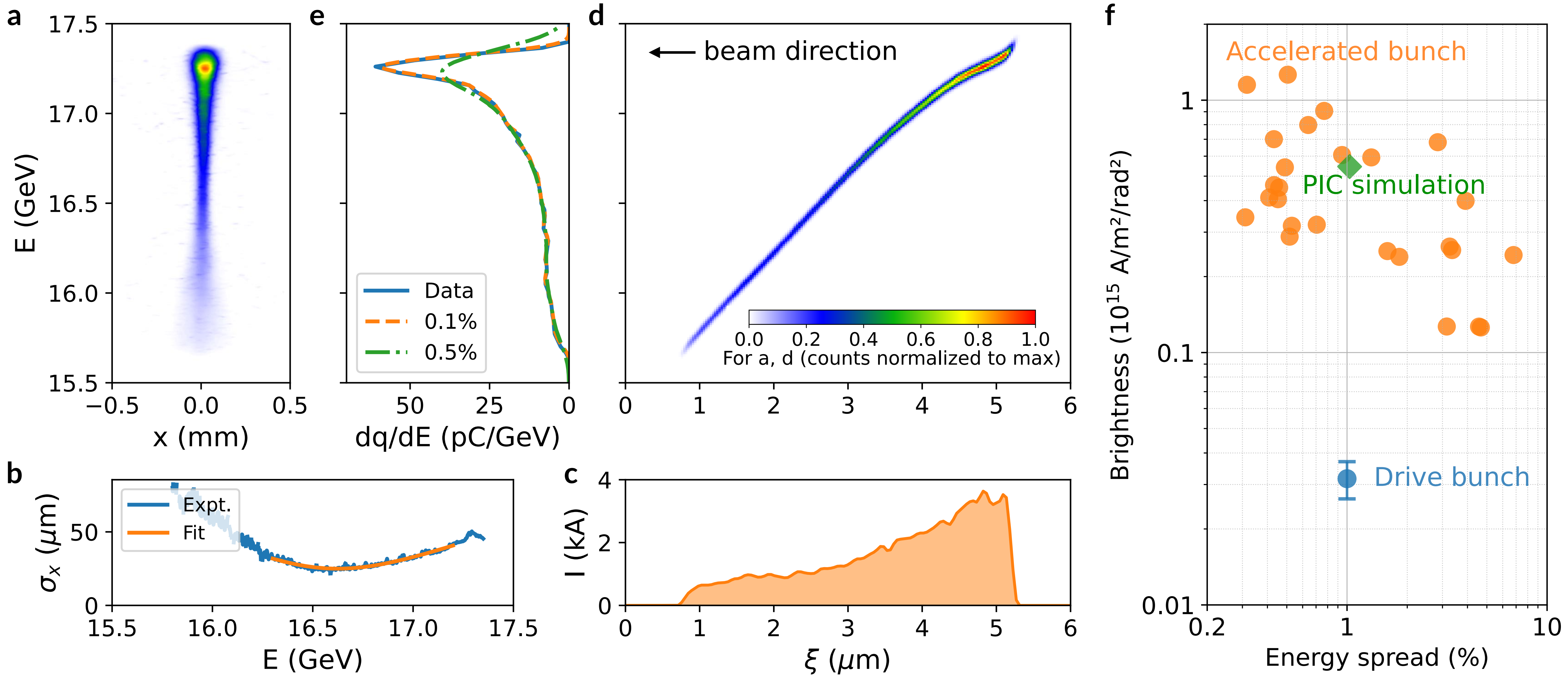


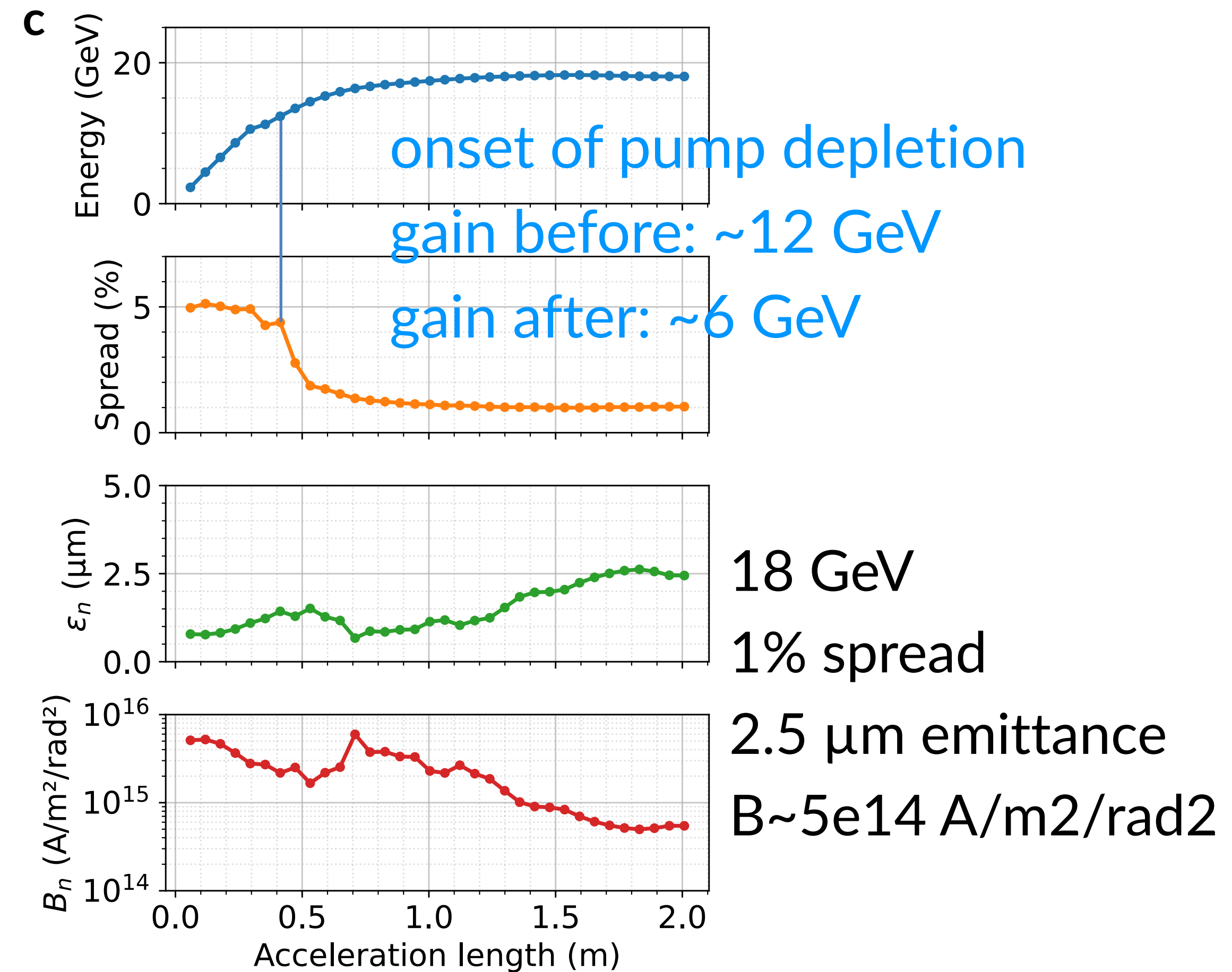
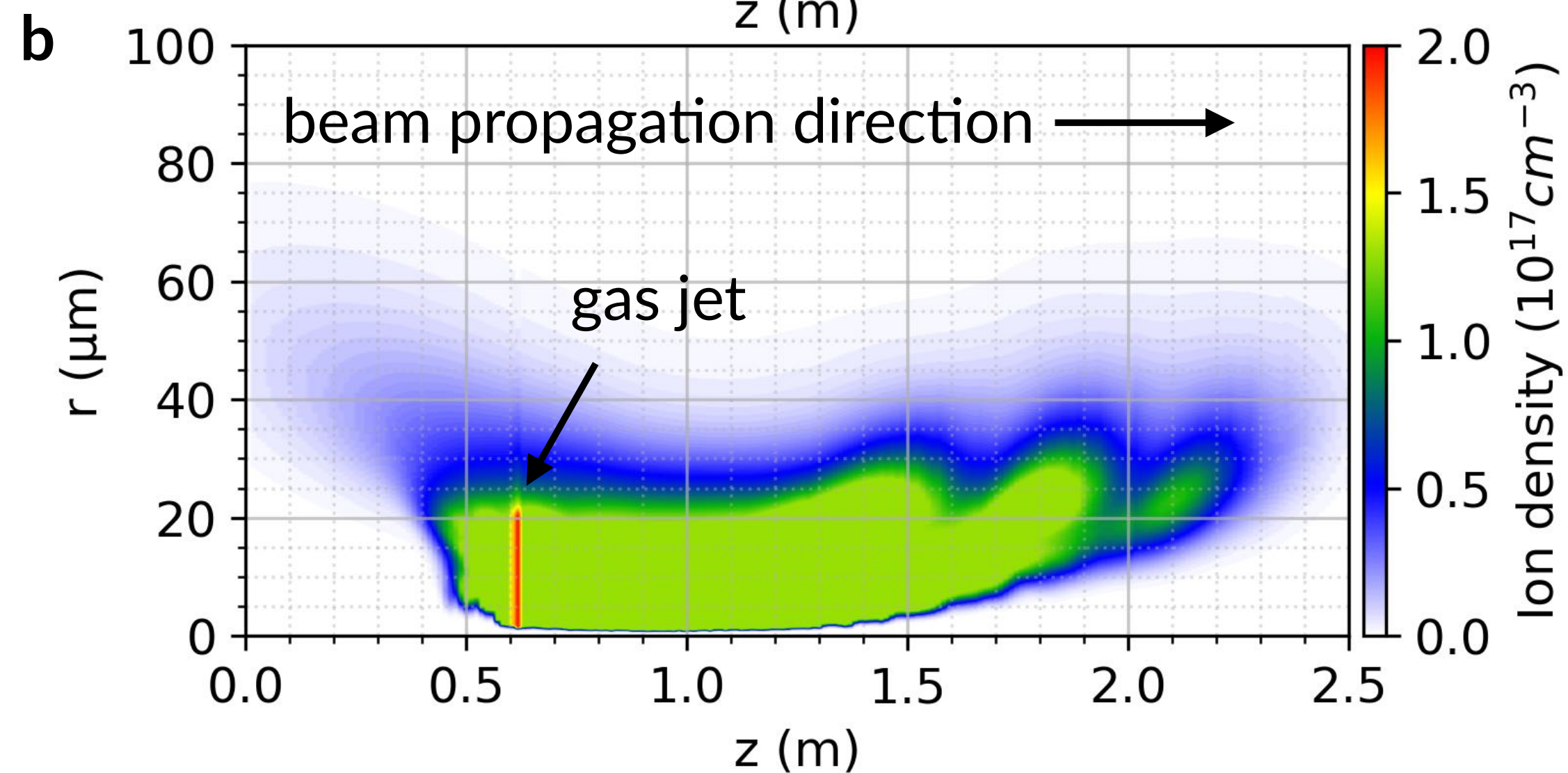
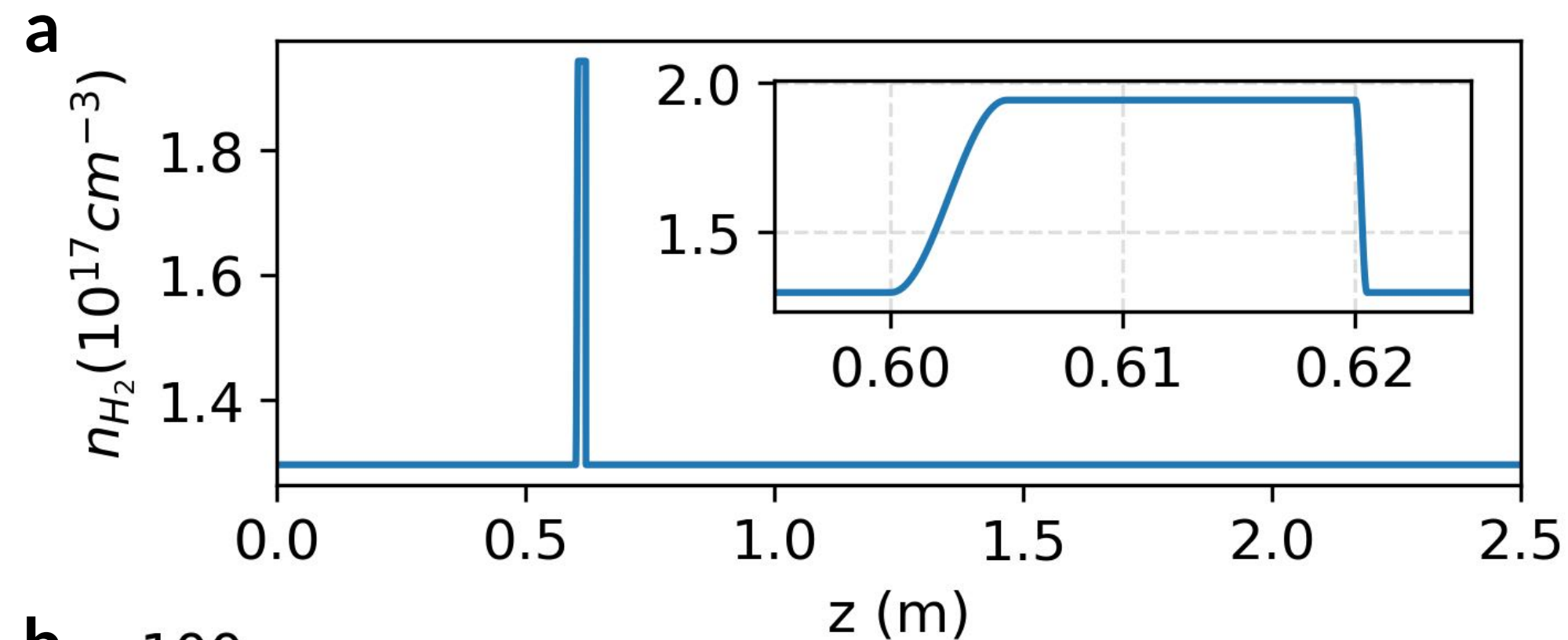
- multiple energy spectra of the injected bunch with energy gain exceeding 20 GeV
- In many shots the spectrum peaks at the high-energy end, with an extended tail towards low energy
- very few shots show betatron oscillation sign  $\rightarrow$  the injected beam is matched to the wake after meter-scale acceleration
- no sign of transverse instability  $\rightarrow$  stable acceleration



- maximum drive beam energy loss is 10 GeV
- energy transformer ratio (E-TR): trailing beam energy gain divided by 10 GeV
- E-TR exceeds 2 in half of the shots
- two slopes: unloaded (<5 pC) vs. loaded (>10 pC)
- the errors indicate that charge presented is a lower limit due to camera saturation

# Brightness transformer: enhancement over an order of magnitude



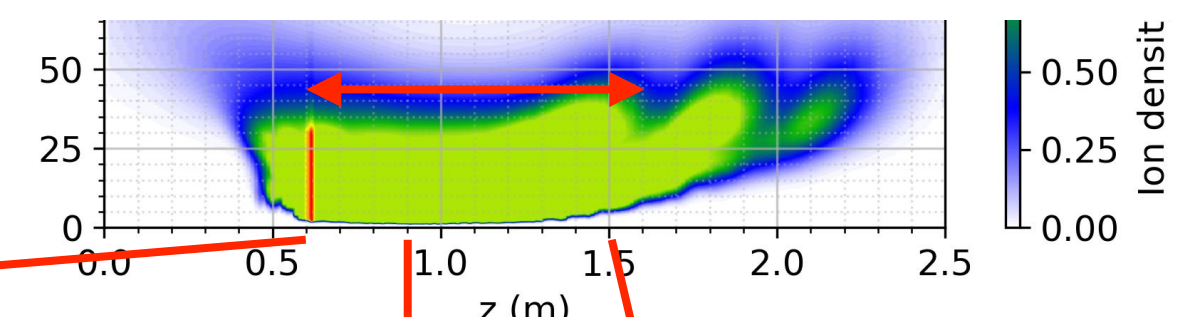


- established a workflow to model the whole process with Thamine
- QPAD (beam focusing prior to injection) + OSIRIS (downramp injection) + QPAD (acceleration)
- not fully self-consistent: 1) used pre-ionized plasma in OSIRIS; 2) reduced injected charge when imported back to the 2nd QPAD simulation

- Transformer ratio:
  - Field-TR: max accelerating field / max decelerating field
  - Energy-TR: max energy gain / max energy loss
- We did not distinguish them under an implicit assumption: non-evolving wake
  
- Observations:
  - the wake does not disappear immediately when the first electron in the drive beam loses all its energy
  - the acceleration continues over an extended length after the onset of pump depletion
  - the accelerating field does evolve due to pump depletion, but may lead to dynamic beam loading that reduces energy spread of the trailing bunch
  
- Question: for an unshaped gaussian beam, what is the maximum achievable E-TR?

# Wake evolution and multi-sheath model

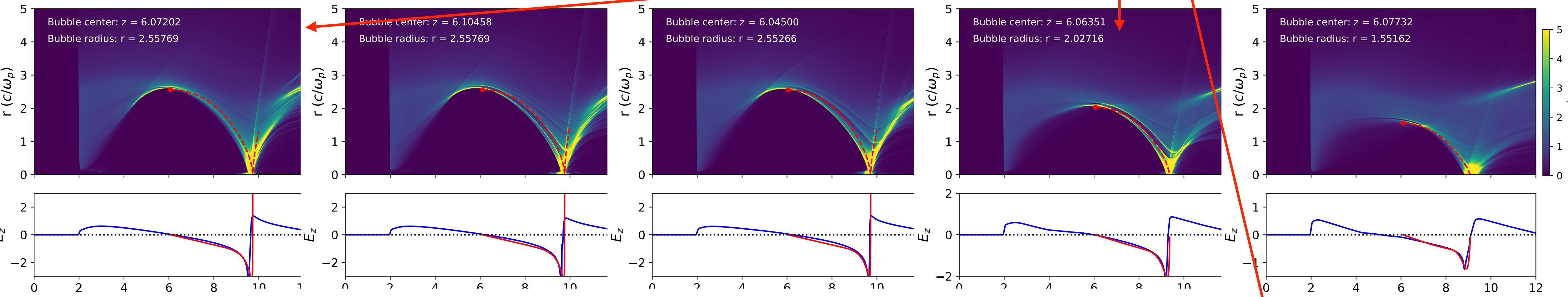
Divide the 1m plasma into 10 sections  
 None-evolving wake within each section **UCLA**



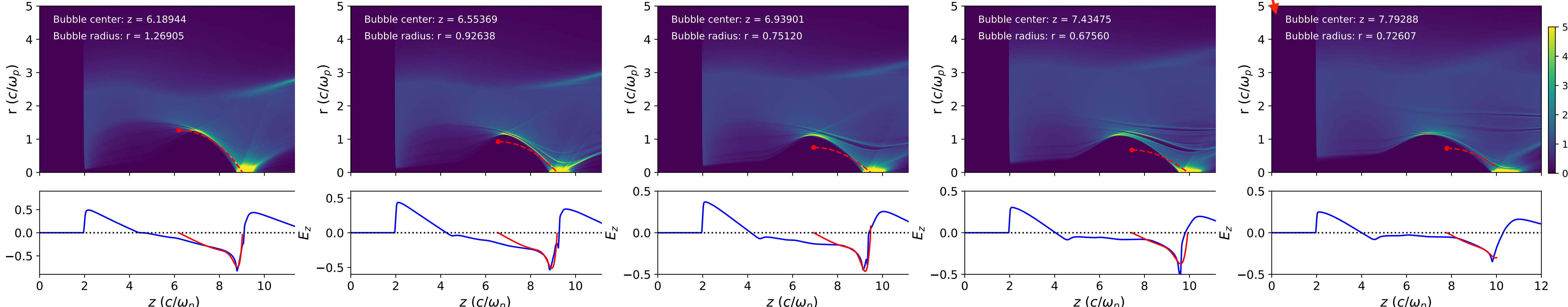
right after injection acc. length  $L=0.1\text{m}$

$L=0.2\text{m}$

$L=0.4\text{m}$



Blue:  $E_z$  field from PIC; Red:  $E_z$  field from the multi-sheath model



$L=0.5\text{m}$

$L=0.6\text{m}$

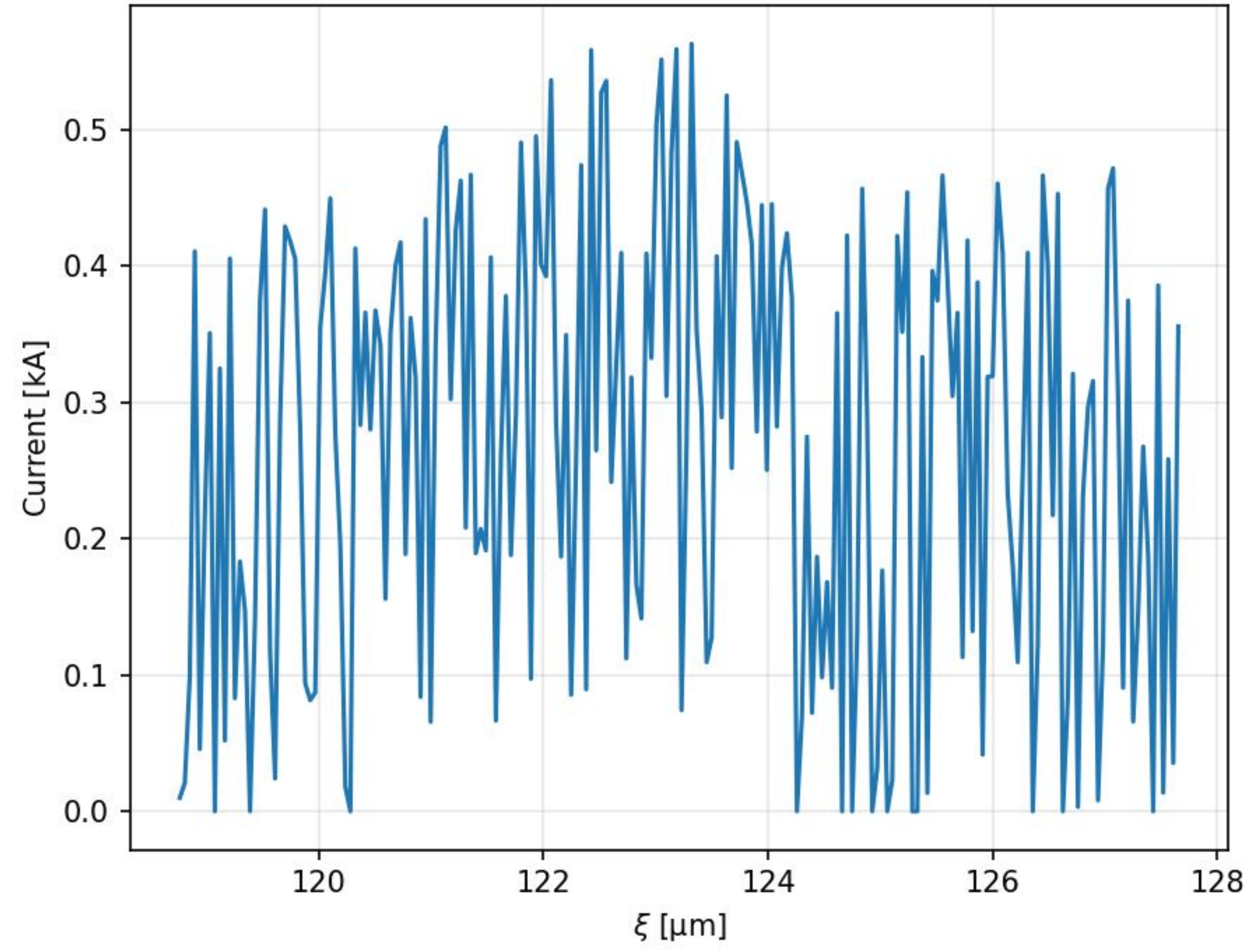
$L=0.7\text{m}$

$L=0.8\text{m}$

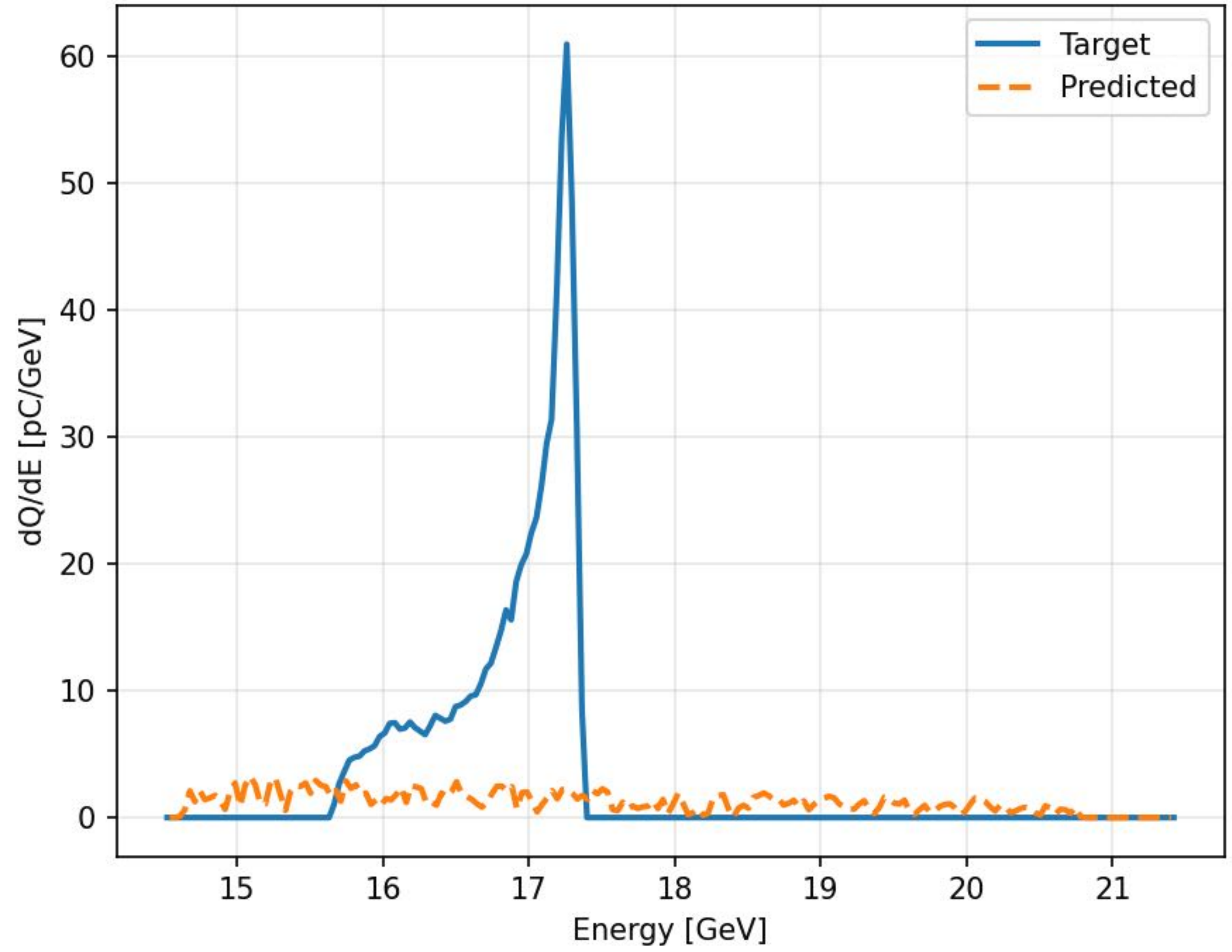
$L=0.9\text{m}$

# LPS reconstruction based on the multi-sheath model

Current Profile - Iteration 1

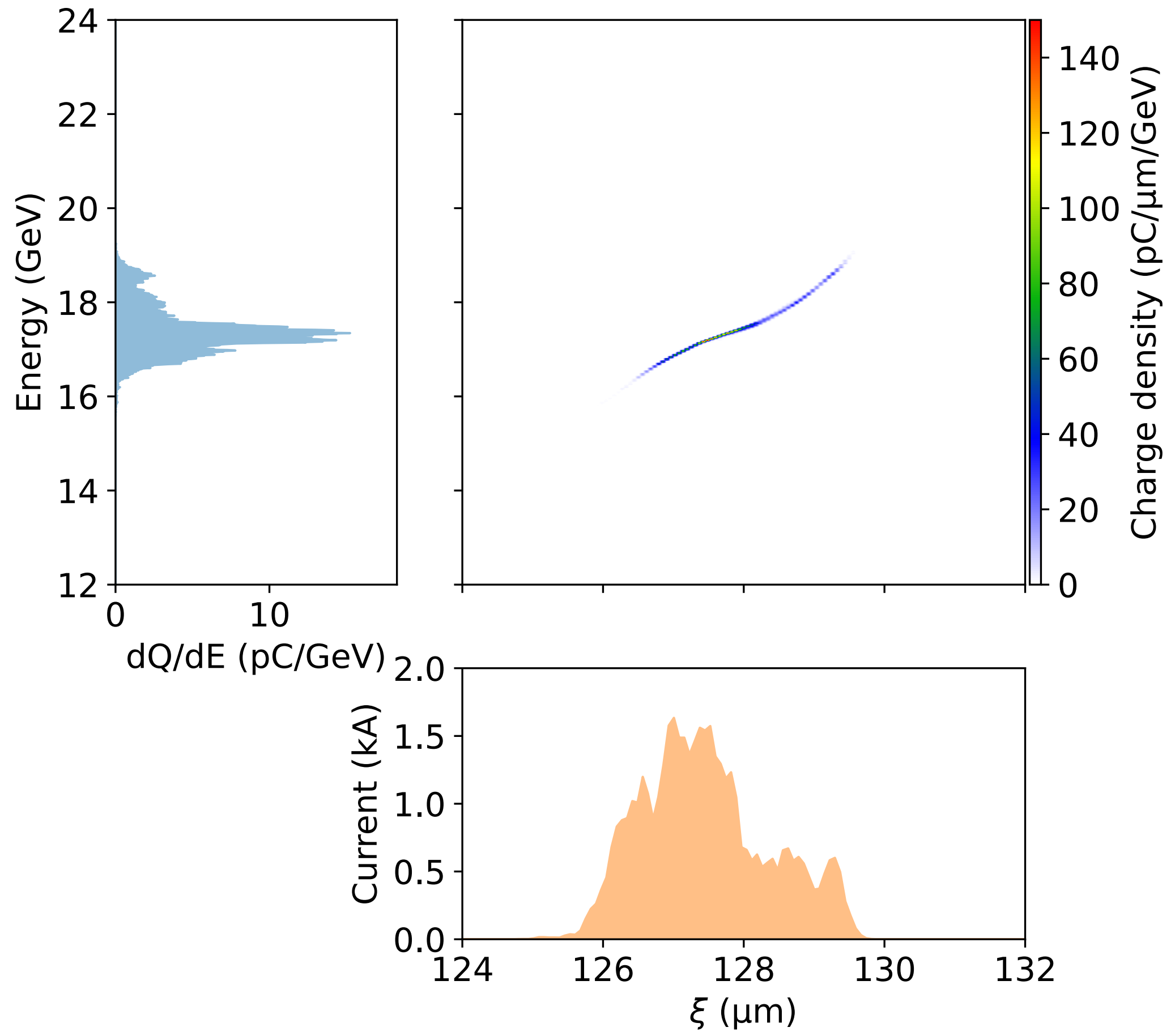


Energy Spectrum - Iteration 1

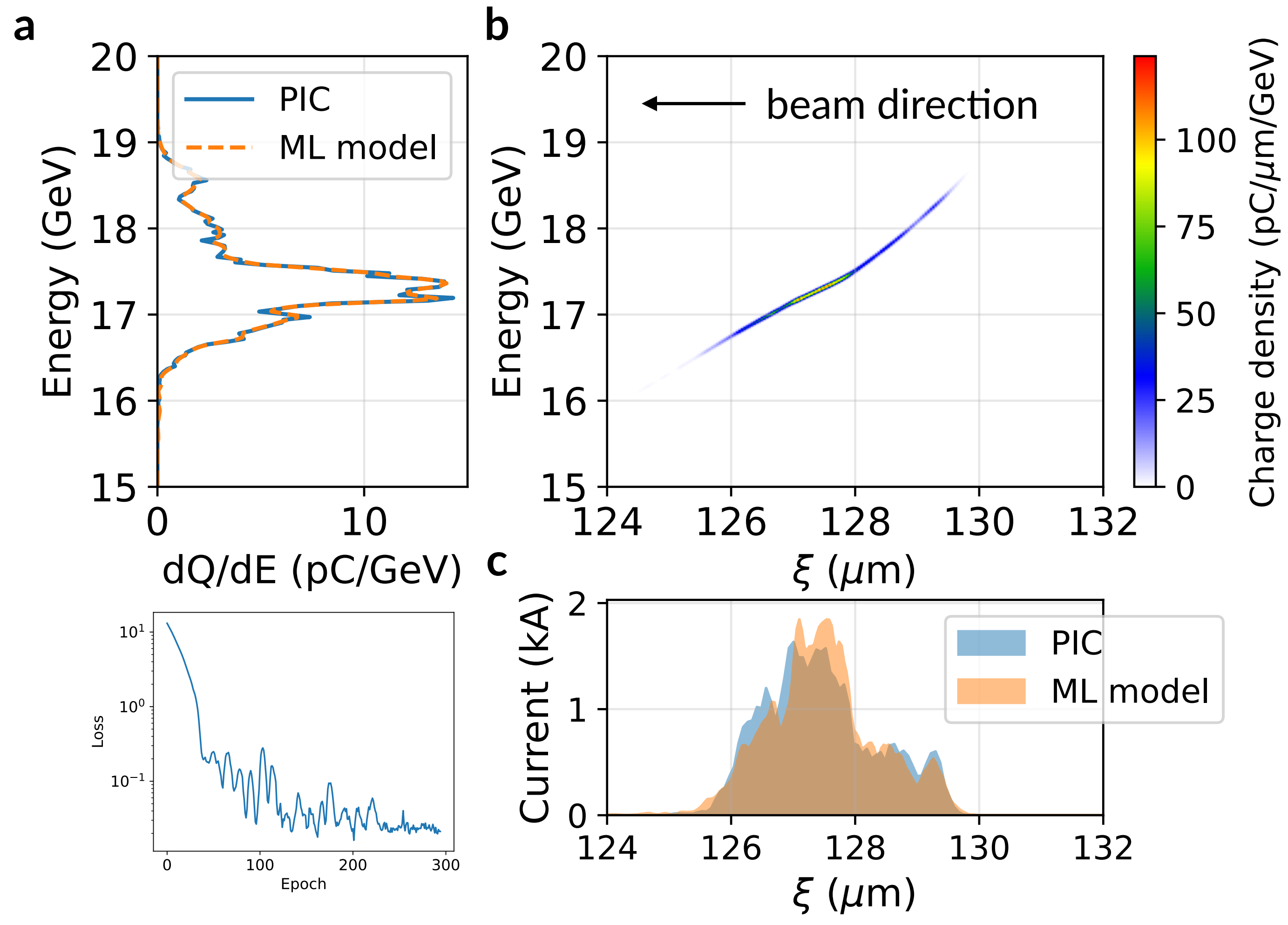


# LPS reconstruction benchmark against PIC simulations

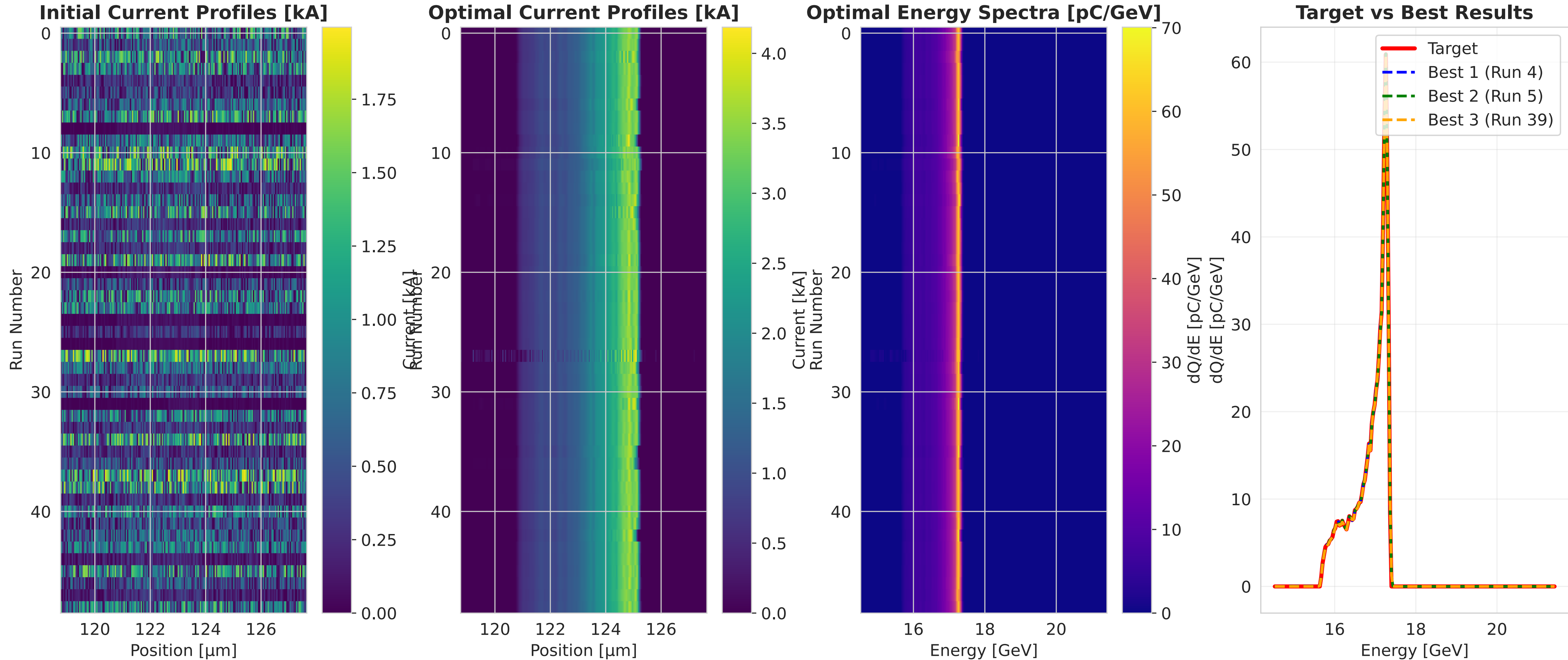
### PIC simulation



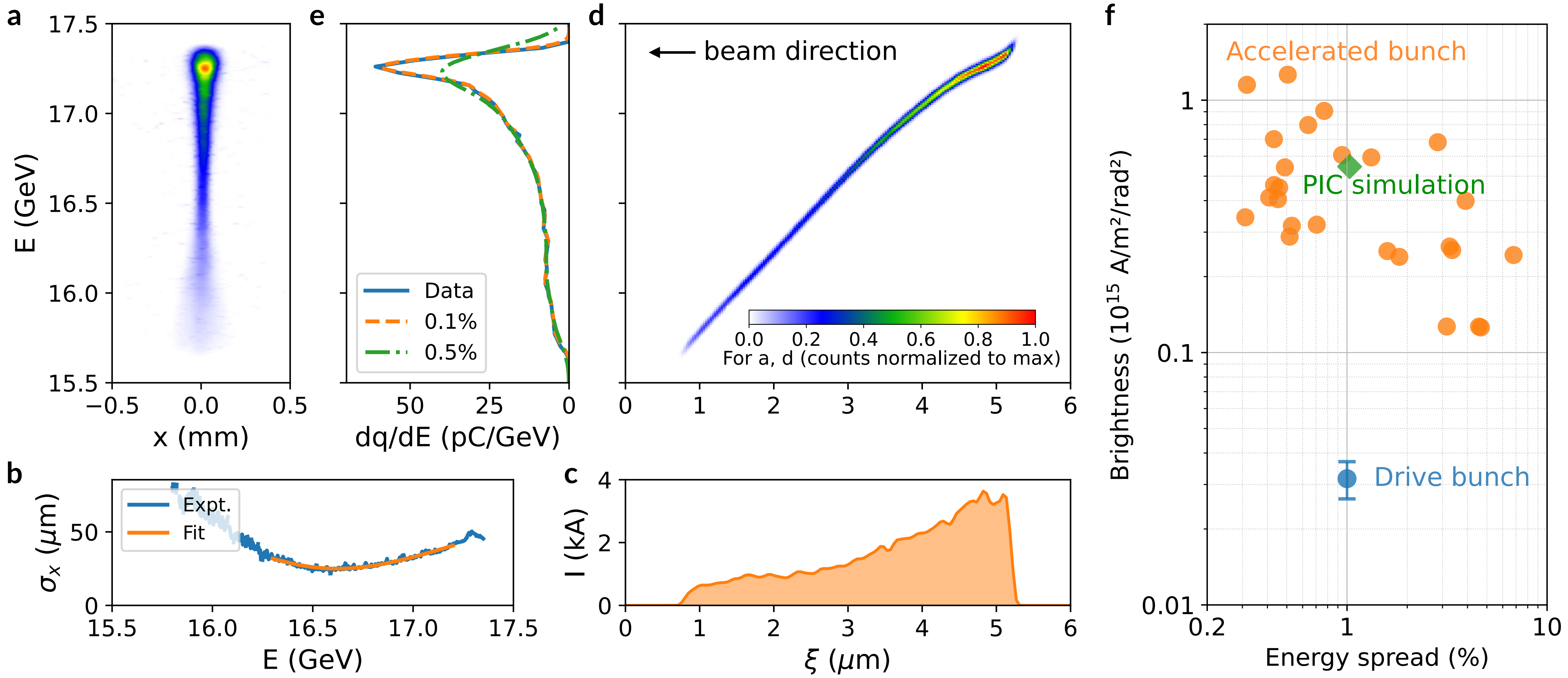
### ML reconstruction



different initial current profiles converge to similar optimal solutions



# Brightness transformer: enhancement over an order of magnitude



- **Demonstrated plasma wakefield transformer concept - first experimental proof**
  - Energy transformer ratio  $>2$  - exceeding previous theoretical limits
  - Brightness enhancement  $>10x$  - simultaneous energy and quality improvement
  - High-quality beams: 20+ GeV,  $<1\%$  energy spread,  $\mu\text{m}$ -level emittance, kA peak current
- **Publications:**
  - **Nature Communications paper under review** - transformer concept demonstration
  - **Additional papers planned:**
    - Machine learning-enabled virtual diagnostics for extreme beams from plasma accelerators
    - A paper that summarizes the simulation results: with a gaussian beam E-TR  $\sim 2$  (done),  $>50$  GeV high-brightness beam from a single-stage PWFA using shaped drive beam (planned)?
- **Next steps:**
  - **Modulated downramp injection**
  - Cross-experiment collaboration on ML diagnostics, beam-compression, analysis methods