E304 Progress in FY24 and Plans for FY25

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(on behalf of the E300 collaboration)

Nov 19, 2024

Work supported by DOE-HEP

E304- Science goals and FY24 achievements

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E304: Generating low emittance beams using downramp trapping in PWFA

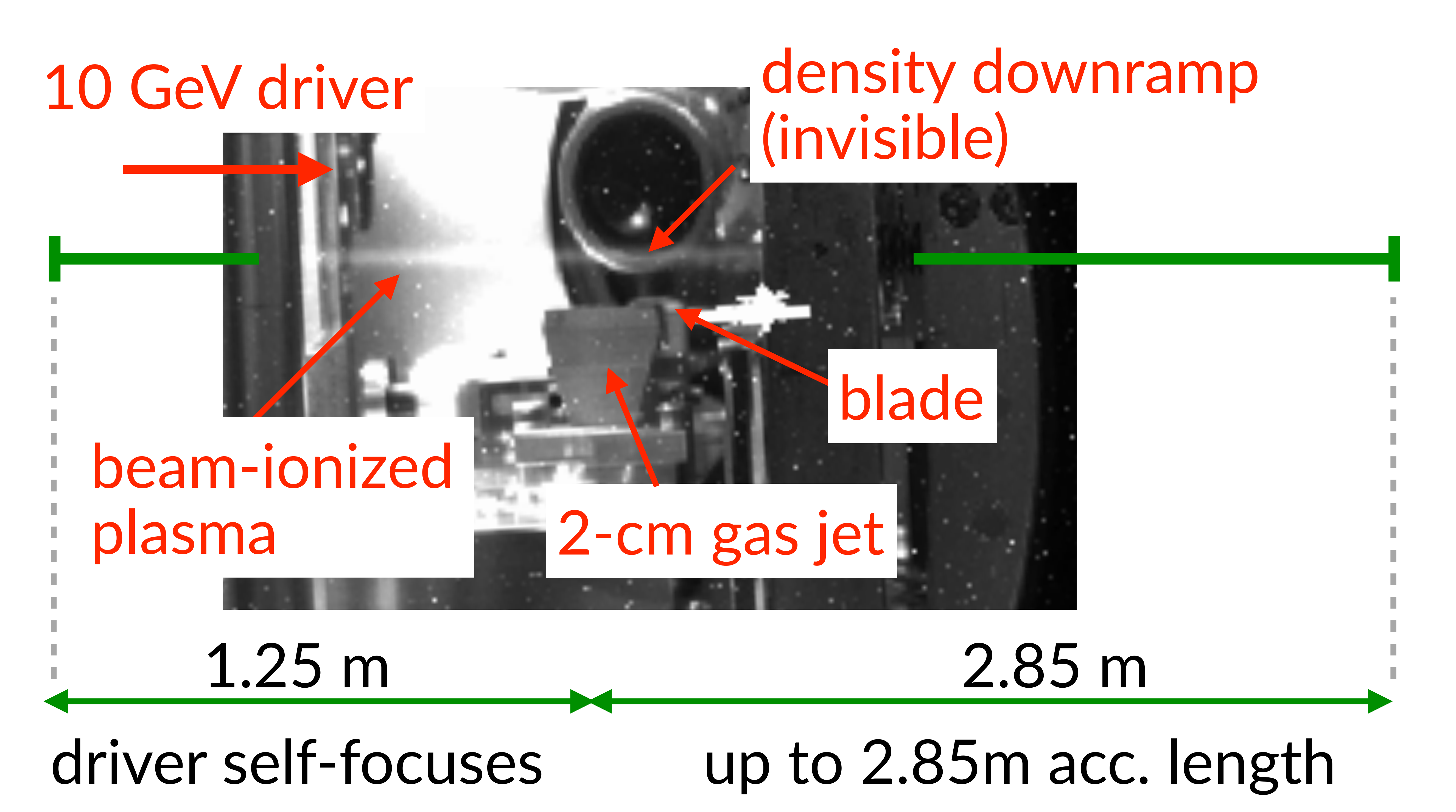
Stage	Planned Goals (FY22)	Key Achievements (FY24)	Next steps
Stage 1 (year 1): Injection demonstration	-Evidence of injection (charge excess, signal on spectrometer)	✔ACHIEVED: Charge excess observed with significant driver energy loss	—
Stage 2 (year 1-2): Injection and acceleration optimization	-Generate stable 1-few GeV beams	✔ACHIEVED: Beams with energy from few GeV to up to 26 GeV; Inj. prob. >10%	-Improve stability -Try different configurations
	-Compare laser and beam ionization (smaller emittance if laser ionized)		-Test laser vs. beam ionization
Stage 3 (year 2-3): Ultralow emittance, high-brightness beams	• emittance < 1 μm • energy > 1 GeV • energy spread < 1% • I > 5 kA	✔ACHIEVED: • emittance ~2 μm • energy up to 26 GeV • energy spread <1% • I up to 8 kA	-Improve diagnostics for measuring <1 μm emittance

Exceeding Expectations: E304 has demonstrated energy gain up to 26 GeV, far surpassing original goals of a few GeV beams!

Experiment setup- Gas-jet in Static-fill

- The original design used a 2-cm plasma, which required high density (10^{18} cm-3) to achieve >GeV energy gain. This, in turn, required a dense driver (σ_r<10 µm, σ_z<10 µm)- currently not available
- Changed to the GIS configuration: a meter-scale beam-ionized plasma; allows the driver to self-focus; can use lower plasma & driver density due to much extended acceleration length

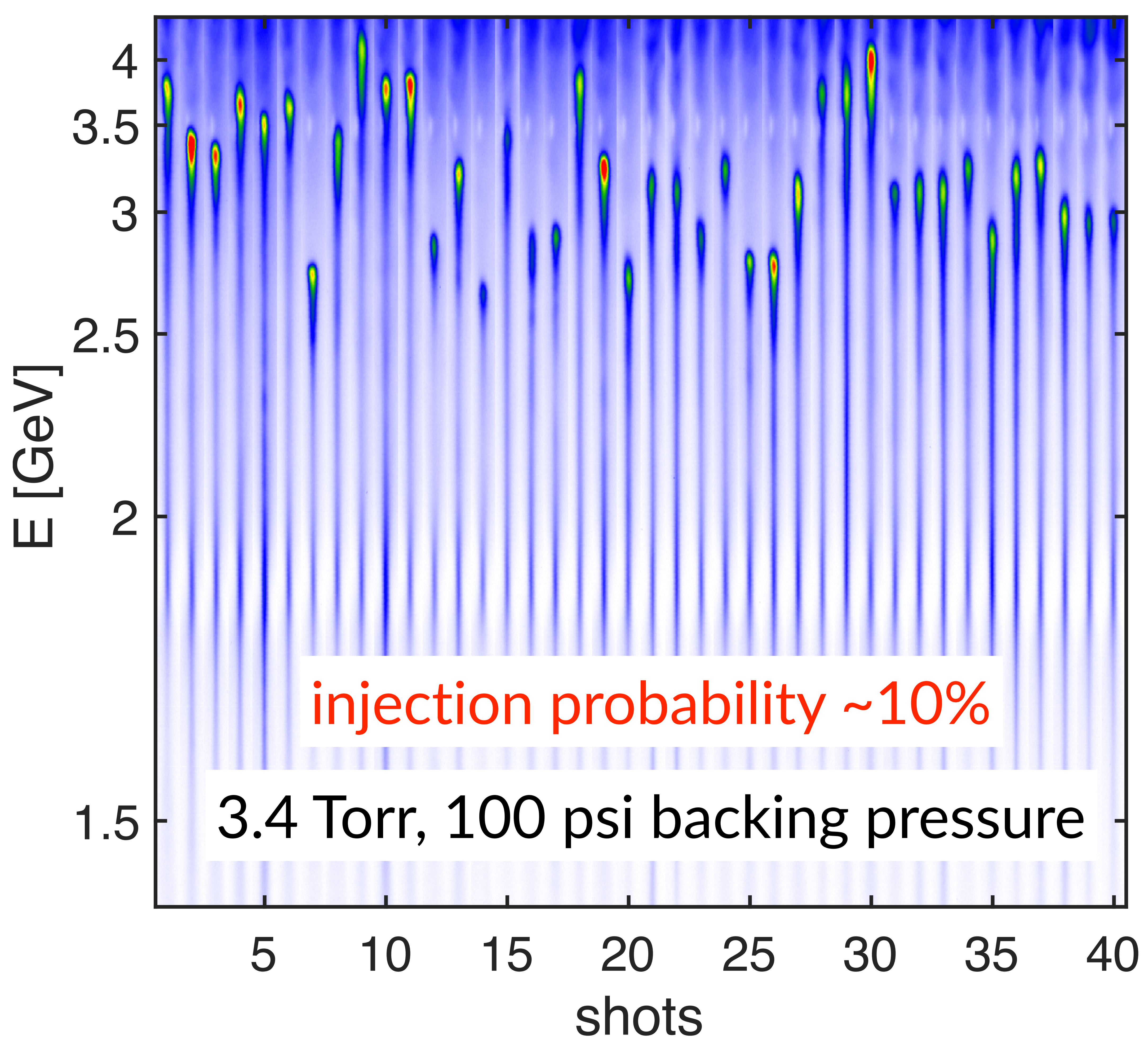
Experimental setup



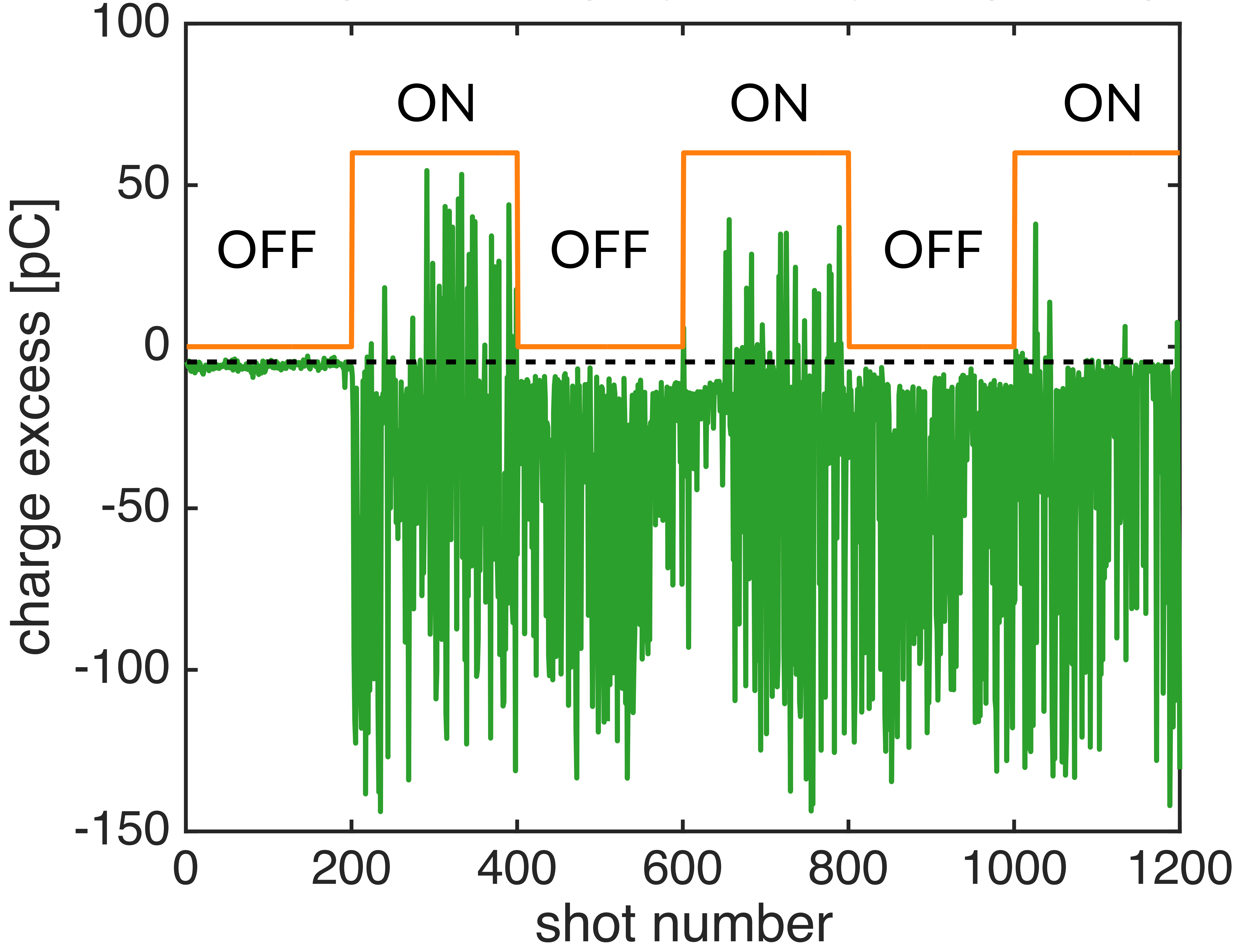
- Four runs in FY24, 10 shifts in total
- March run:
  Observed downramp injected electrons, few to >10 GeV gain
- June run:
  Systematic optimization + Higher energy gain + emittance measurement + more data collected

March data: Multi-GeV energy gain of downramp injected electrons

Selected shots to highlight the injected bunch (energy 2.7-4 GeV with ~5% FWHM spread)



Confirmation of downramp injection: turning OFF the gas jet or adjusting timing



E304_06341, static fill 3.4 Torr, gas jet backing pressure 100 psi, e- beam height 2 mm. Quad 1.8 GeV, Dipole 3.5 GeV

June data: Example dataset demonstrating >20 GeV energy gain

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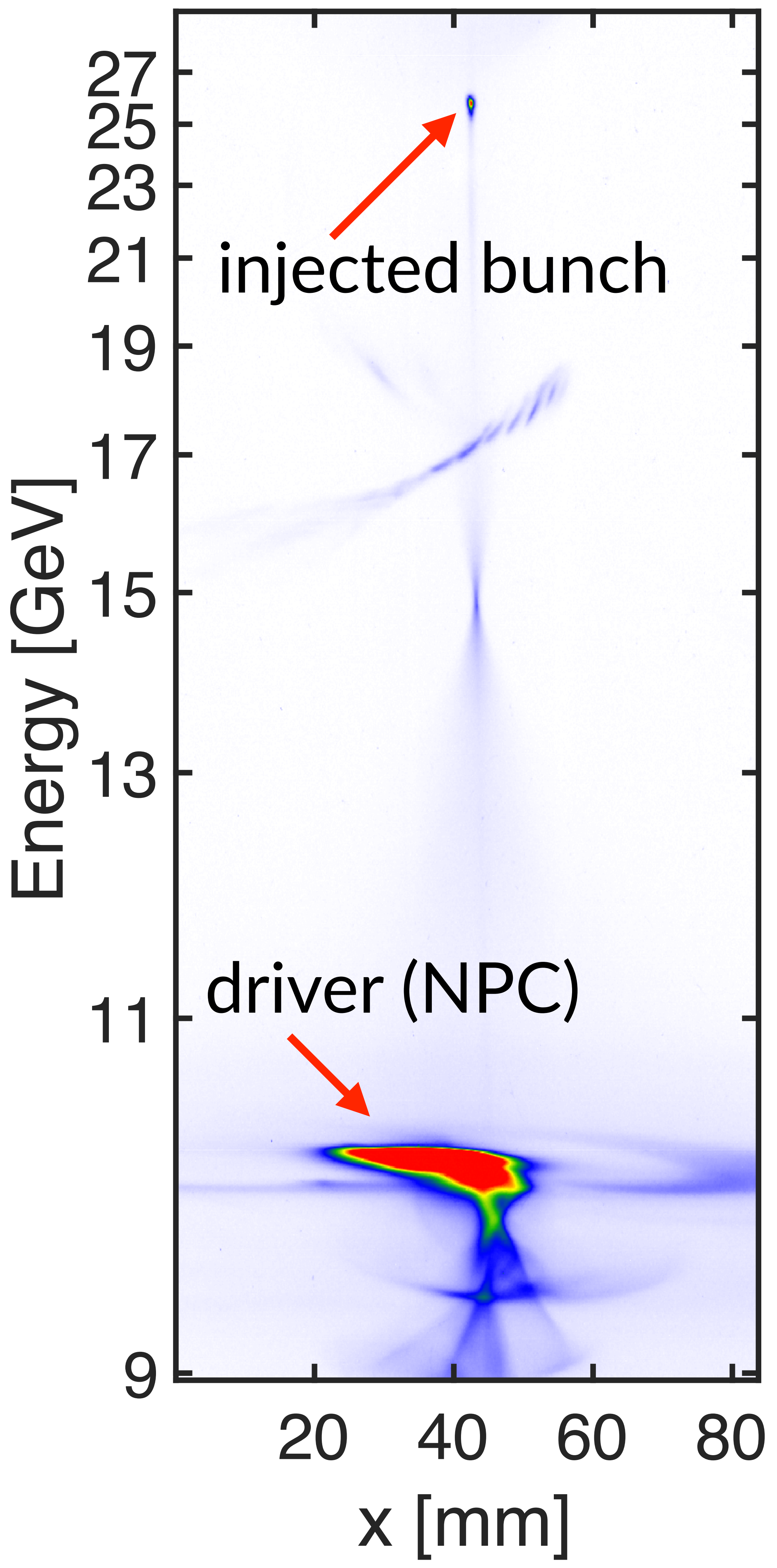
Significant improvement with optimized driver (64x50x38 μm in March → 32x23x21 μm in June)

- ~20 GeV energy gain
- ~10 pC injected charge
- narrow beam divergence

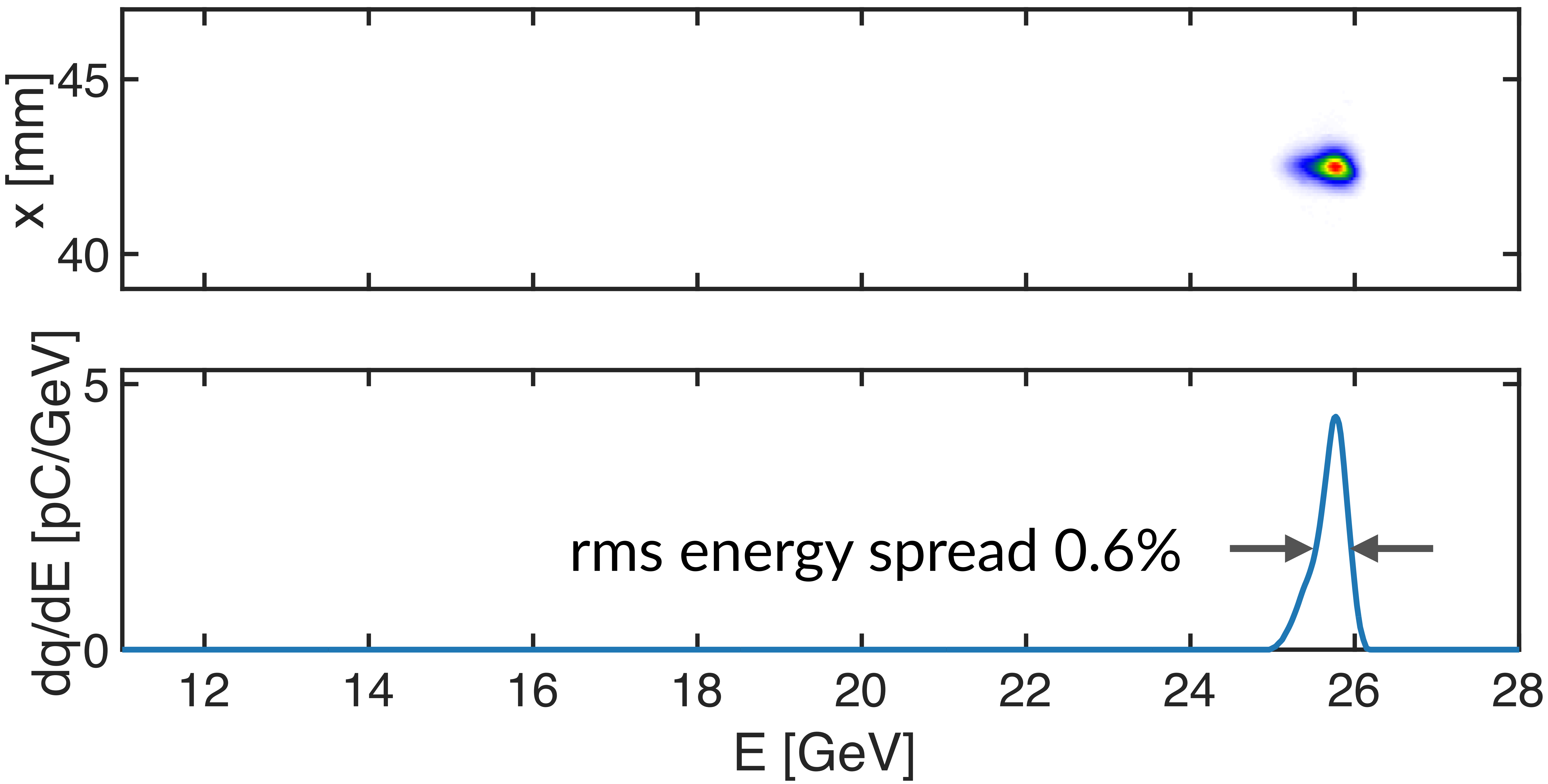
Energy gain of 26 GeV with <1% rms energy spread

E304_08878, shot 146



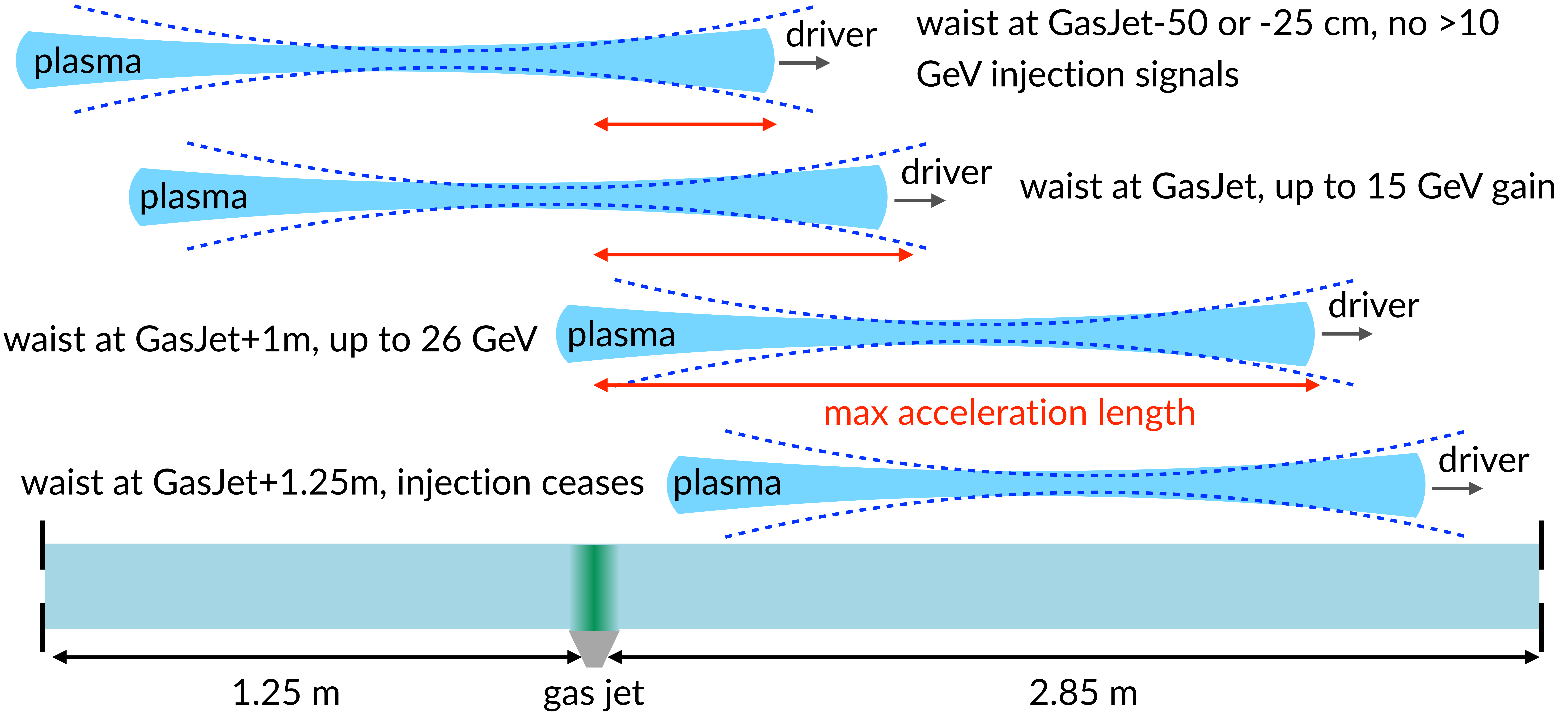
Injected bunch:

Energy gain 25.8 GeV, rms energy spread 0.6%, charge 2.0 pC



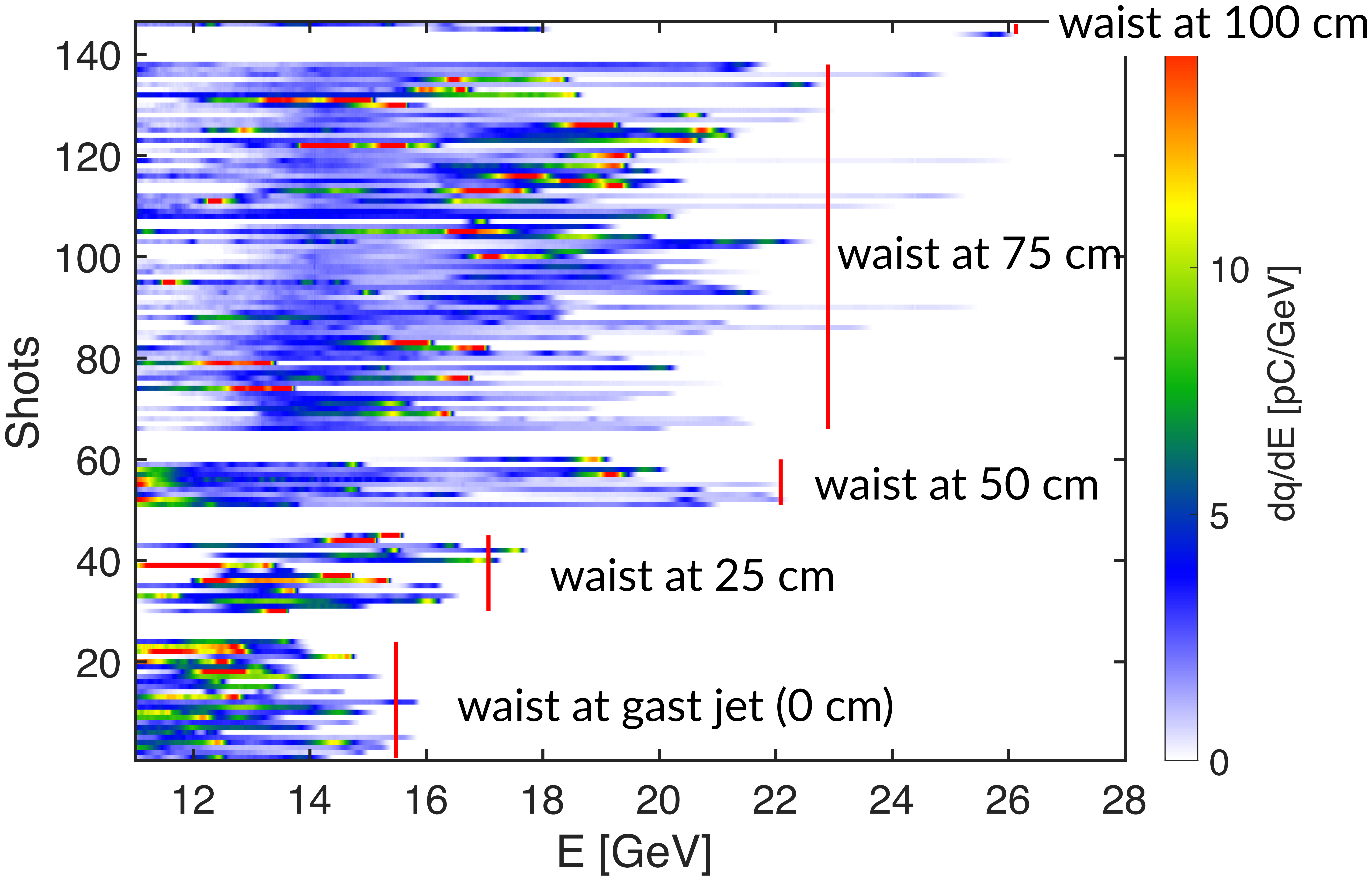
- More than doubling the energy of the 10 GeV driver
- Loaded transformer ratio (E_{gain}/E_{loss}): 2.6 (w/o beam shaping)

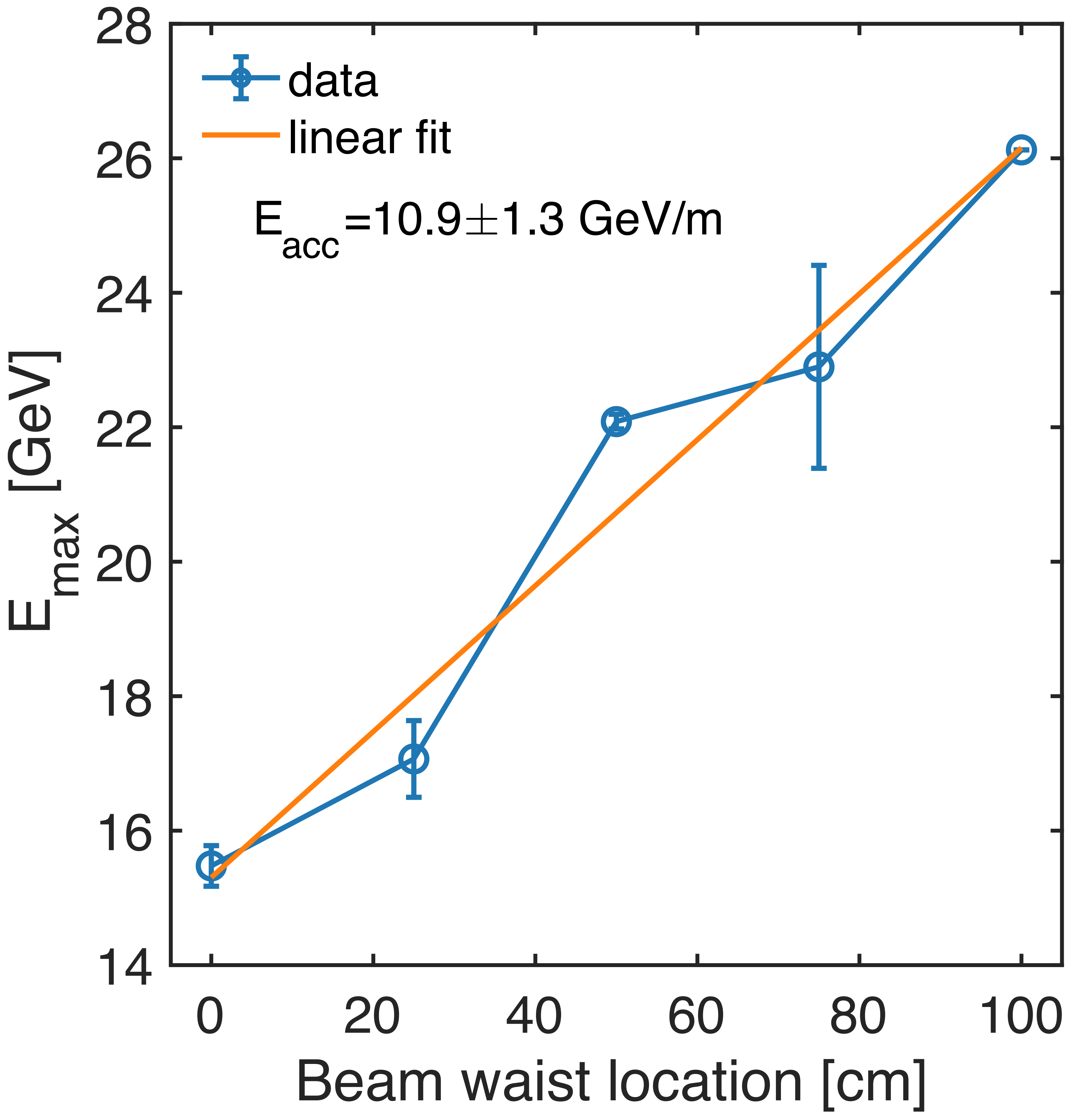
Energy tunability through acceleration length control



Energy tunability and extracted accelerating gradient

- Acceleration length increases as the beam waist location is moved downstream in vacuum
- Max energy scales linearly with acc. length, yielding an avg. gradient of 10.9 ± 1.3 GeV/m.





Narrow energy spread observed across varying acceleration lengths

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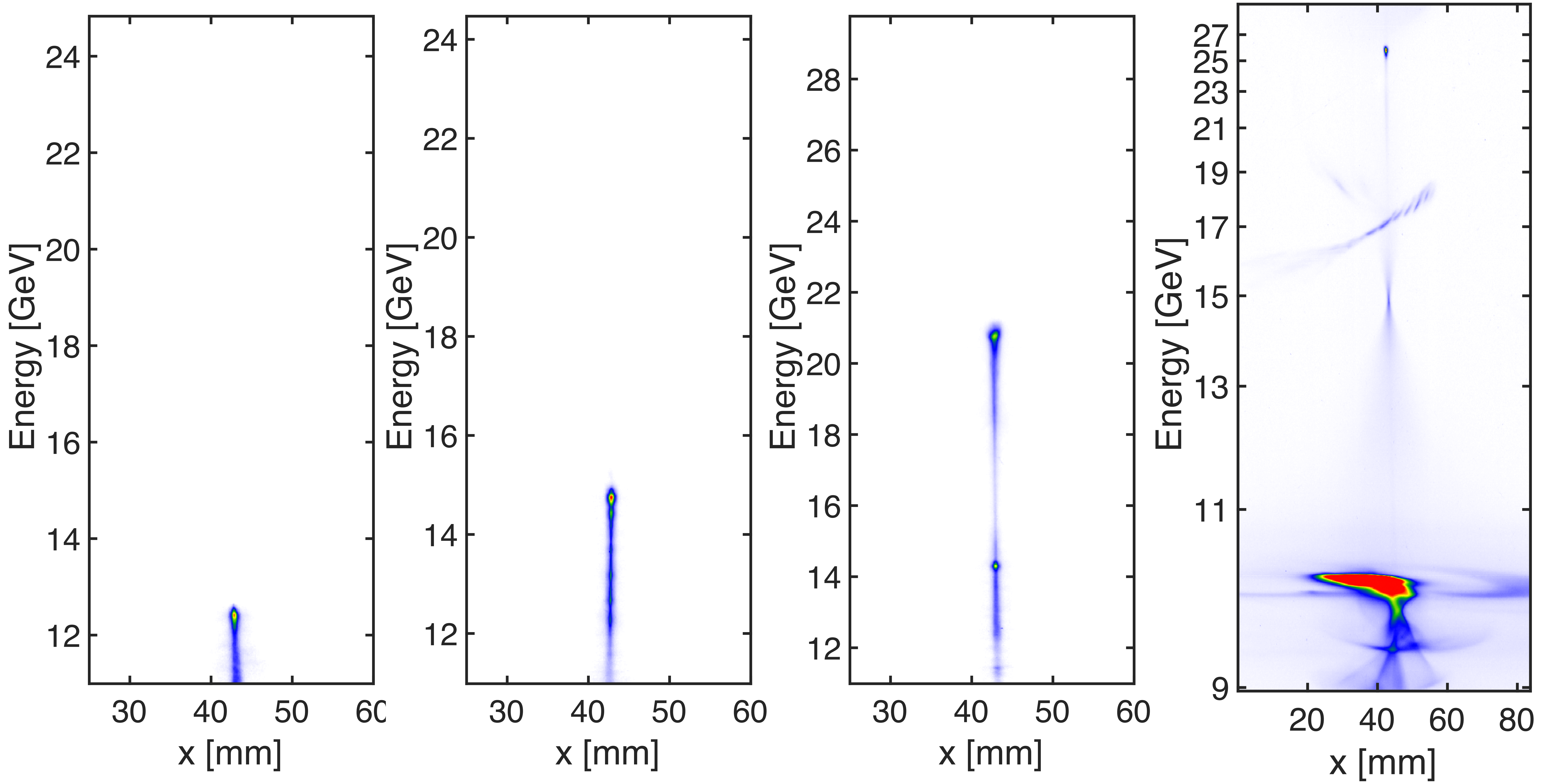
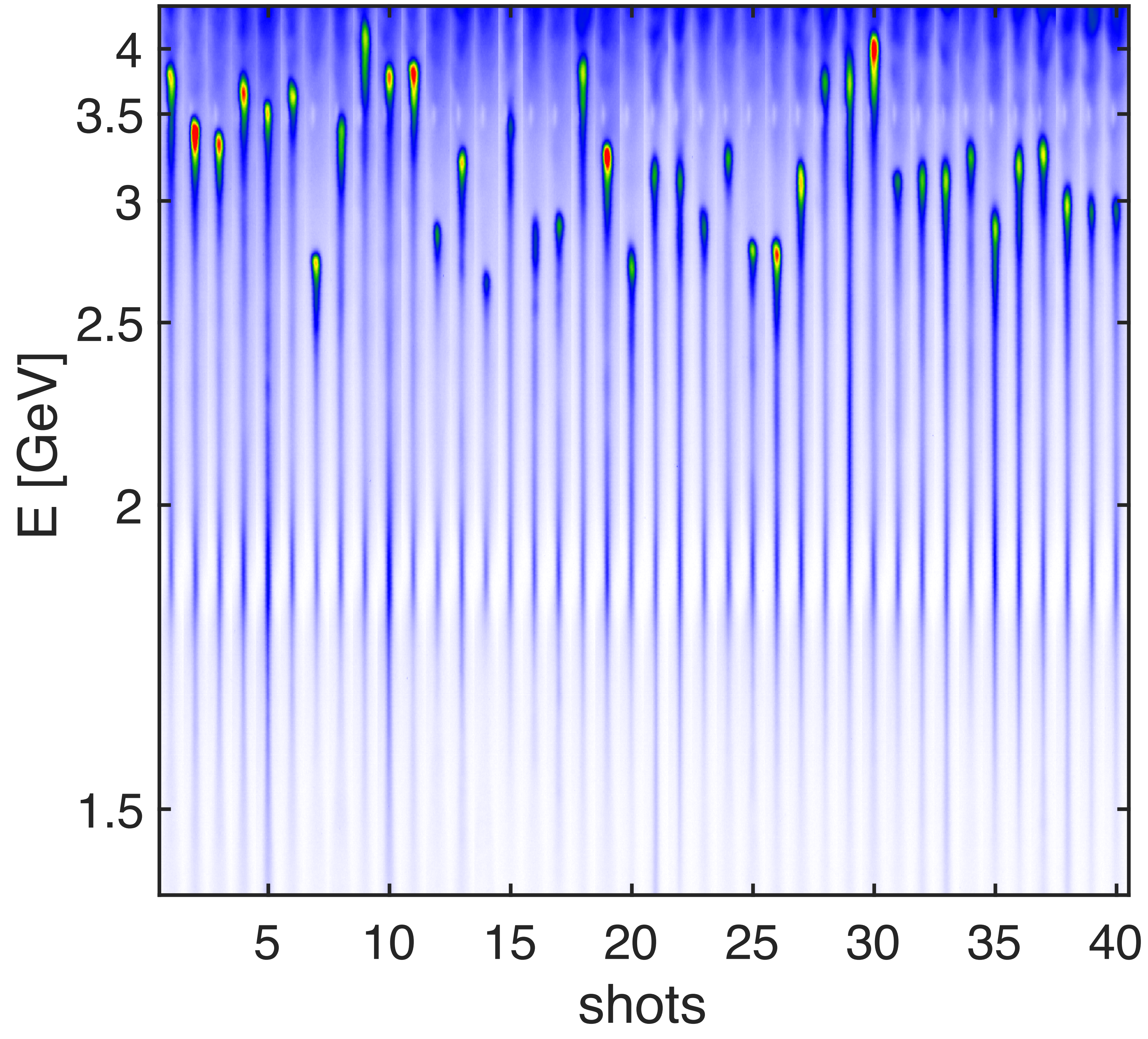
acc. length 1.3 m 1.8 m 2.1 m 2.3 m



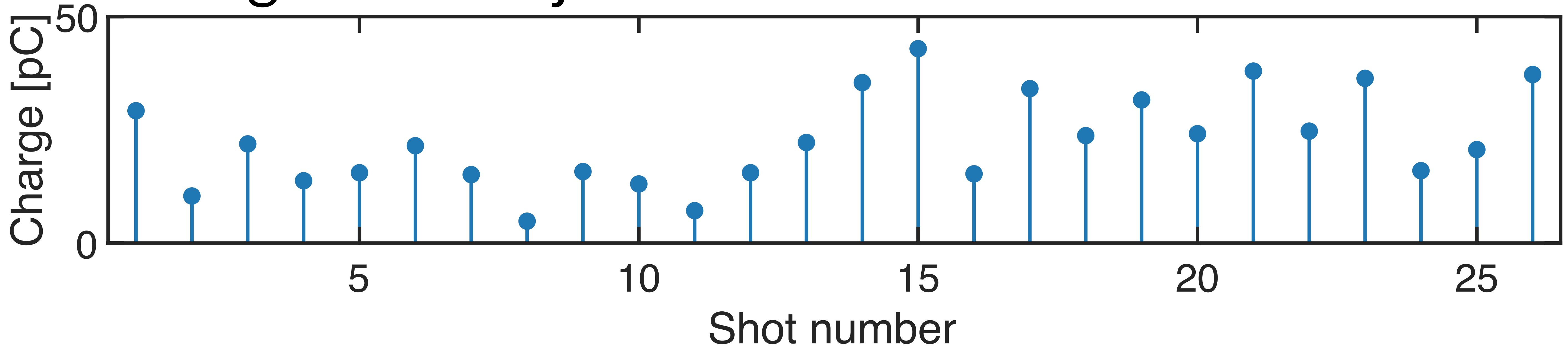
March data
energy gain ~3 GeV
also with small spread



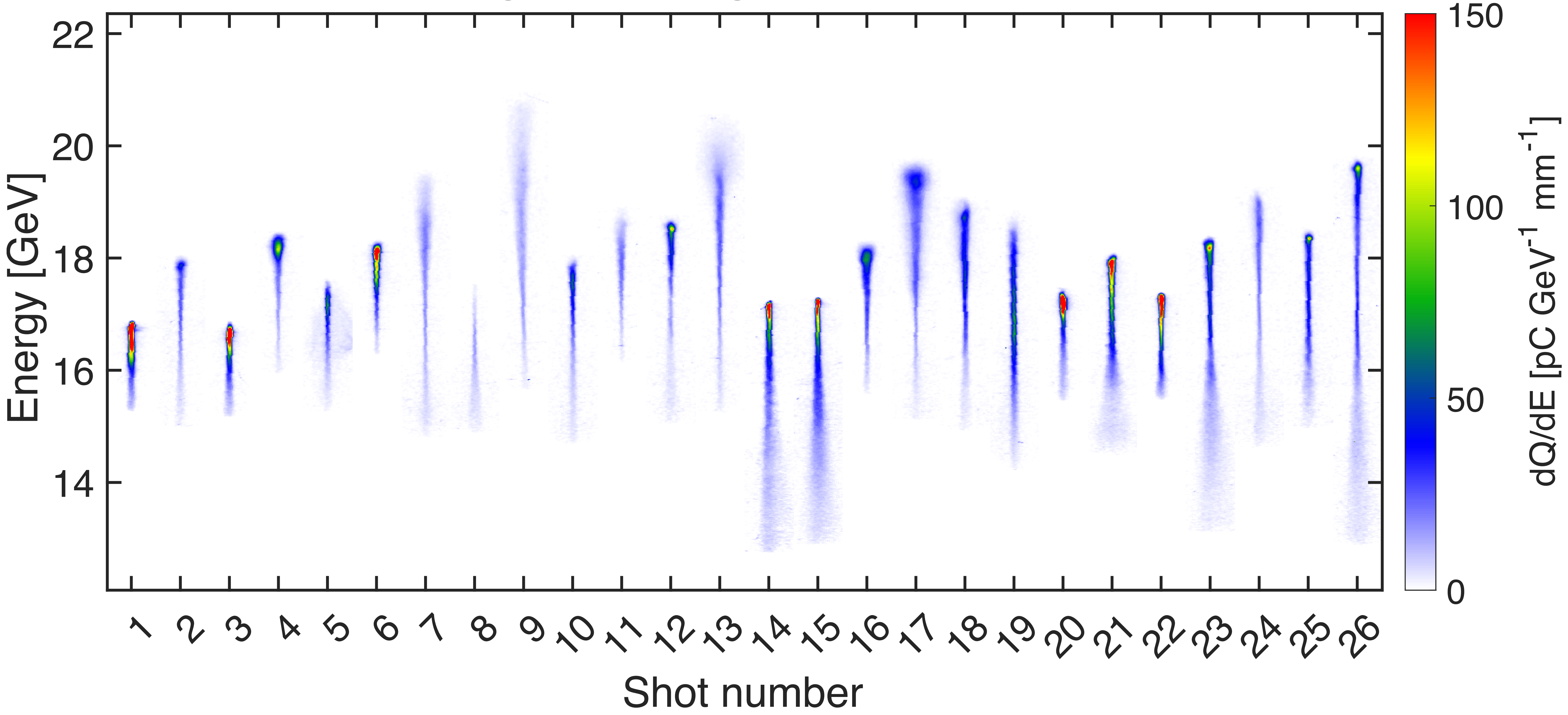
- Likely **NOT** caused by ***dynamic beam loading***, which would require an optimal acceleration length to fully compensate the accumulated energy chirp
- **Results indicate a locally loaded wake**

Well characterized dataset for emittance and phase space analysis

Charge of the injected bunch



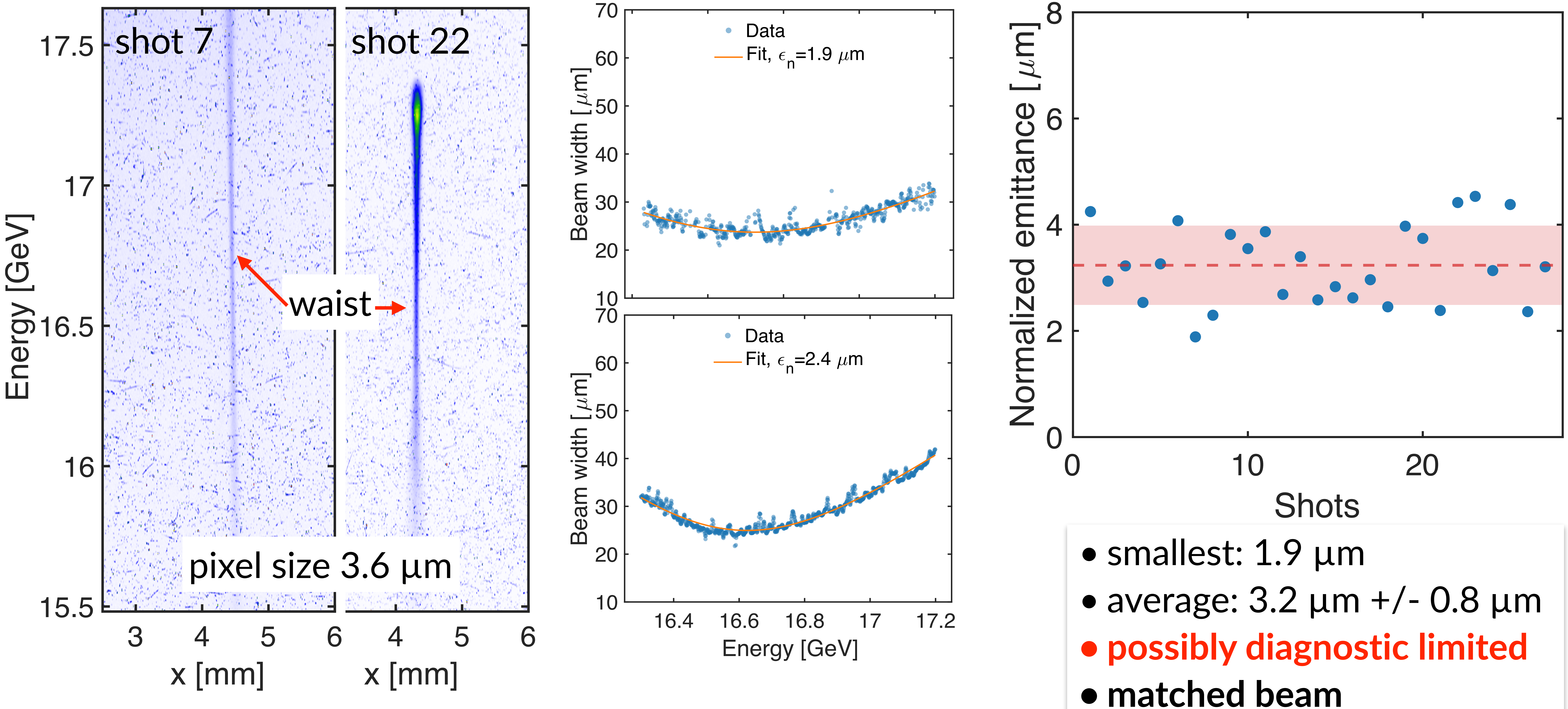
Consistent energy & energy spread across multiple shots



- Injection probability: ~13% (66 out of 500 shots)
- Injected charge: ranges from a few to 50 pC
- Energy: ~ 17 GeV

µm-Level emittance of the ~17 GeV injected beam

linearized energy spectra | fit to extract emittance | retrieved emittance

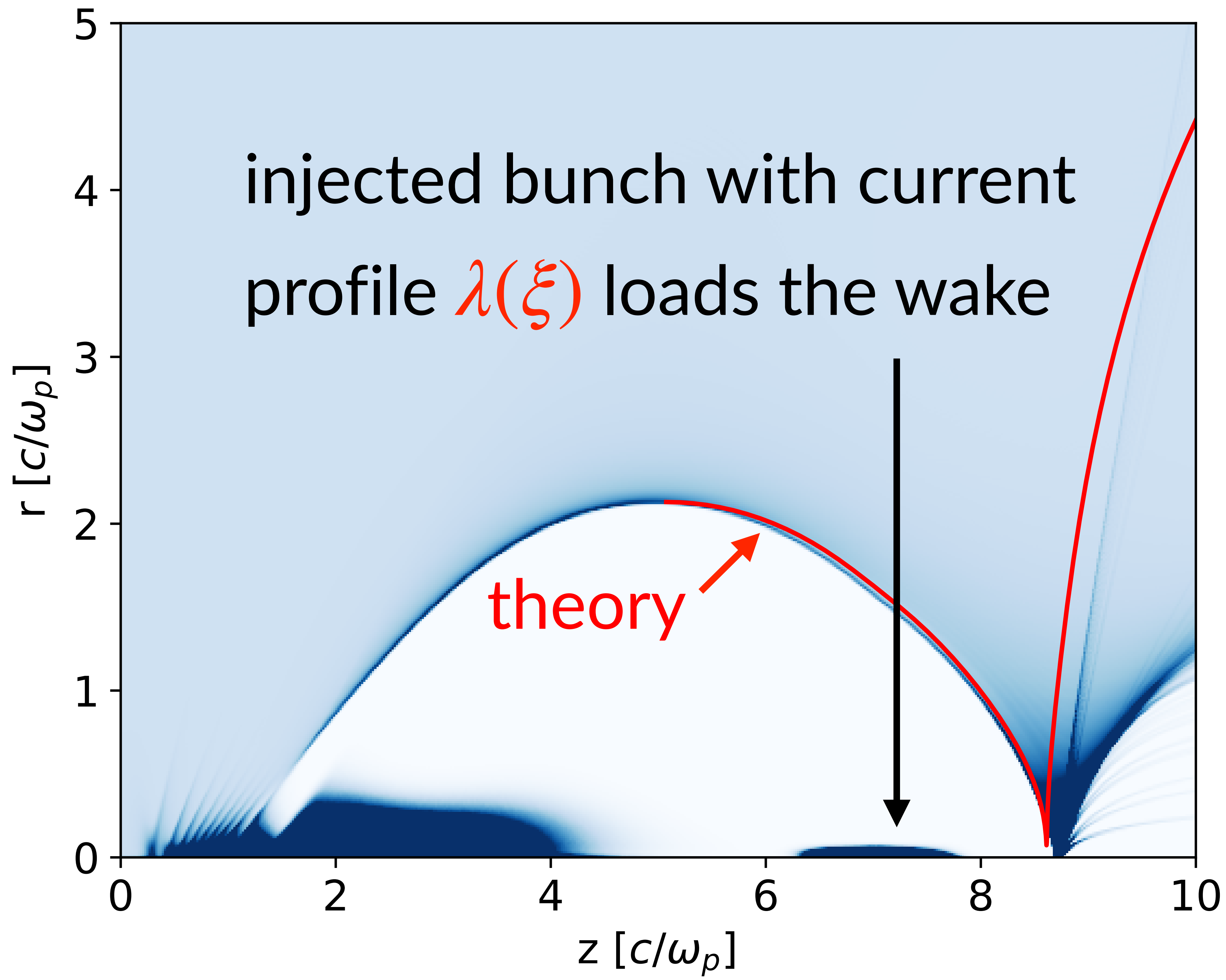


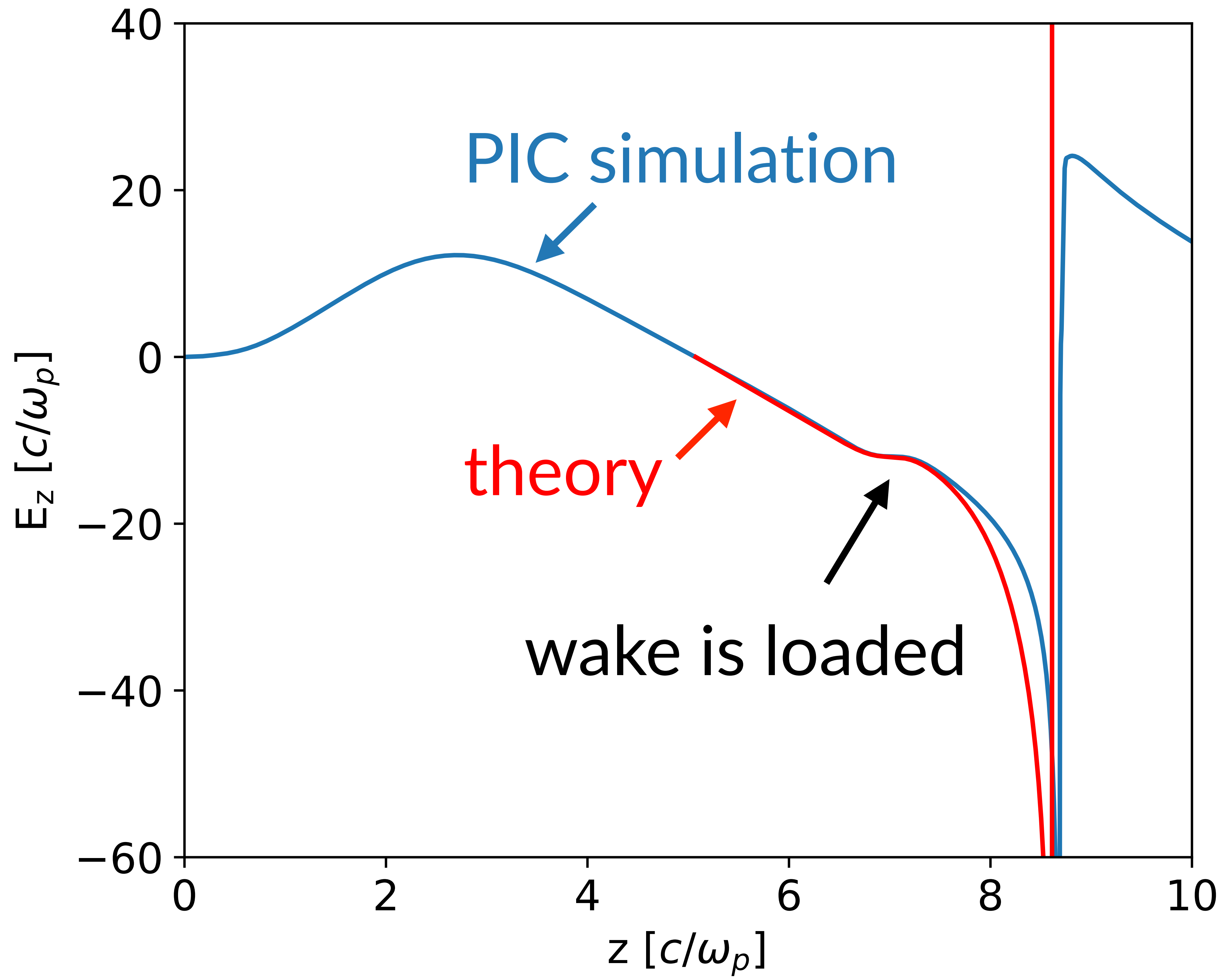
- smallest: 1.9 µm
- average: 3.2 µm +/- 0.8 µm
- **possibly diagnostic limited**
- **matched beam**

Reconstructing longitudinal phase space from measured energy spectrum

A precise model for PWFA enables the reconstruction of the injected bunch's current profile

for a given injected bunch with current profile $\lambda(\xi)$ → solving an ODE $A'(r_b)\frac{d^2r_b}{d\xi^2} + B'(r_b)r_b(\frac{dr_b}{d\xi})^2 + C'(r_b)r_b = \frac{\lambda(\xi)}{r_b}$ to get r_b and the accelerating field E_z → energy spectrum determined by $\lambda(\xi)$ and $E_z(\xi)$



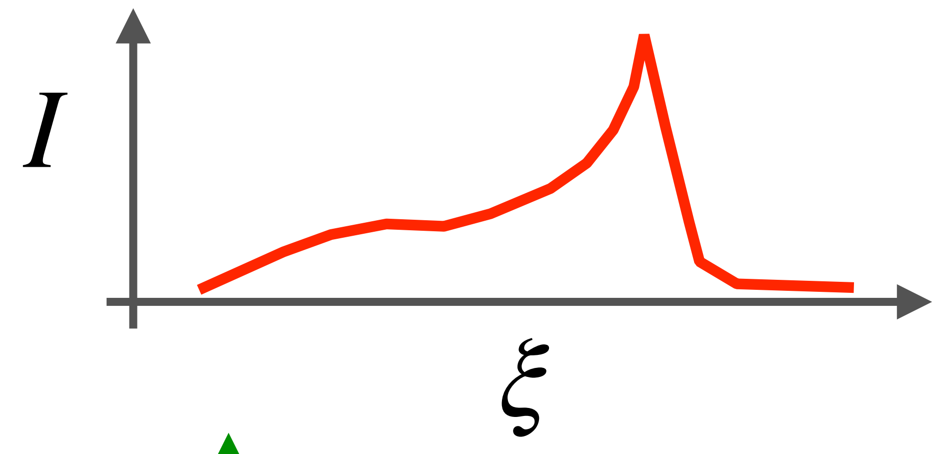


The injected charge must be distributed to load the wake such that the resulting energy spectrum matches the measured one

W. Lu et al., PRST-AB (2007), T. Dalichaouch et al., Phys. Plasmas (2021)

Reconstructing longitudinal phase space from measured energy spectrum

make a guess on the current profile



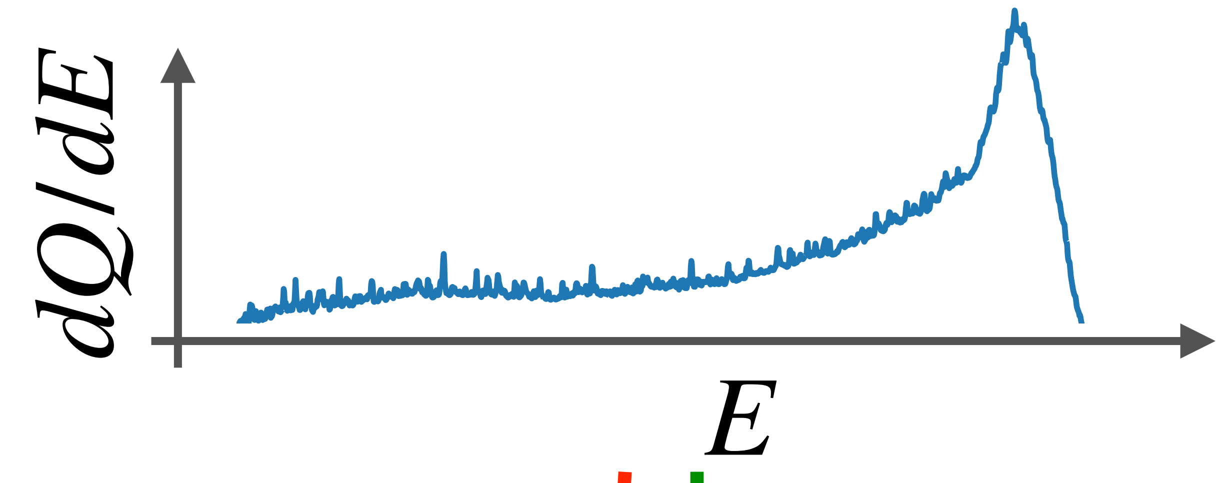
solve the ODE, do the mapping

$$A'(r_b)\frac{d^2 r_b}{d\xi^2} + B'(r_b) r_b (\frac{dr_b}{d\xi})^2 + C'(r_b) r_b = \frac{\lambda(\xi)}{r_b}$$

$$\lambda(\xi), E_z(\xi) \ \text{−>}\ dQ/dE$$

Assumes 1) non-evolving wake 2) acceleration length determined by Energy/(11 GV/m)

calculate energy spectrum



- compare the calculated and measured spectrum
- iteratively adjust the current profile to minimize the error
- simulated annealing (10,000s Forward Calculations)
- **gradient descent with auto differentiation (100s FCs)**

- neural network that mimics the function f(E—>I)
- data preparation (100,000s FCs) + training (hours)
- predicting in real time

Reconstructed current profile of the injected bunch

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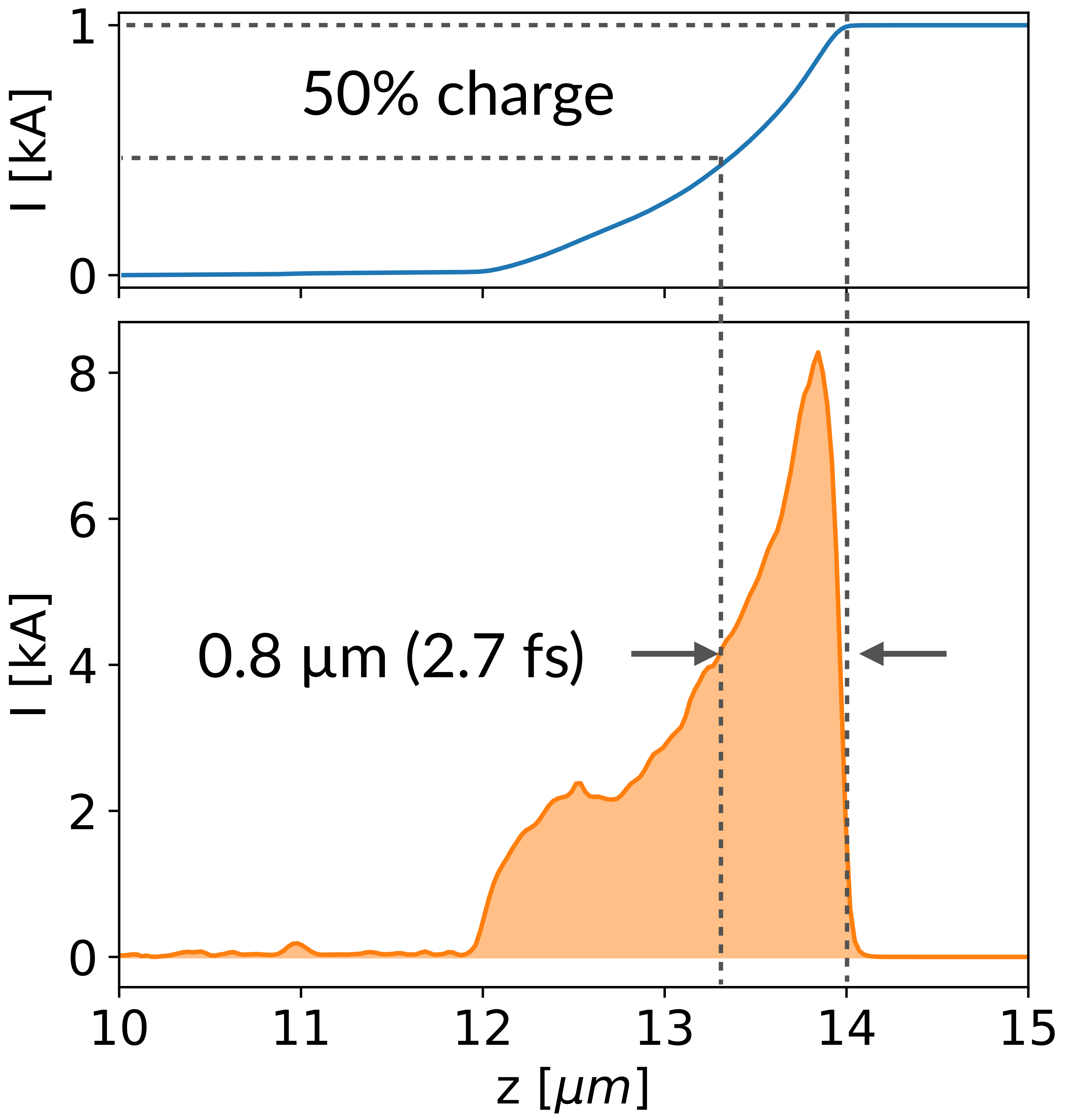
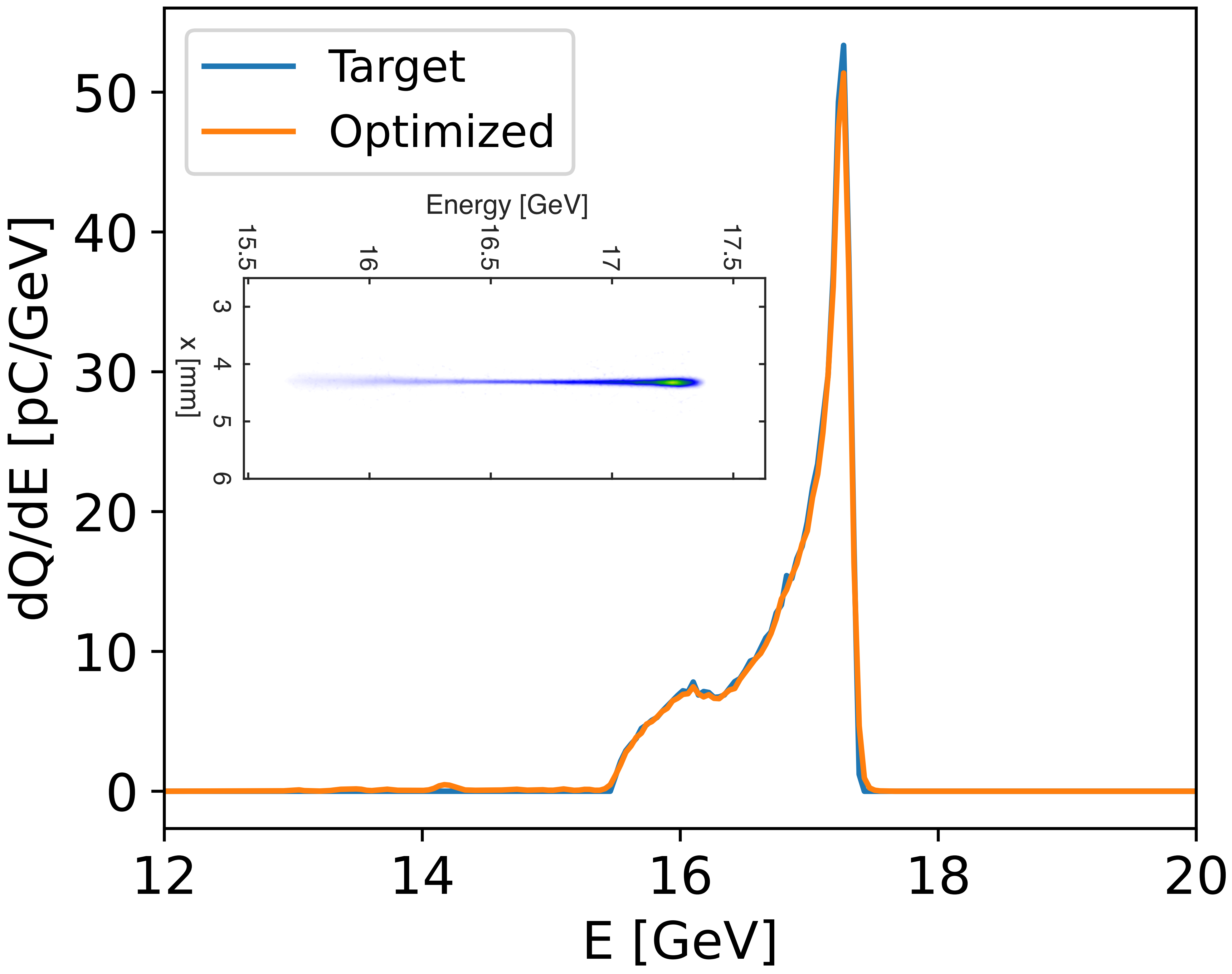
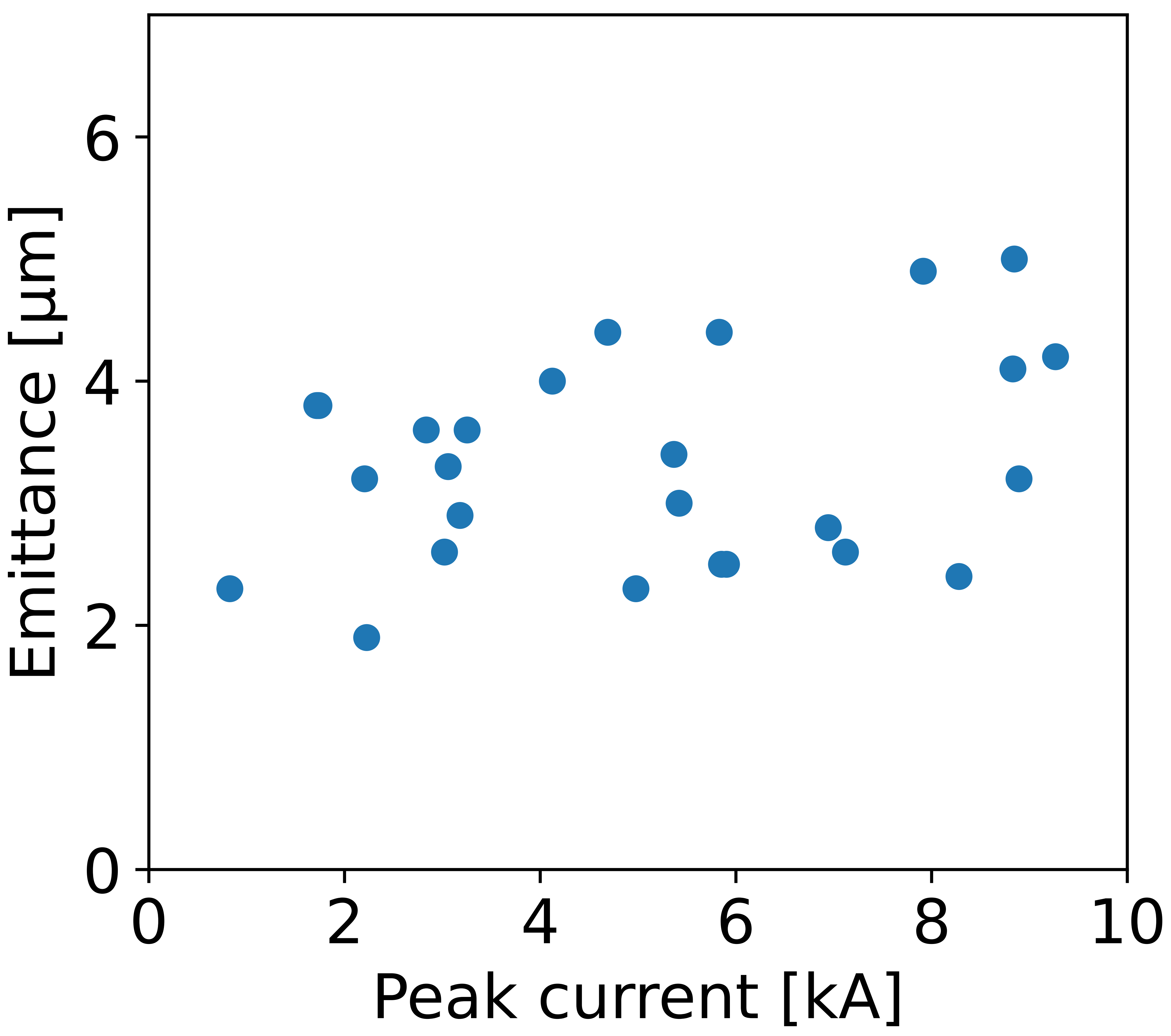


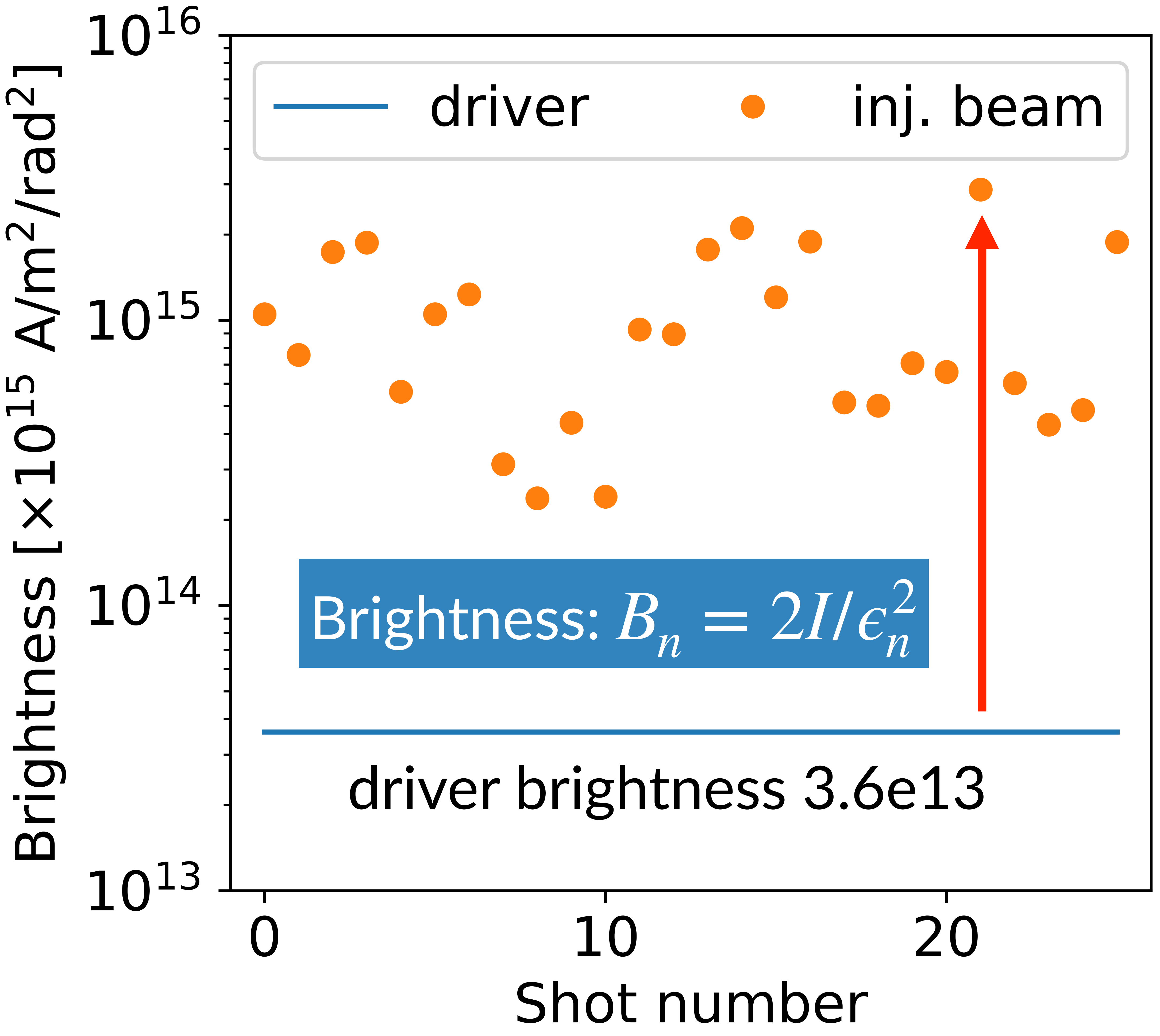
- 50% charge bunch length ~0.8 µm (2.7 fs)
- full length ~2 µm
- **peak current 8 kA**
- total charge ~25 pC



All three methods (SA, SGD with Auto Differentiation, Neural Network) give similar results

PWFA as a beam brightness booster





Emittance shows no obvious dependence on peak current

Brightness boost:

Max: 80x, Min: 6.6x, Average: 28x

E304 injected beam brightness comparable to state-of-the-art machines

The E304 experiment shows beam brightness comparable to leading facilities such as LCLS, highlighting the potential of PWFA to transform low-brightness beams into significantly higher-brightness beams, suitable for light sources and collider applications.

Parameters	*Drive beam*	*Injected beam*	*LCLS**	*Unit*
Charge	***1,600***	***25***	***180***	***pC***
Length	***20***	***~1***	***3 — 16***	***μm***
Emittance	***23***	***2.4***	***0.5 — 1.6***	***μm***
Peak current	***9.6***	***8.0***	***1.0 — 5.0***	***kA***
Brightness	***3.6E+13***	***2.8E+15****	***8E+15***	***A/rad²/m²***
Energy	***10***	***17***	***3.5 — 16.5***	***GeV***

**LCLS FEL Parameters – Updated July 19, 2024*

***boosted by ~80 times. probably can go higher if 1) post compress the bunch or 2) using higher density plasmas*

E304 progress summary

PIs: C. Zhang, S. Corde, X. L. Xu

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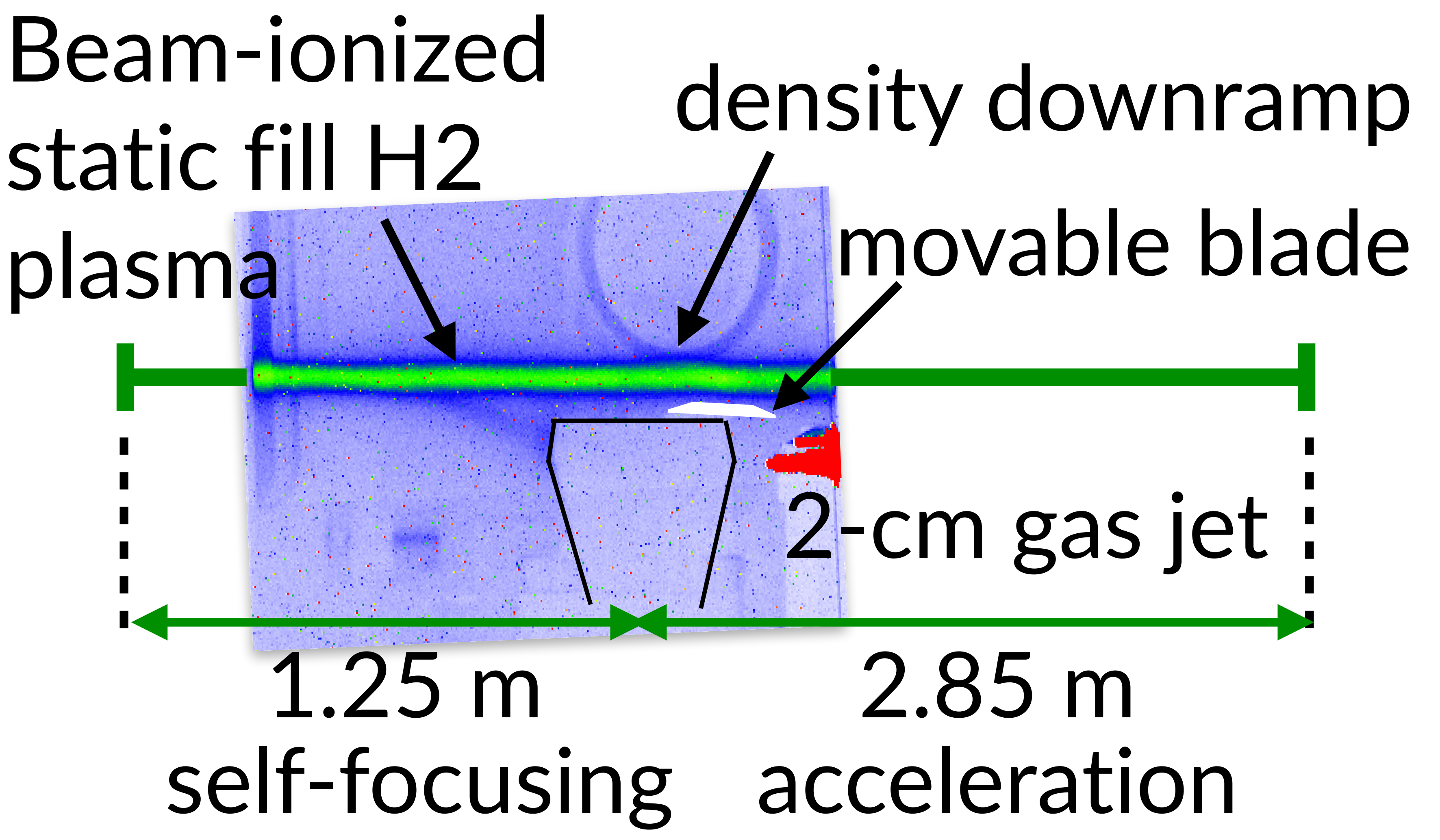
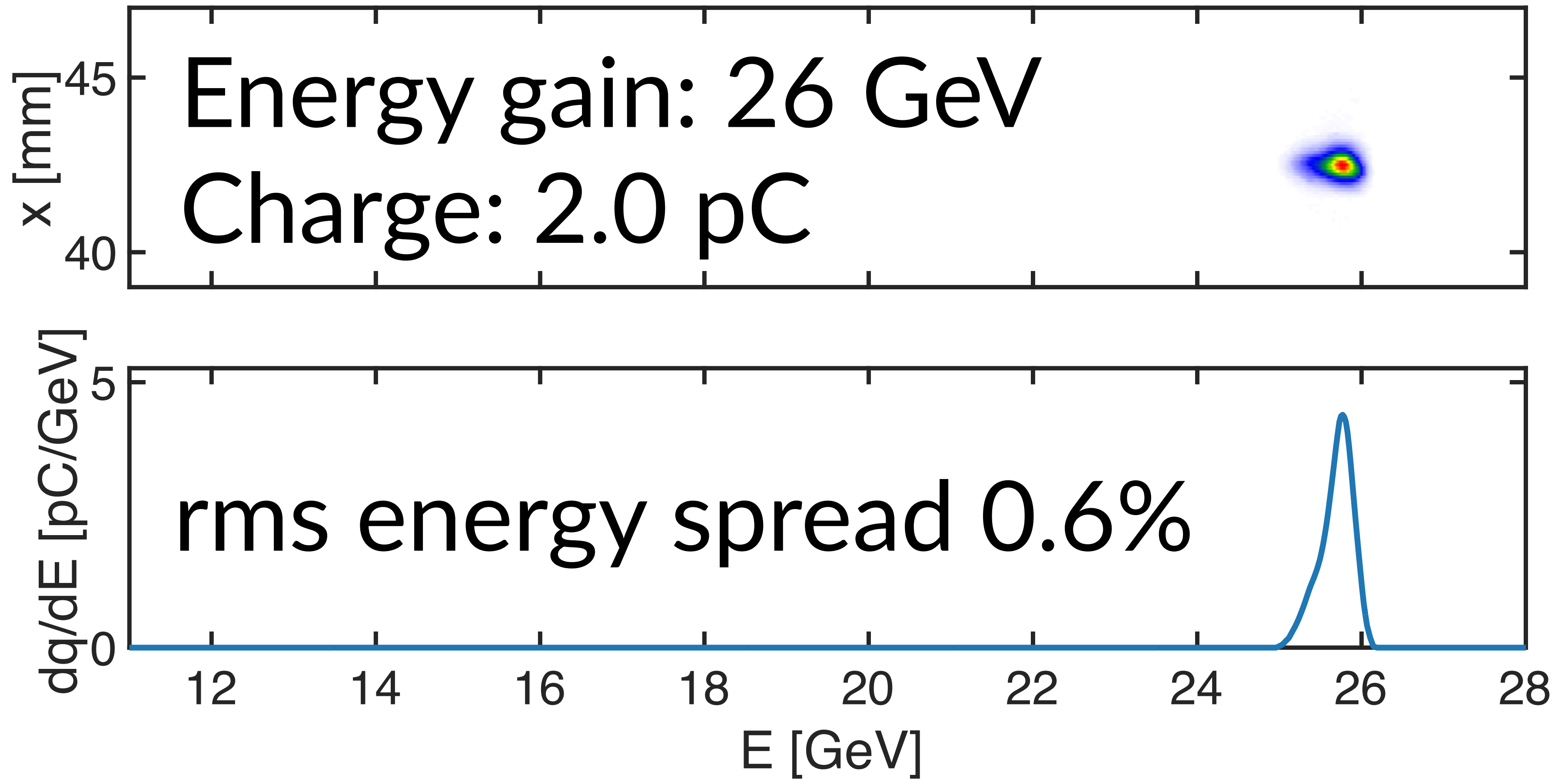
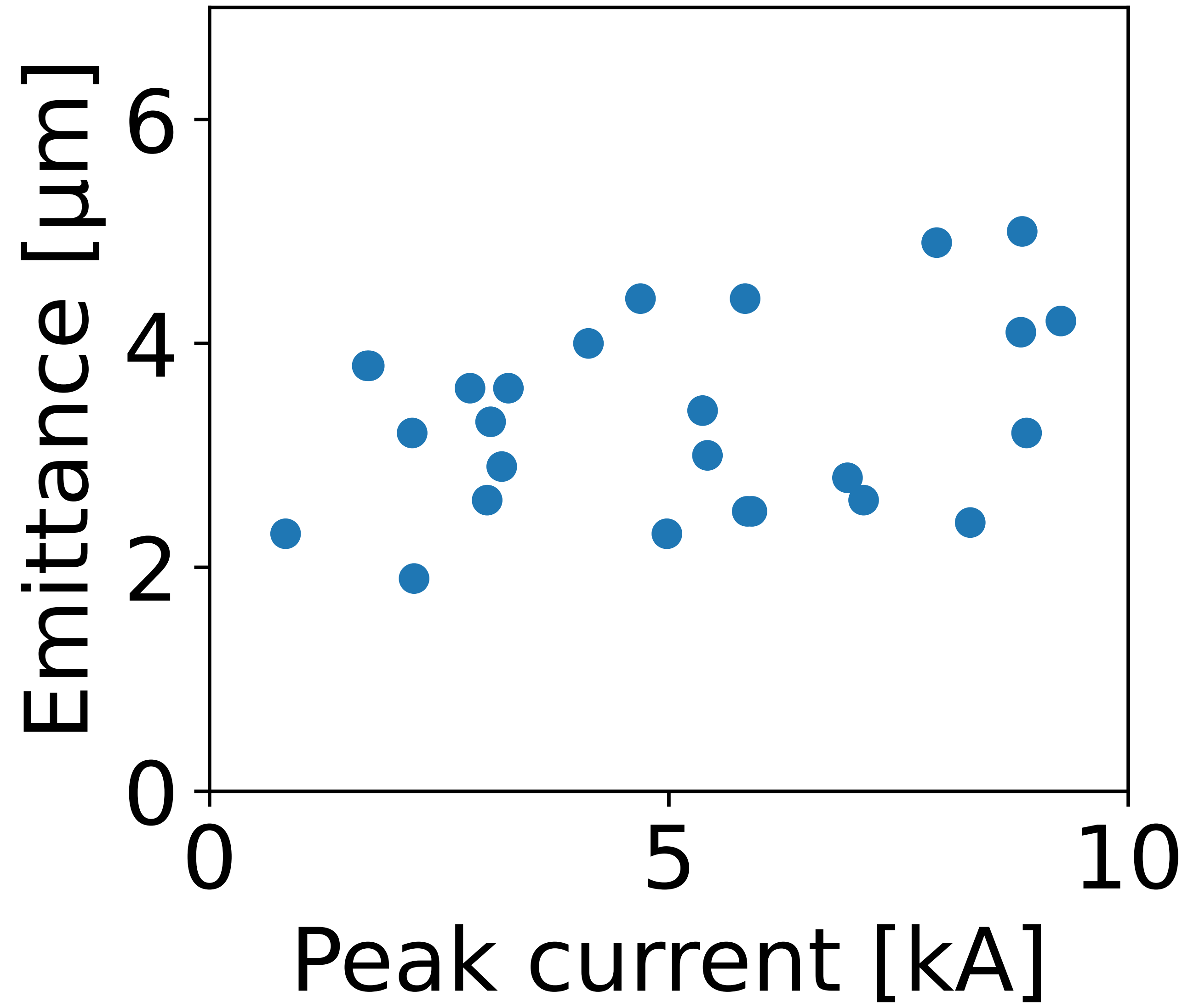
Gas jet in static fill configuration

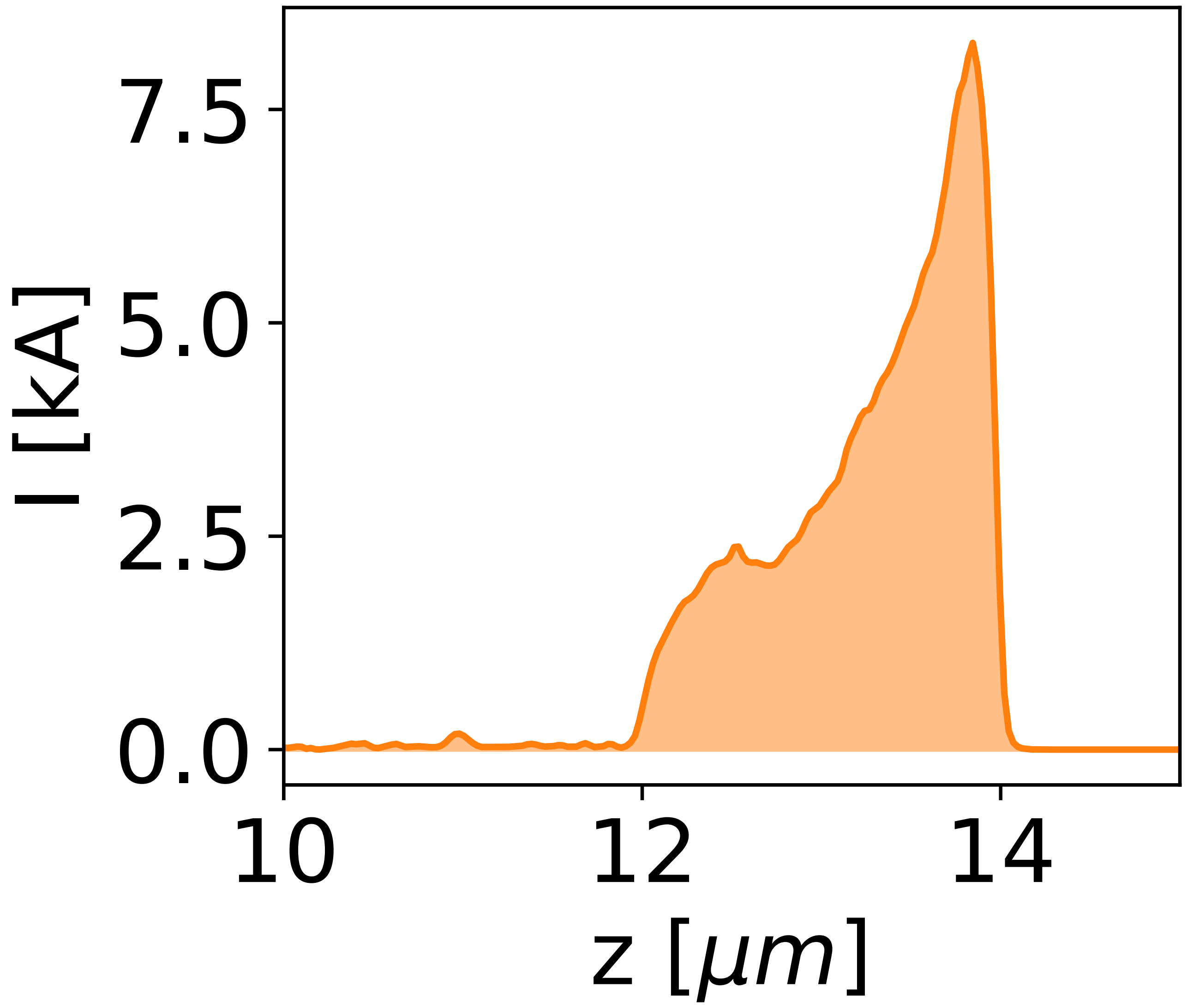


Energy doubling, <1% energy spread

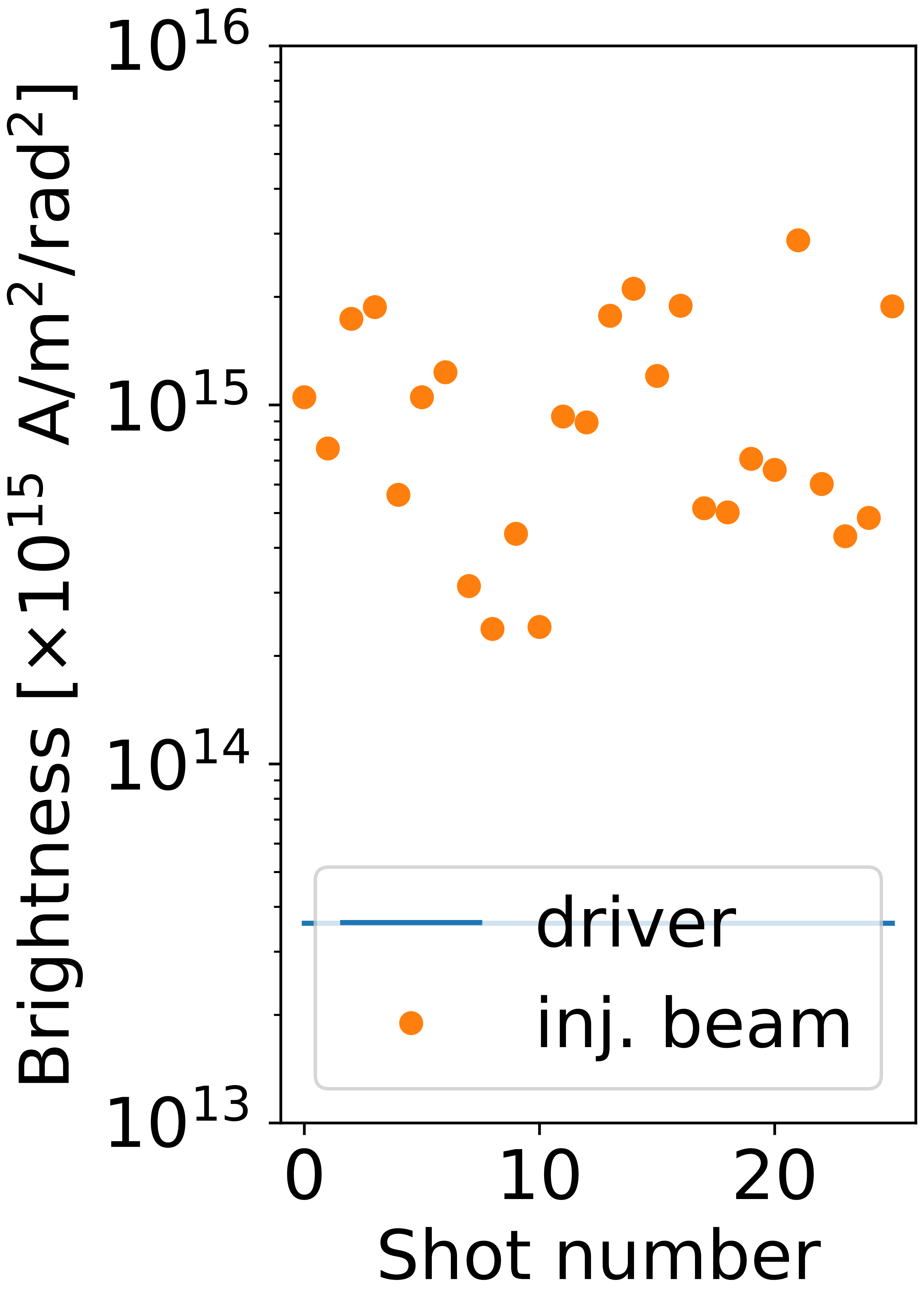


µm emittance, kA peak current





Beam brightness booster



Beam brightness booster:
~80x (Max), ~28x (Avg)

What's next for E304

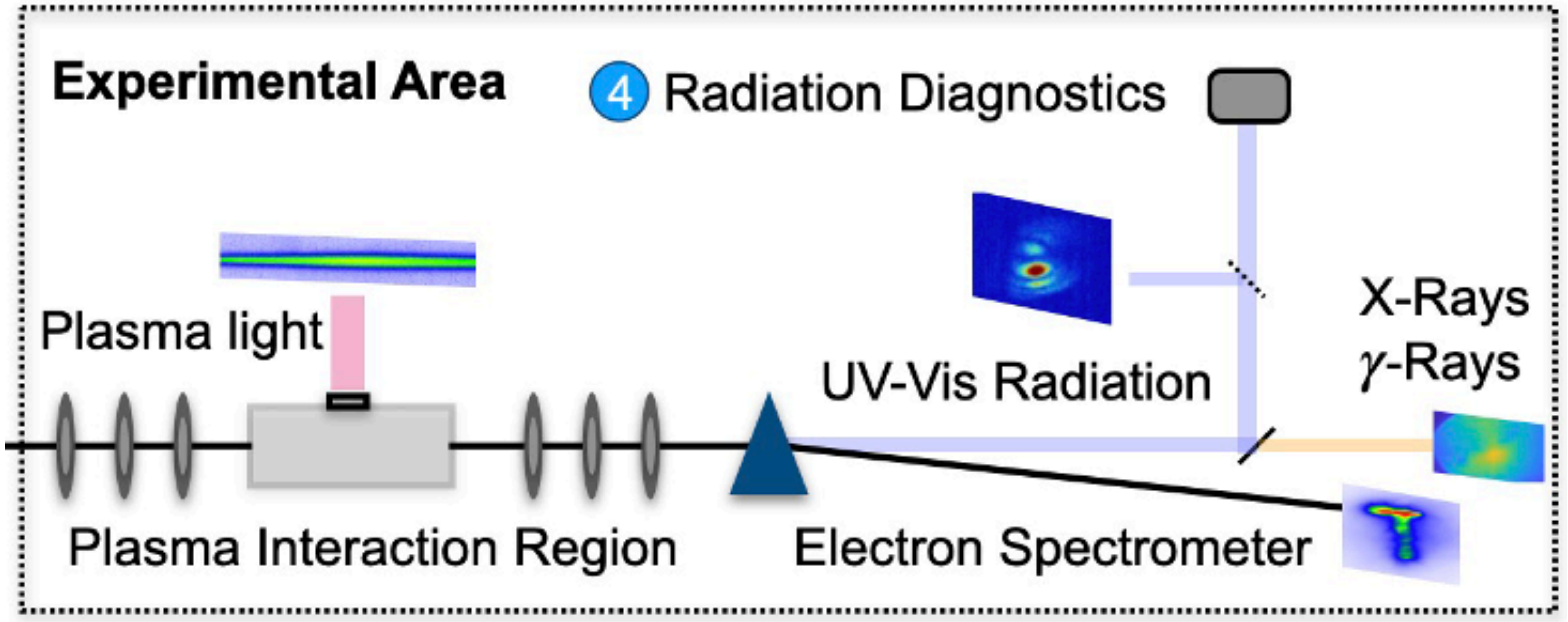
Near-term plan:

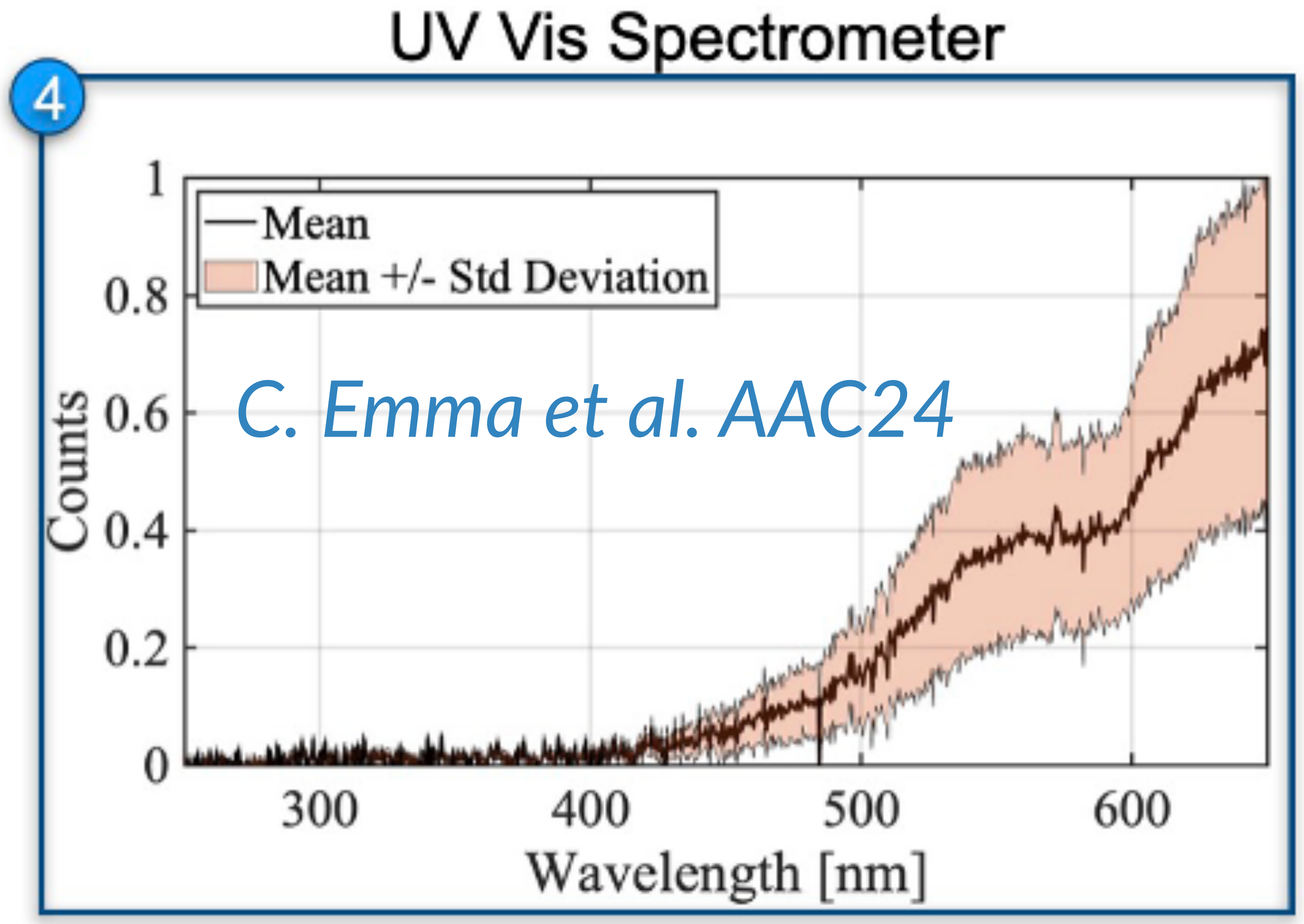
1) measure the μm-level bunch length (Nov 26-27, 2024)
2) improve stability and explore different configurations

Mid-term evolution:

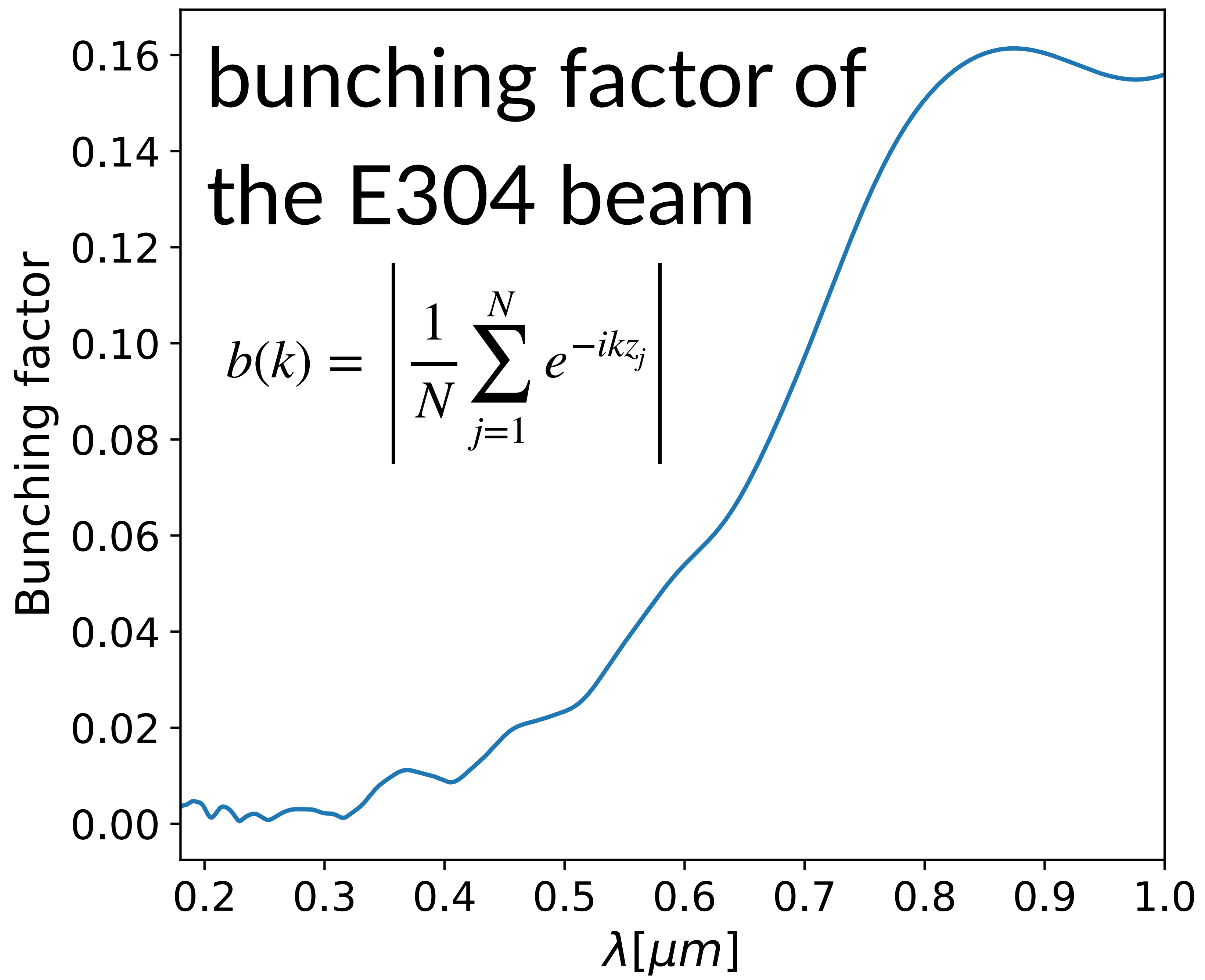
1) post compression of the injected bunch (in collaboration with E338)
2) modulated downramp injection for generating pre-bunched beams

Near-term plan #1: try to measure the μm-level bunch length using CSR





C. Emma et al. AAC24



- Separate the injected bunch signal from the driver signal by defocusing the driver beam at the dipole location (by leveraging the smaller divergence of the injected bunch)
- **Observables:** peaks or exponentially growing signals within the UV-Vis wavelength range (currently 180-650 nm, with a **planned upgrade to 190-1090 nm**).

Near-term plan #2: improve stability and explore different configurations

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We have tested the Gas-jet in Static-fill configuration and achieved remarkable results

- pros:
  - static-fill plasma focuses the drive beam to increase the beam density
  - long plasma enables high energy injected bunch
- cons:
  - relies on beam-ionization (requires a large current spike to ionize H_2)
  - large fluctuations due to variations in drive beam evolution and plasma length

The original design relied solely on the 2-cm gas jet for both injection and acceleration

- pros:
  - fixed plasma length improves reproducible **(better for post-compression/FEL)**
  - laser pre-ionized plasma may reduce emittance of the injected beam
- cons
  - requires a high quality drive beam (e.g., 10x10x10 μm)
  - low energy (<~1 GeV)
  - reduced rep. rate (1 Hz or lower to clear background gas)

Mid-term plan #1: generating attosecond bunches via post-compression

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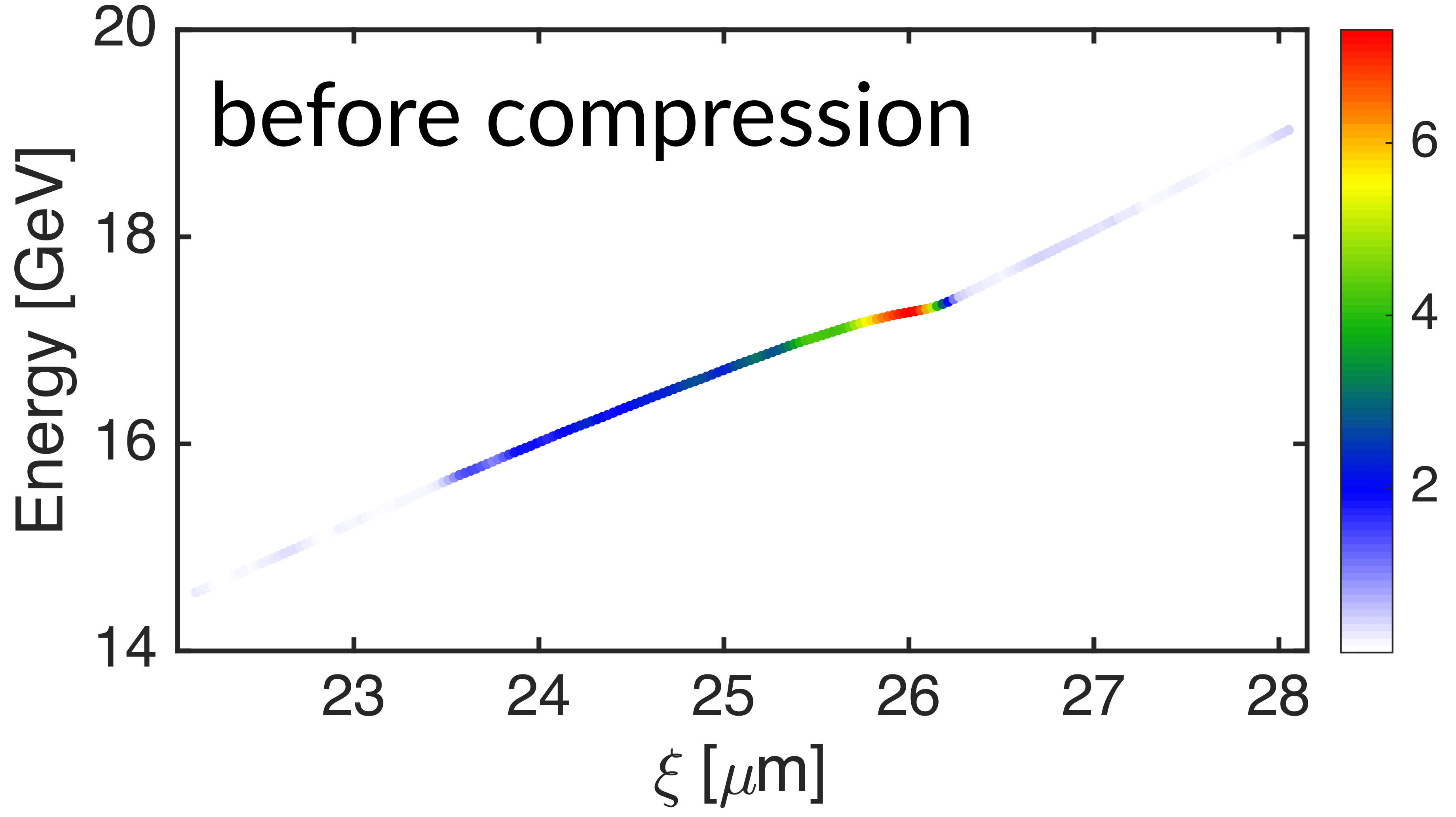
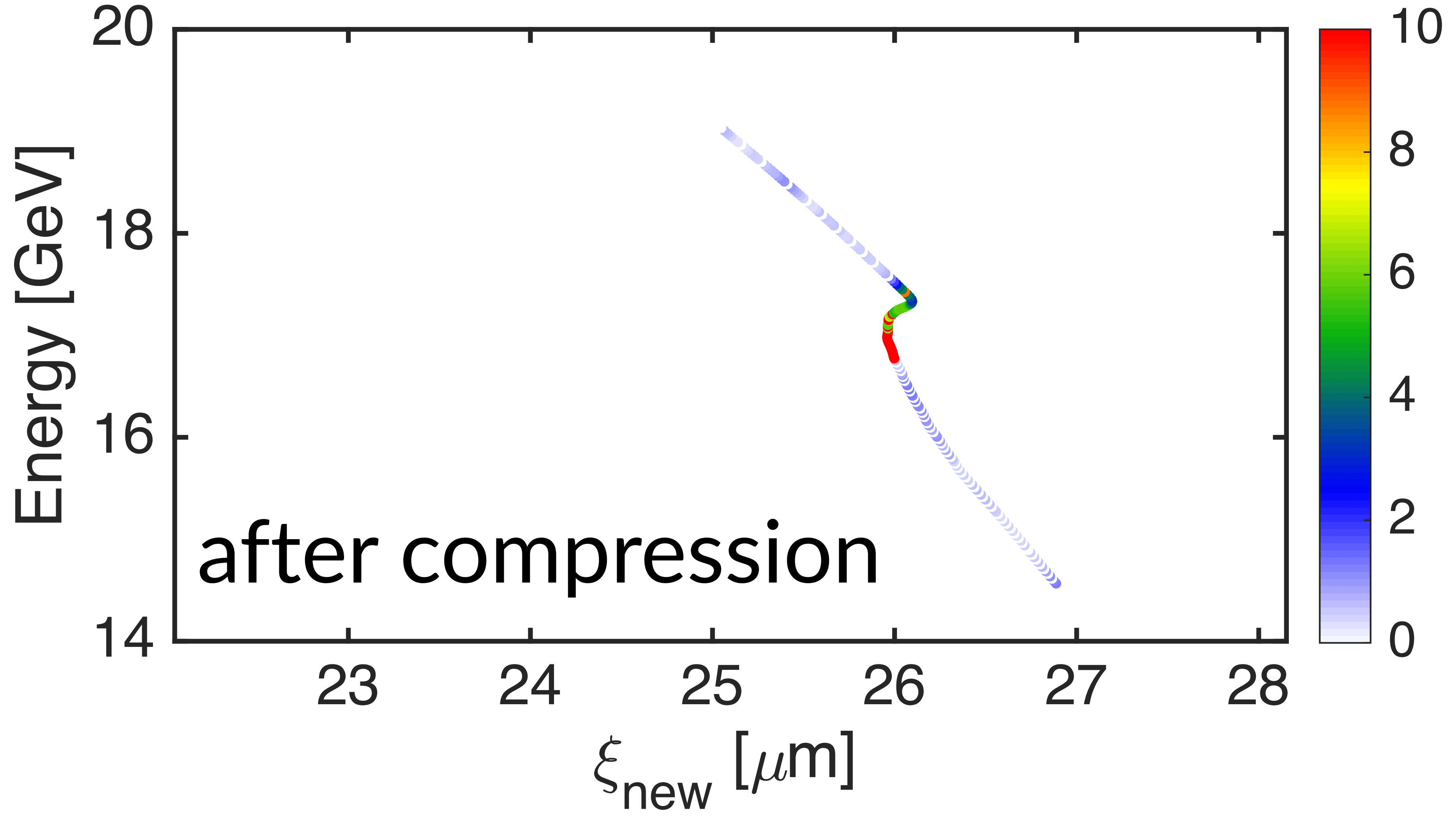
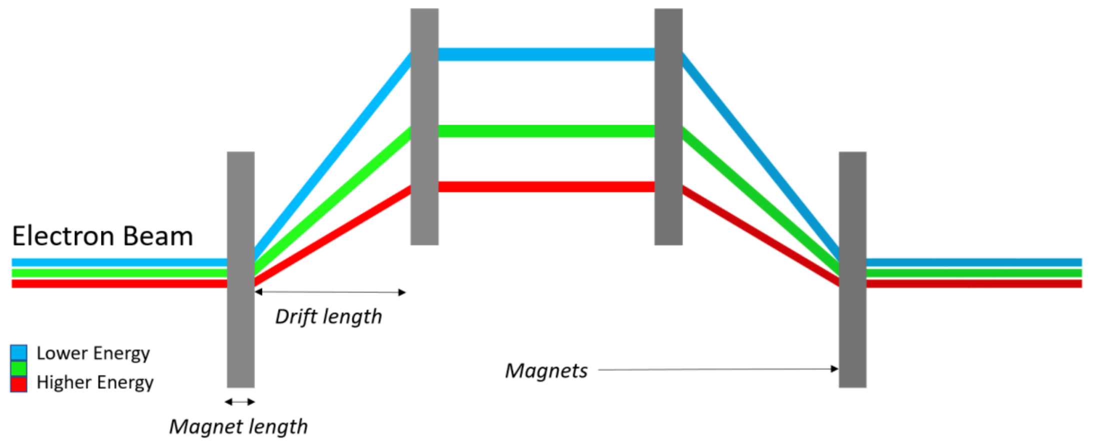
← beam direction



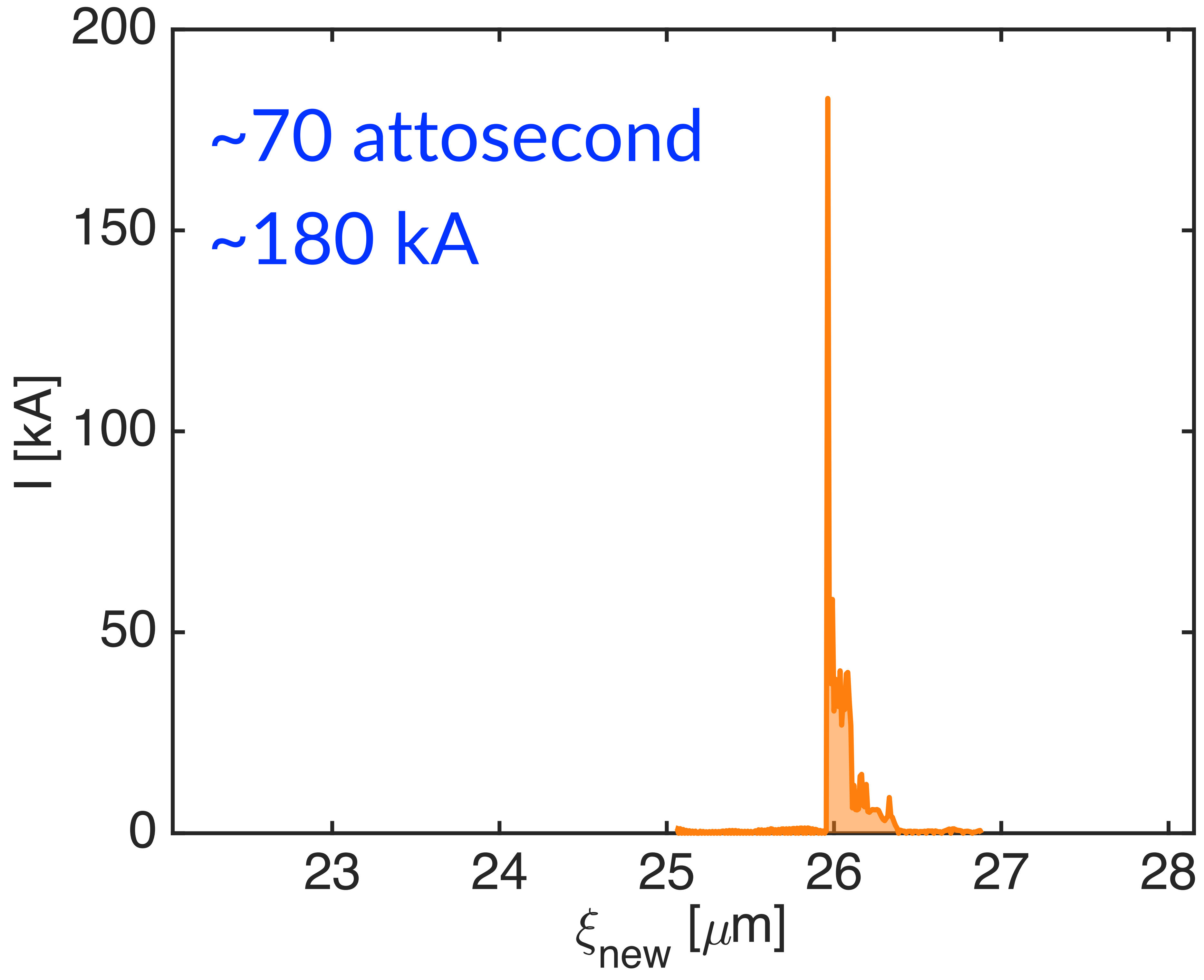


chicane: magnetic compressor for beams

$$\xi_{\mathrm{new}} = \xi + R_{56} \cdot \frac{\Delta E}{E_0}$$



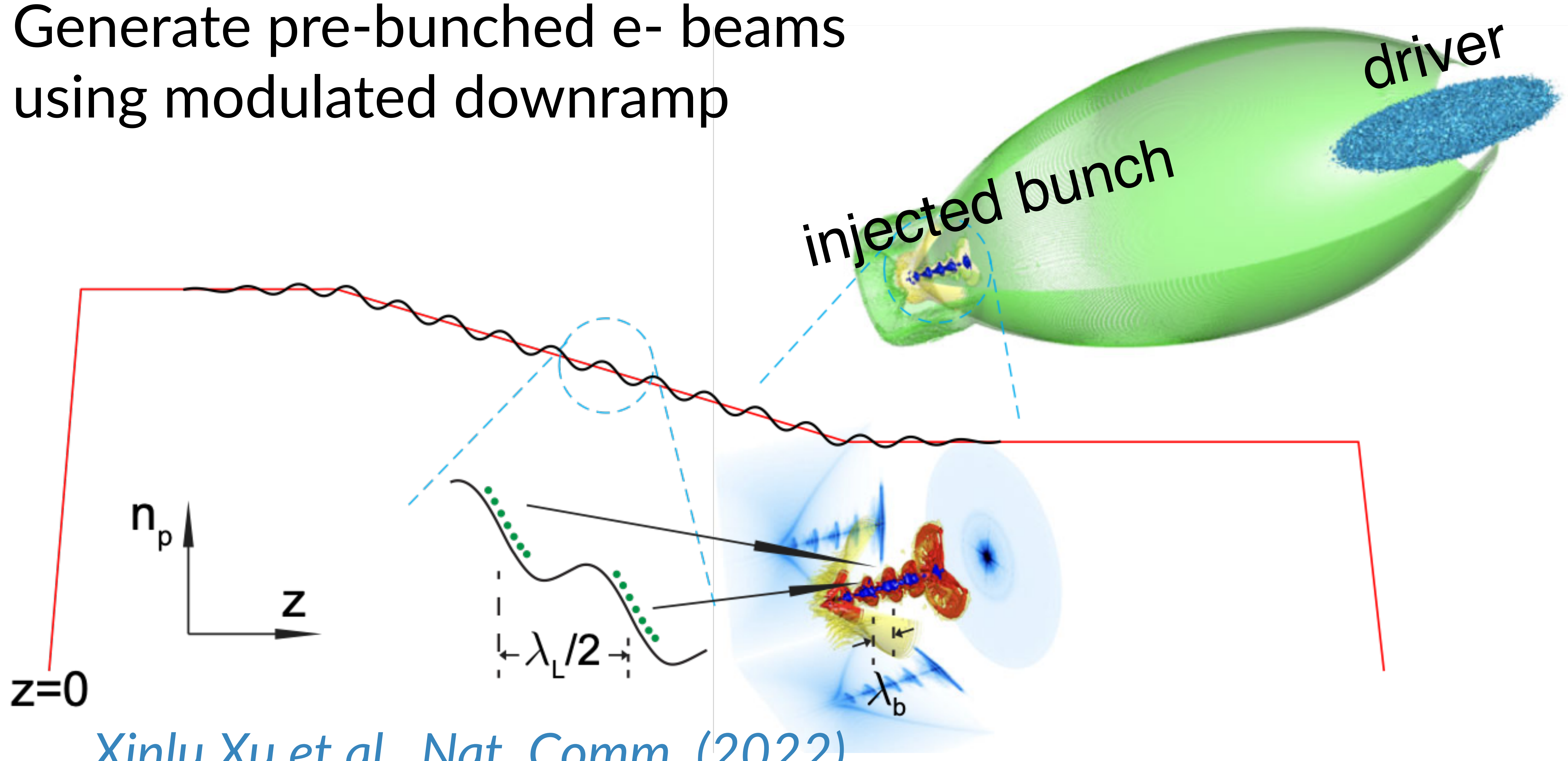
compression with R_{56}=30 μm



Assuming no emittance growth in compression, B~5.8e16 A/m²/rad² , brighter than LCLS beams

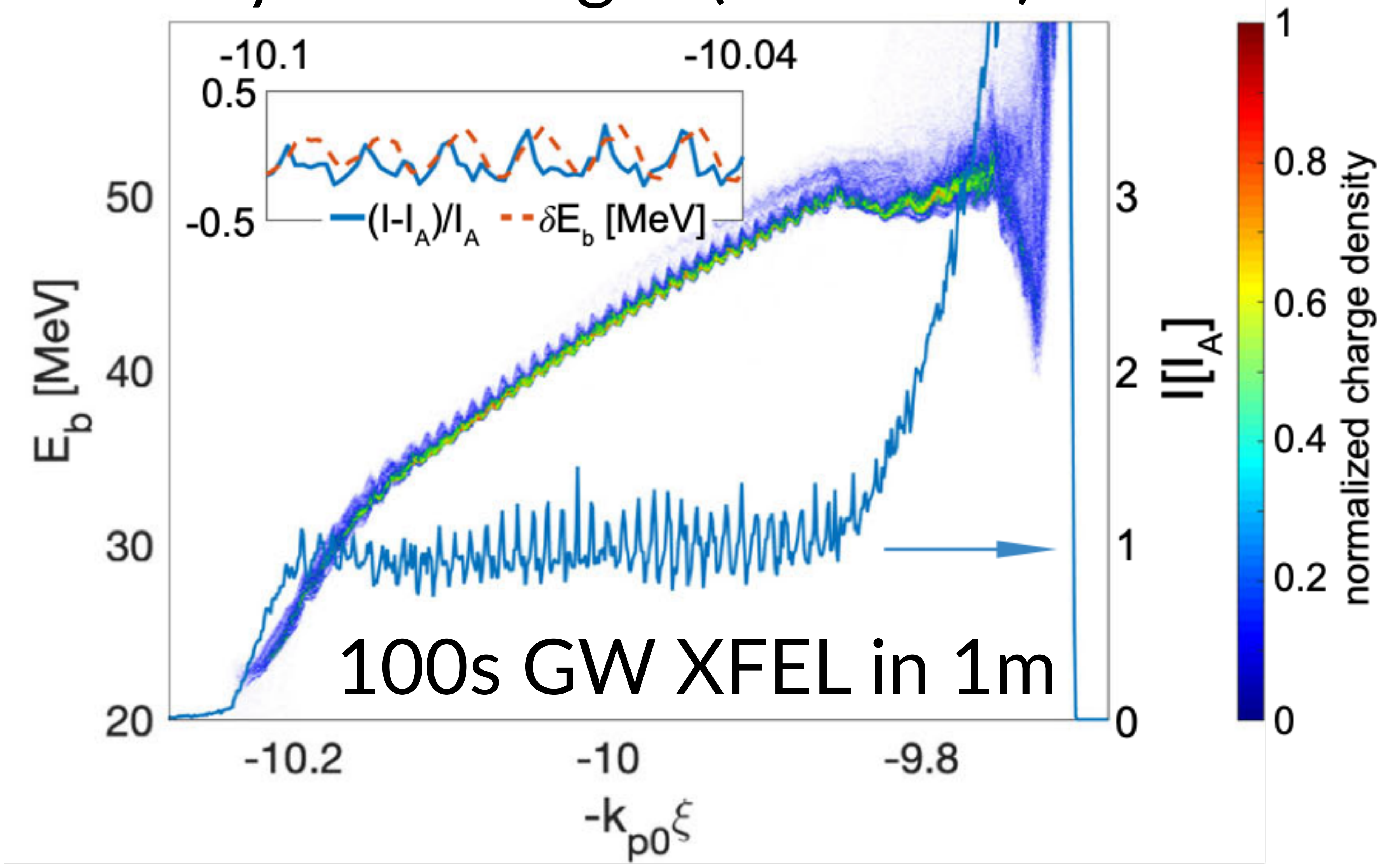
Mid-term plan #2: generating nano-bunched beams using Modulated-DDR

Generate pre-bunched e- beams using modulated downramp



Xinlu Xu et al., Nat. Comm. (2022)

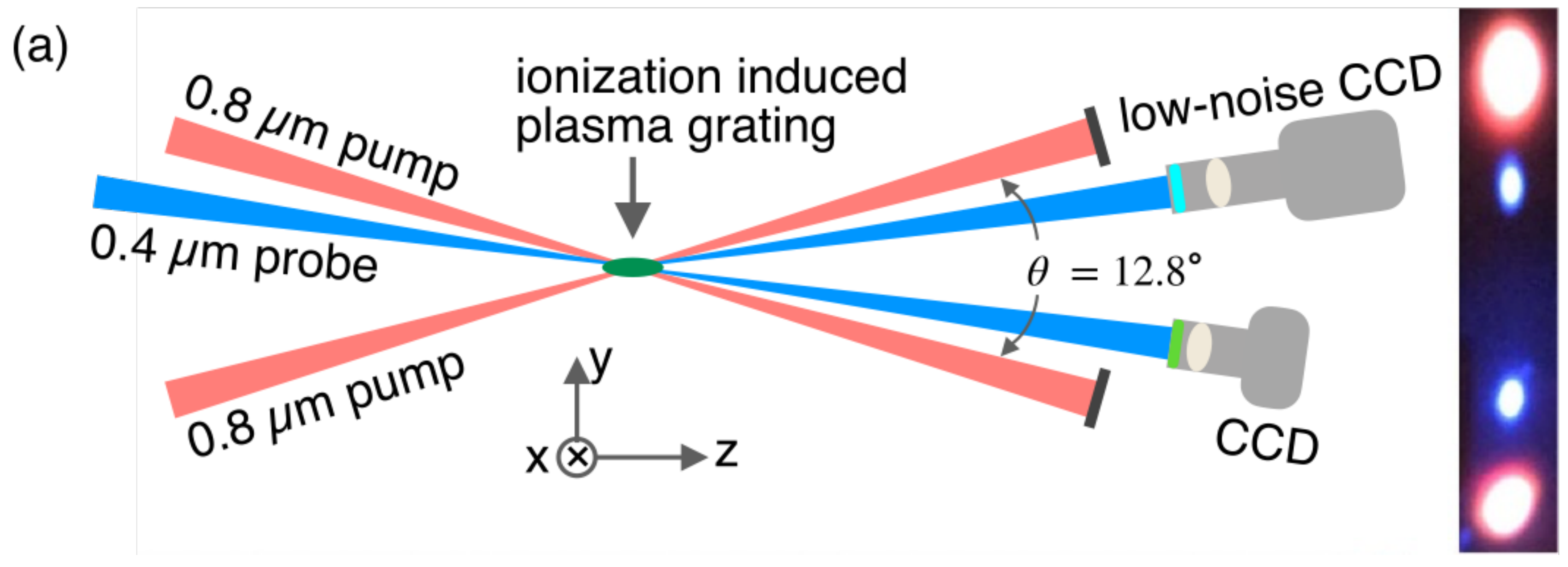
injected beam bunches at X-ray wavelength (~10s nm)

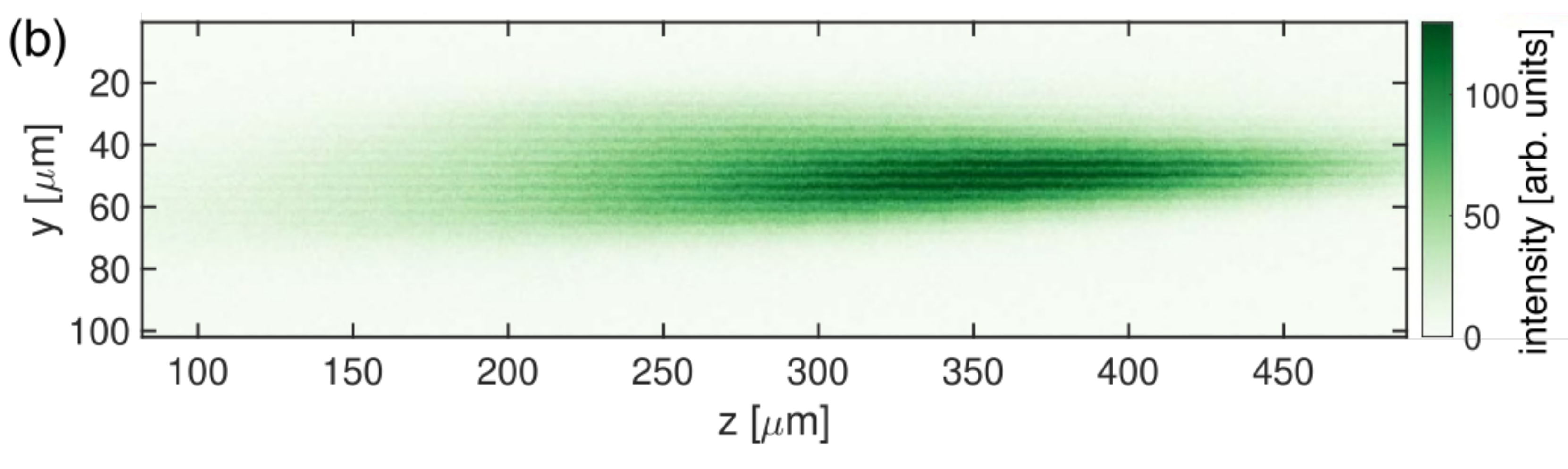


Enabling techniques:

- produce a modulated downramp via plasma grating
- measure bunched beams using CSR

producing modulated downramp via plasma grating





Chaojie Zhang et al., PPCF (2021)

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