Latest Results on PWFA Experiments from FACET-II

Chaojie Zhang, UCLA
on behalf of the E300 collaboration

July 25, 2024

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SLAC NATIONAL ACCELERATOR LABORATORY

aac 24 ADVANCED ACCELERATOR CONCEPTS
A Chicagoland meeting of the global Advanced Accelerator Concepts community

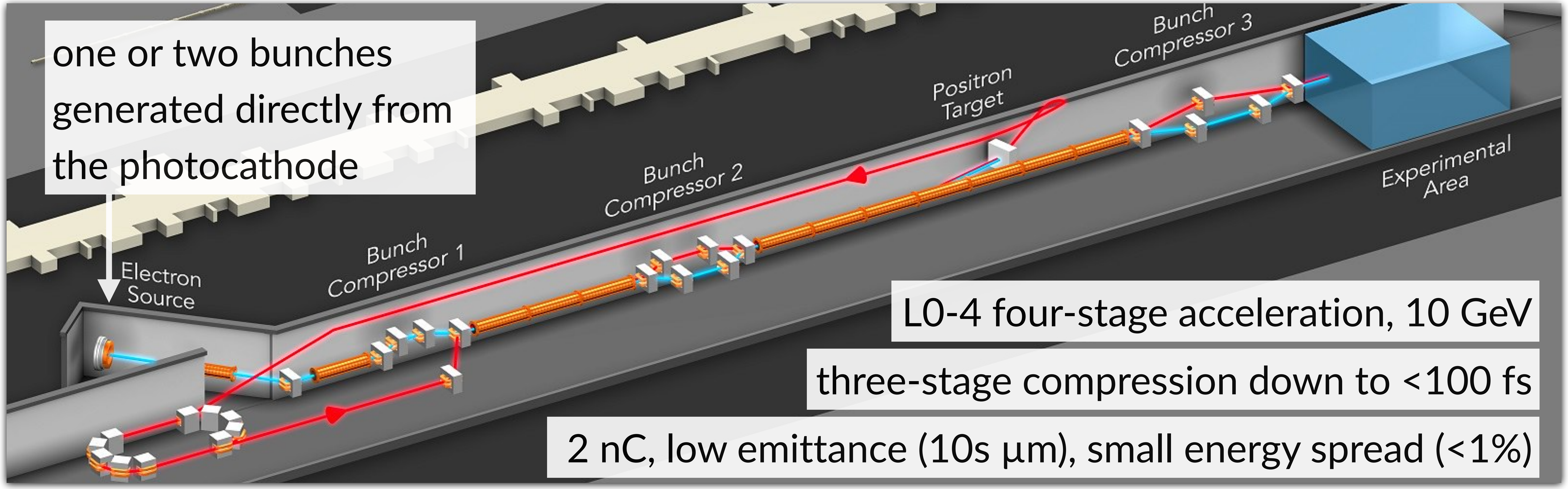
FACET-II facility is operated by SLAC, funded by DOE-HEP

U.S. DEPARTMENT OF ENERGY

What is FACET-II?

FACET-II Facility for Advanced Accelerator Experimental Tests

- FACET-II is a national User Facility operated by SLAC and funded by DOE that provides a unique capability for developing advanced acceleration and coherent radiation generation techniques using a high-energy electron beam.



- Has been operated with the single bunch configuration since 2022
- Started two-bunch configuration in May, 2024

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E300 collaboration

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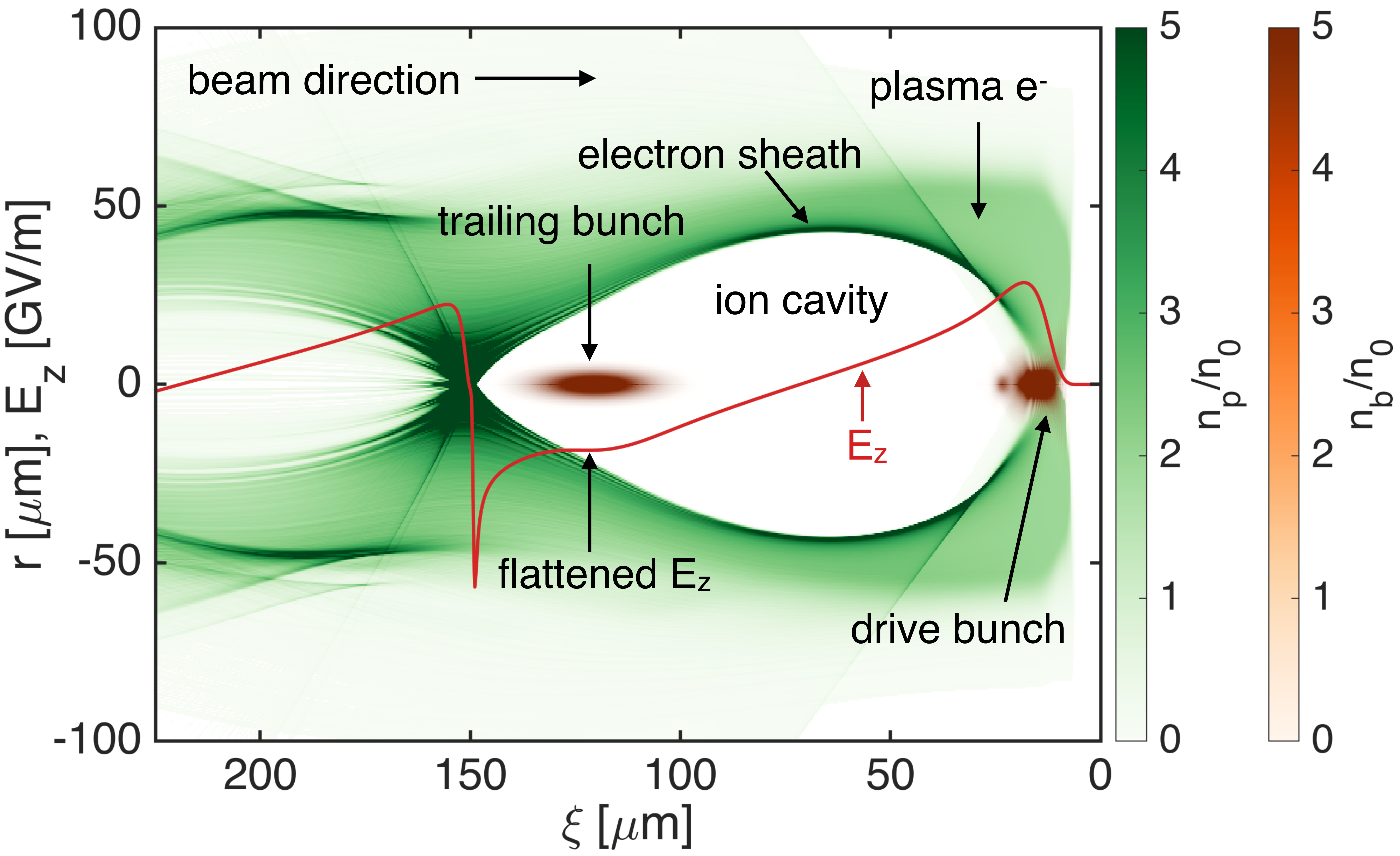
Plasma wakefield acceleration (PWFA) and the E300 experiment

two-bunch PWFA in the Blowout regime



- E300 aims at demonstrating a single stage 10 GeV PWFA
- Energy doubling in <1 m
  - 10 GeV—>20 GeV
- Narrow energy spread
  - <1%
- Preserving emittance
  - a few μm
- High efficiency
  - Driver to witness >40%
    - Driver to wake 80%
    - Wake to witness 50%

Highlights of the results

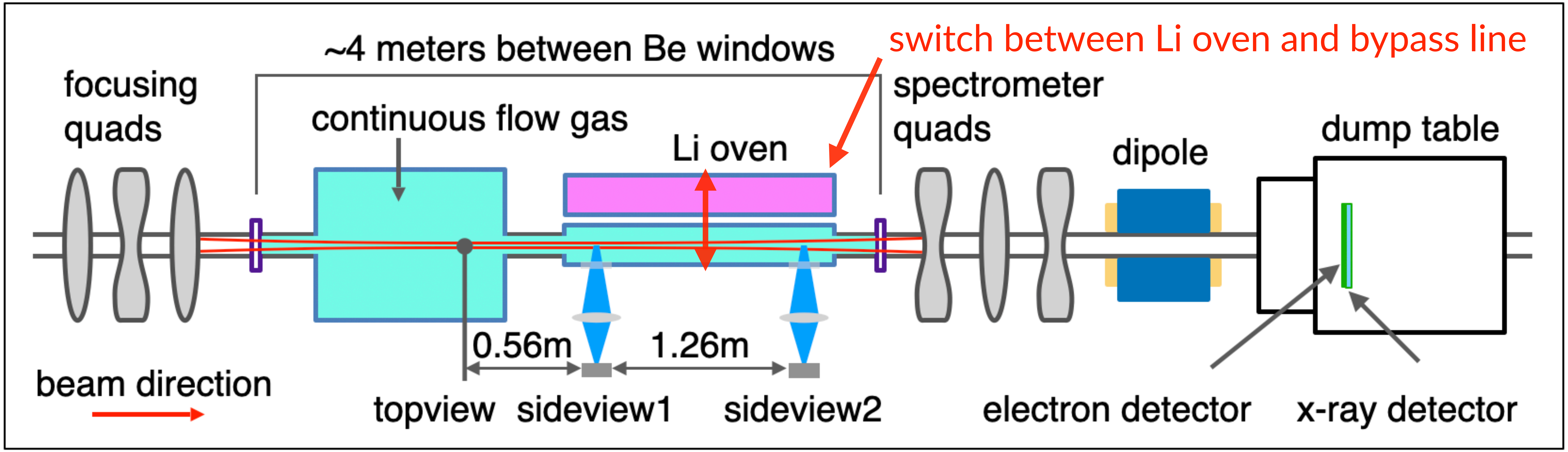
Single-stage 10 GeV PWFA

- **Repetition**
  - Meter-scale plasmas in hydrogen, needed for high rep rate future work have been formed
- **Efficiency**
  - Pump depletion of the 10 GeV drive beam accomplished
  - Driver-to-wake energy transfer efficiency without beam-shaping has been measured
  - Introduced machine learning to optimize experimental outcomes faster
- **Matching**
  - Preliminary data obtained on the matching of a single beam to the high density plasma wake
- **Two-bunch** (2 GeV energy gain)

High-brightness beam generation

- **Ionization injection**
  - multi-GeV, multi-color, potential μm-nm scale current modulation
- **Downramp injection**
  - up to 26 GeV, ~1% energy spread, a few μm emittance, brightness booster

Experimental setup



- e- beam: 10 GeV, 1-1.6 nC, 50 cm beta function at the IP, ~50 μm emittance, 20-50 μm spot size, >20 μm bunch length (with >30 kA current spikes)
- plasma:
  - beam or laser-ionized lithium vapor bounded by helium gas
  - beam or laser ionized continuous flow of H2/He gas isolated by differential pumping system
- Main diagnostics: imaging spectrometer, x-ray intensity profile monitor and spectrometer, visible plasma light at various locations

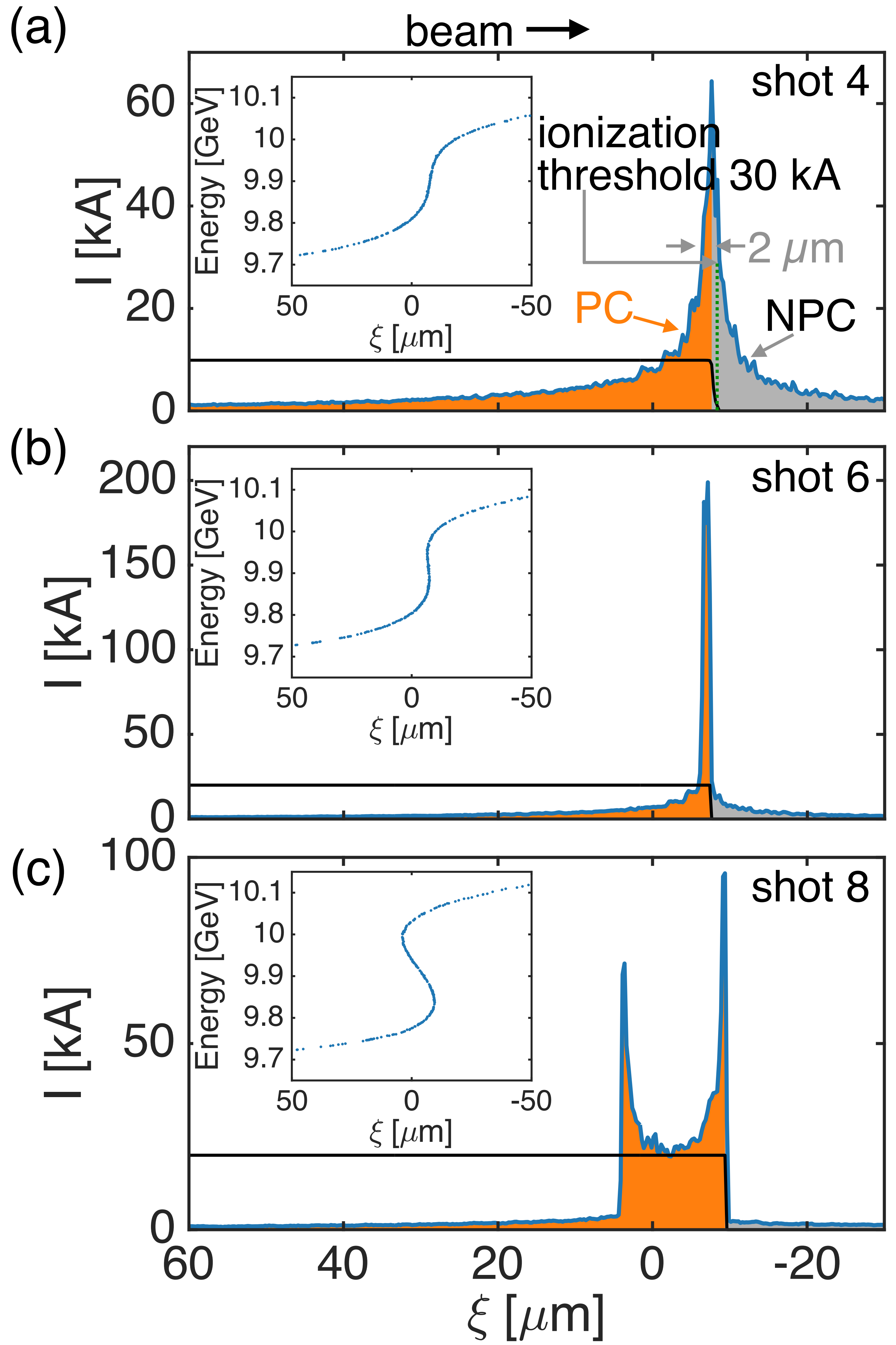
Ionization and wake generation in a meter-scale hydrogen plasma, evidence of pump energy depletion, and energy transfer efficiency

why hydrogen?

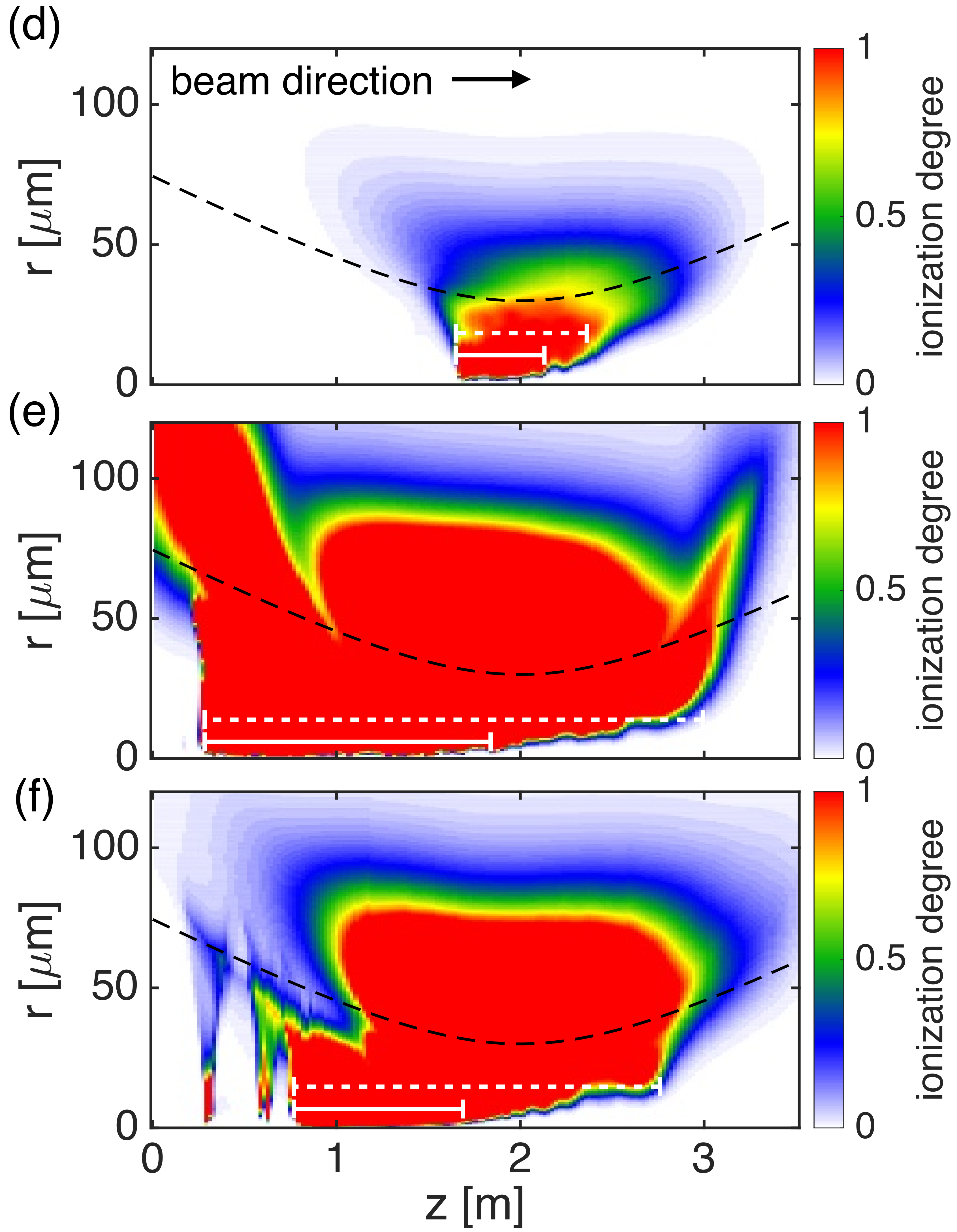
- Future colliders will need to operate at kHz or greater rep rates.
- At 1 TeV (CM) beams will contain ~5 MW of average power. Assuming 50% efficiency this means 2.5 MW will be left behind in a thin plasma column.
- This will rapidly heat the gas and create a time dependent density depression on axis.
- The plasma medium will have to be created in a refreshed gas. H2 is the natural choice due to its low and simple ionization energy levels.
- We first ionize H2 and excite a wake using the transverse field of the drive beam - need a peak current of 30 kA (for a 30 μm spot size).

The FACET-II compressors can produce 100 kA peak current beams

Current profiles from beamline simulation (by C. Emma)



Meter-scale plasma generation (in 2.0 Torr Hydrogen)

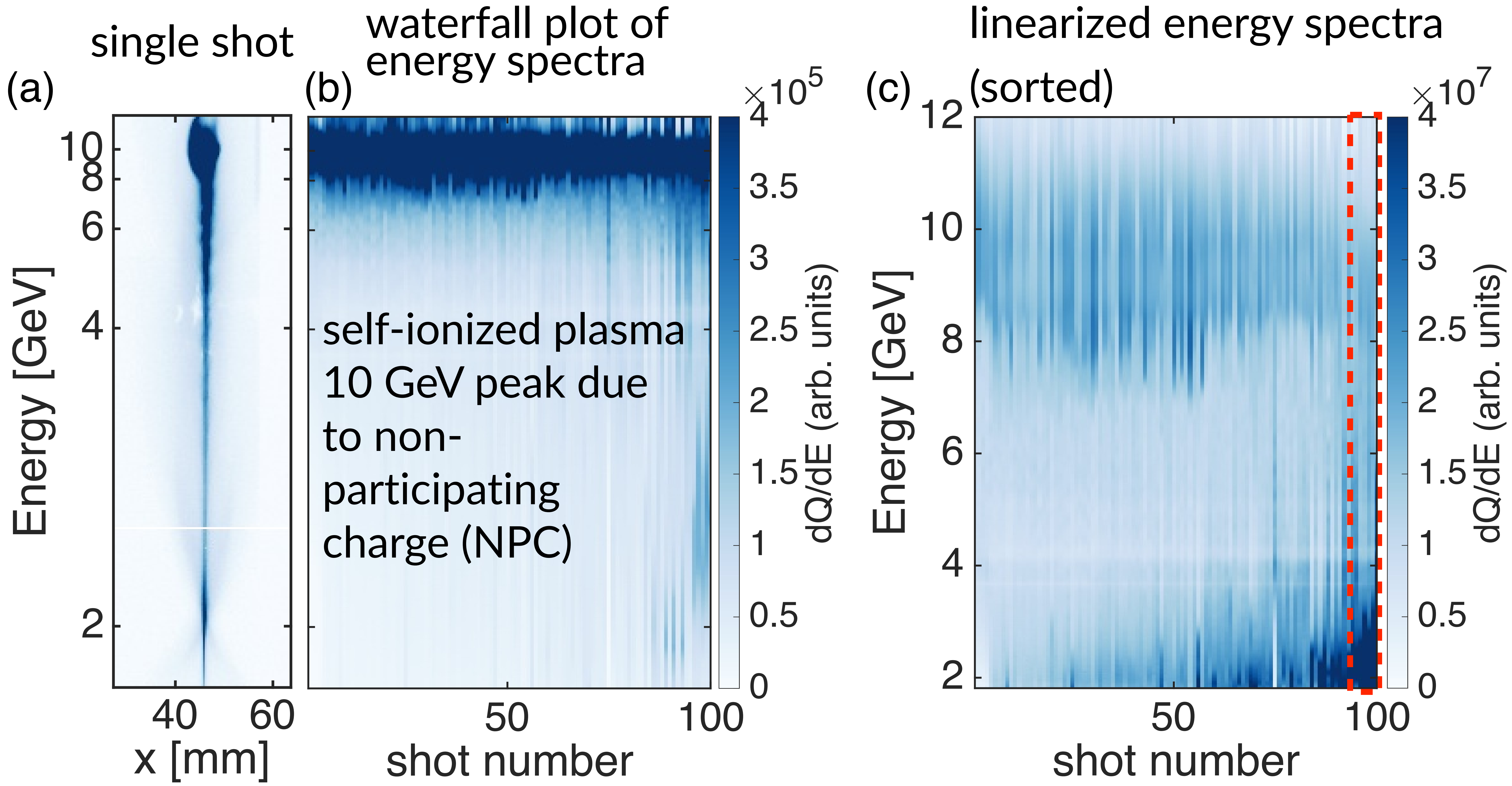


- **Beam dynamics simulations showed large fluctuations in current profiles from small jitter in RF phase and amplitude.**
- **The final compressed current profiles can be very different.**

C. Zhang et al, PPCF 66, 025013 (2024)

Drive beam energy depletion in 1.5 Torr H2 gas (~5e16 cm^{-3})

- 1.5 nC driver. Spectrometer setting: lower dipole strength + imaging energy at 2 GeV
- <2 GeV electrons recorded
- In 73 out of 100 shots, the charge of <3 GeV electrons exceed 100 pC



C. Zhang et al, PPCF 66, 025013 (2024)

Driver to wake energy transfer efficiency in meter-scale H2 plasma

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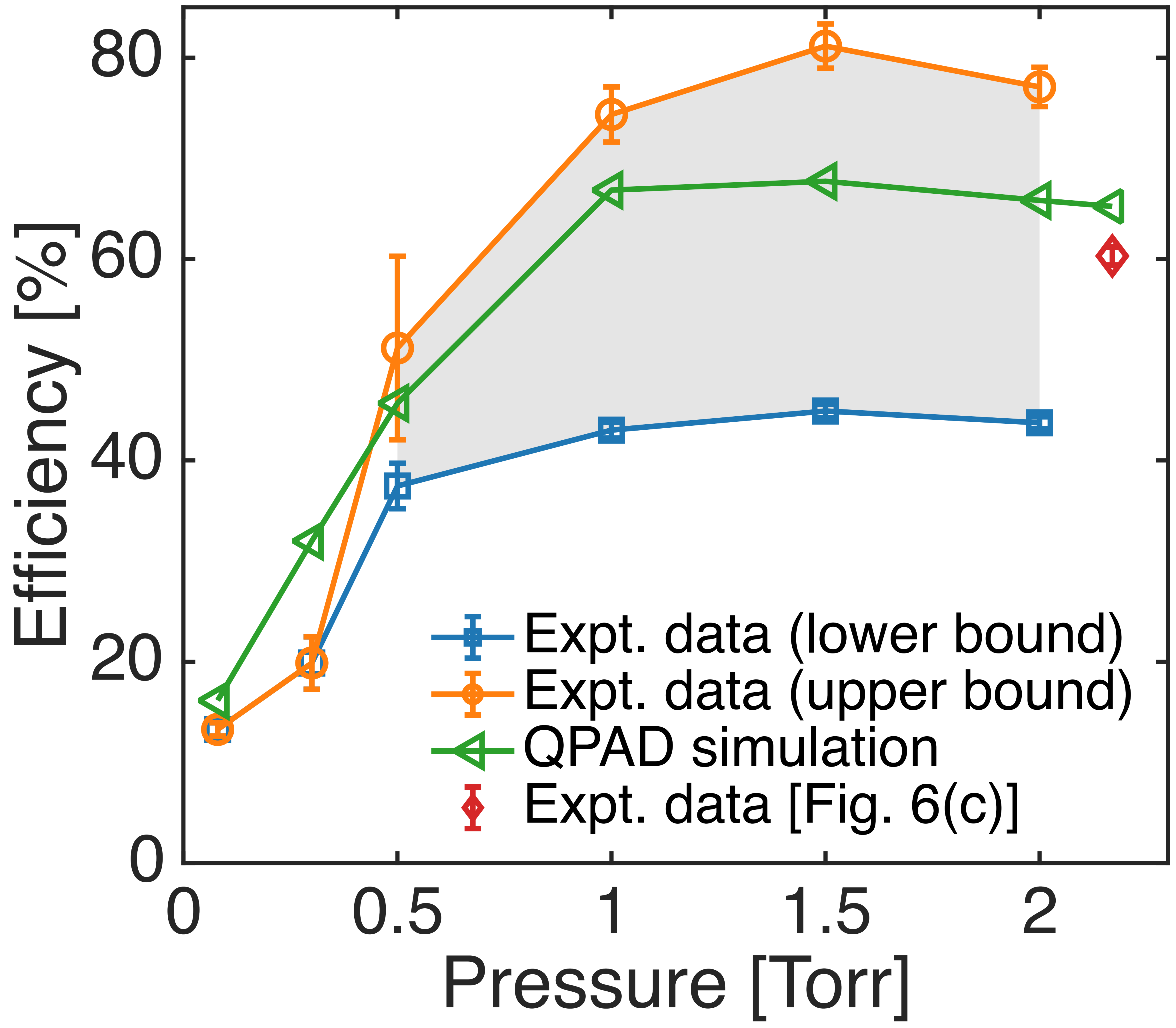

- Achieved 60% beam-to-wake energy transfer efficiency (excluding non-participating charge)

- goals: overall efficiency 40%
  - drive beam to wake: 80%
  - wake to witness: 50%

- Spectrometer captures >5 GeV electrons
  - Max energy loss < 5 GeV, no missing charge, calculate deposited energy directly
  - Max energy loss > 5 GeV, with missing charge, estimate upper and lower bounds
- Red point: using a dataset where 2-8 GeV signals are available

C. Zhang et al, PPCF 66, 025013 (2024)

Machine learning enabled PWFA optimization in 40-cm Li plasma

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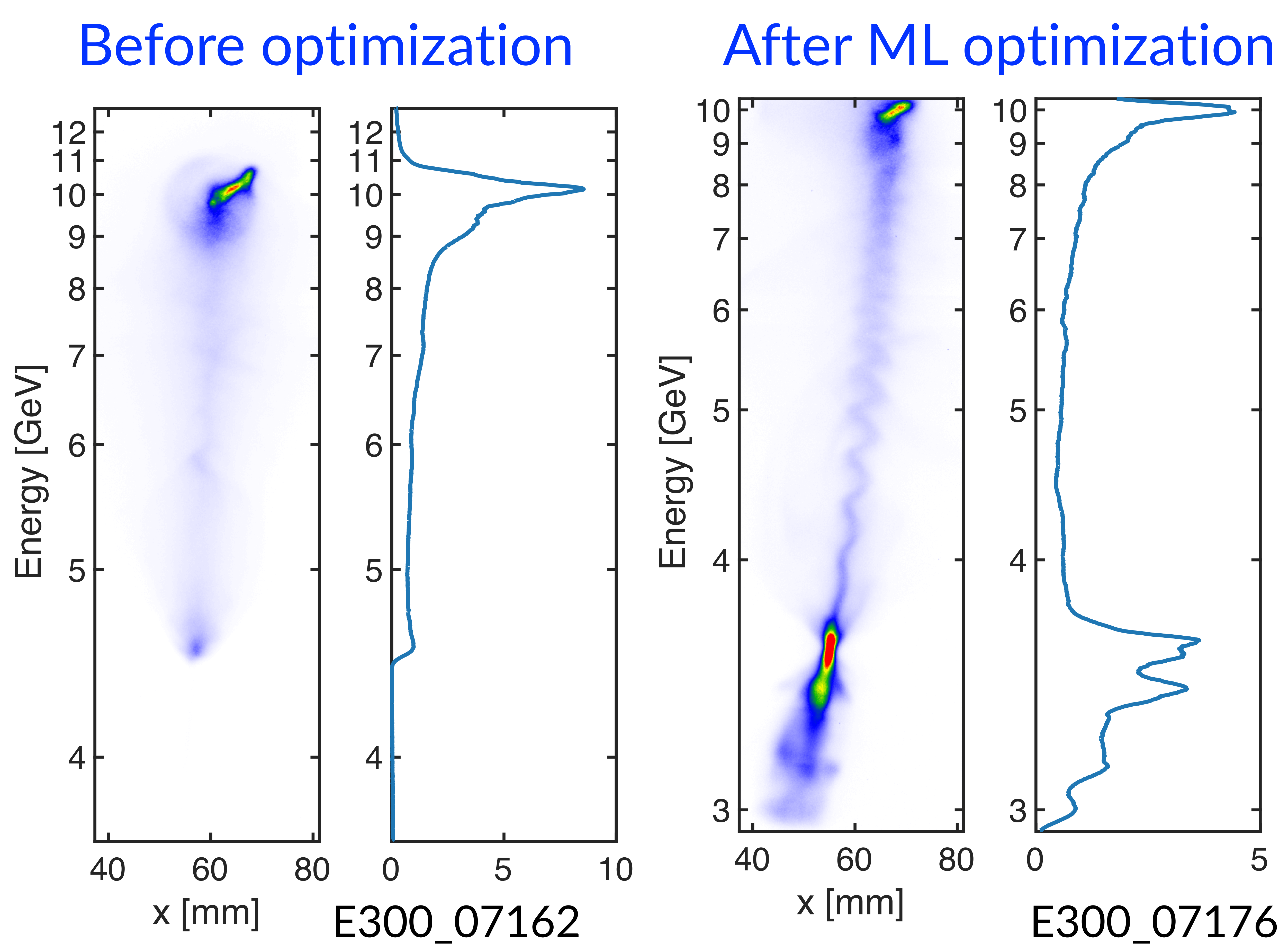
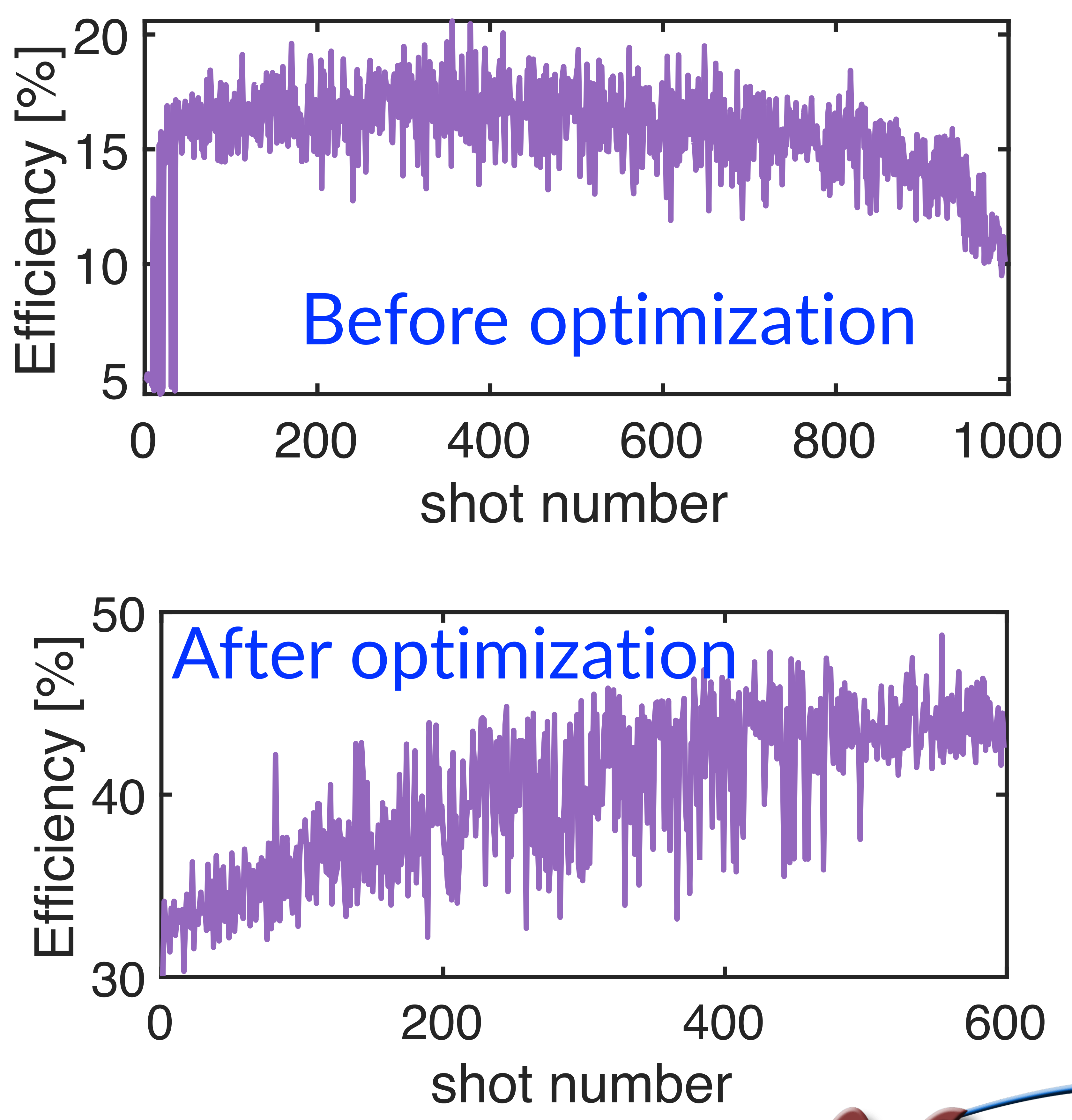
Energy loss



Energy transfer efficiency



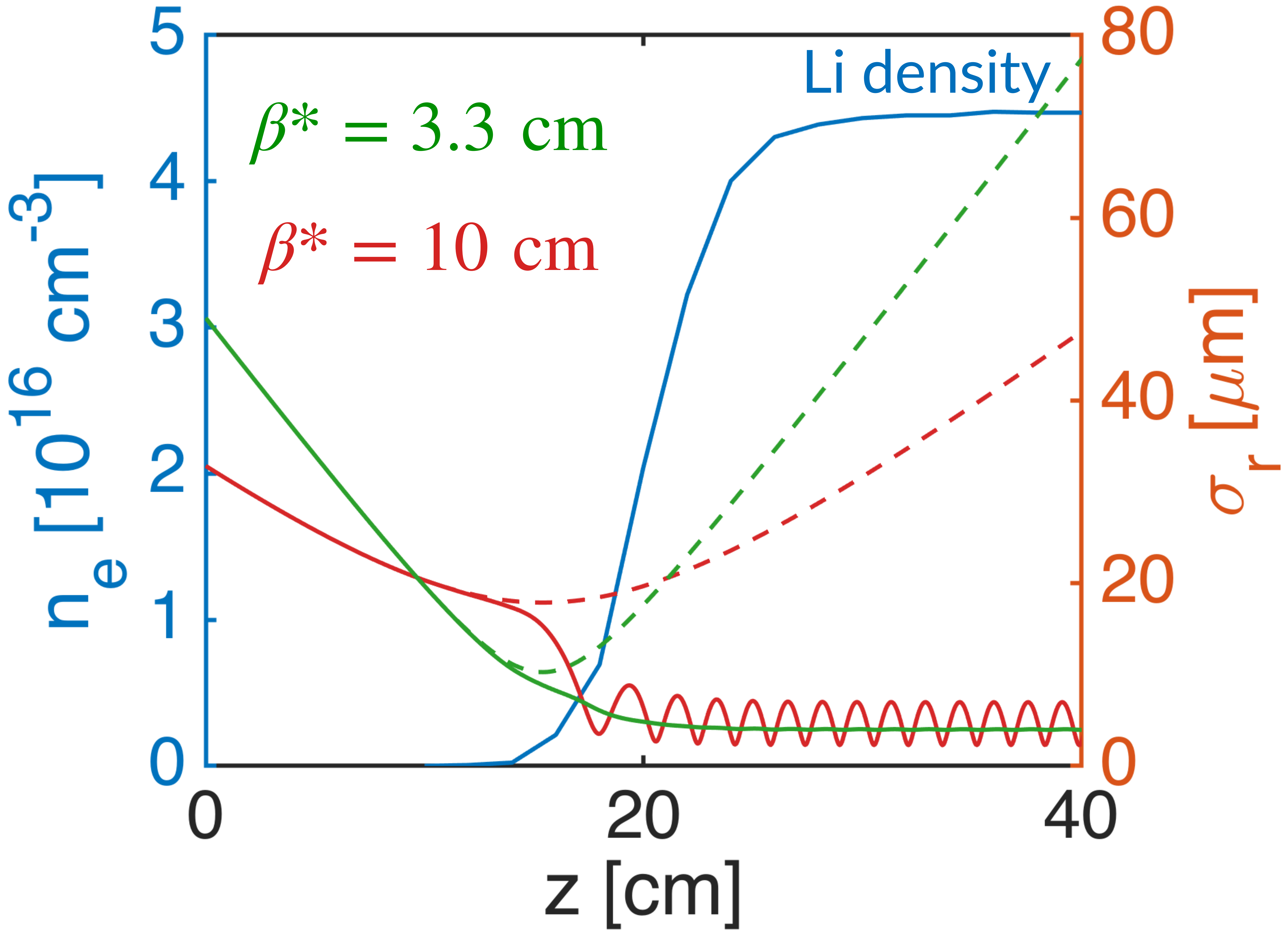
See Robert Ariniello's talk in WG3 on Tue.

First experiments on beam matching to a Li density upramp (ongoing work)

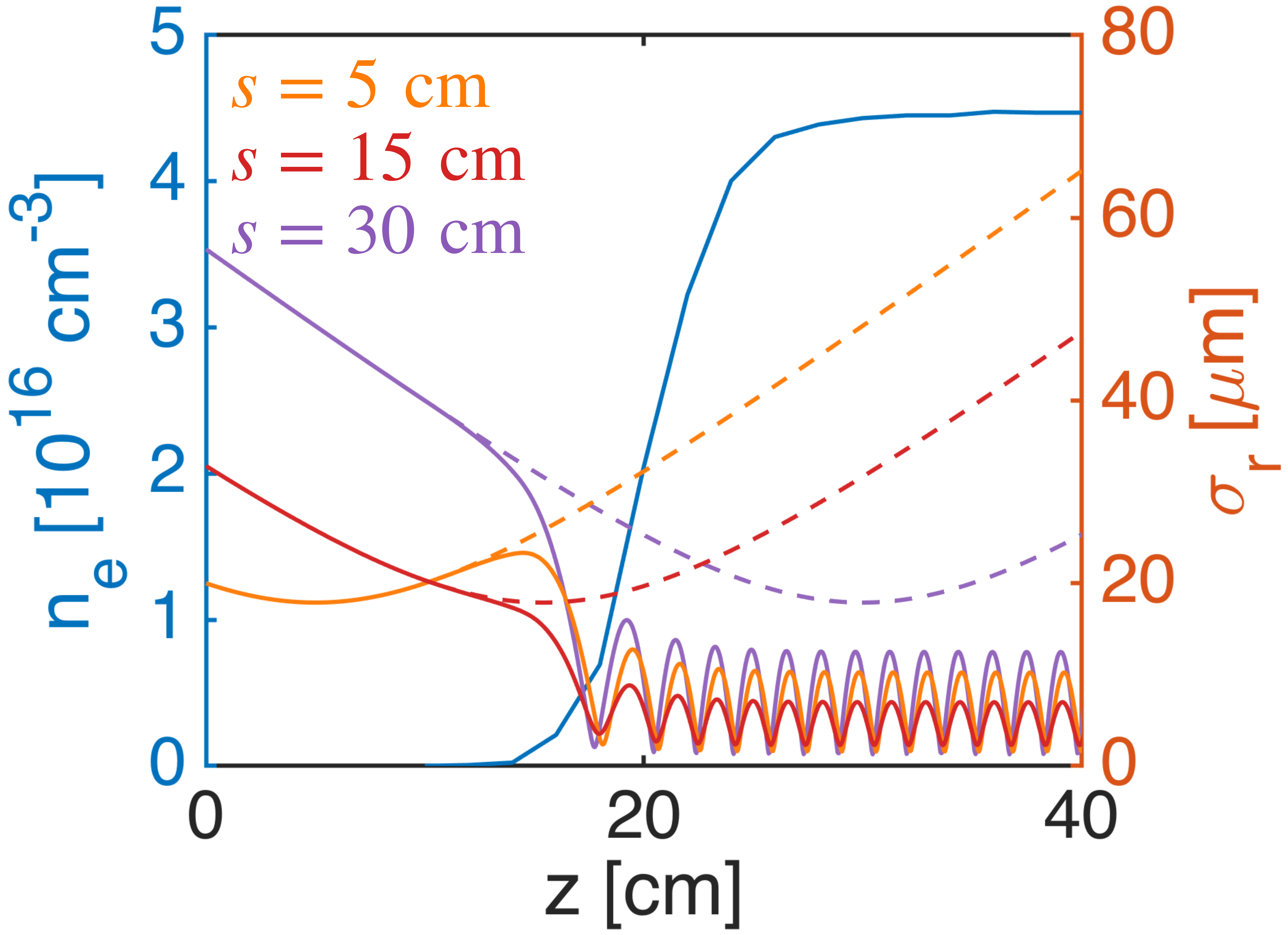
- Many parameters can affect matching
  - beam emittance, beta
  - vacuum waist location
  - density upramp profile
  - actual density at the vacuum focus
  - ...

Effects of beta and waist location on matching

spot size evolution for matched vs. unmatched beam

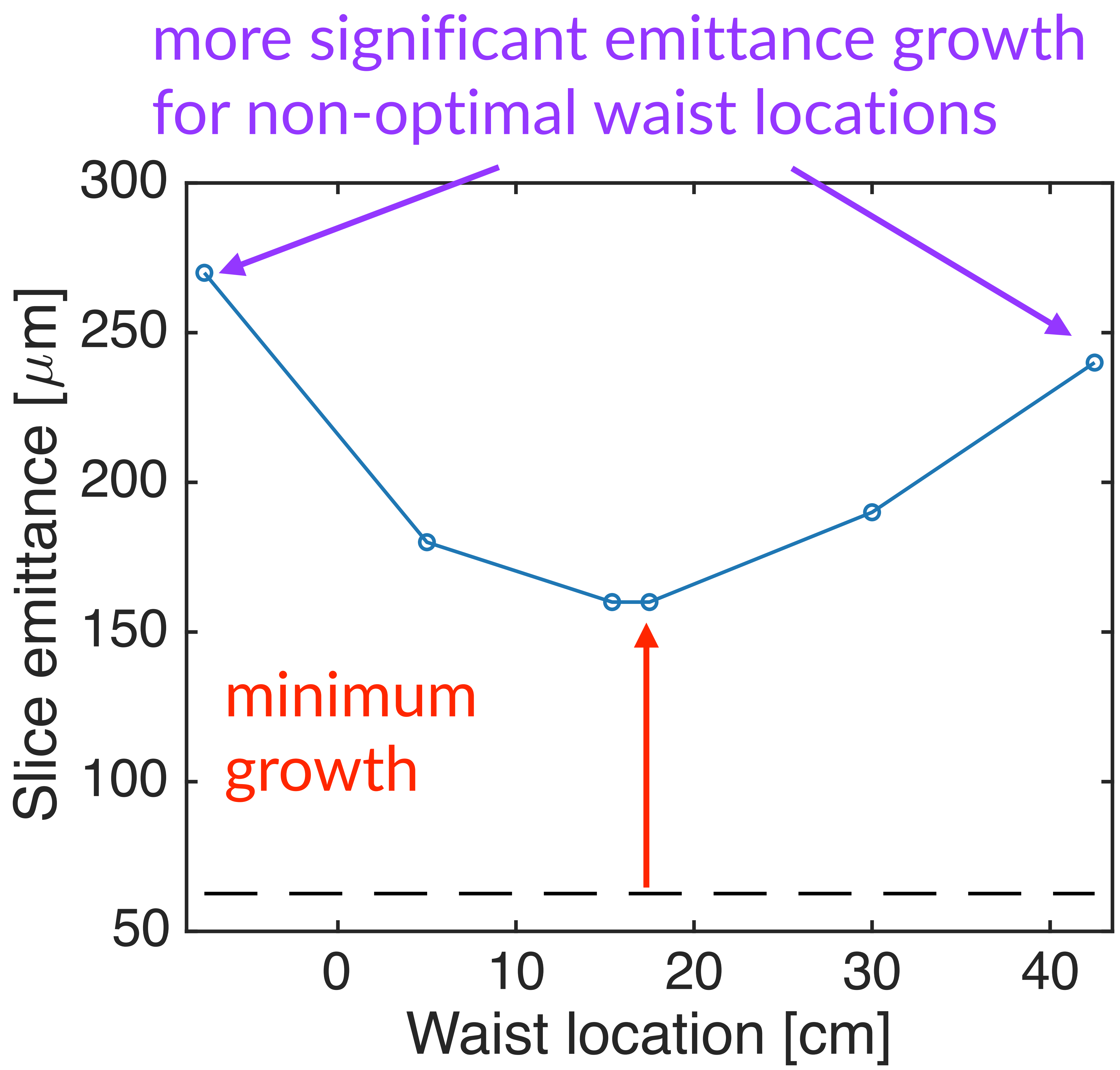


spot size evolution for beams with 10 cm beta, focused at different waist locations

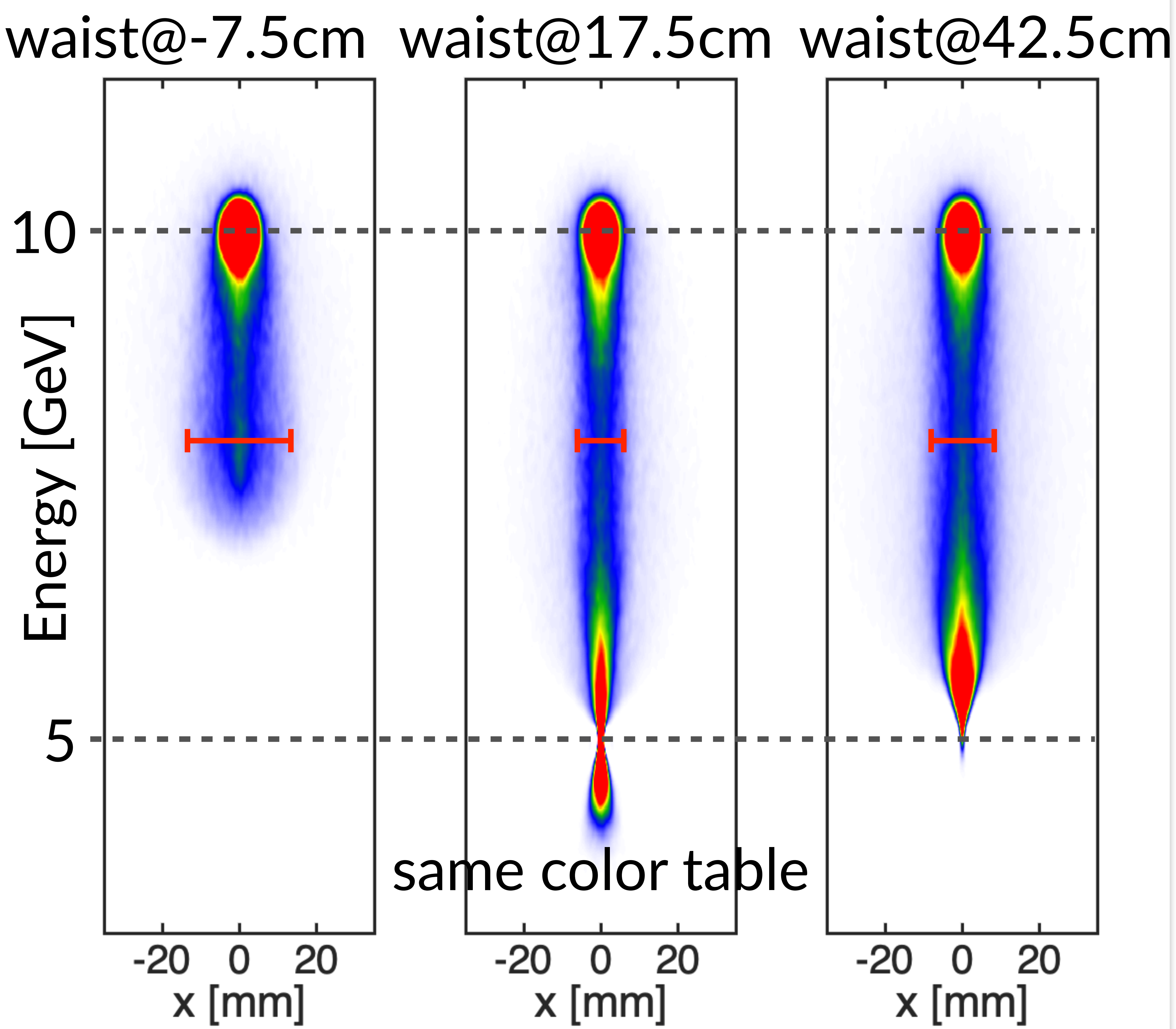


Effects waist location on matching- simulations

QPAD simulation, 5 Torr Oven, $\beta = 25\ \mathrm{cm}$
$\varepsilon_n = 63\ \mu\mathrm{m}$, single bunch, scan waist location



synthetic spectra
(PIC simulation + beam transport)



Experimental evidence of (non-optimal) matching

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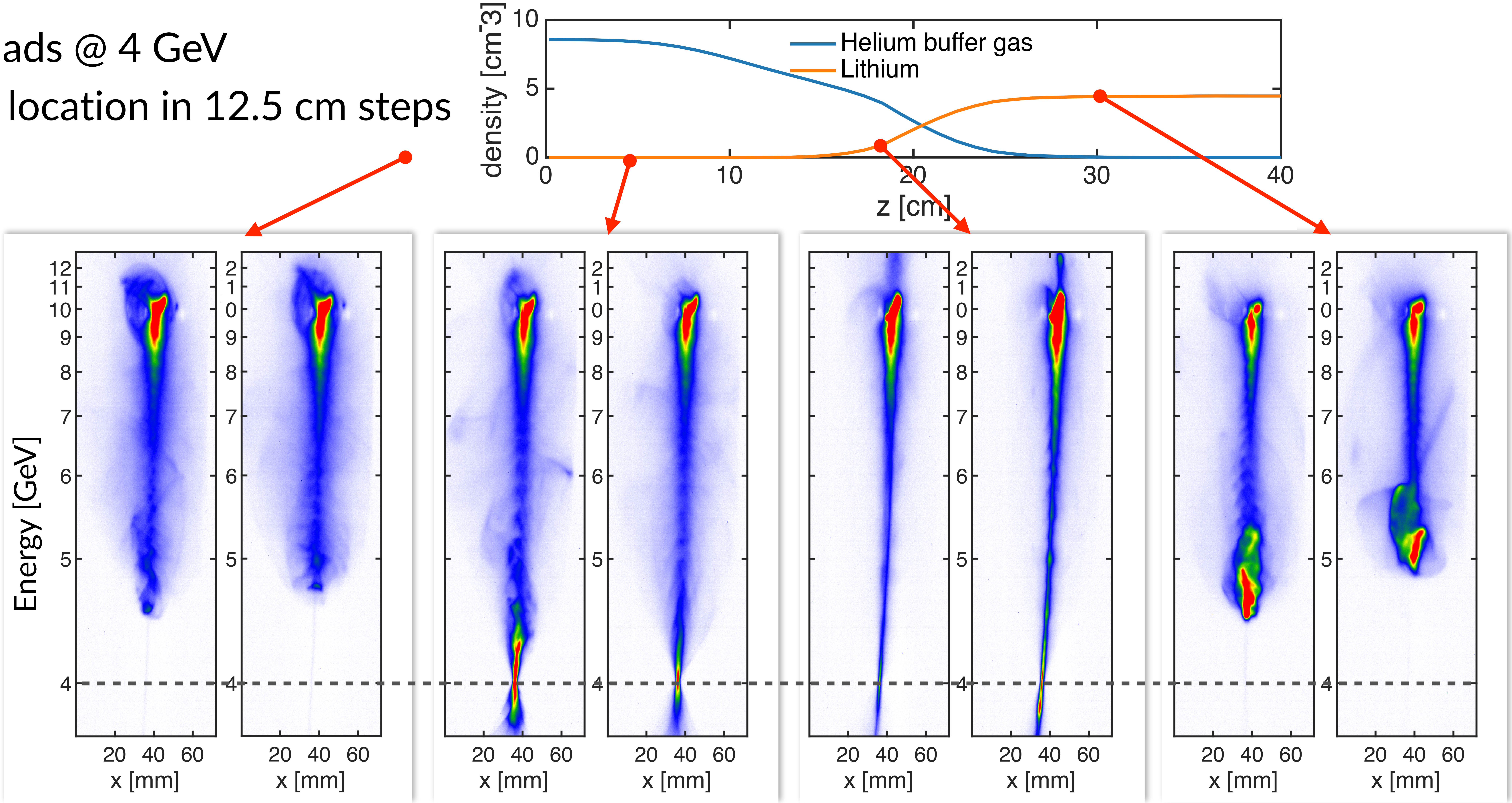
25 cm beta, quads @ 4 GeV
scanning waist location in 12.5 cm steps



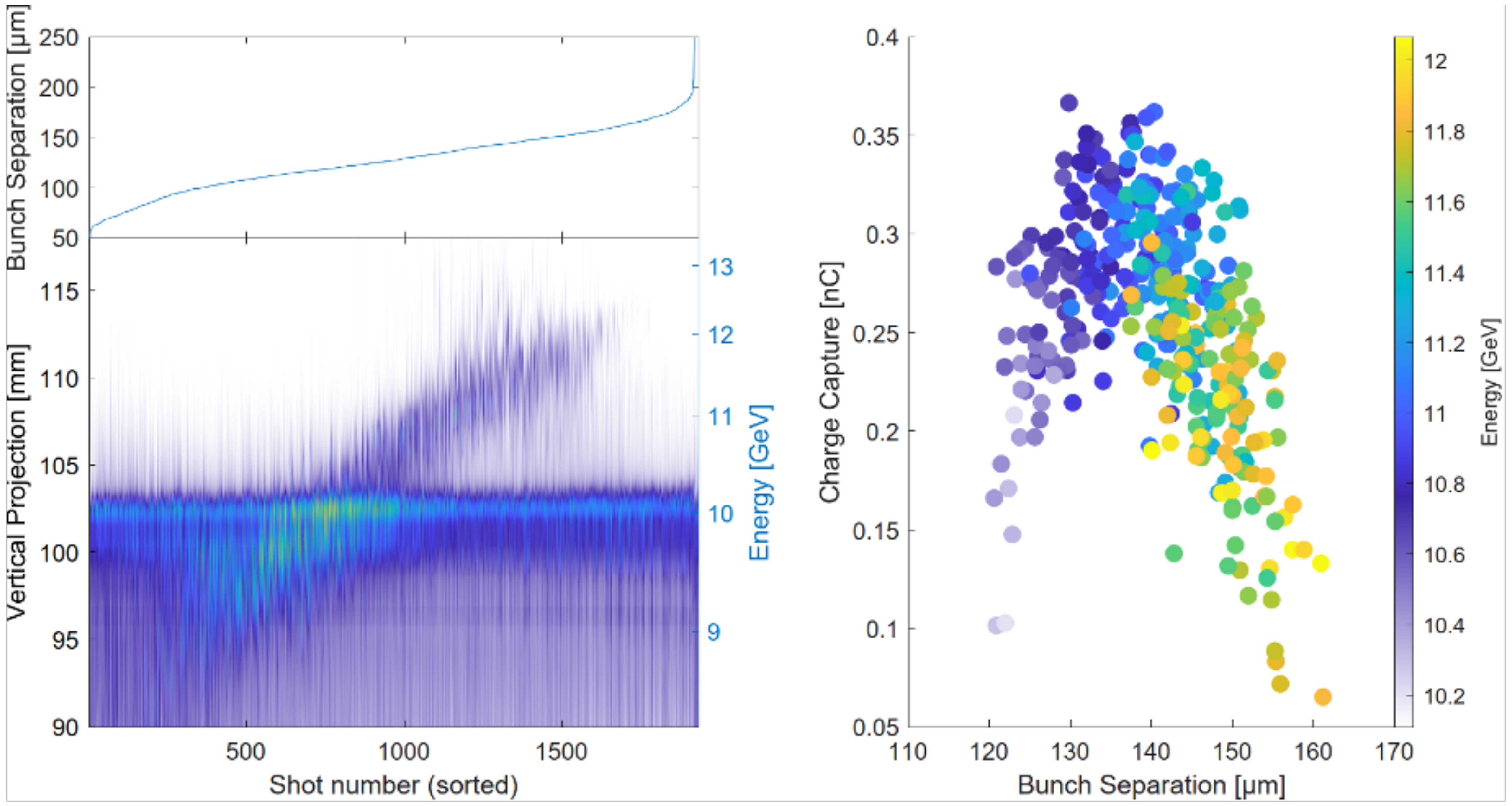
The next step is to reduce beta to approach optimal matching

Energy loss increase and narrowing of the beam slices as matching is approached

First two-bunch operation!

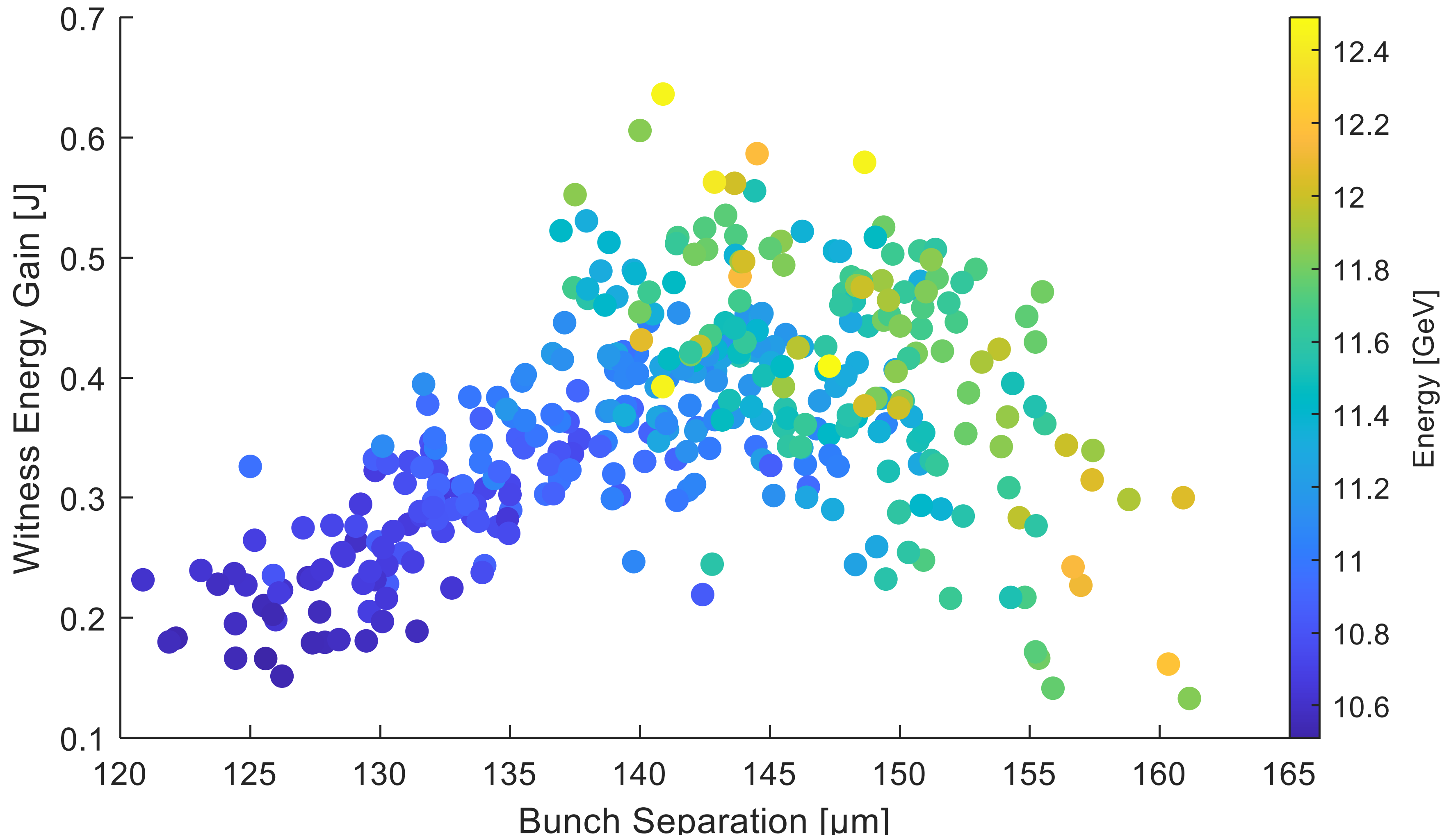
Preliminary results on two-bunch PWFA

See Doug Storey's talk in WG3 on Tue.



Acceleration of the witness by up to ~2 GeV

- Near complete capture of the witness at the optimal bunch spacing
  - Max witness capture at bunch separation ~ 138 um
  - FWHM of distribution ~ 25 um
  - 5 Torr Li oven → λ_p ~ 160 um



Estimate of energy transfer efficiency

- 0.3 to 0.5 J energy transfer to witness
- Maximum 35% wake-to-witness energy transfer efficiency

Beam quality of the accelerated witness bunch

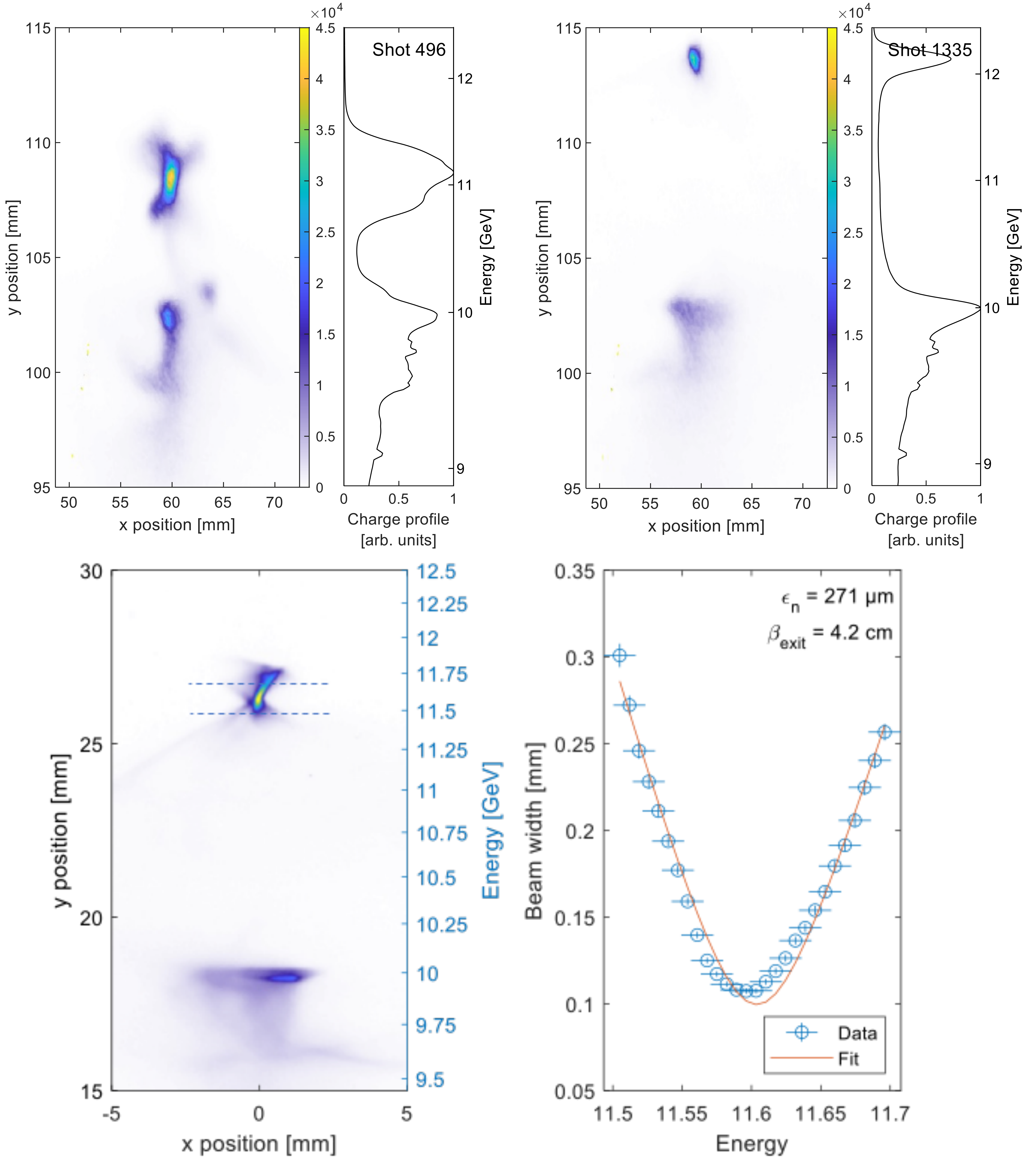
See Doug Storey's talk in WG3 on Tue.

Energy spread

- Order 1-2 GeV of acceleration at optimal bunch separation
- Energy spread of 1-4% of accelerated witness
  - Shot 496: 320 pC at 11 GeV, 3% energy spread
  - Shot 1355: <100 pC at >12 GeV, 1% energy spread

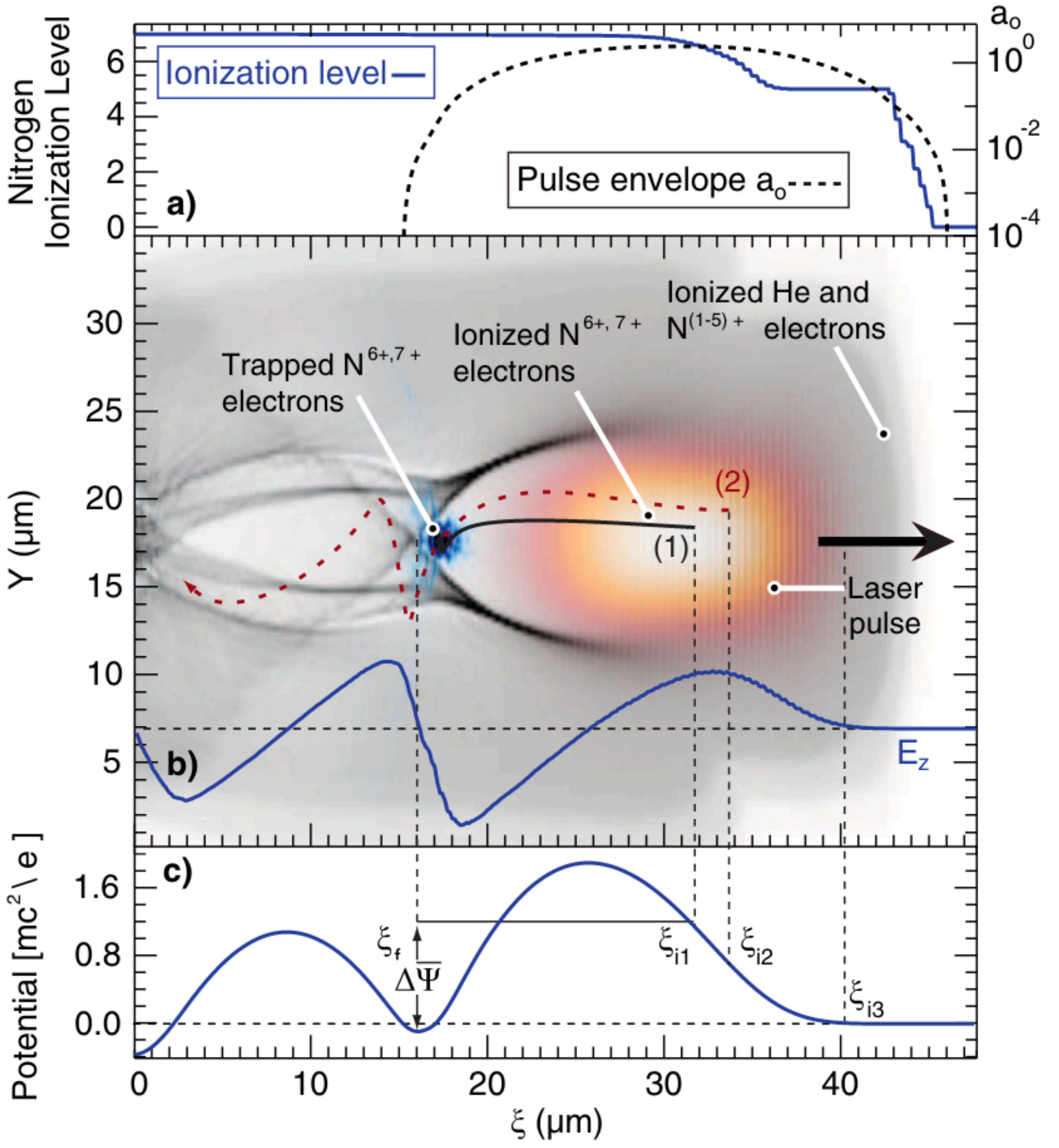
Single shot emittance measurements

- Minimum accelerated witness emittance of ~ 250 µm
  - Beam not matched to plasma
  - Large fluctuations due to long. and transverse jitter
- Alignment of the two bunches into the plasma is critical!
  - *See **O. Finnerud's** talk in **WG3** on Mon.*



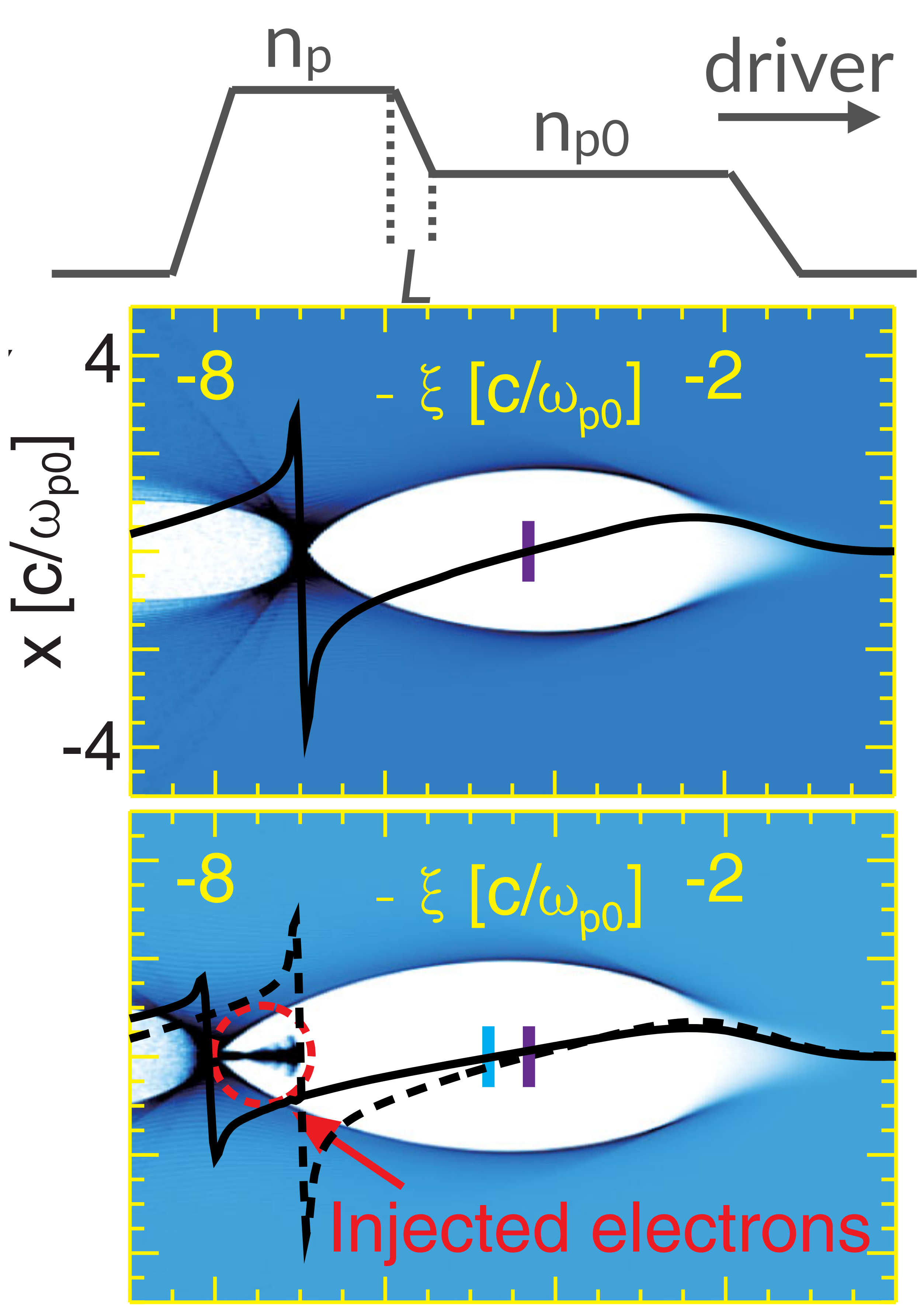
Ionization injection and downramp injection

ionization injection



A. Pak et al, PRL 104, 025003 (2010)

downramp injection

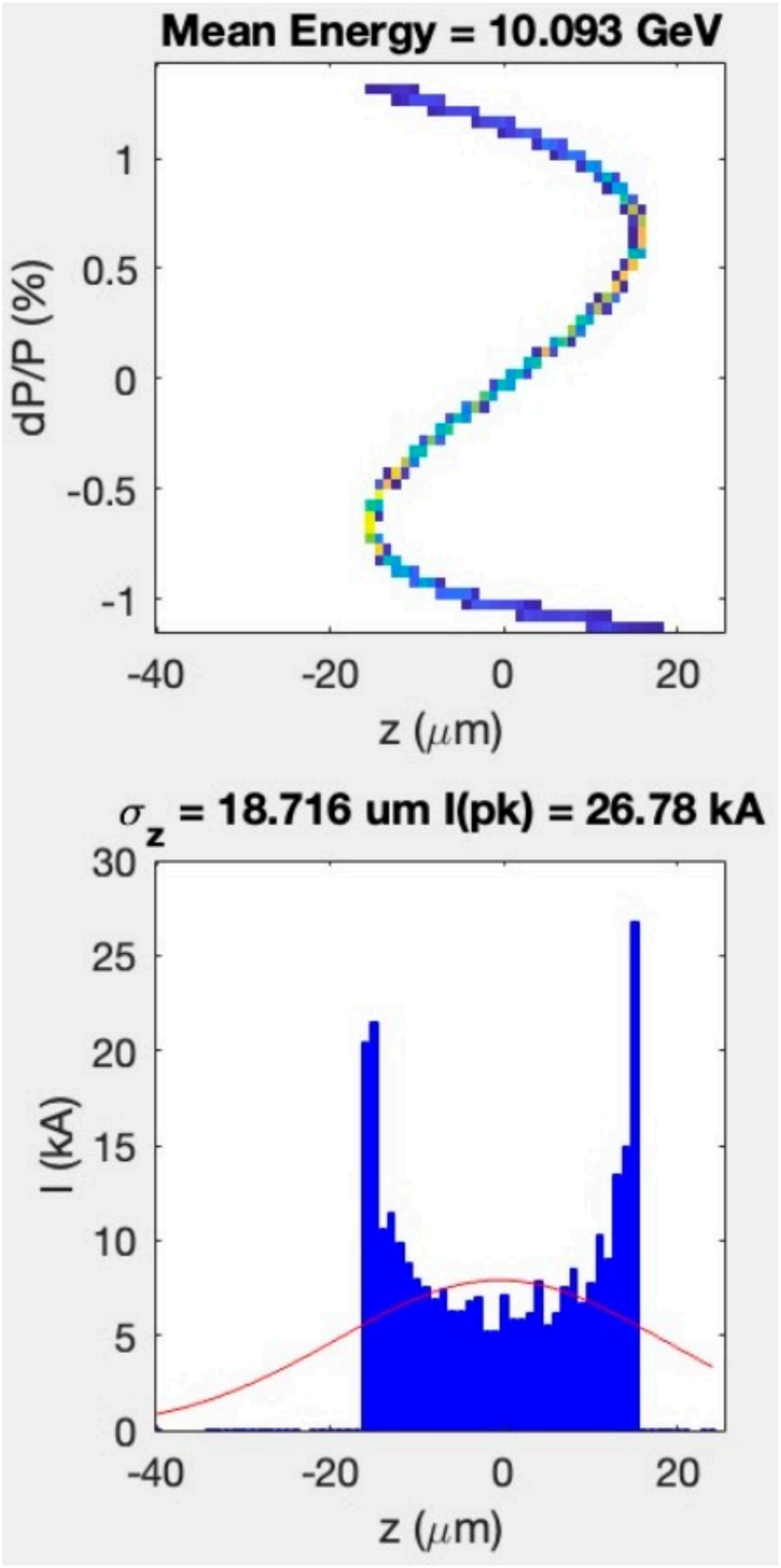


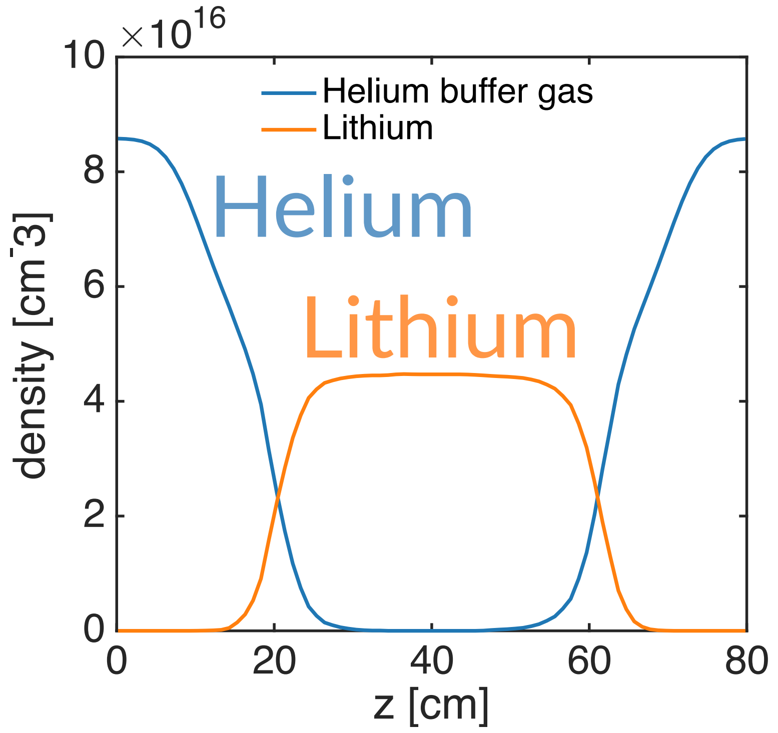
X. L. Xu et al, PRAB 20, 111303 (2017)

Both mechanisms have the potential of generating ultralow emittance (<1 μm), high brightness (>10^{19} A rad^{-2} m^{-2}) electron bunches for near-term applications such as driving free electron lasers.

Ionization injection of helium electrons in lithium plasma wake

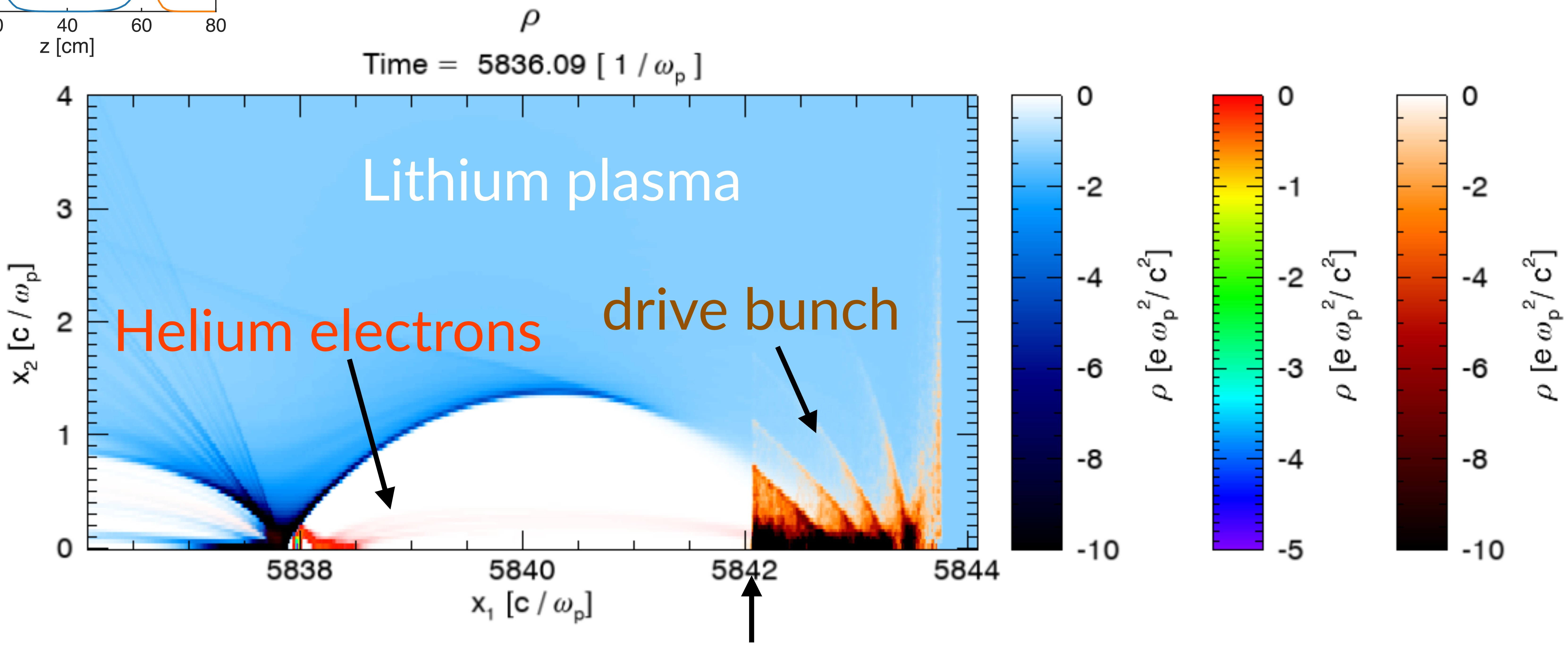
Over-compressed beam results in a double-horn current profile. As the second horn pinches, it can ionized the helium buffer gas at both ends of the lithium oven, leading to ionization injection.





Osiris-q3d simulation using the following e- beam parameters:

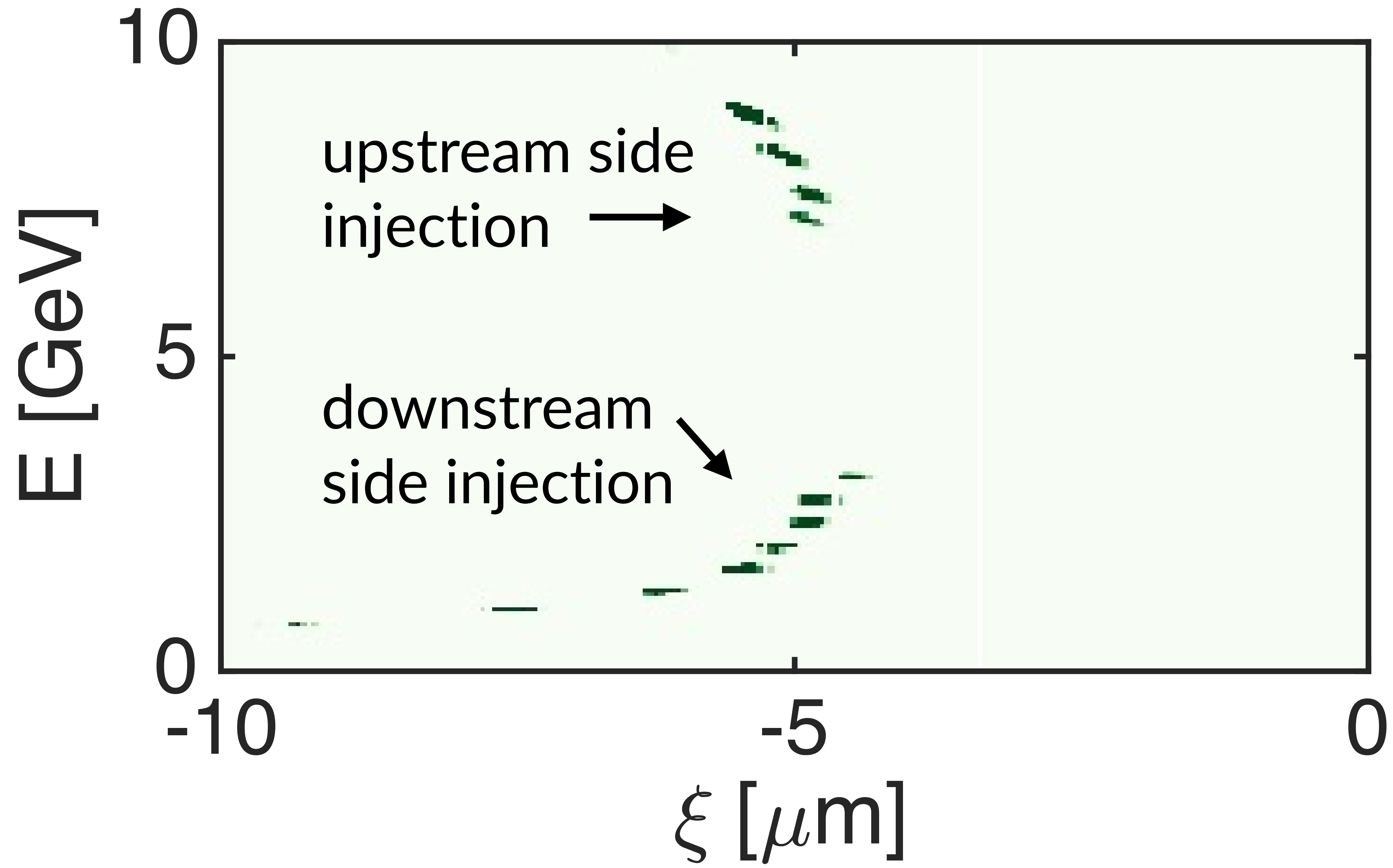
- 54 cm beta, focused at the start of lithium density plateau
- 45 μm emittance to have a 35 μm spot size (experimental)
- Q = 860 pC, horn separation 46 μm



each time the second current spike pinches, it triggers ionization injection of helium e- once

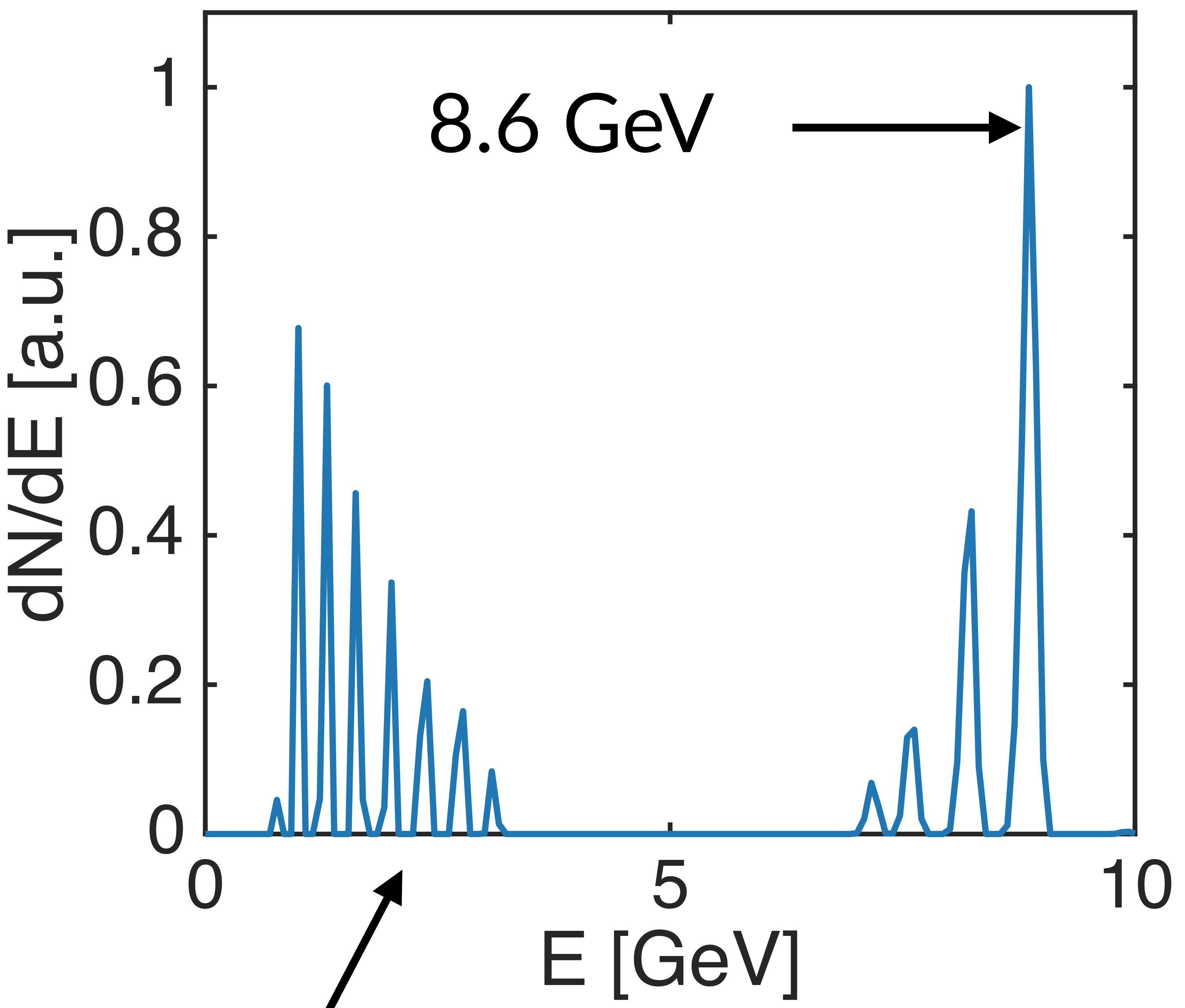
Injected electrons with multiple energy peaks (simulation)

longitudinal phase space of
the injected beam



total charge ~ 20 pC
emittance < 1 μm

final energy spectrum of
the injected beam

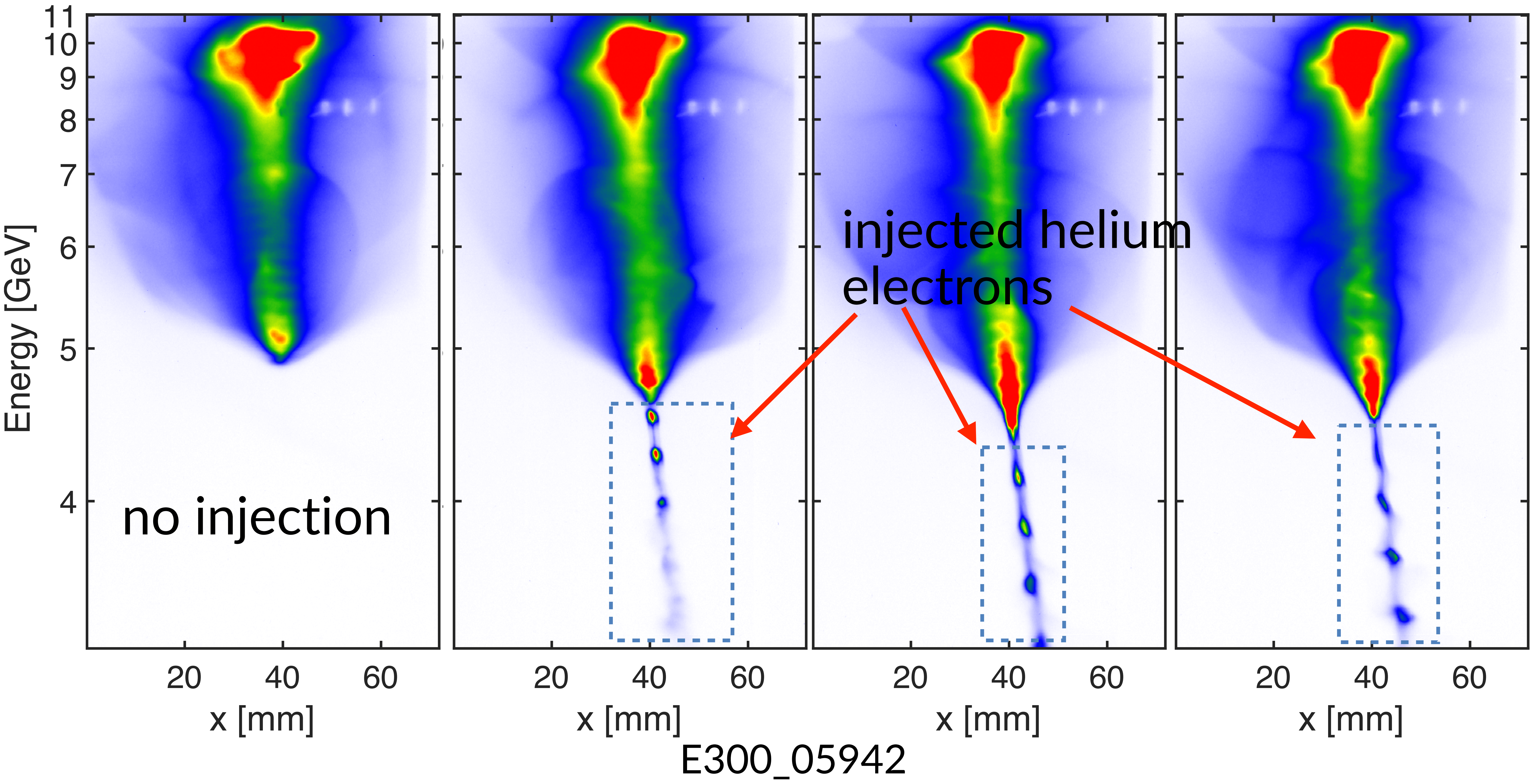


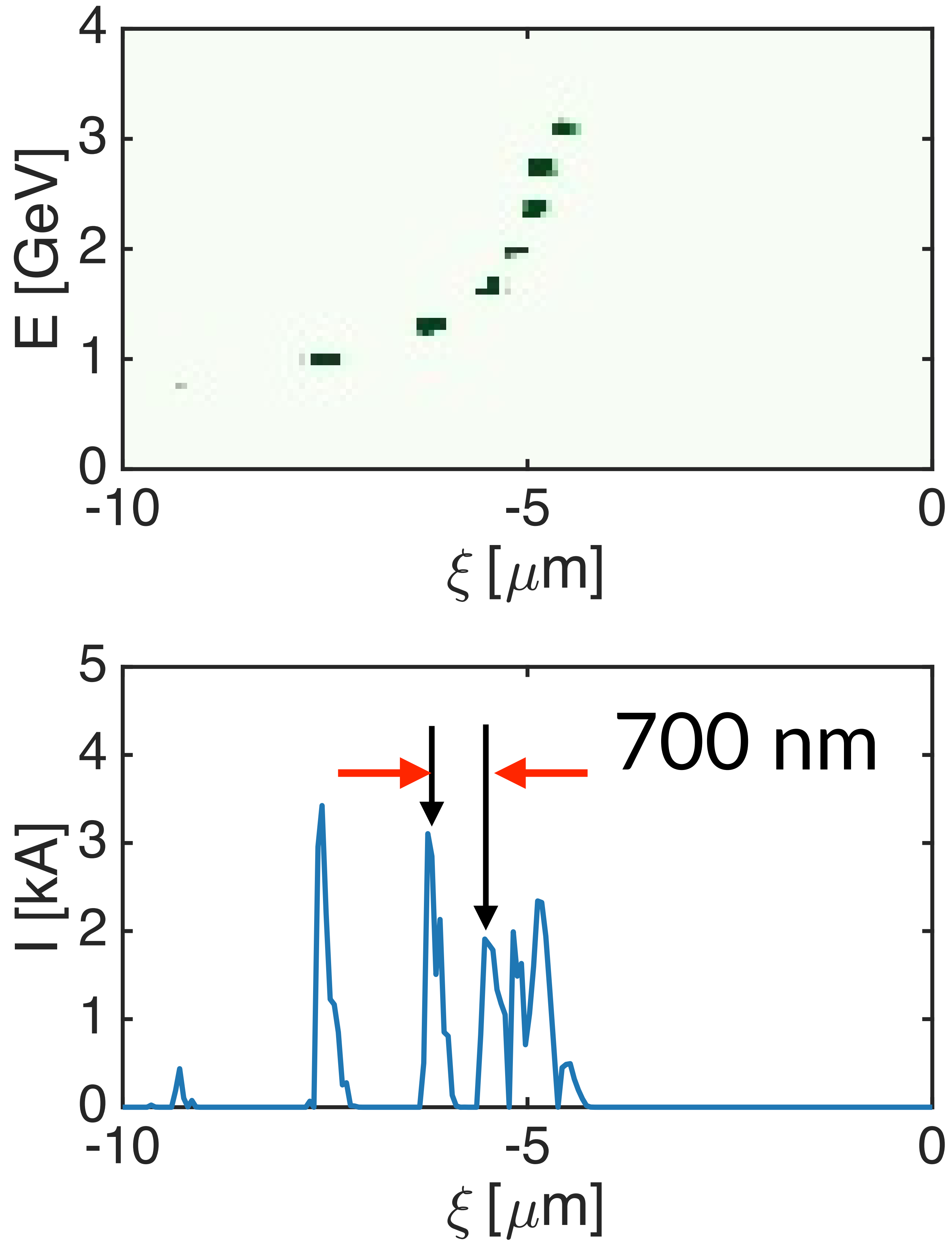
multi-GeV, almost equally spaced energy peaks

Generation of multi-GeV, multi-color beams in experiment

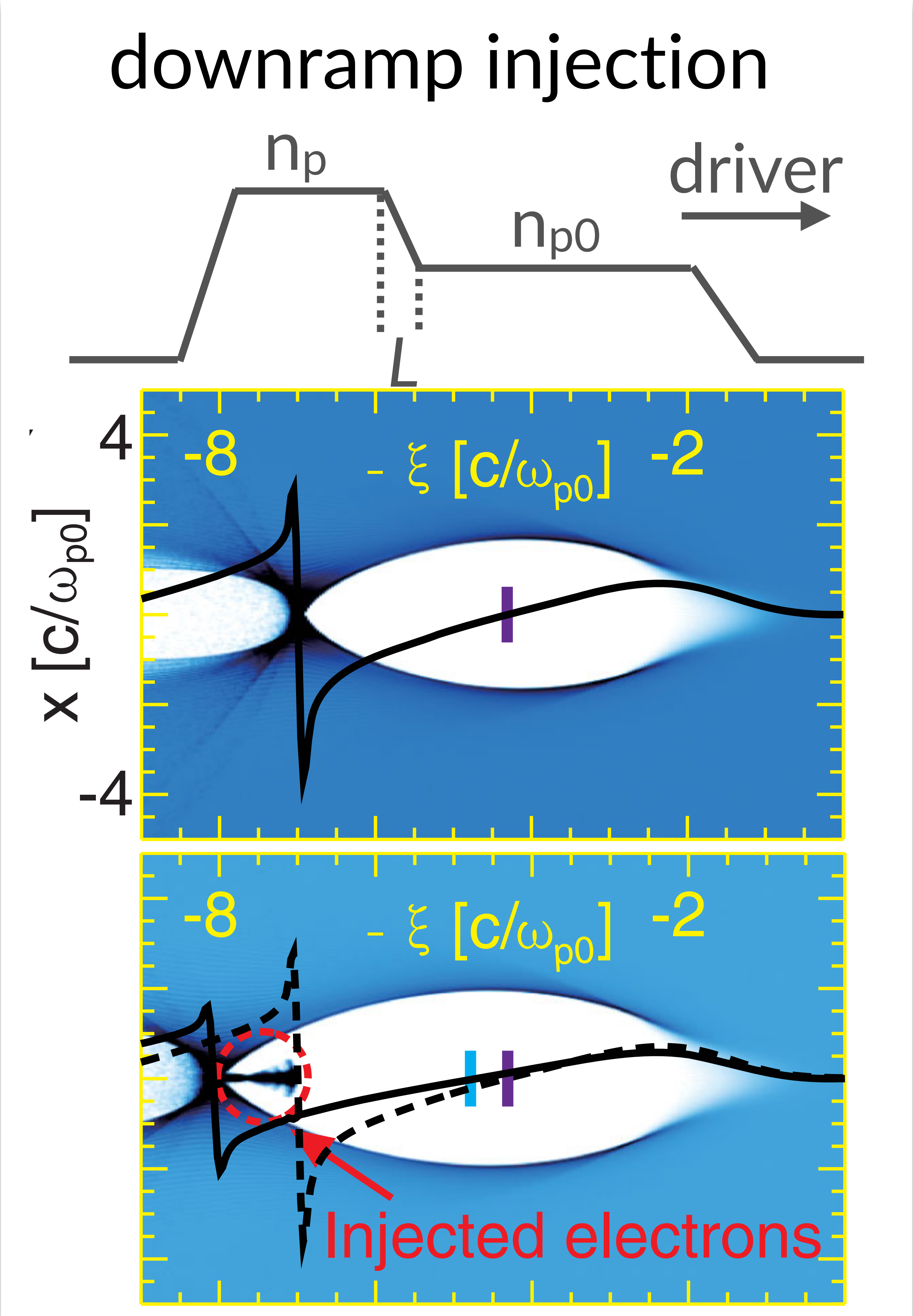
The injected charge

- appears as distinct beamlets due to multiple ionization injections
- is accelerated to multi-GeV (<6 GeV)

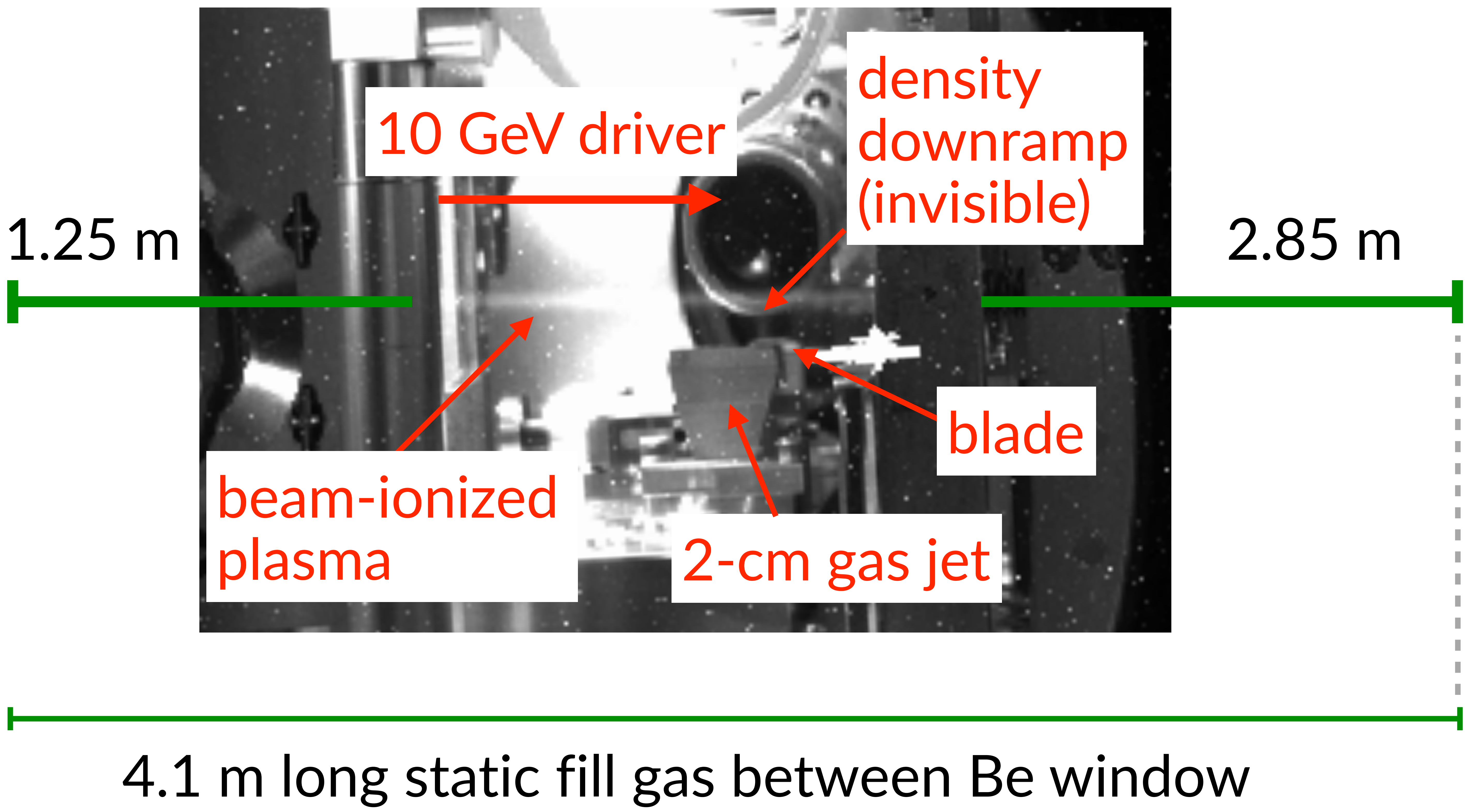




High brightness beam generation via downramp injection

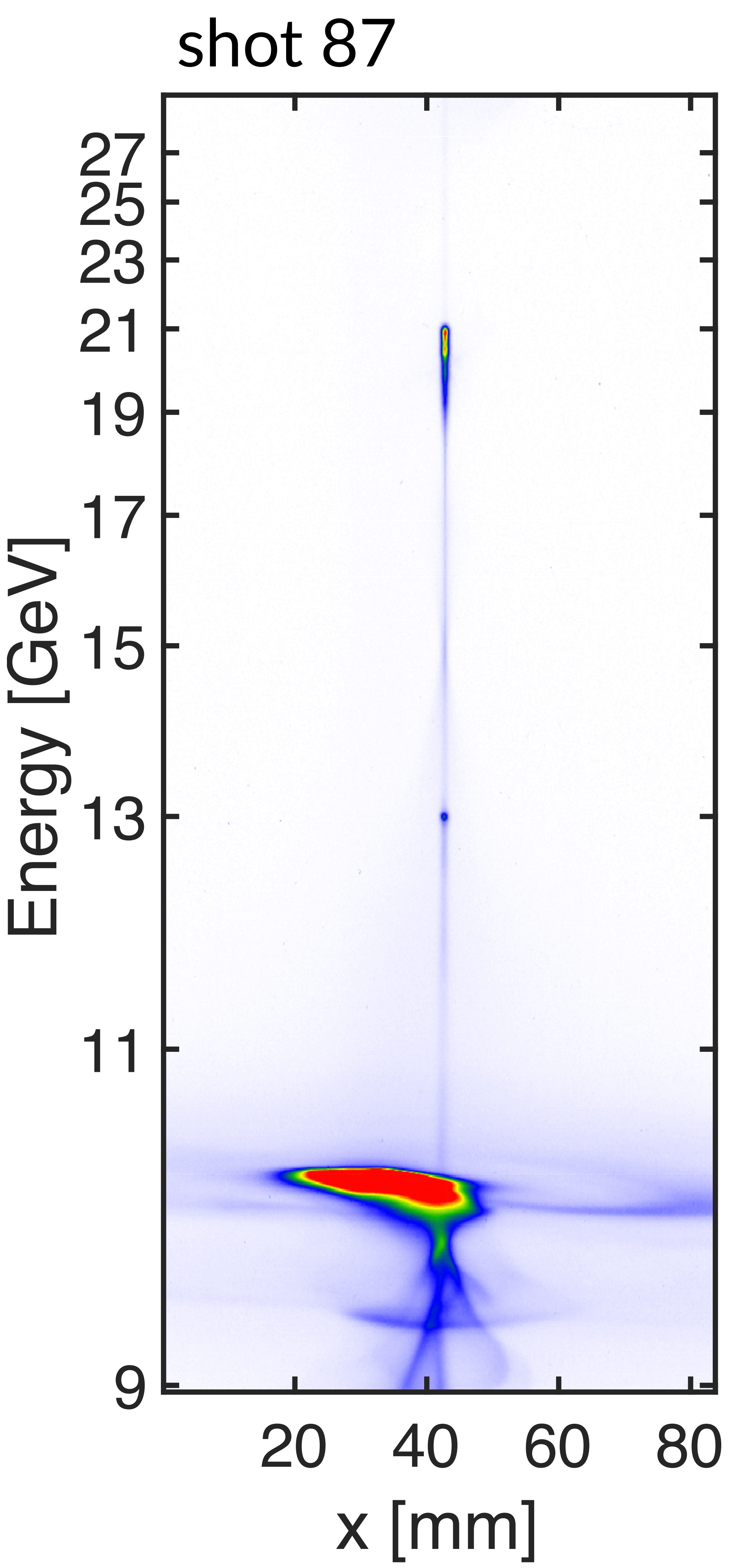


4 Torr H2 static fill, gas jet backing pressure 100 psi



An example dataset showing >20 GeV energy gain

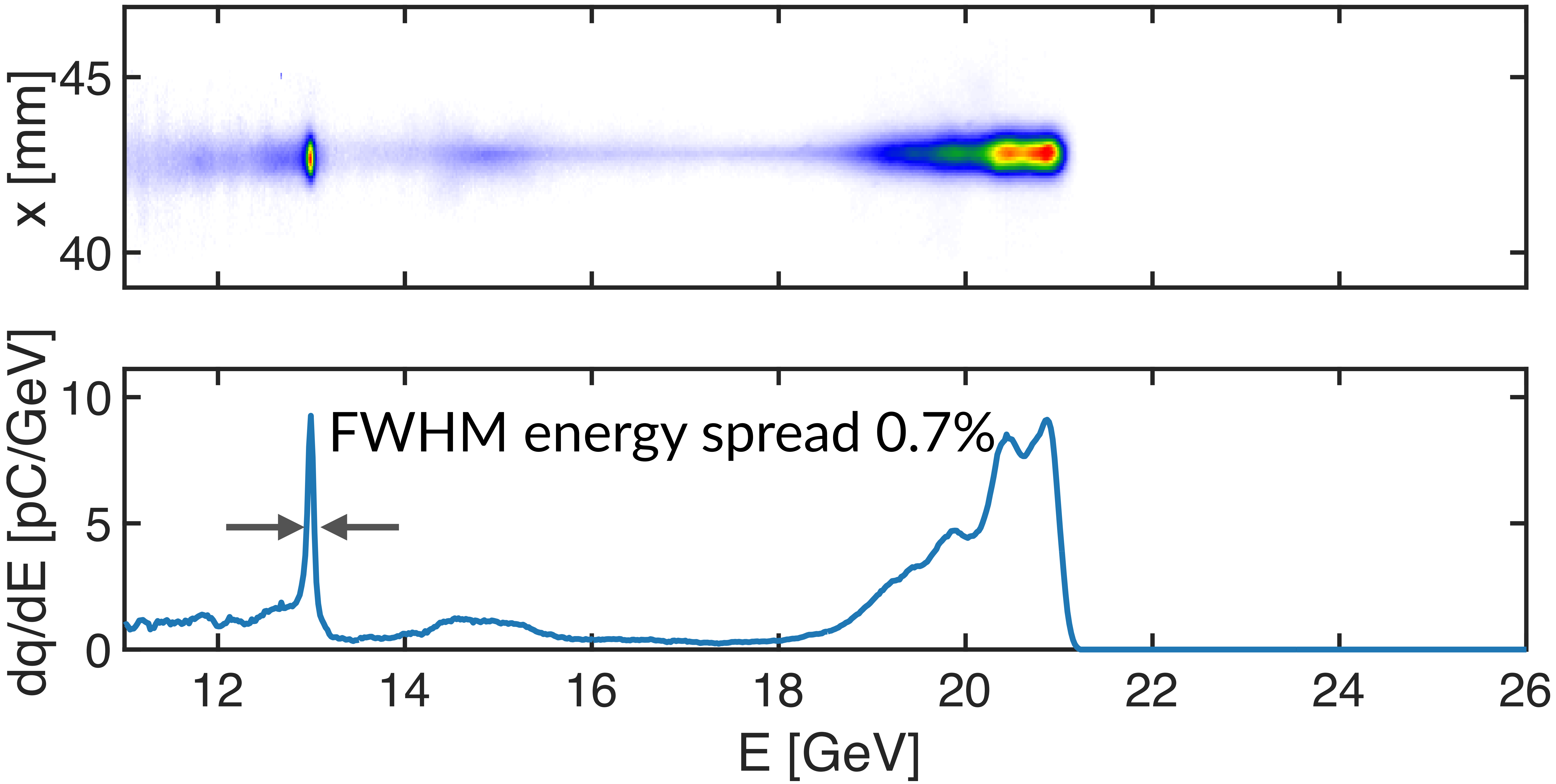
Sub 1% energy spread



Injected bunch:

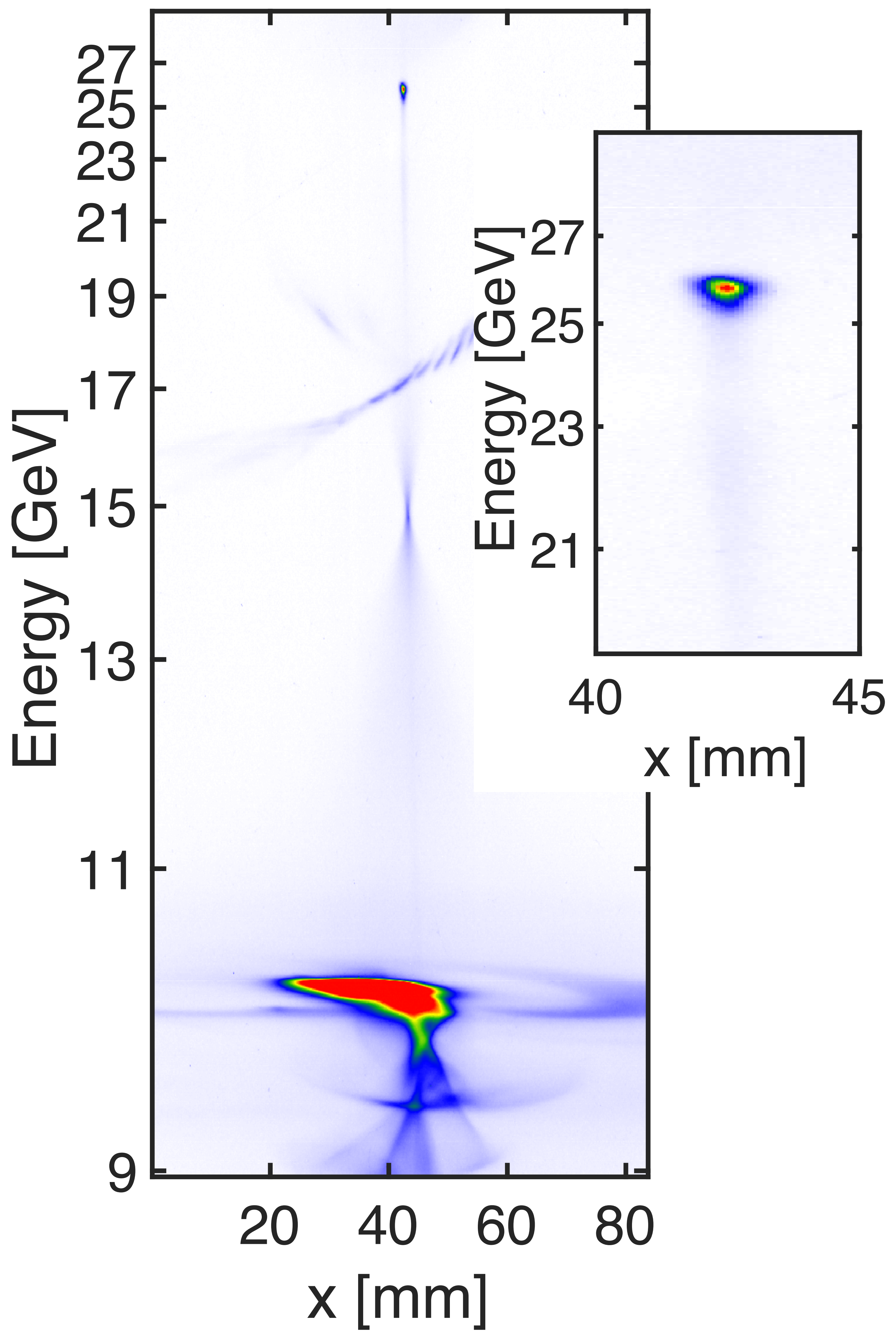
Energy gain: 13 GeV FWHM spread 0.7%, 21 GeV

Charge: 17.8 pC



Energy gain up to 26 GeV with ~1% energy spread

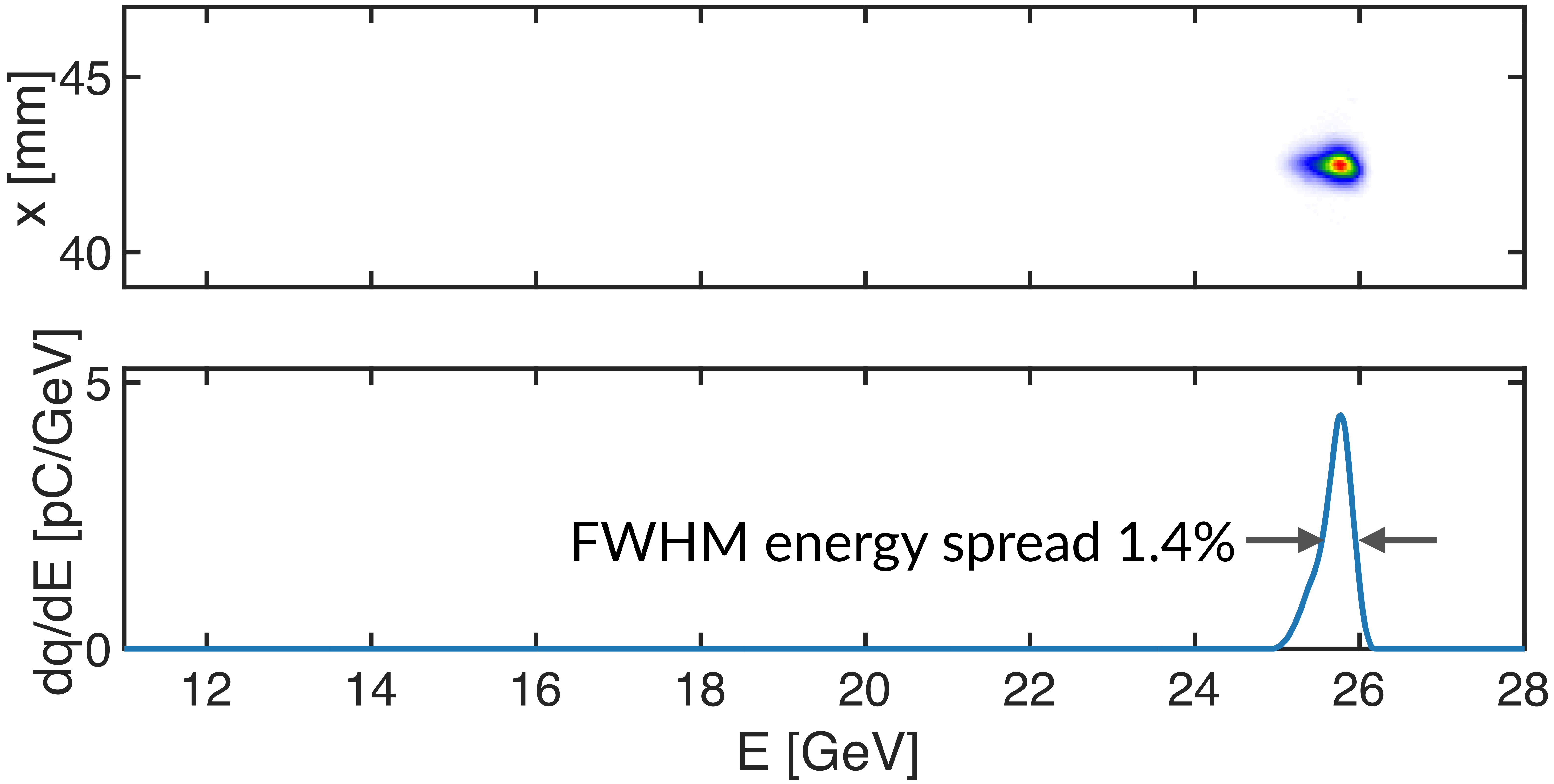
E304_08878, shot 146



Injected bunch:

Energy gain: 25.8 GeV, FWHM energy spread 1.4%

Charge: 2.0 pC



loaded Transformer Ratio (E_{gain}/E_{loss}): 2.6 (w/o beam shaping)

µm level normalized emittance measured using the butterfly technique

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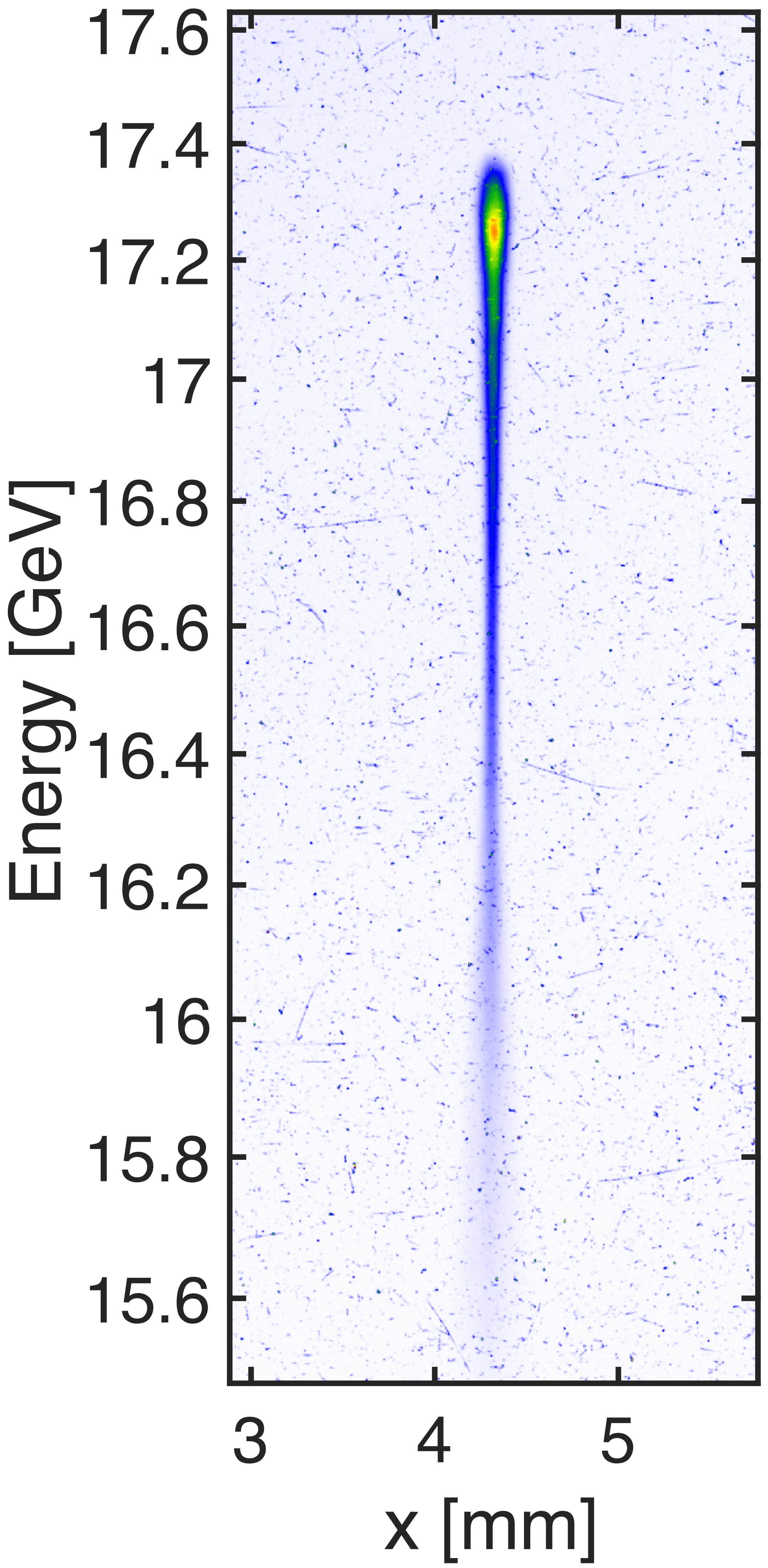
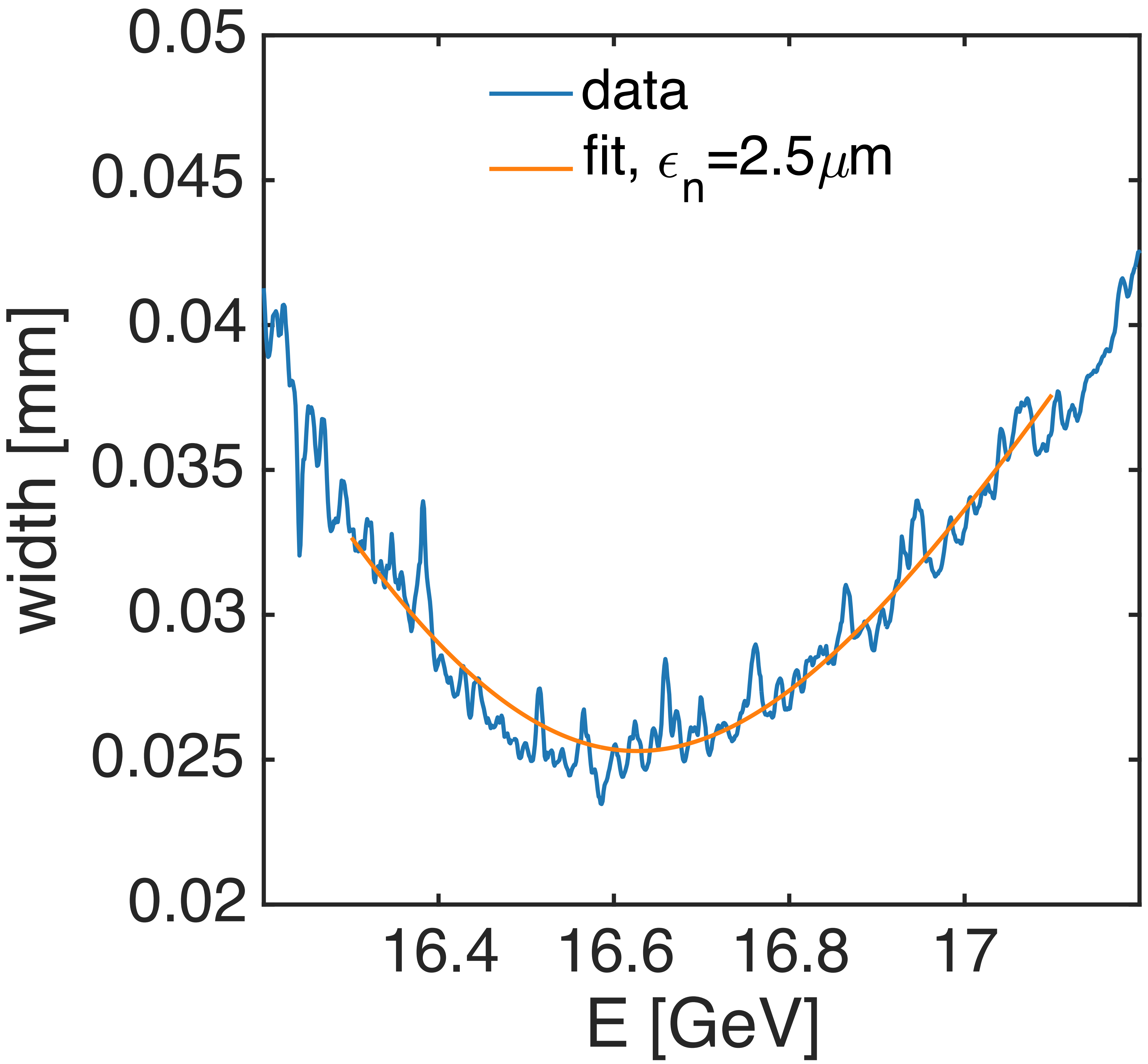
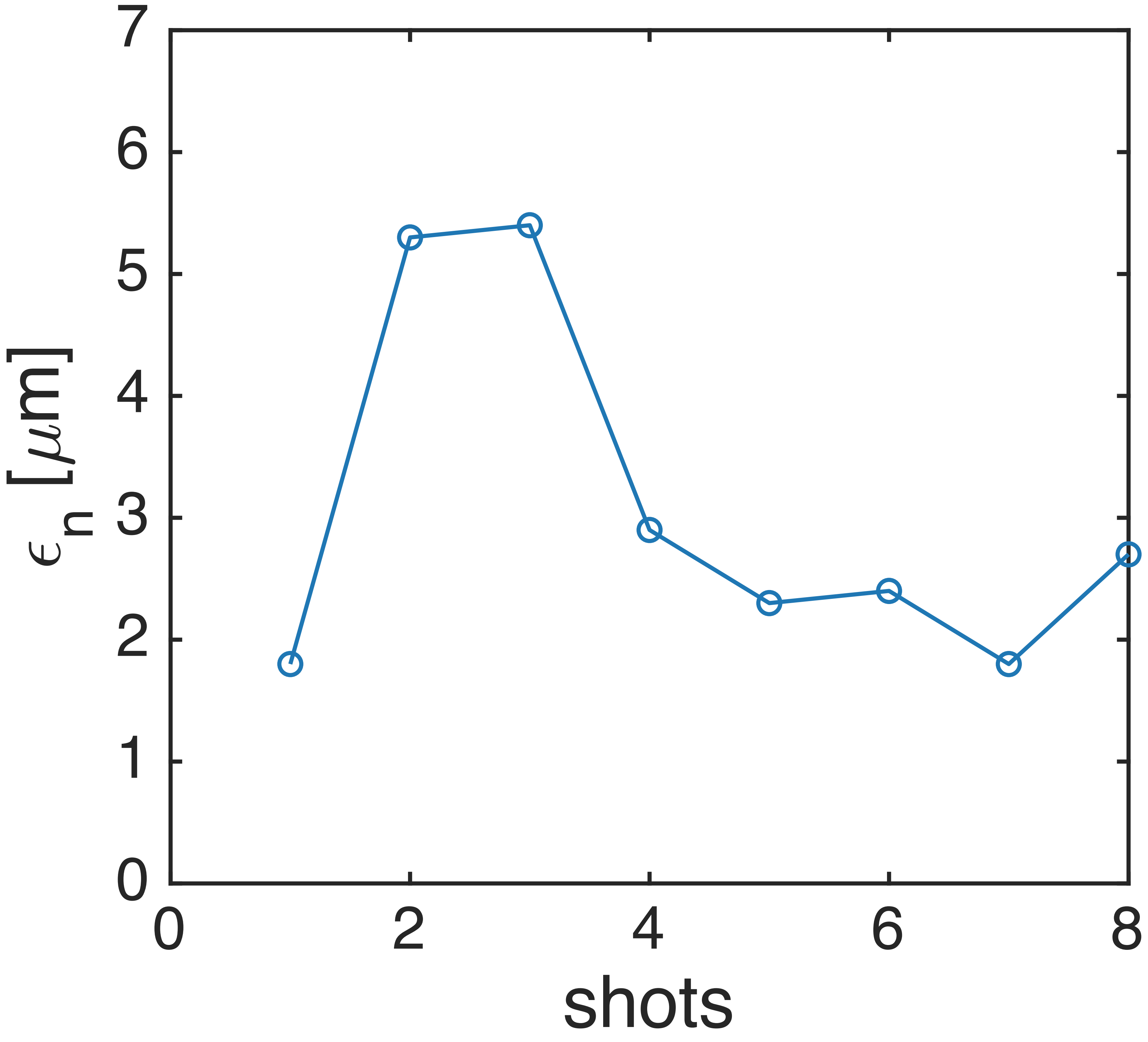


17.3 GeV, dE(FWHM)=0.17 GeV, 1%



measured emittance of 8 shots

minimum emittance 1.8 µm



PWFA as a beam brightness booster

Collider, light source and many other applications require high brightness beams

Brightness: $B_n = \frac{2I}{\epsilon_n^2}$

peak current [e.g. kA]

normalized emittance squared [μm²]

drive beam:
I~9 kA
ϵ_n~40 μm
B_n~10^{13} A/rad²/m²
10 GeV

injected beam:
I~1 kA
ϵ_n~1.8 μm
B_n~6×10^{14} A/rad²/m²
60x brighter
17 GeV

SXFEL:
I~0.7 kA
ϵ_n~1.5 μm
B_n~6×10^{14} A/rad²/m²
1.5 GeV (upgrade)

LCLS:
I~3.5 kA
ϵ_n~1.6 μm
B_n~3×10^{15} A/rad²/m²
13.6 GeV (hard x-ray)
<7 GeV (soft x-ray)

Summary: highlights of the first results

Single-stage 10 GeV PWFA

- **Repetition**
  - Meter-scale plasmas in hydrogen, needed for high rep rate future work have been formed
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