Wakeless and PWFA regime experiments at FACET-II

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Outline

- Introduction and motivations for finite plasmas
  - Beam-plasma physics in finite plasmas: PWFA and wakeless regimes
  - Light sources: ion channel laser
  - Positron acceleration scheme
- Observations in beam-ionized helium plasmas from FACET-I and FACET-II
  - Helium for finite plasmas, and a challenge for the beam to ionize
  - Accelerating field and accelerated electrons as a regime signature
  - FACET-I to FACET-II: from full deceleration to acceleration
- Beam compression to control transition between PWFA and wakeless regimes
- Particle-in-cell simulations using beam current profiles from linac simulations

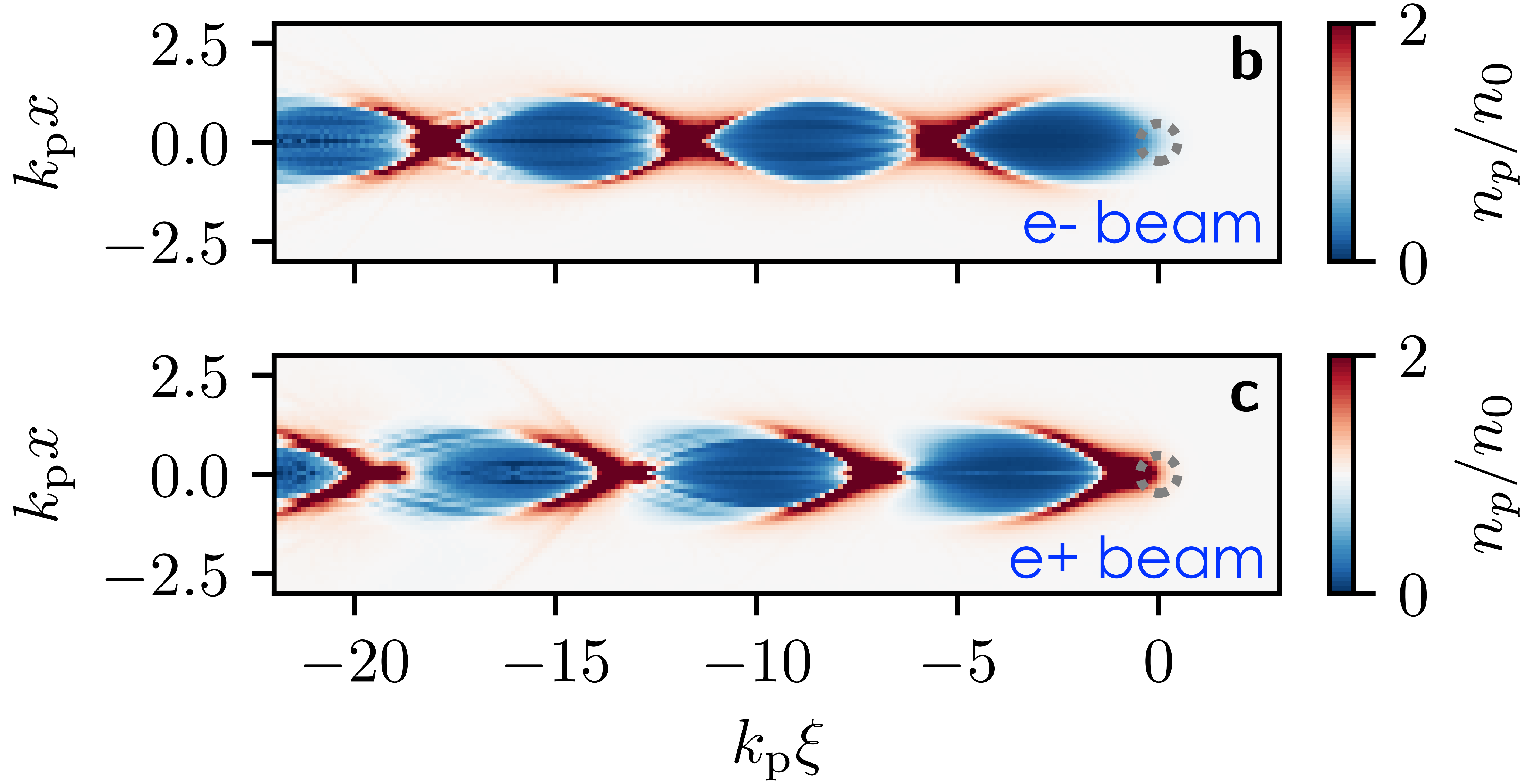
Introduction

Infinitely-wide plasma

Basic beam-plasma interaction with short, small and dense beams:

$$k_p\sigma_r = k_p\sigma_z = 0.42$$

$$n_b/n_0 = 3$$



Infinitely-wide plasma

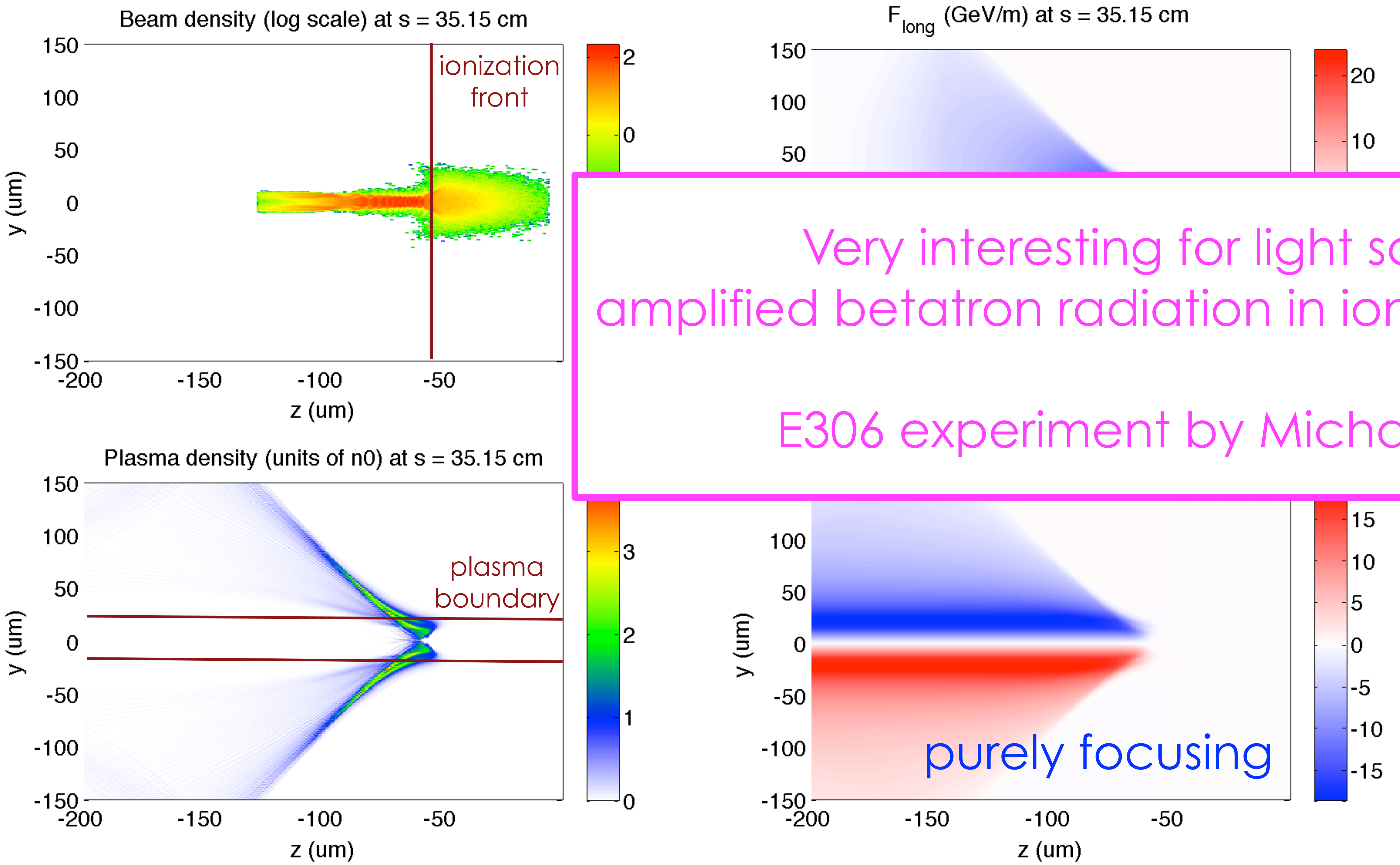
↓

Oscillating Wakefield
in the wake of the beam

here in the blow-out regime
referred later as standard PWFA regime

Finite-width plasma

Example of beam-ionized plasma:



Very interesting for light source:
amplified betatron radiation in ion channel laser

E306 experiment by Michael Litos

If blowout radius greater than plasma radius

↓

…ut plasma electrons …ot return to axis

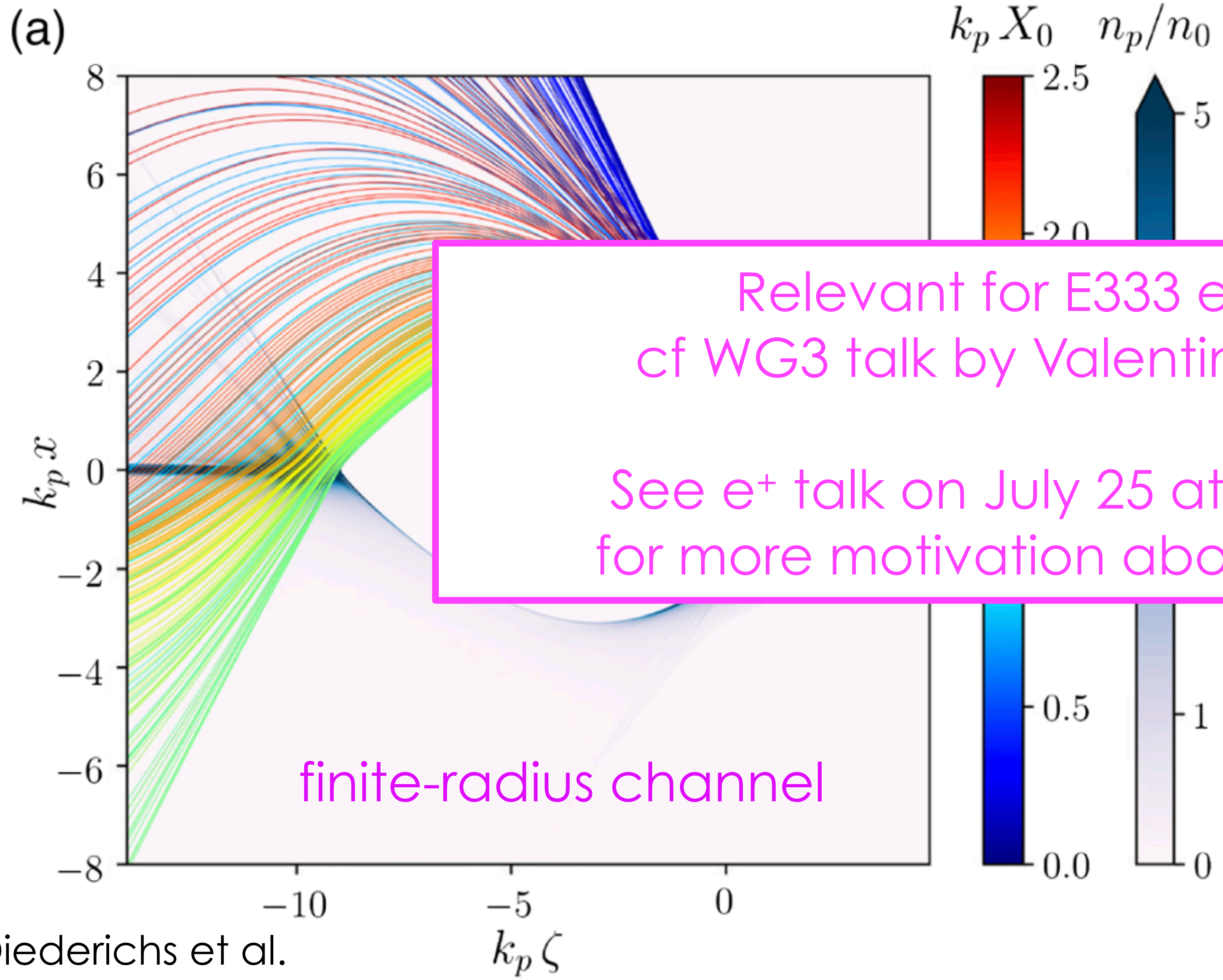
↓

Ion channel but no wakefield oscillations in the wake of the beam

here referred as wakeless regime

Finite-width plasma

Finite-radius plasma column scheme for positron acceleration:



S. Diederichs et al.
PRAB 22, 081301 (2019)

Relevant for E333 experiment:
cf WG3 talk by Valentina Lee - July 22

See e⁺ talk on July 25 at 5:15pm in WG7
for more motivation about this e⁺ regime

When blowout radius approx matches plasma radius

↓

lasma electrons
t return positions
l longitudinally

↓

extended area focusing and accelerating for e+

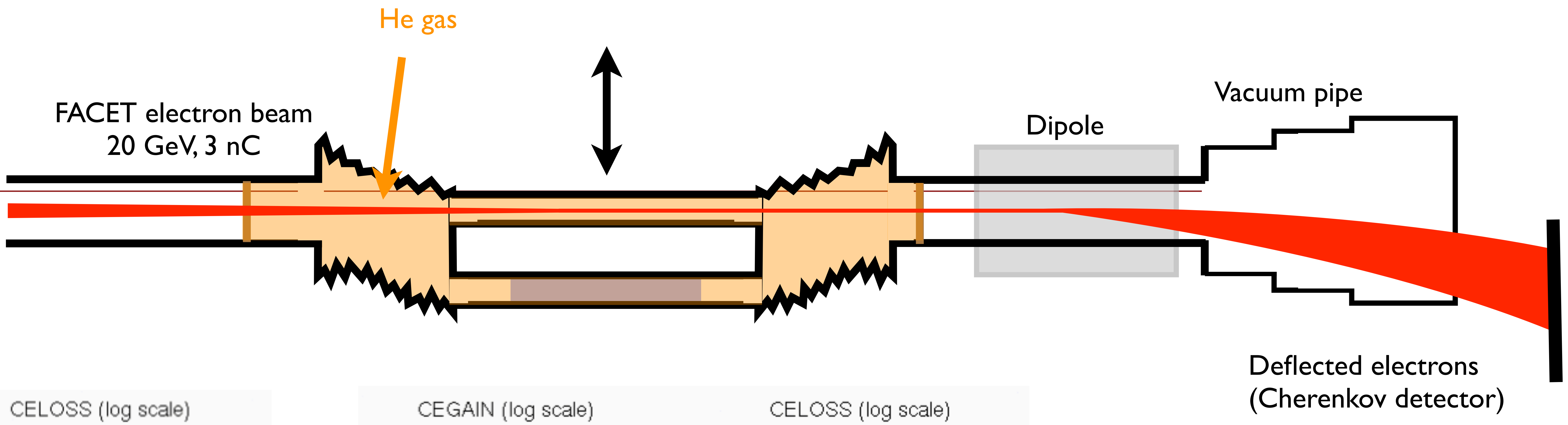
right at the transition between wakeless and standard PWFA regimes

Observations at FACET-I and FACET-II in beam-ionized He

FACET-I

- Experimental set-up:
  - Lithium oven OUT: using helium buffer gas
  - NO laser: the plasma source is obtained by field-ionisation of helium by the beam itself ("self-ionized plasma" or "beam-ionized plasma"); very challenging: ionization potential = 24.6 eV!
  - 20 GeV 3 nC electron beam focused to 20x20x20 um³ in helium gas volume delimited by Be windows

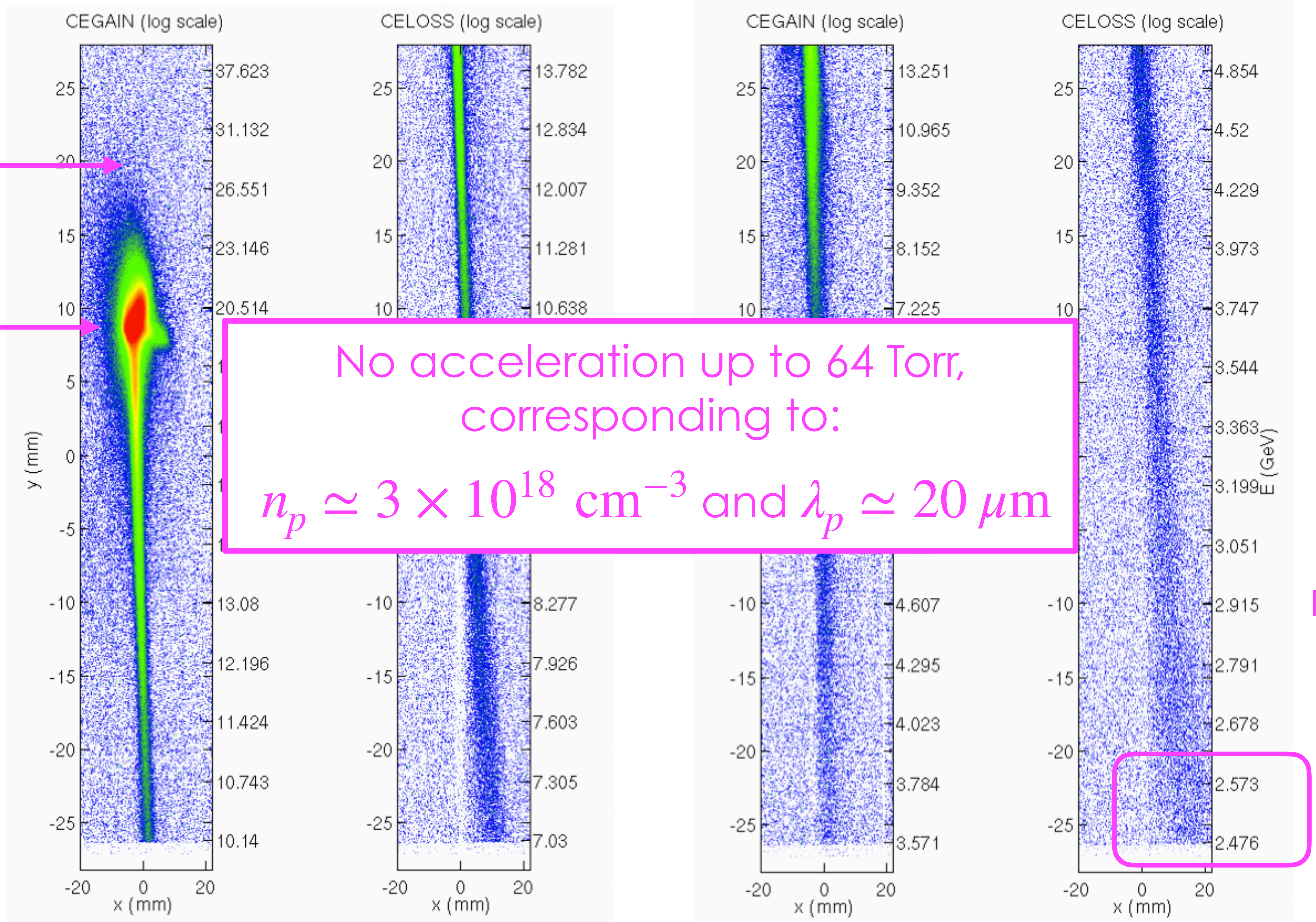
FACET-I



Experimental results

No acceleration

Initial 20 GeV energy

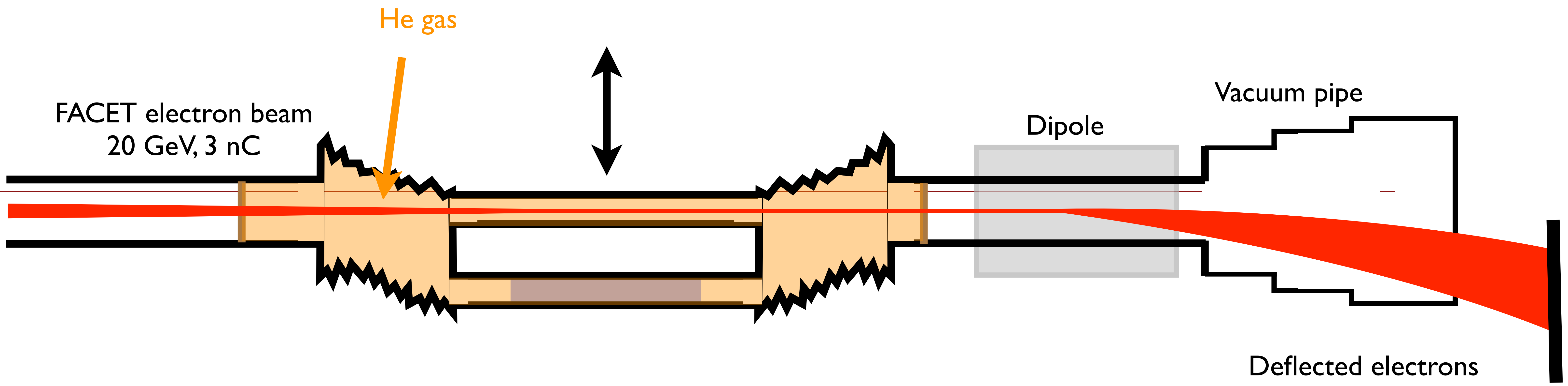


No acceleration up to 64 Torr, corresponding to:

$n_p \simeq 3 \times 10^{18}\ \text{cm}^{-3}$ and $\lambda_p \simeq 20\ \mu\text{m}$

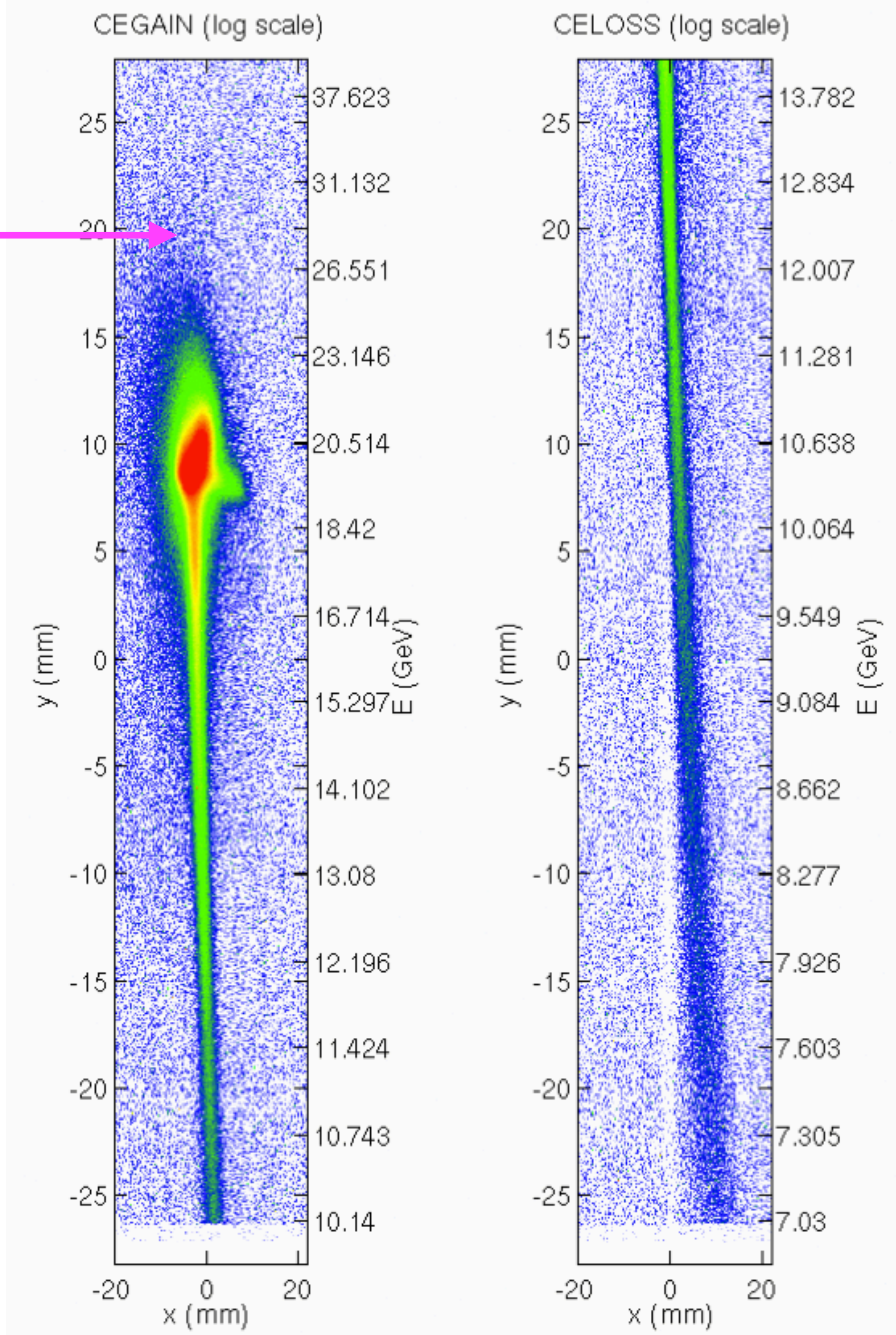
Electrons decelerated from 20 GeV to 2.5 GeV, **losing nearly 90% of their energy**

FACET-I



Experimental results

No acceleration

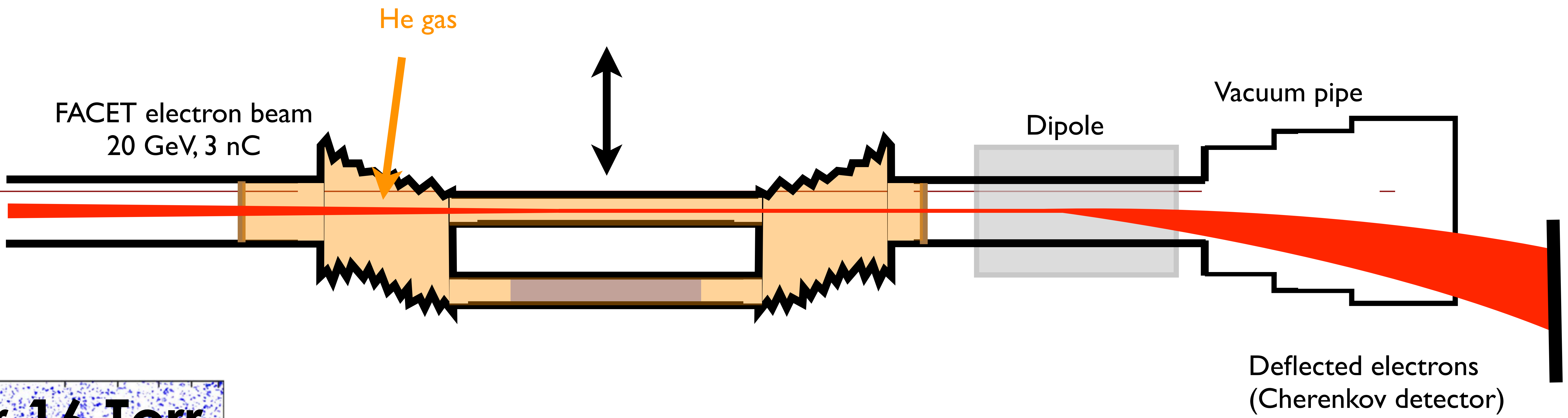


Summary of FACET-I observations:

- Pure He: never observed any acceleration despite full energy loss, tested up to 64 Torr
- He-Ar mixture at 32 Torr: acceleration observed above 40% Ar
- Pure Ar: energy-doubling acceleration observed from 16 Torr

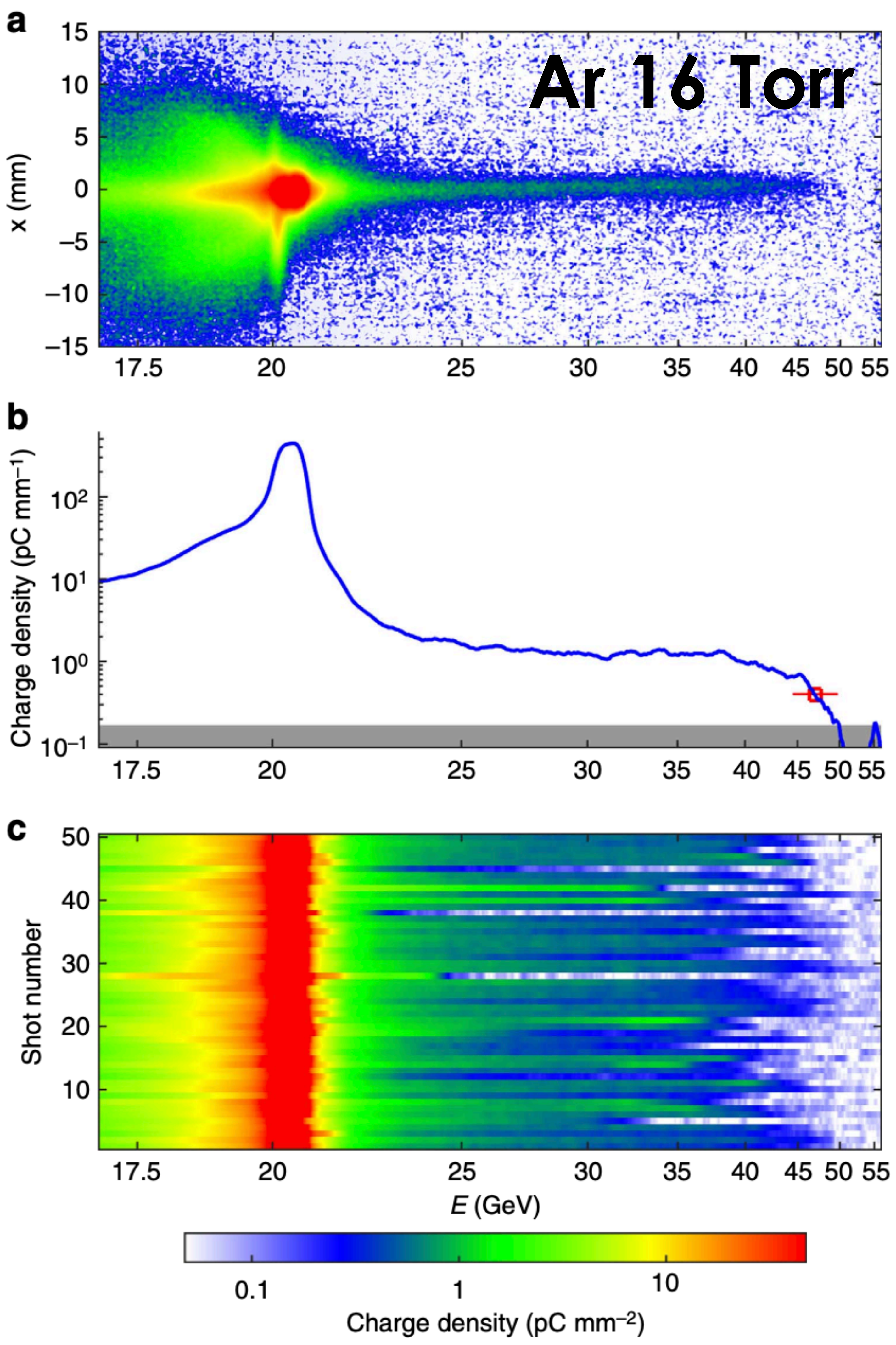
Keeping high density ($k_p\sigma_z \gg 1$), going to lower ionization potential (24.6 eV for He to 15.8 eV for Ar) leads to wider plasma and transition from wakeless to standard PWFA regime

FACET-I



Experimental results

Nature Commun. 7, 11898 (2016)



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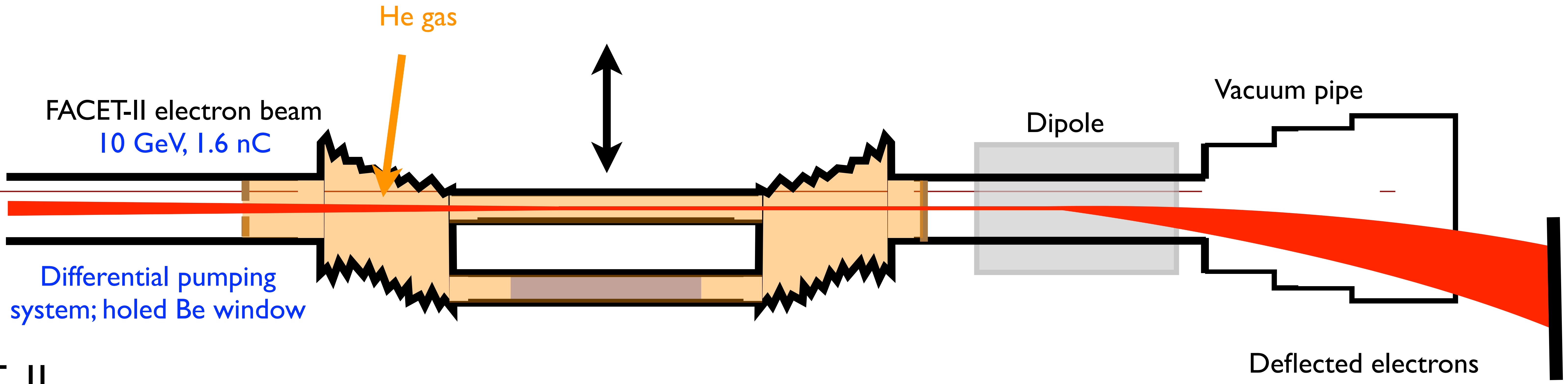
FACET-II



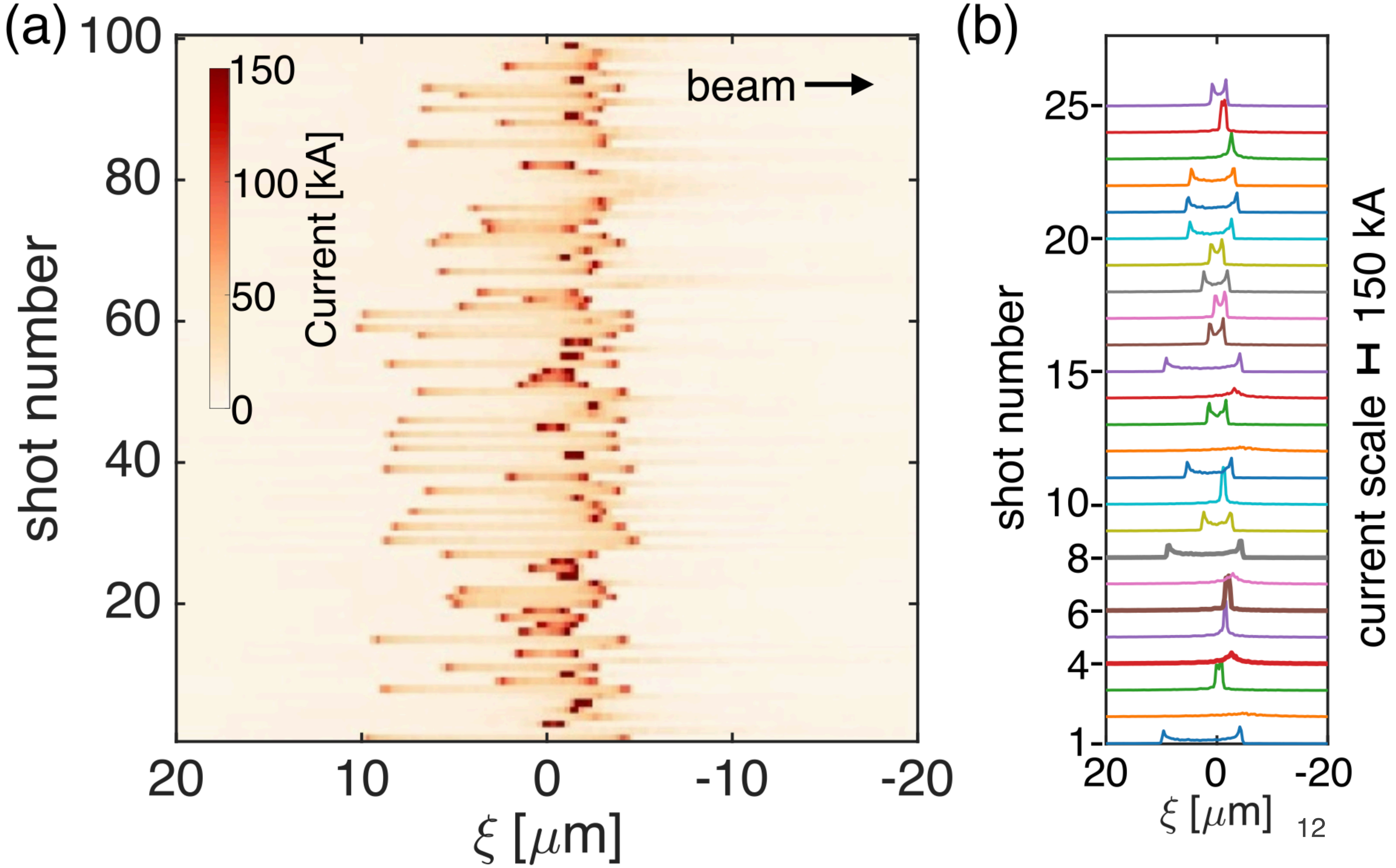
Experimental results from FACET-II

FACET-II: higher peak currents up to 50-100 kA

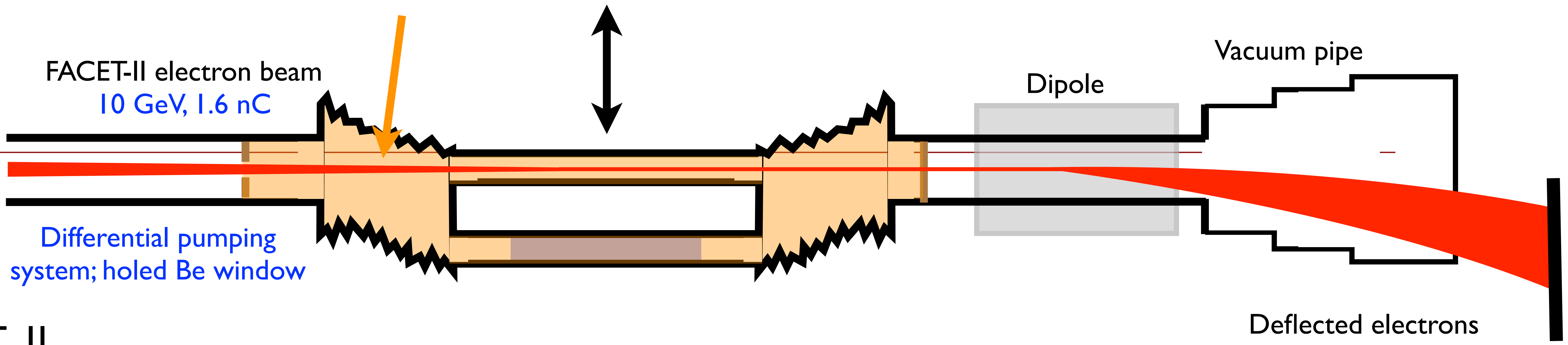
Temporally-structured current profiles with high-current peaks/spikes

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

From FACET-I to FACET-II: beam-ionized at lower plasma densities, potentially over much longer plasma lengths



FACET-II

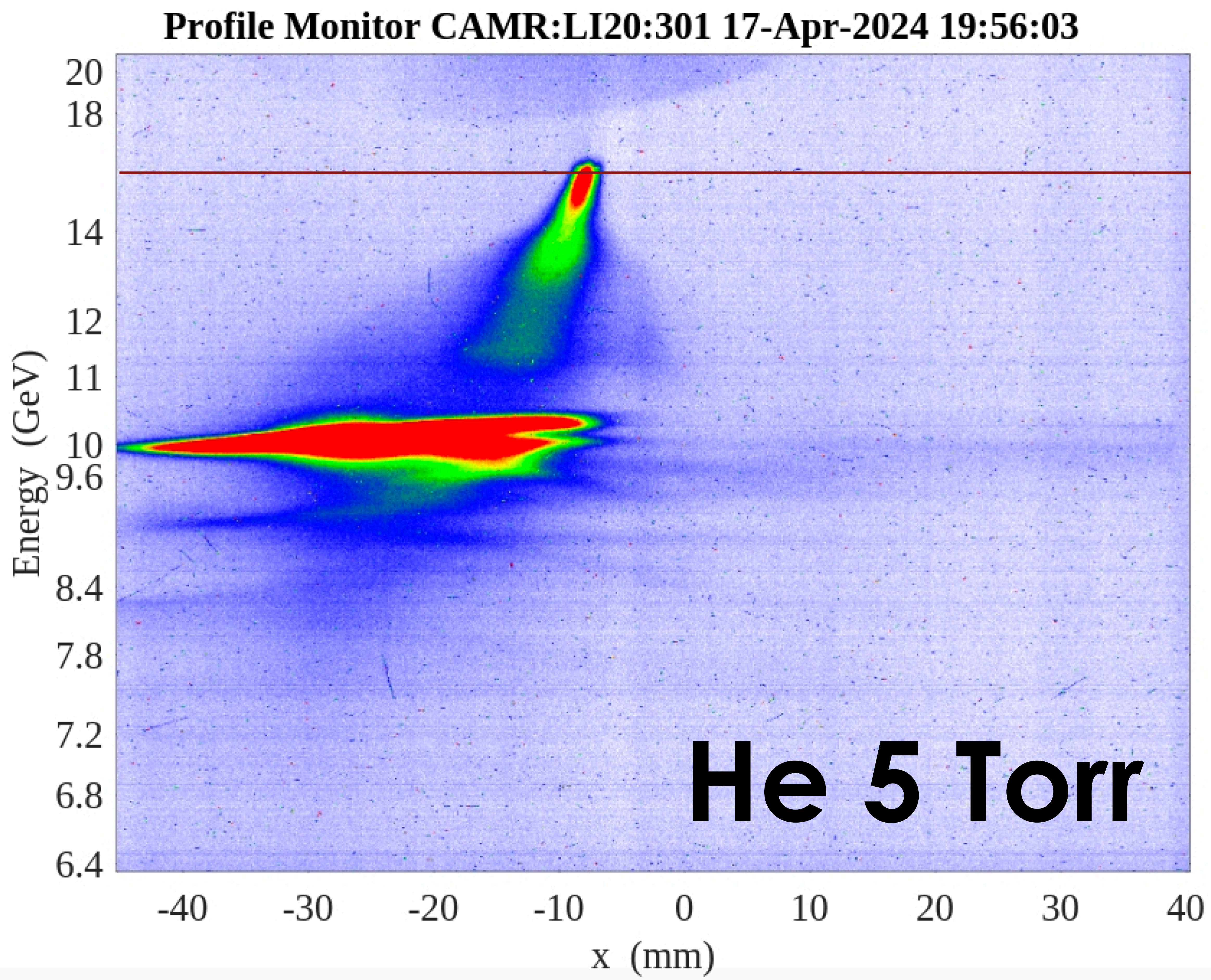


Experimental results from FACET-II

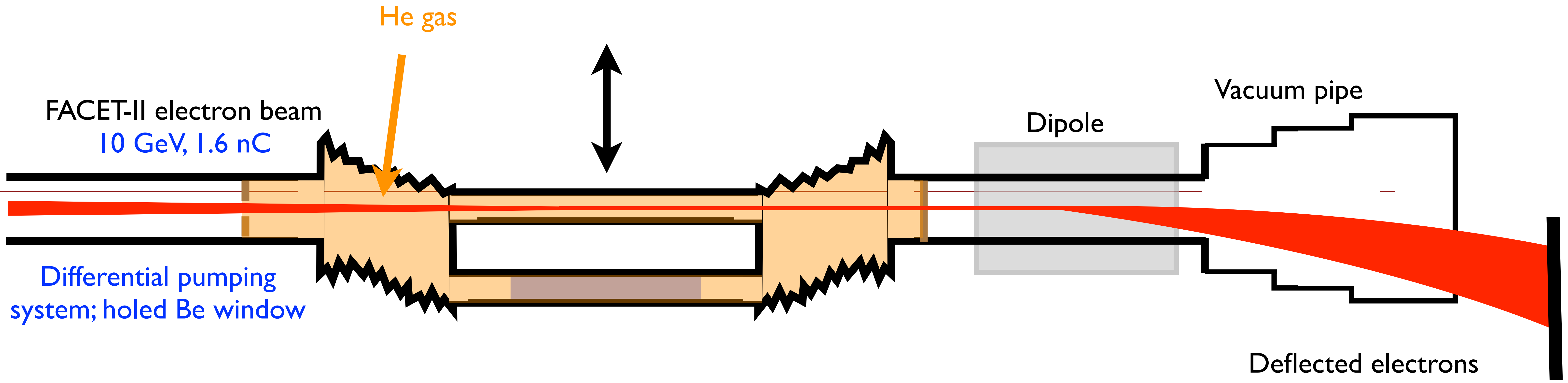
What about beam-ionized He?

Electrons accelerated from 10 GeV to >15 GeV

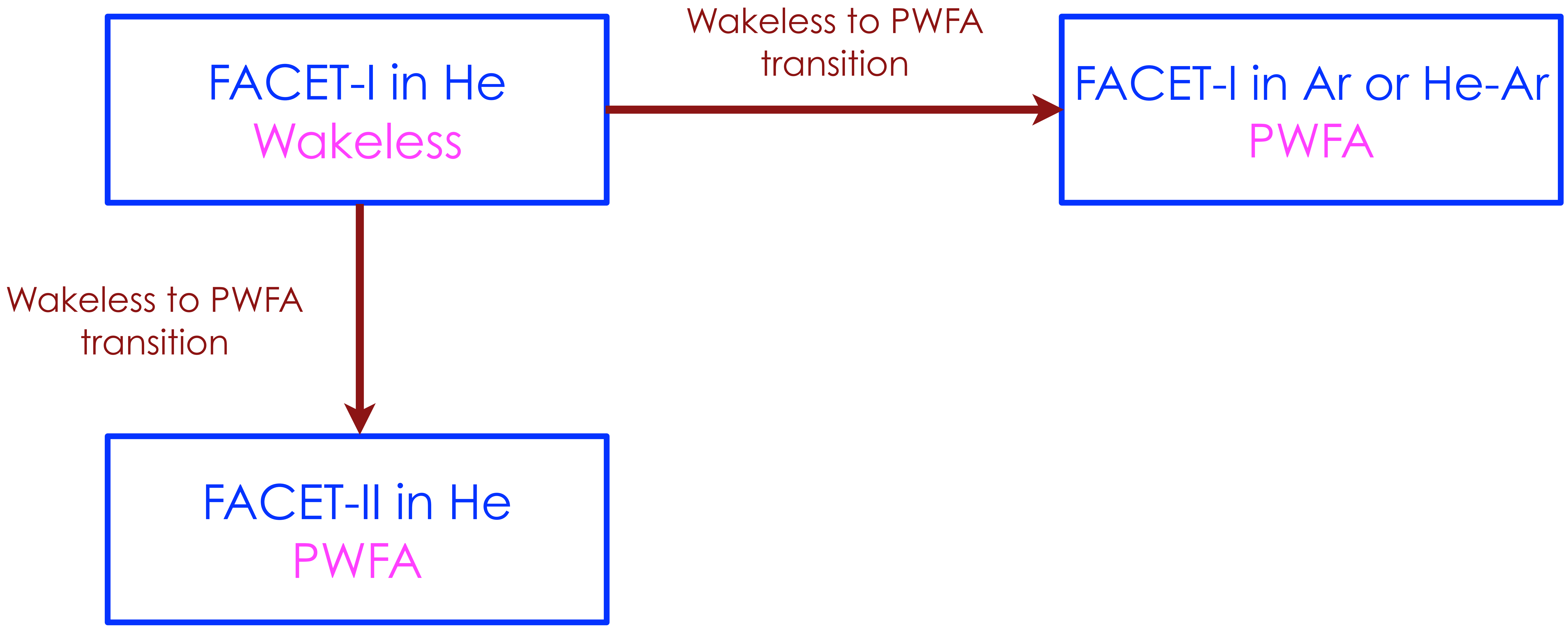
PWFA regime in beam-ionized He
for the first time, with sufficiently wide plasma to
sustain an oscillating plasma wakefield



FACET-I & FACET-II



Summary of observations from FACET-I and FACET-II so far:



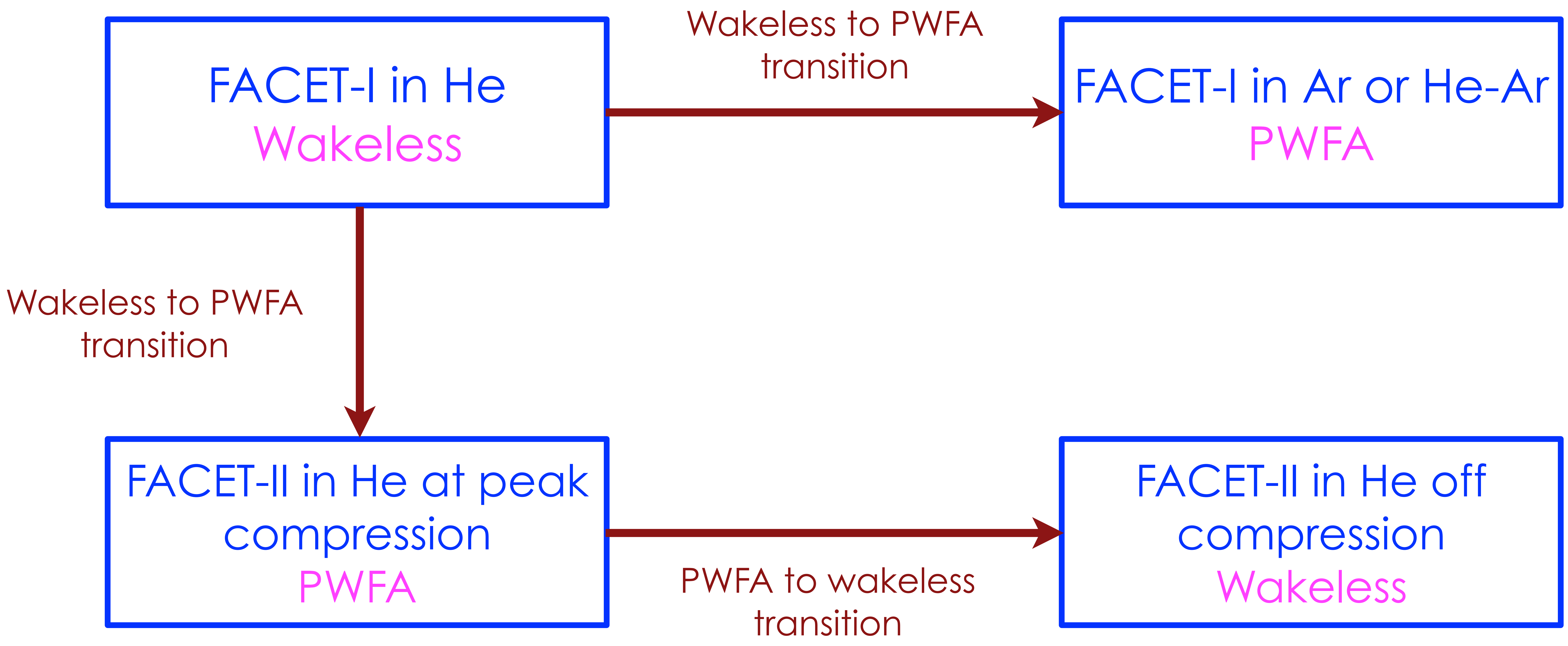
Beam compression to control transition between PWFA and wakeless regimes

FACET-II compression scan in He 10 Torr

- Experimental set-up
  - Laser heater configuration to enhance ionization/interaction - see Claudio Emma's talk on July 25 at 4:48pm in WG5
  - Measurement of bunch length in Sector 14 (BLEN S14) used as a feedback set point
  - BLEN S14 set point is scanned to vary beam compression

FACET-I & FACET-II

Summary of observations from FACET-I and FACET-II so far:



Particle-in-cell simulations

Particle-in-cell (PIC) simulations

Work of Viktoriia Zakharova (LOA PhD Student)

Simulation set-up:

Simplified by keeping current profile and using Gaussian distribution transversely

Linac Lucretia simulations → Beam distributions → 3D quasi-static PIC simulations with HiPACE++

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

S. Diederichs et al., Comp. Phys. Commun. 278, 108421 (2022)

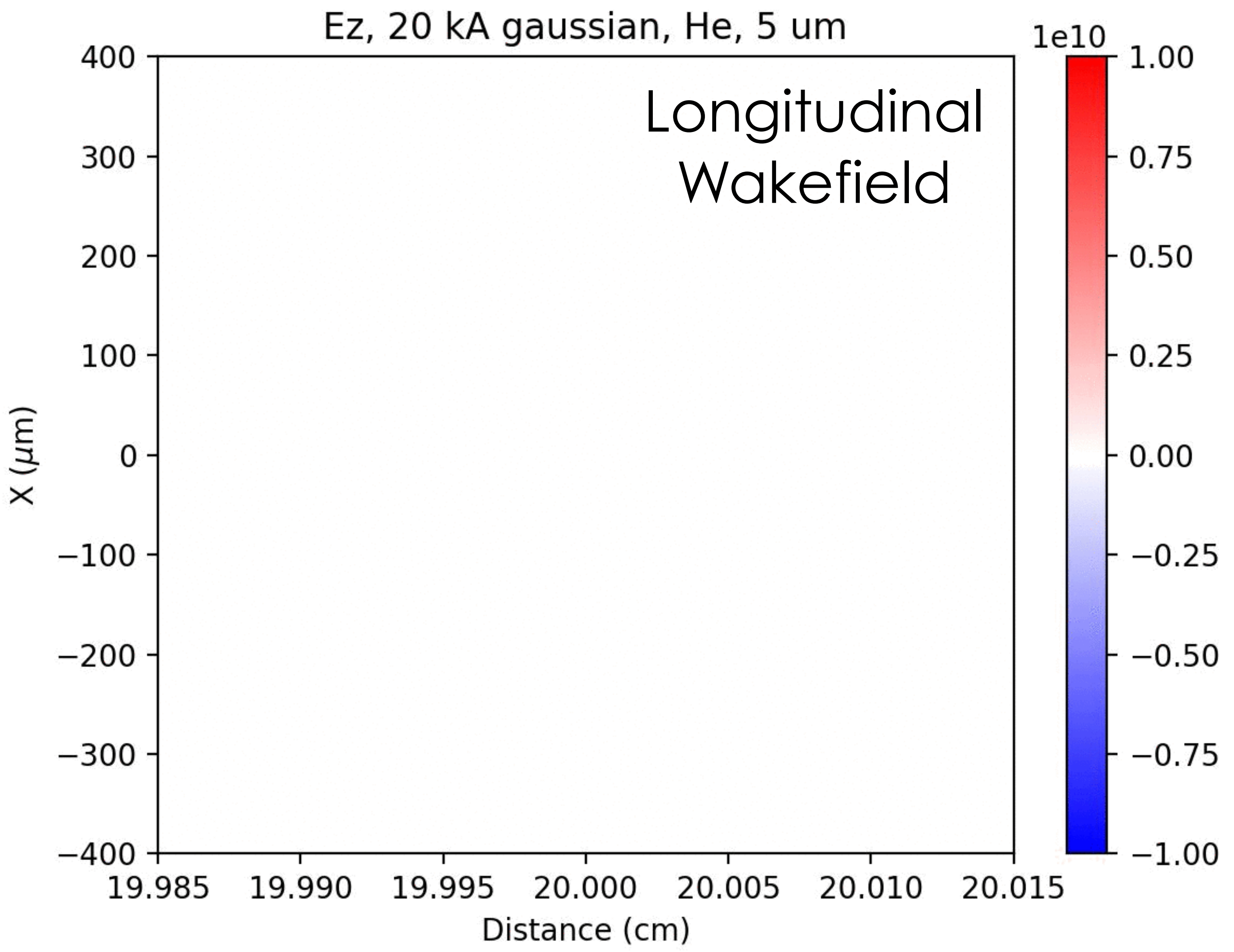
PIC simulation starting before waist without any ionization.

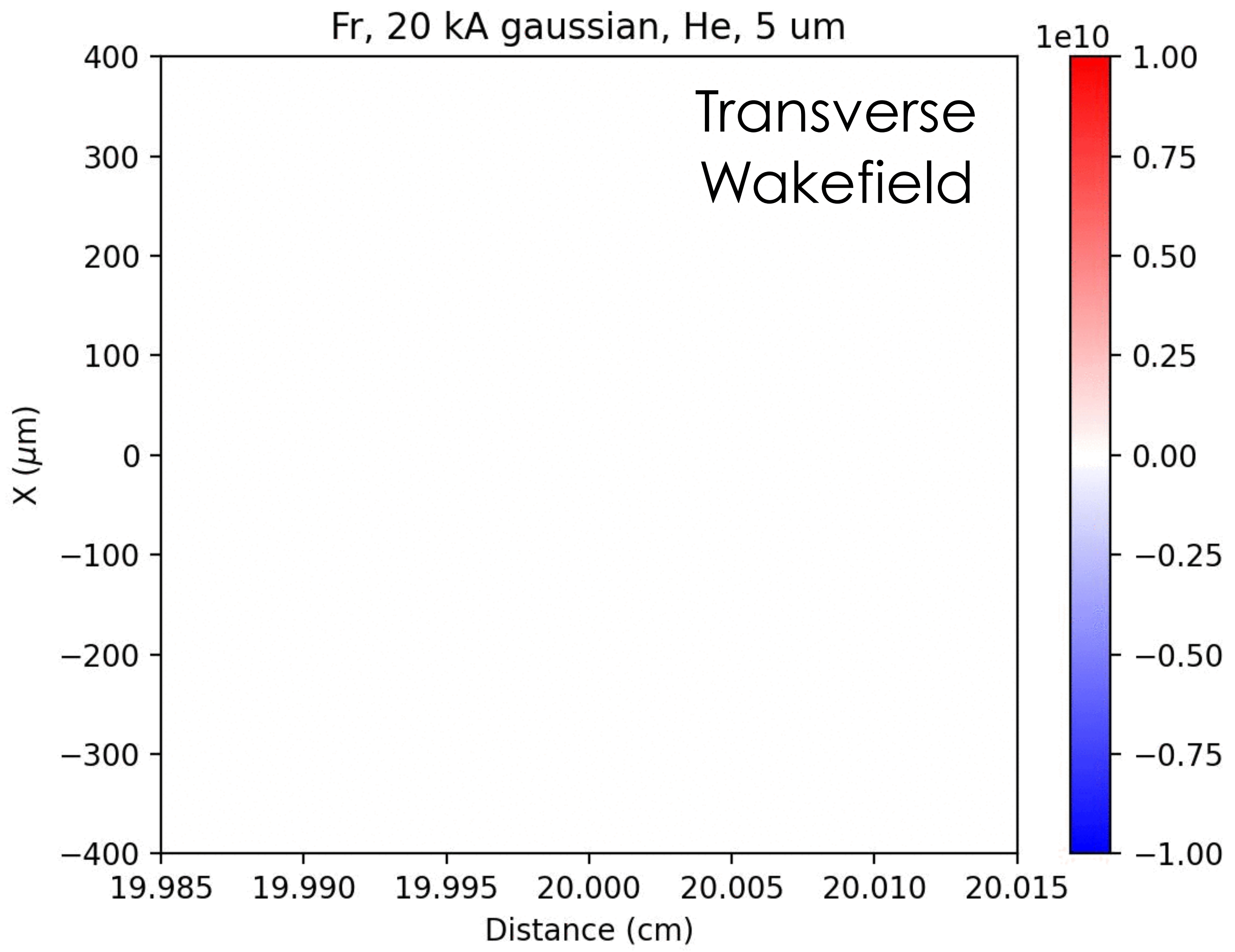
Assumed 13 um normalized emittance for Gaussian transverse distribution, neutral gas of He at 10 Torr.

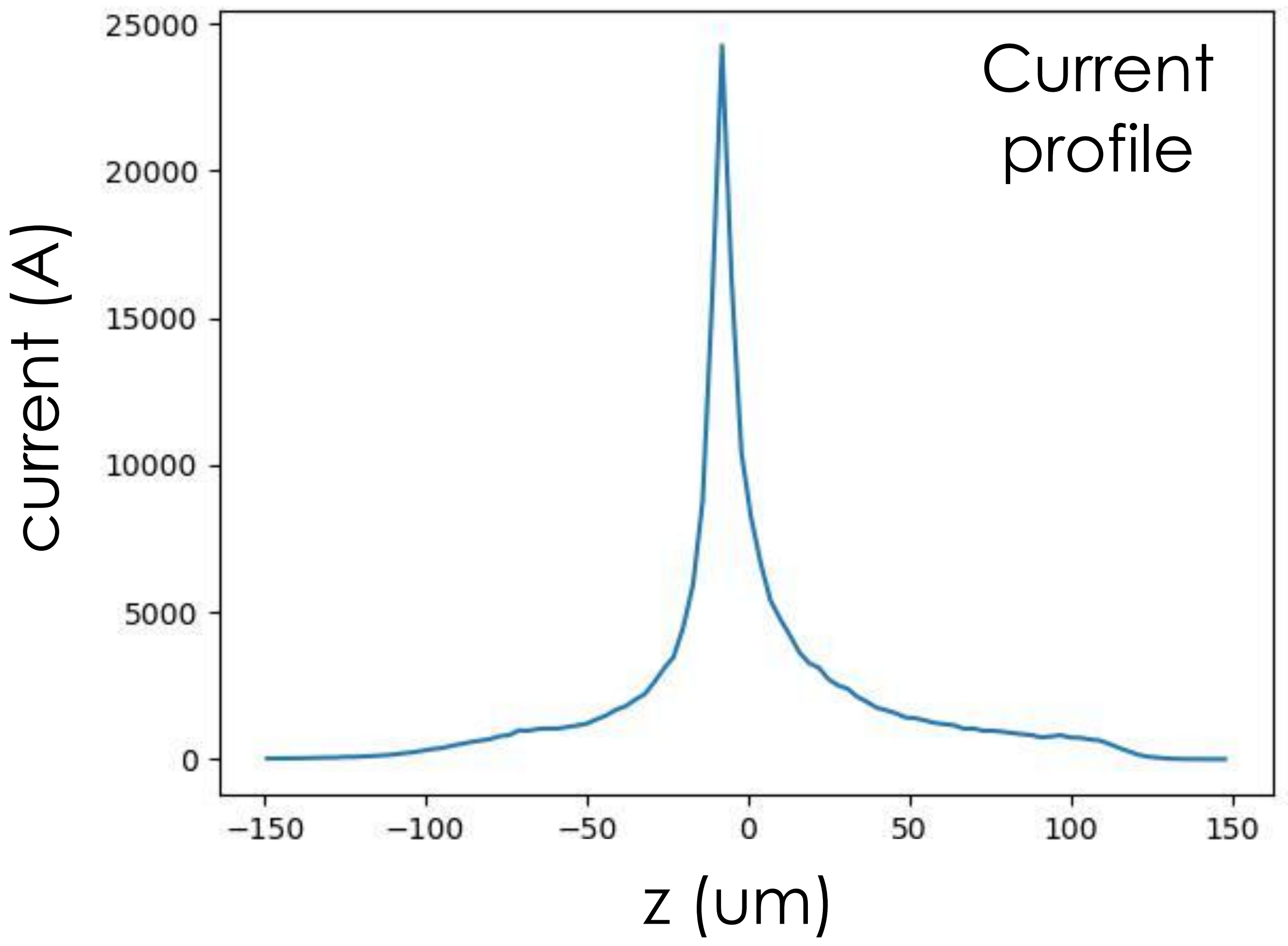
Current profiles and longitudinal phase spaces from Lucretia:

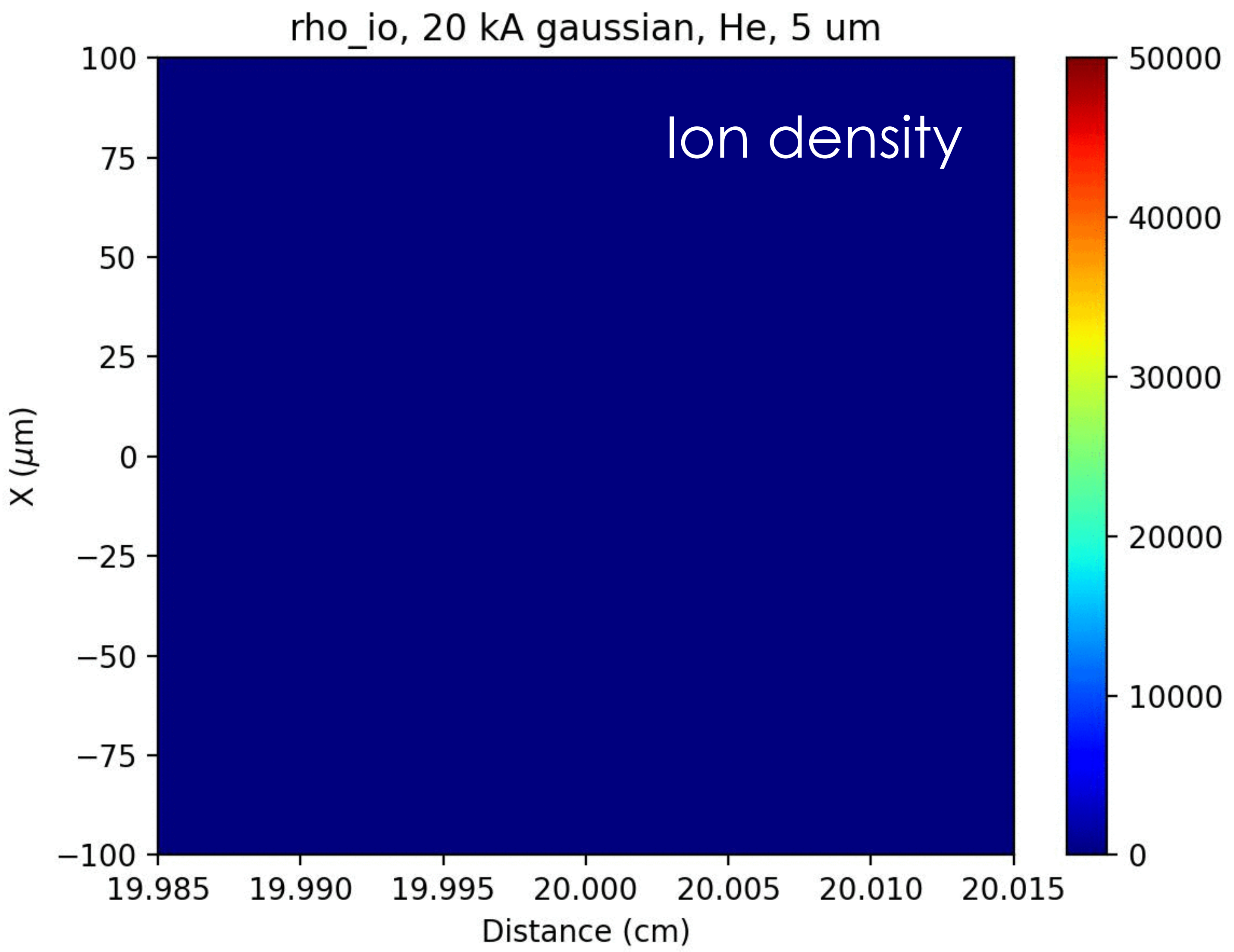
Particle-in-cell (PIC) simulations

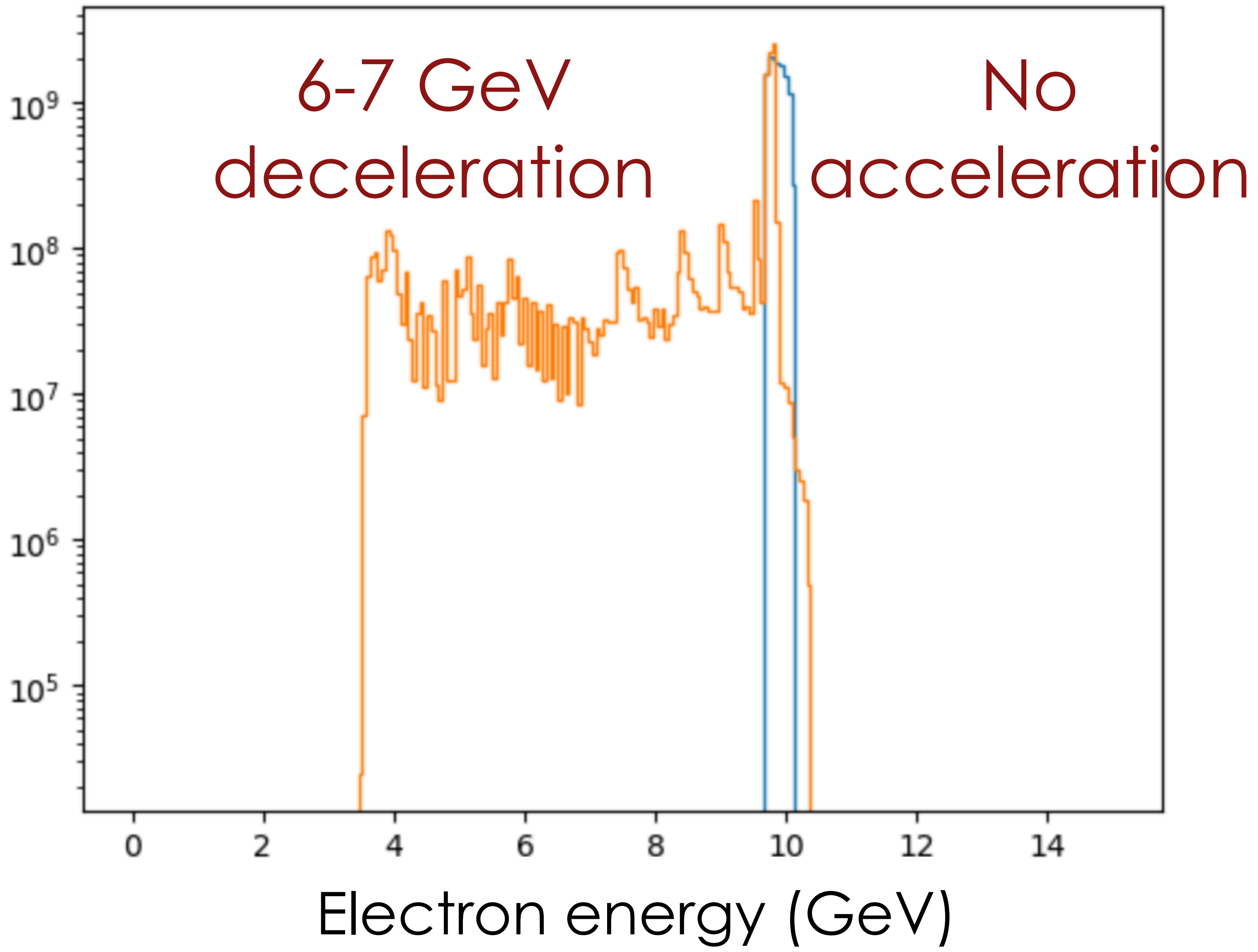
Work of Viktoriia Zakharova (LOA PhD Student)









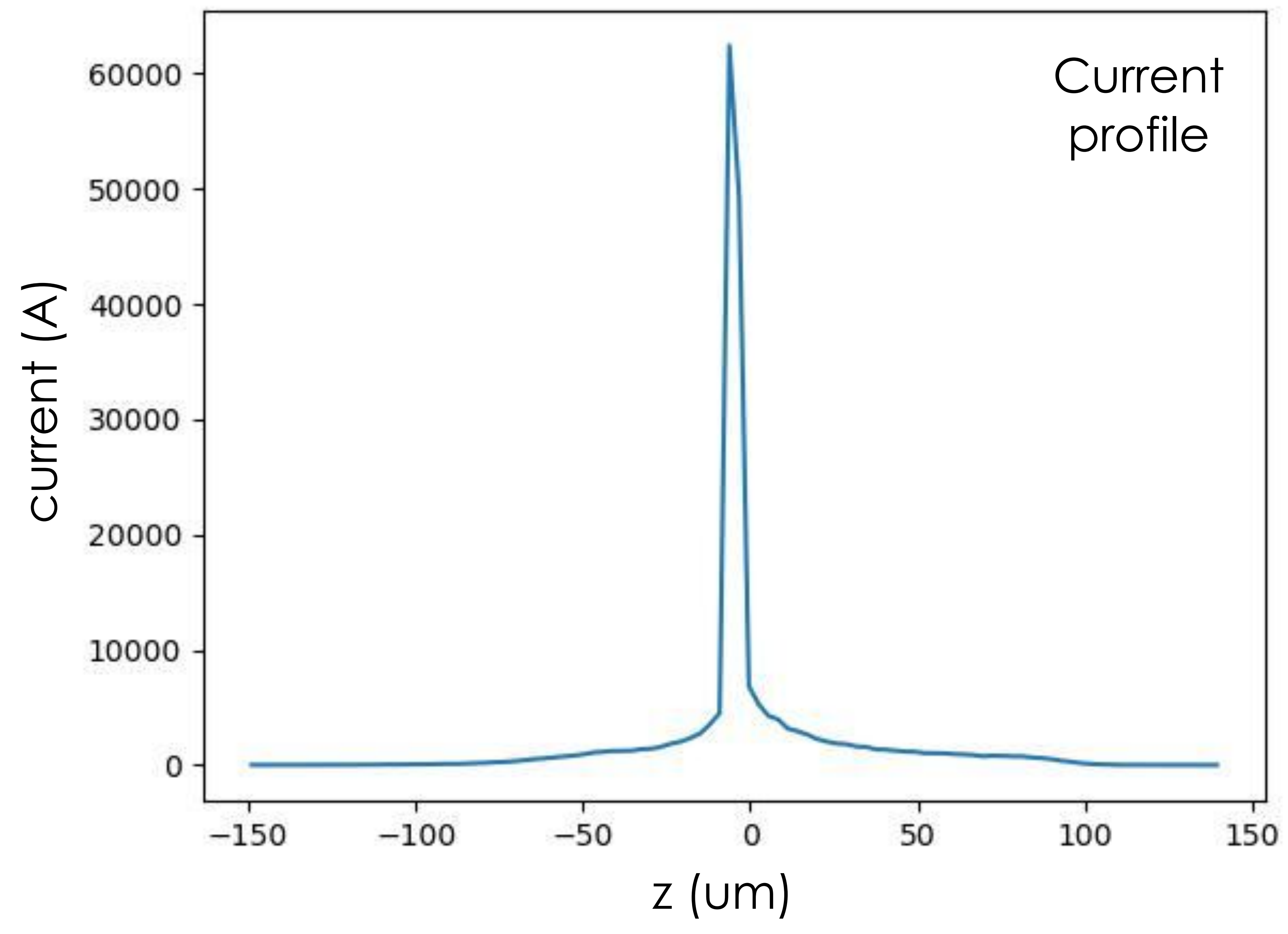


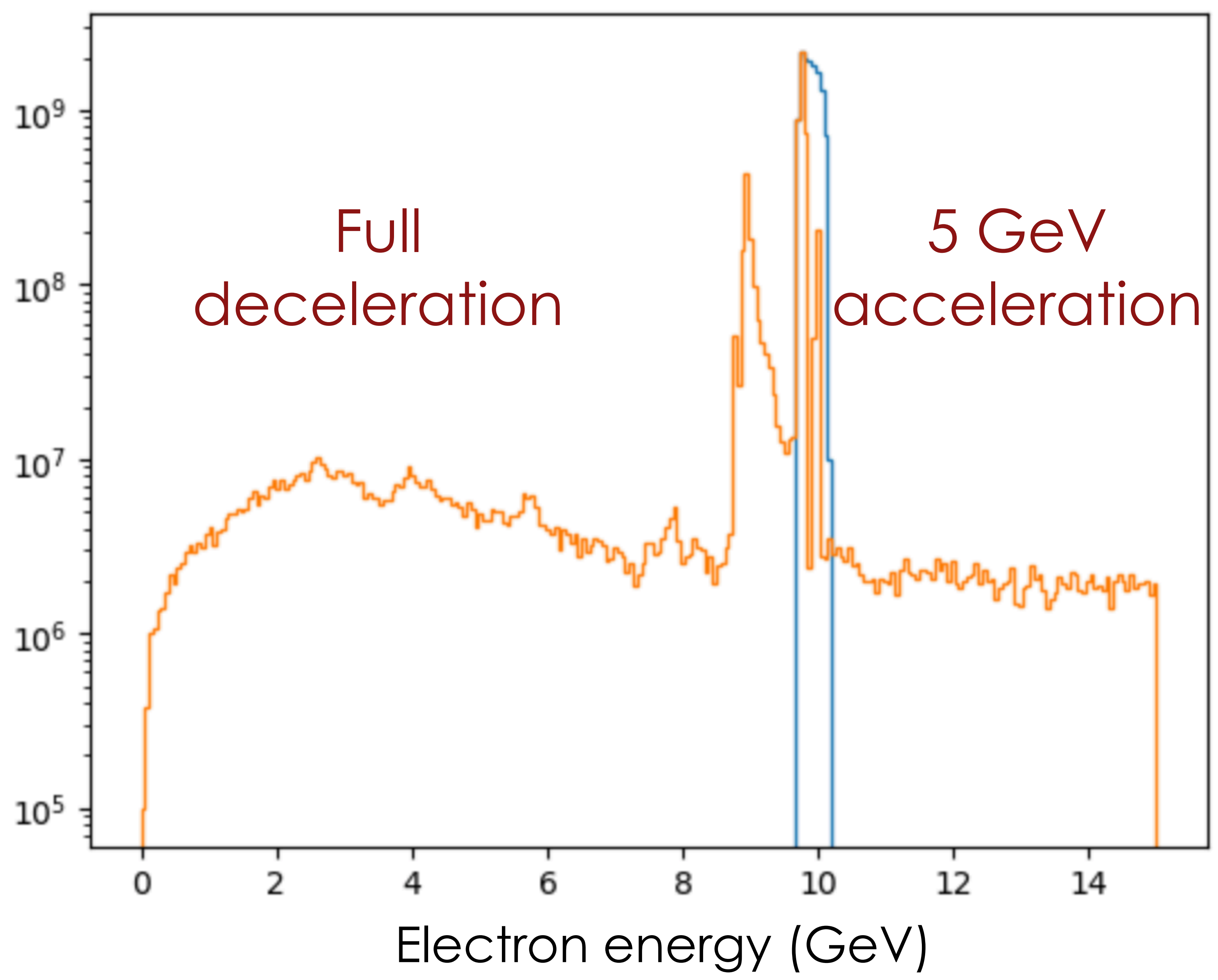
Off compression

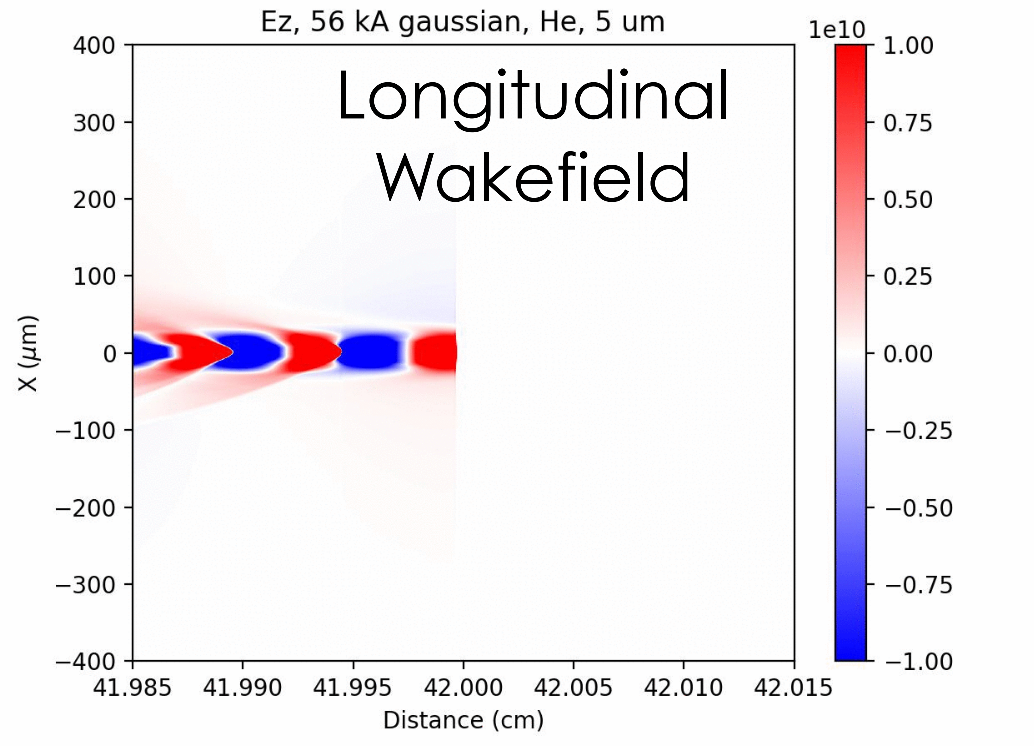
Wakeless

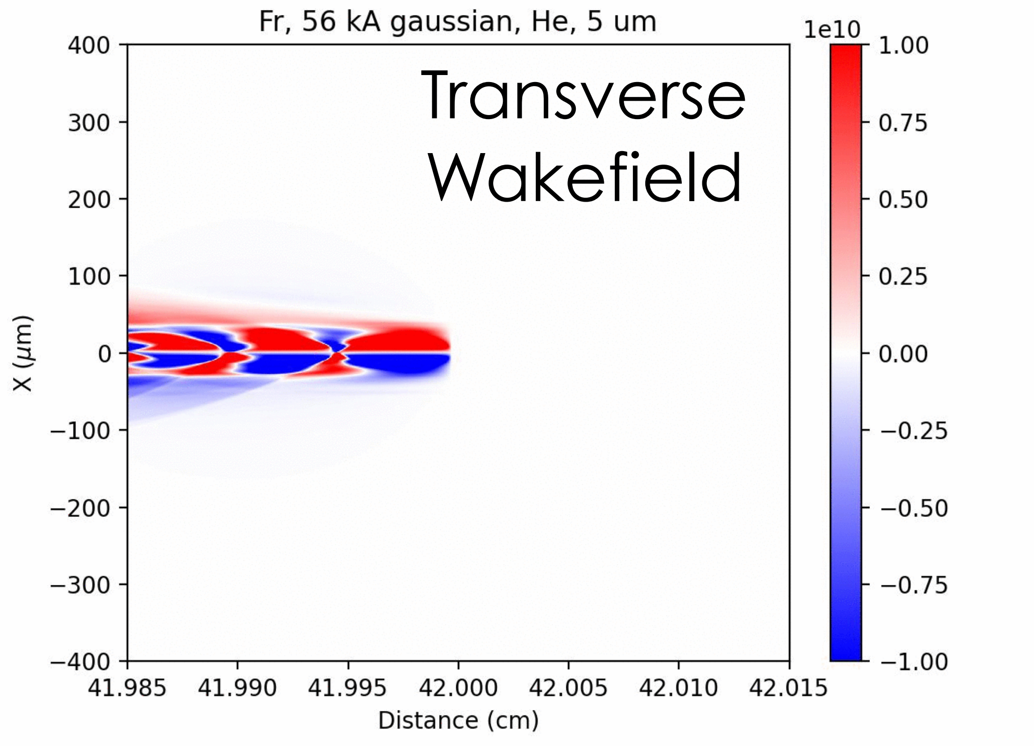
Work of Viktoriia Zakharova
(LOA PhD Student)

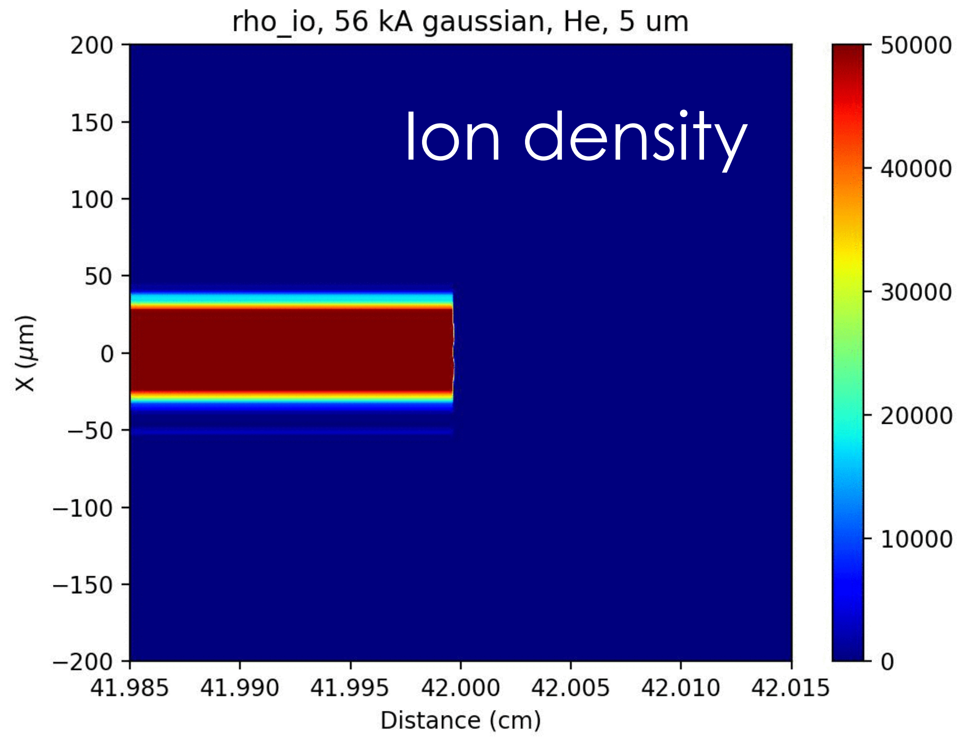
Particle-in-cell (PIC) simulations











Peak compression
PWFA

Conclusion

- Wakeless to PWFA transition observed:
  - Changing gas from pure He, mixture He-Ar to pure Ar at FACET-I
  - From FACET-I to FACET-II in He
  - By controlling beam compression at FACET-II
- Simulations support transition between PWFA and wakeless regimes with compression:
  - Peak compression leads to wider plasma able to sustain oscillating wakefield
  - Off compression with moderate current leads to narrower plasma, and plasma electrons do not return to axis

Thank you for your attention