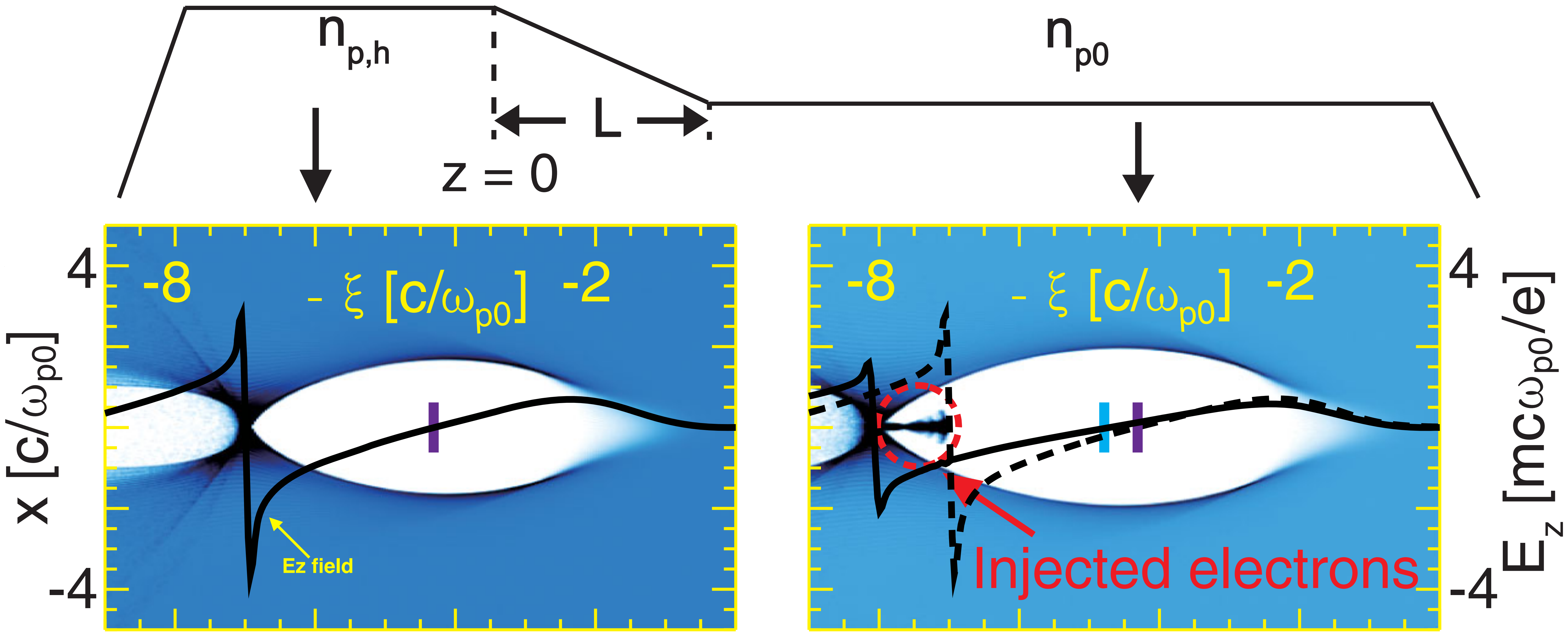
E304 status and plans for FY2023

Chaojie Zhang, Xinlu Xu, Sebastien Corde
on behalf of the E300 Collaboration

Oct 26, 2022

Internal generation of low-emittance, high-brightness bunches using density downramp



Xinlu Xu et al., Phys. Rev. Accel. Beams (2017)

Example parameters: driver: Λ=4, $\sigma_r=\sigma_z=\varepsilon_n=5.3\ \mu m$

$\Lambda = 2I_b/I_A \quad I_A \approx 17\ \mathrm{kA}$

n_{ph} [cm^{-3}]	n_{p0} [cm^{-3}]	ramp [mm]	I [kA]	ε_n [nm]	B [$A/m^2/rad^2$]	E [MeV]	σ_E/E	Q [pC]
1.5×10^{18}	10^{18}	1.3	14	80	4E+18	620	0.15%	140

Science goals, definition of success and target time for each goal

UCLA

E304: generate low emittance beams using downramp trapping in PWFA

Year 1

Demonstrate downramp trapping

- Significant energy loss of driver in a cm-scale high-density (10^{18} cm^{-3}) plasma
- Evidence of injection (charge excess)
- Trapped electron signal on spectrometer (E$\gtrsim$0.5 GeV)

Year 1-2

Systematic study of the injection

- Stable 1-multiple GeV beams, measure emittance
- Sharp ramp vs. gentle ramp (minimize energy spread by longitudinal phase space rotation)
- Laser- vs. beam-ionization (different emittance)

Year 2-3

Generate and measure ultralow emittance beams

- Measure ultralow emittance (<1 μm, e.g., using undulator radiation)

- $E > 1$ GeV
- $\delta E/E < 1\,\%$
- $\varepsilon_n \lesssim 1\ \mu$m
- $I \gtrsim 5$ kA

Experimental timeline

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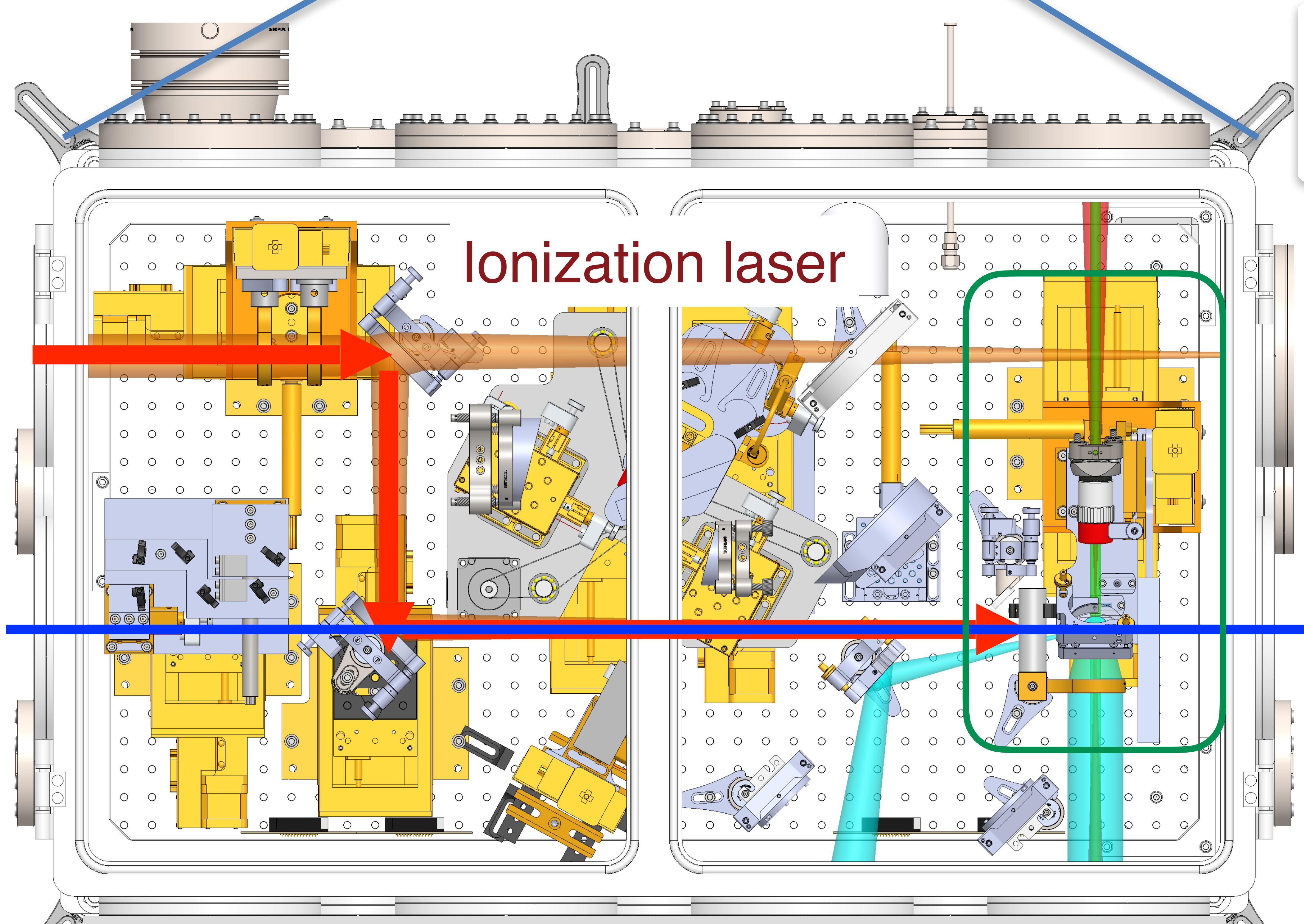
- Experimental design (90%): Dec, 2022 for the first run
- Installation plan: Target assembly same as E305 but change nozzles. Ready to install in Nov.
- Ready for experimental safety review: Review docs submitted in 2020
- Ready for commissioning: Anytime after installation (2022 Nov)
  - Beam requirements: achieved beam parameters for E300 (**10 GeV, 1.5 nC, $\sigma_{r,z} \lesssim 25\ \mu m$**)
- First science: demonstrate injection and understand emittance dependence on the driver/ plasma parameters (2023)
  - Beam requirements: E=10 GeV, $\sigma_r \sim \sigma_z < 10\ \mu m$, $\varepsilon_n < 40\ \mu m$, Q>1 nC (I>12 kA)
- 2nd phase of the program: generating ultralow emittance beams
  - Prerequisites: E=10 GeV, $\sigma_r \lesssim 4\ \mu m$ β~5-10 cm (same as E300), $\sigma_z \lesssim 10\ \mu m$, $\varepsilon_n < 20\ \mu m$, Q>1 nC (I>12 kA)
  - Date: year 2 and 3 (2024-2025)

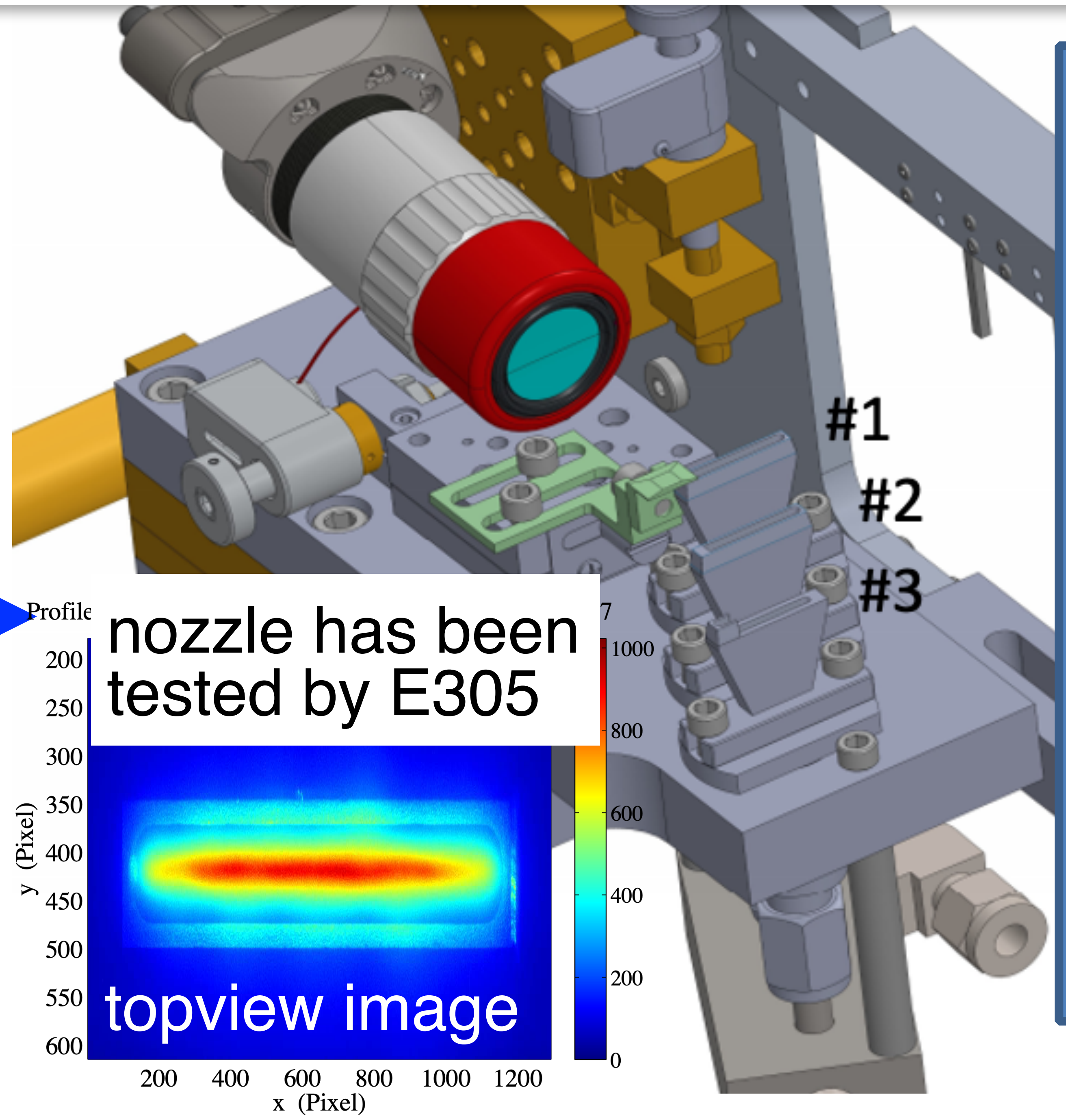
Experimental layout

UCLA



CAD drawings made by Robert Ariniello, CU

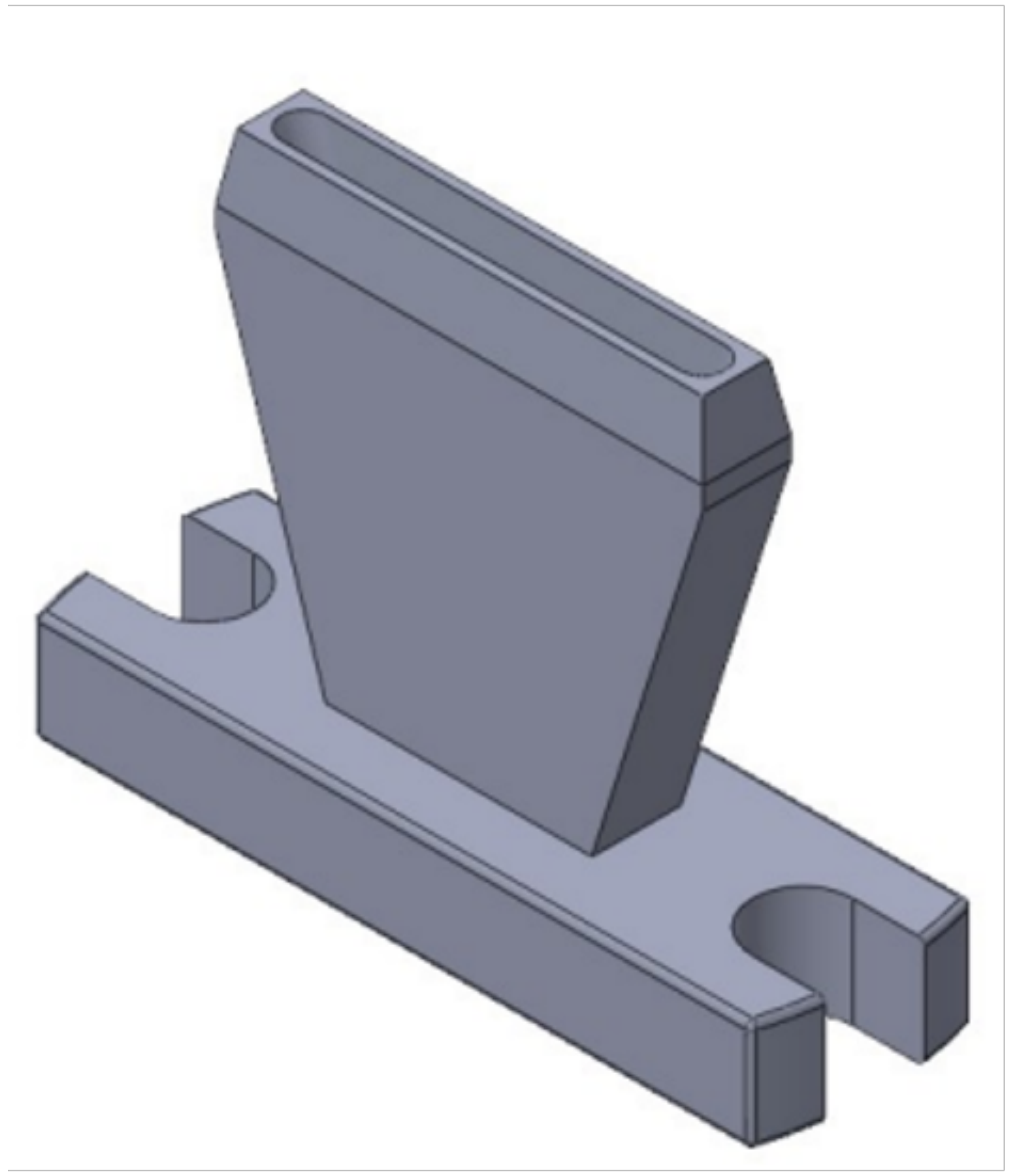
Same target assembly as E305 but different nozzles.



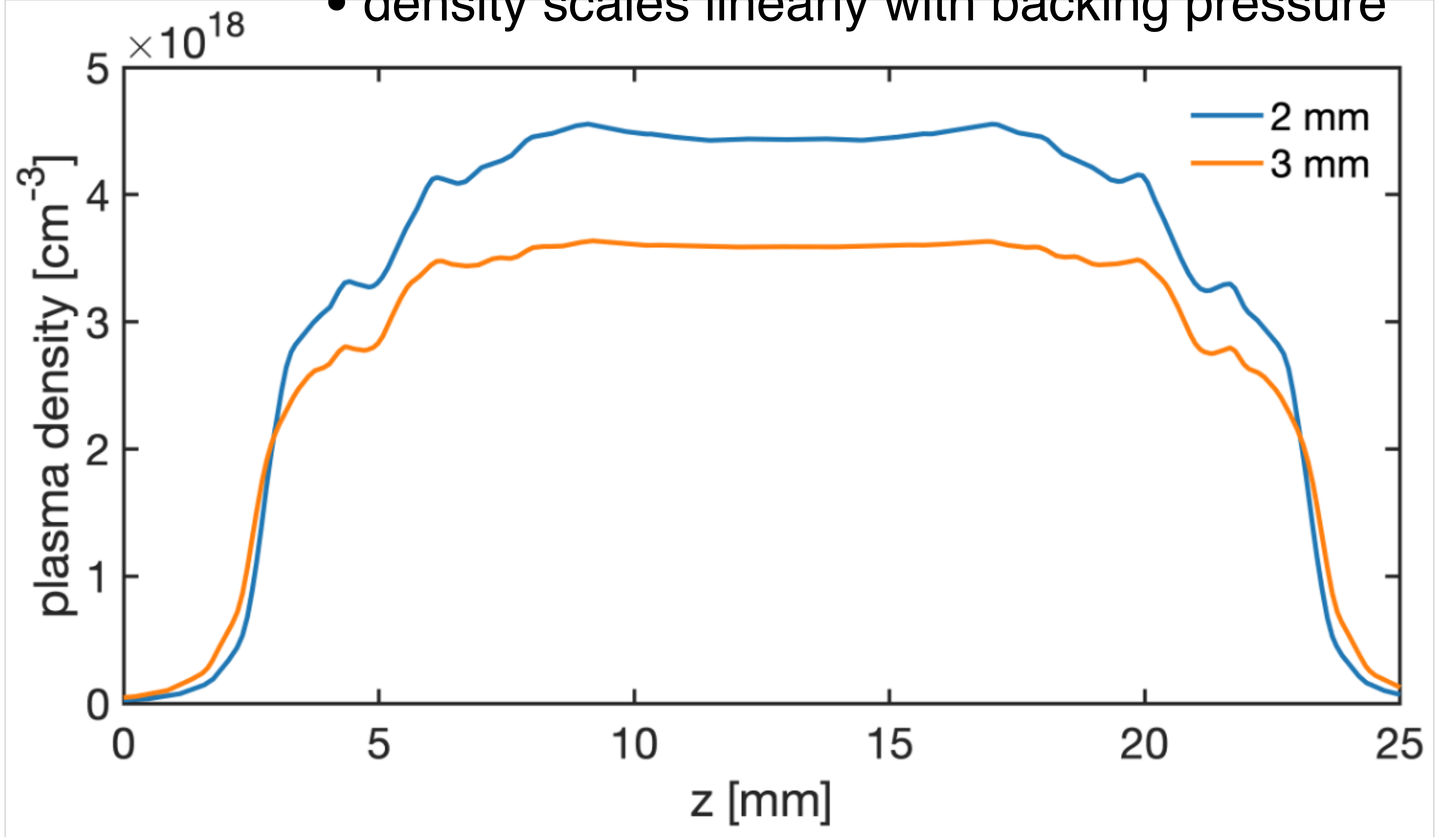
- E304 plasma source:
- 2-cm gas jets
  - Sharp downramp (~10 c/ω_p) by shock front
  - Gentle downramp (~100 c/ω_p) by structured nozzle
  - Laser ionization & beam ionization

Plasma source option #1

2-cm slit nozzle with blade (movable sharp ramp, blade not shown)



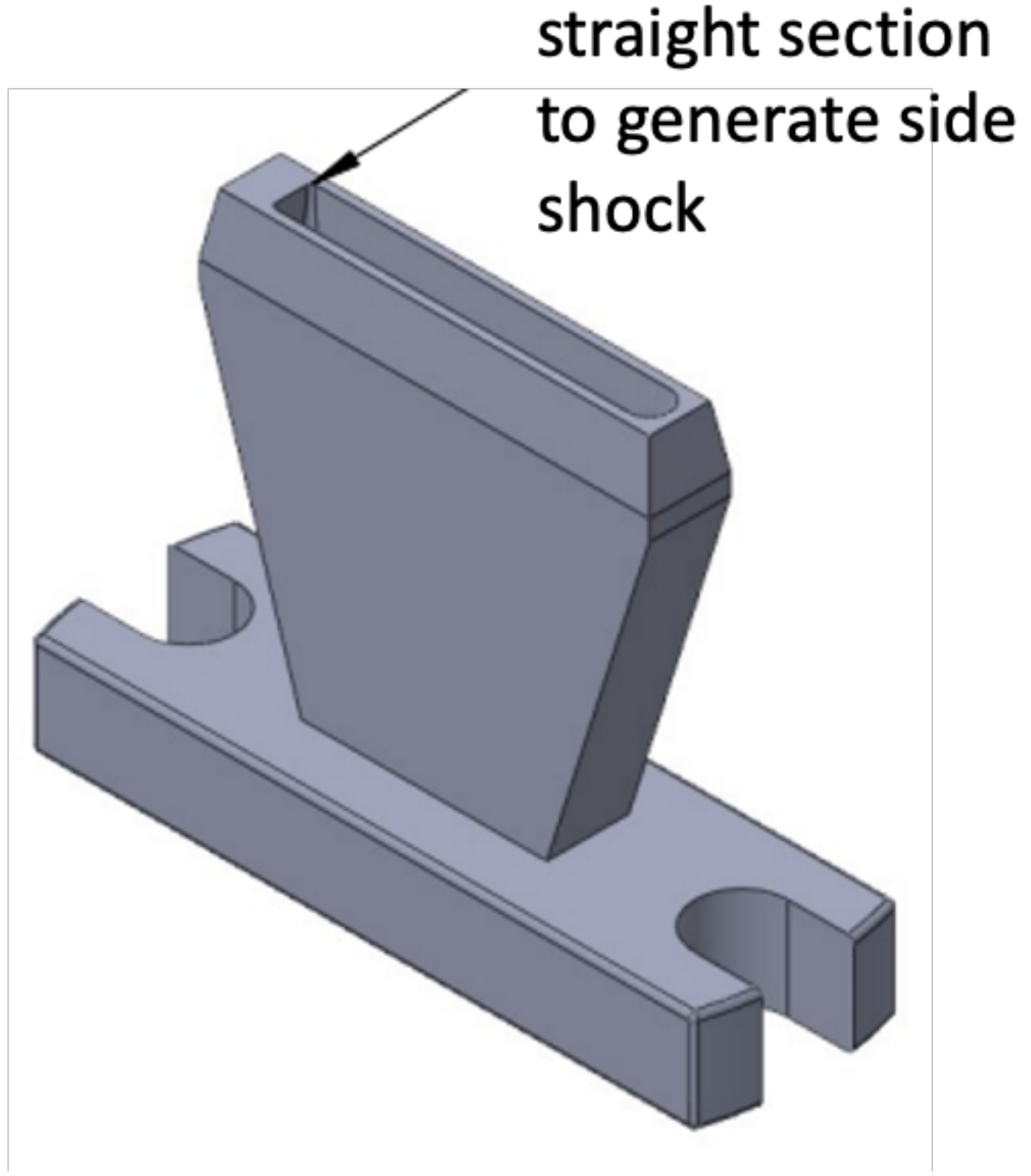
- backing pressure 200 psi
- density scales linearly with backing pressure

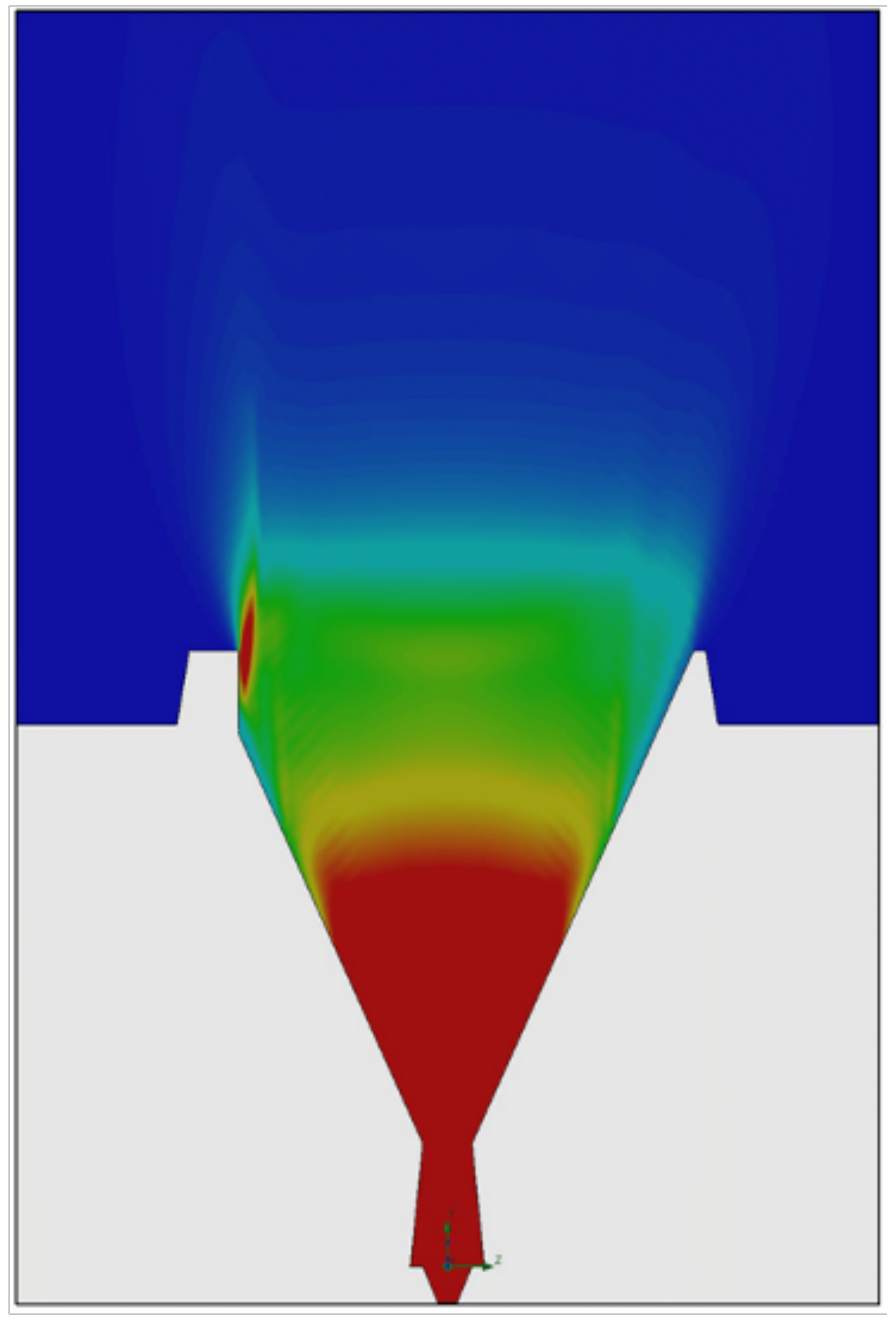


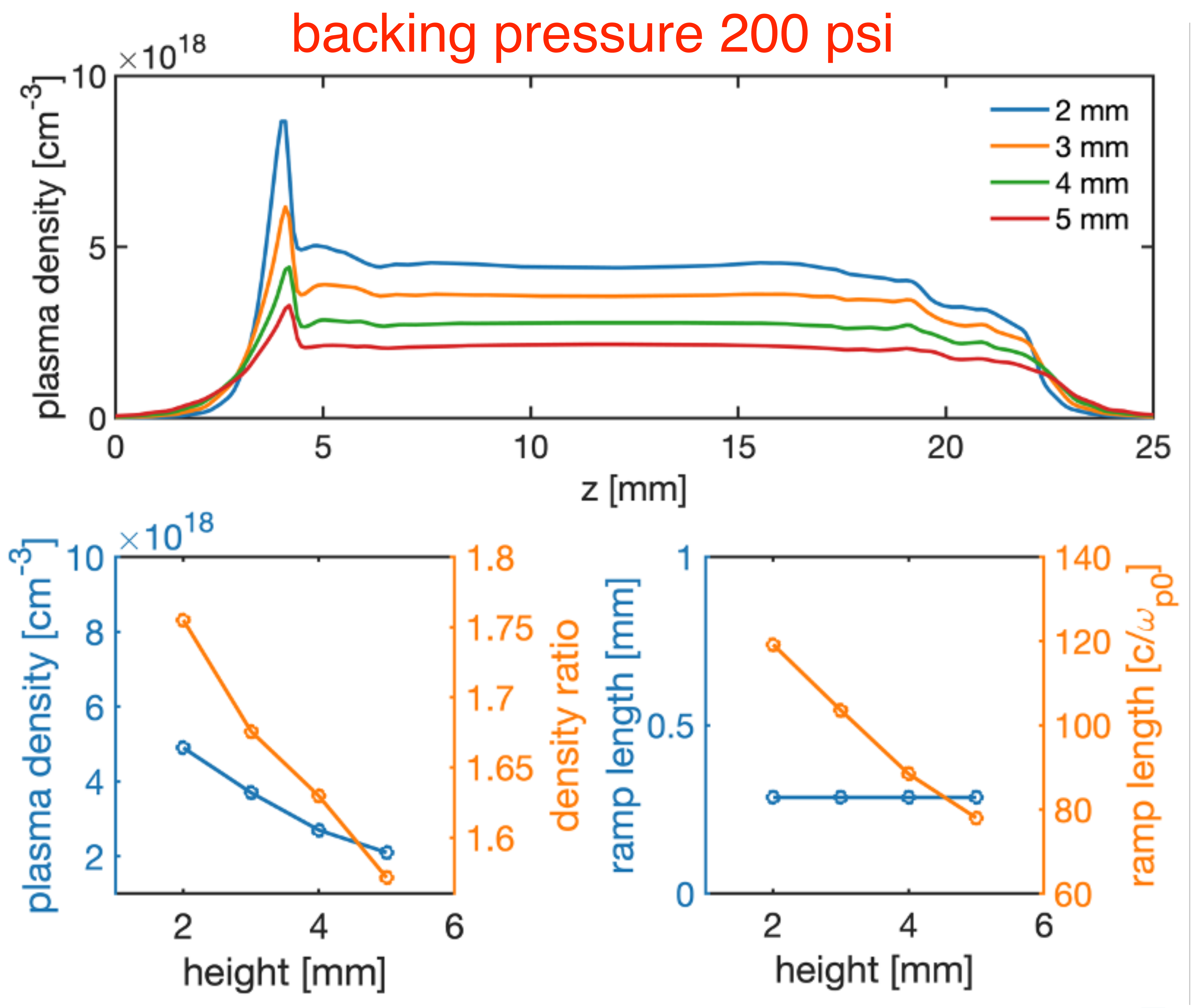
Plasma source option #2

A movable blade allows to change the position of the down ramp.
Pros: 1) null test by moving the blade out 2) injected bunch energy correlation with the down ramp location (in a limited range because we need E>1 GeV)
Cons: What if it stops moving in a high radiation environment?

An alternative: a nozzle with a built-in shock inducer

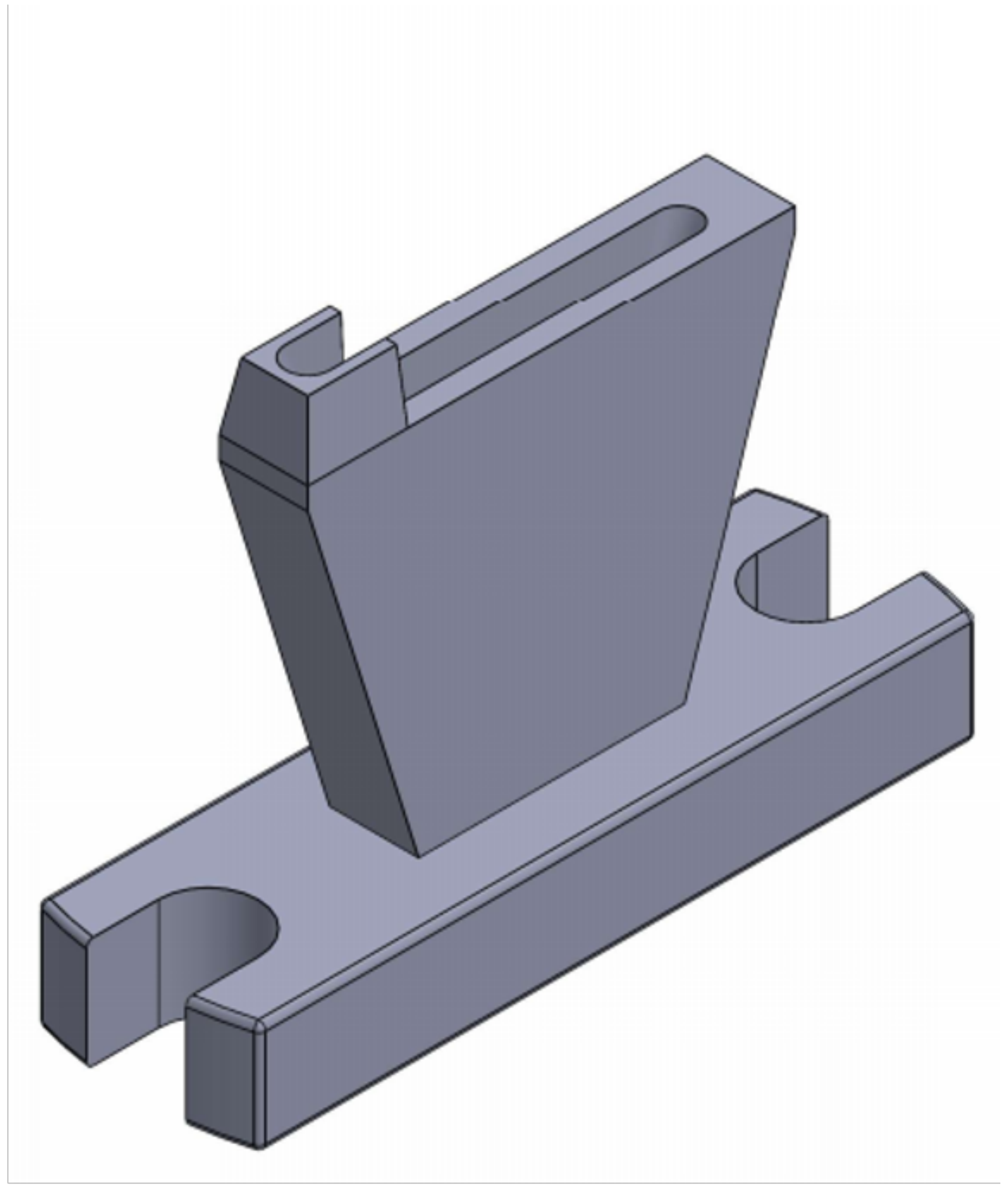


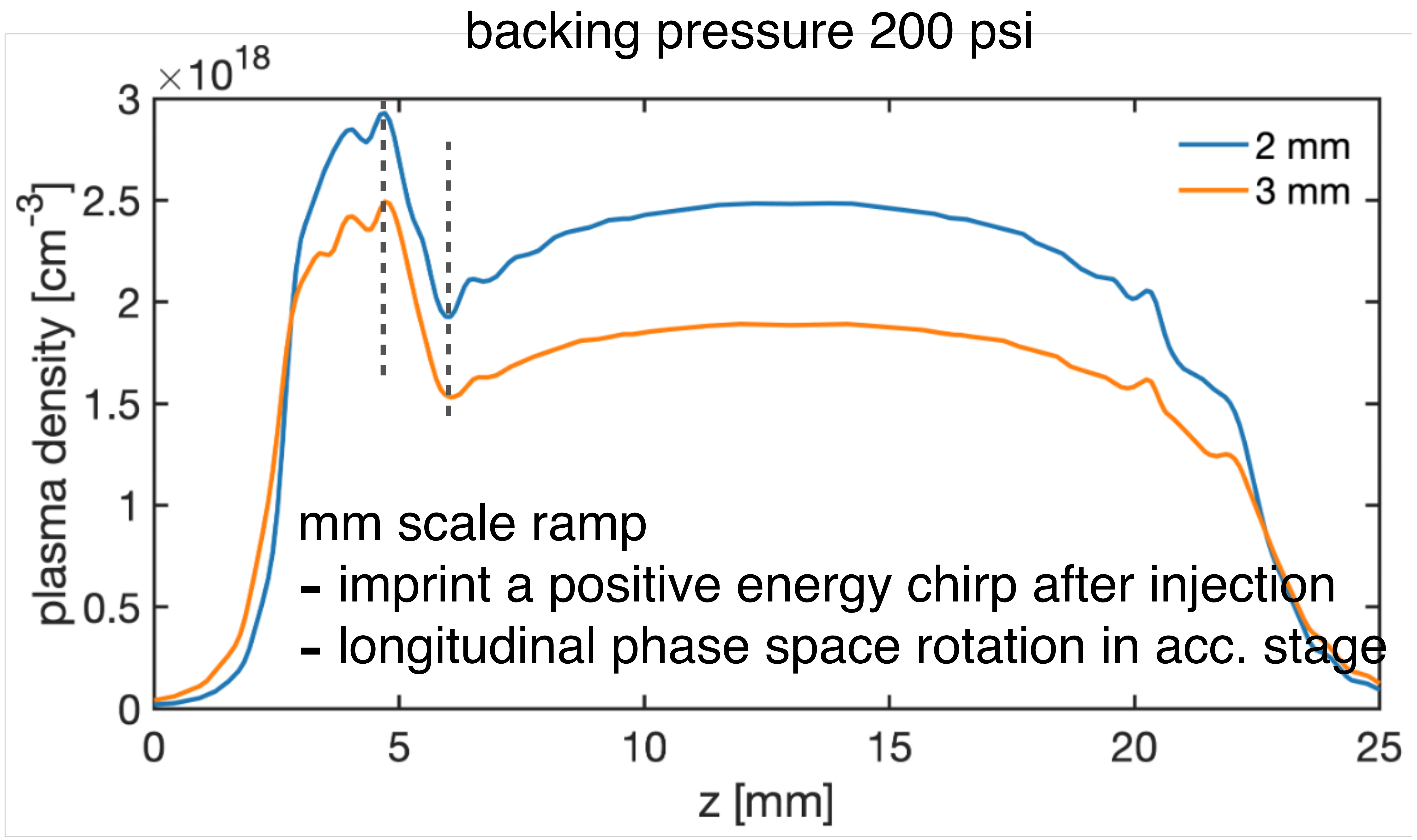




Plasma source option #2

UCLA



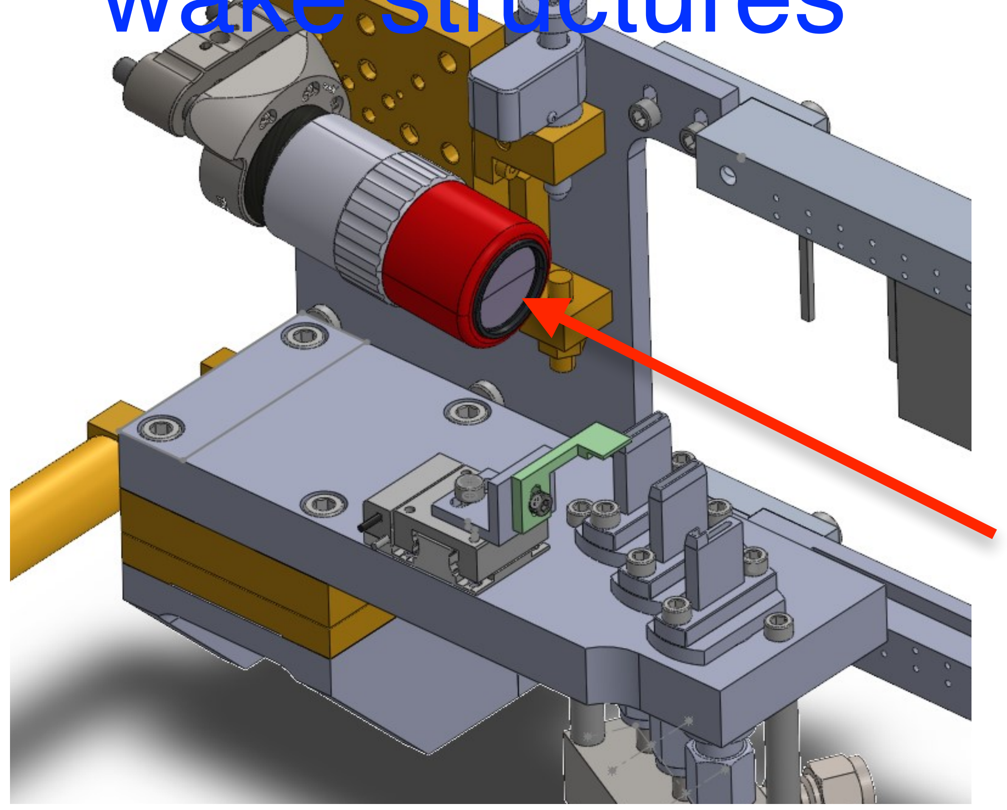


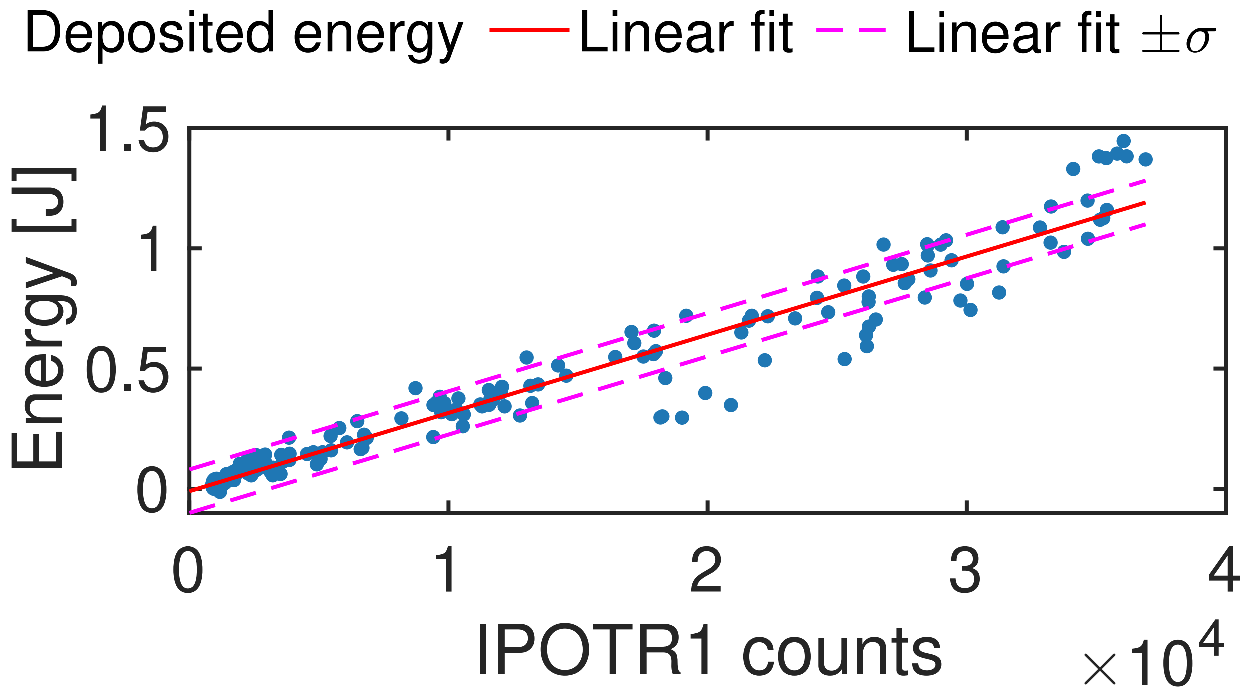
Diagnostics and observables

- **Diagnostics for e- bunches**

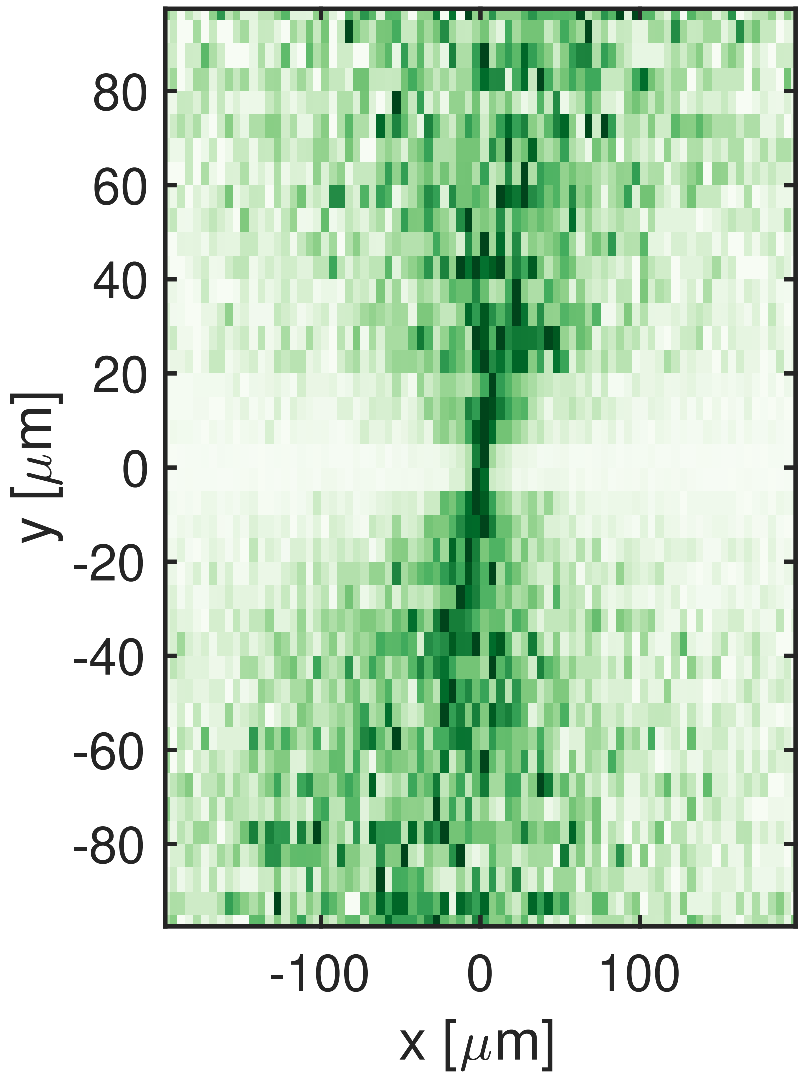
	Driver	*Injected bunch*
Charge	***upstream toroids; energy spec. (LFOV);***	***downstream toroids;***
Bunch length	***XTCAV***	***N/A***
Energy spectrum	***energy spec. (LFOV);***	***energy spec. (LFOV or EDC);***
Emittance	***butterfly technique (DTOTR)***	***butterfly technique; undulator radiation;***

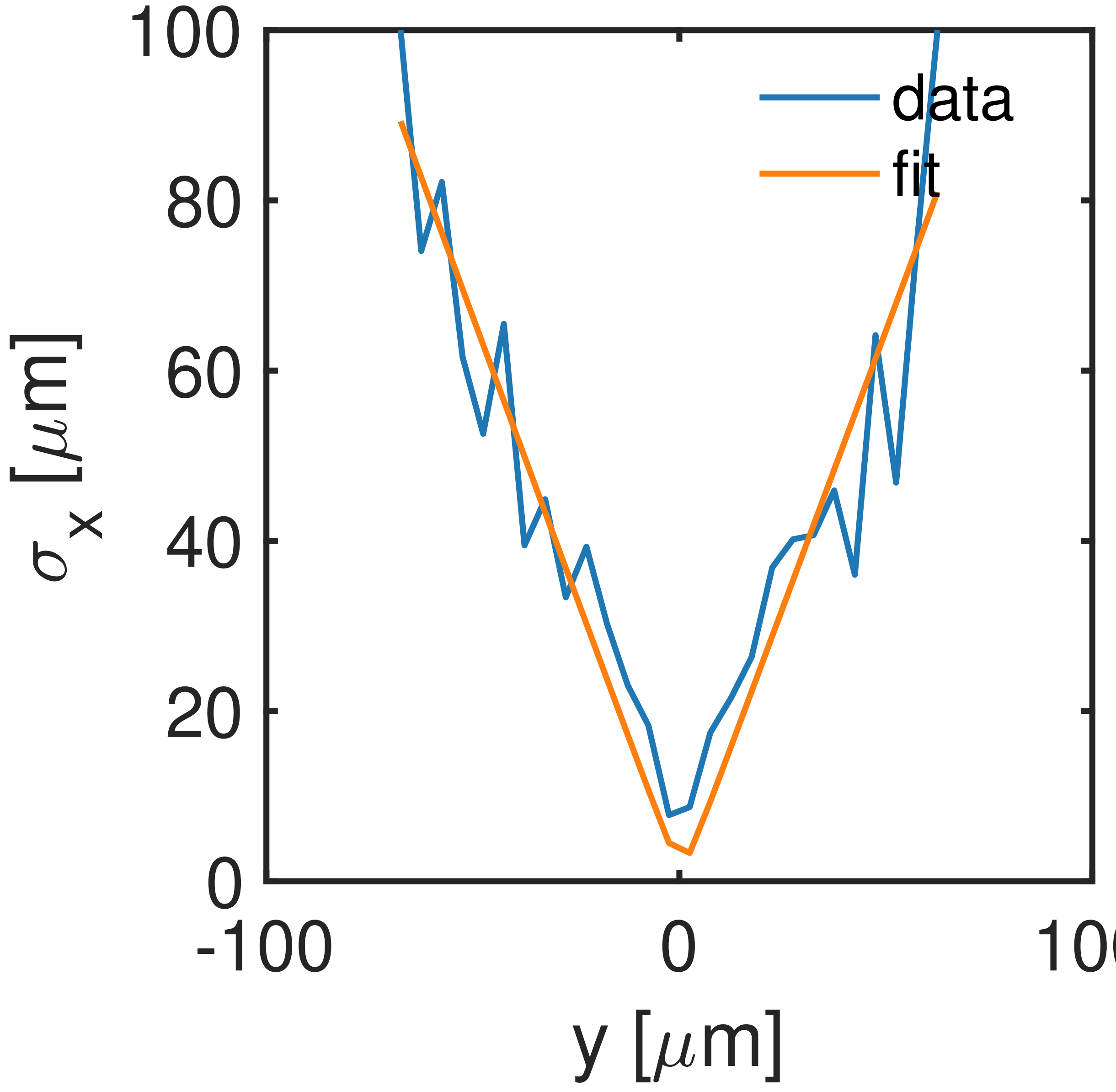
- **Diagnostics for wakes**
  - Shadowgraphy for wake structures
  - Topview for plasma emission (beam-to-wake efficiency)

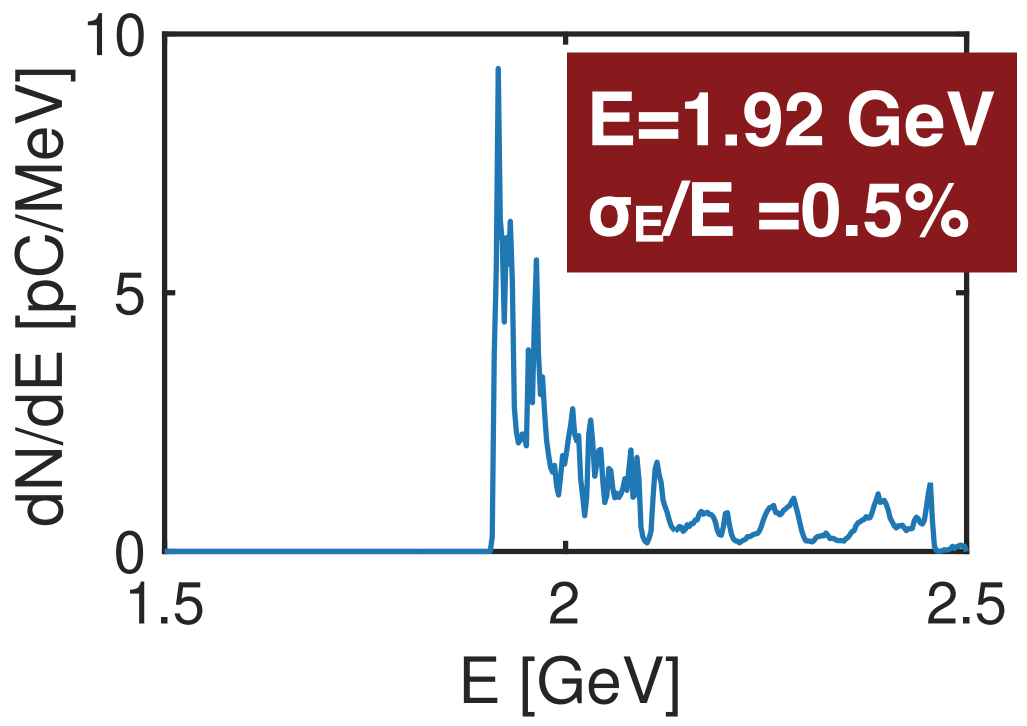




The injected bunch is tracked from the IP to the dump table (DTOTR1 detector, σ_{reso}~4.5 μm)





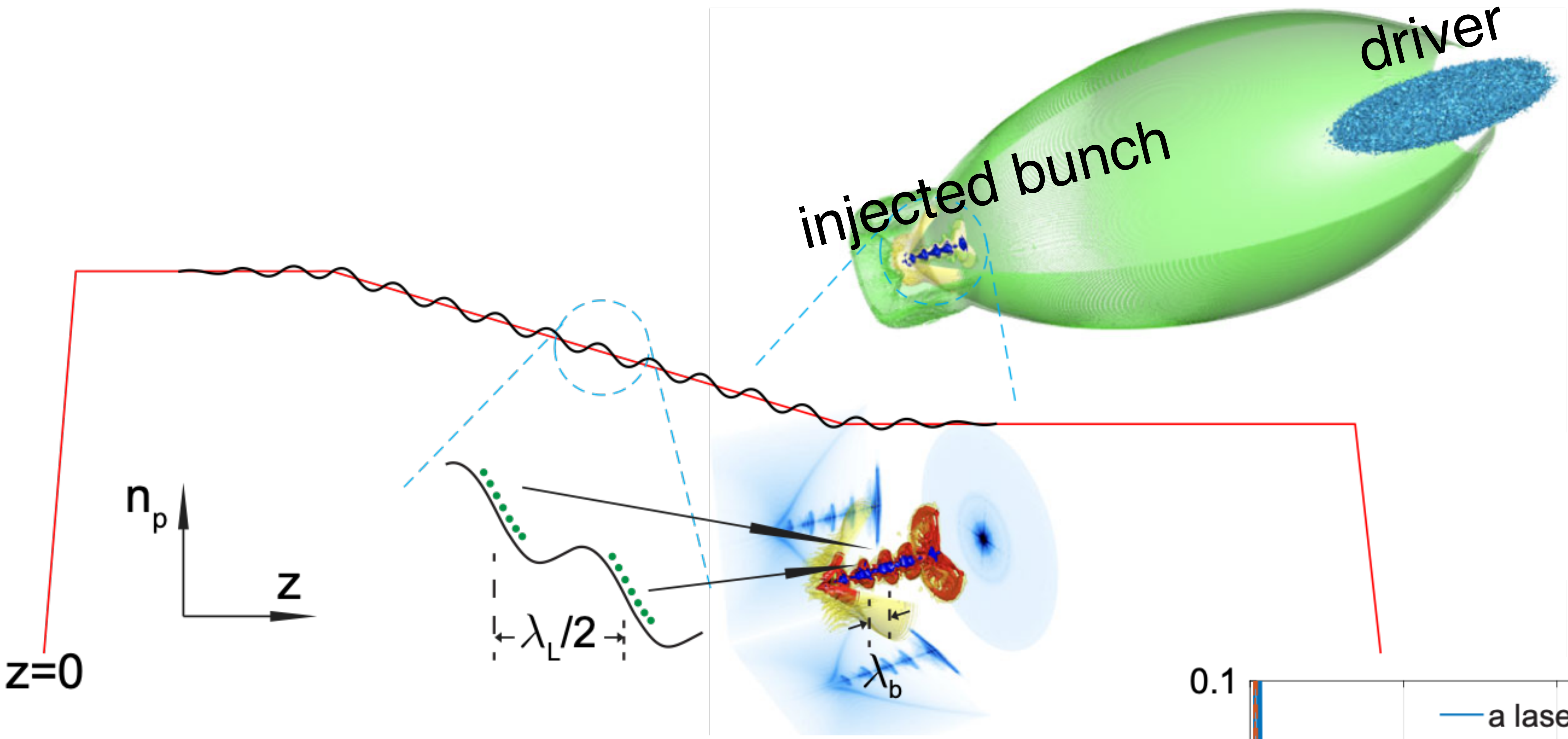


Fit: $\varepsilon_n \approx 1.5$ μm; Simulation: ~1.7 μm (projected) ~0.5 μm (slice)

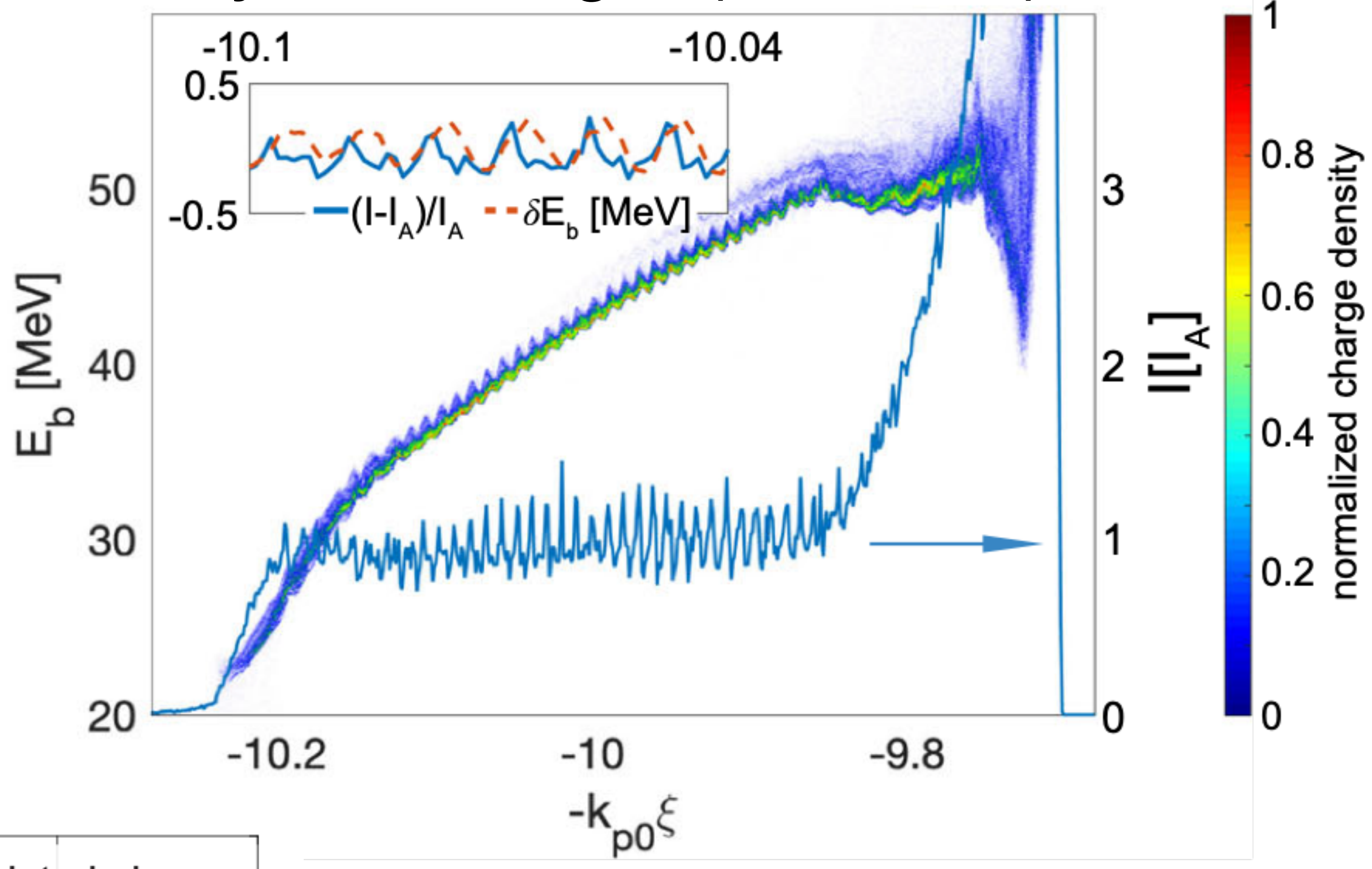
Potential future evolution of the experiment

UCLA

Generate pre-bunched e- beams using modulated downramp

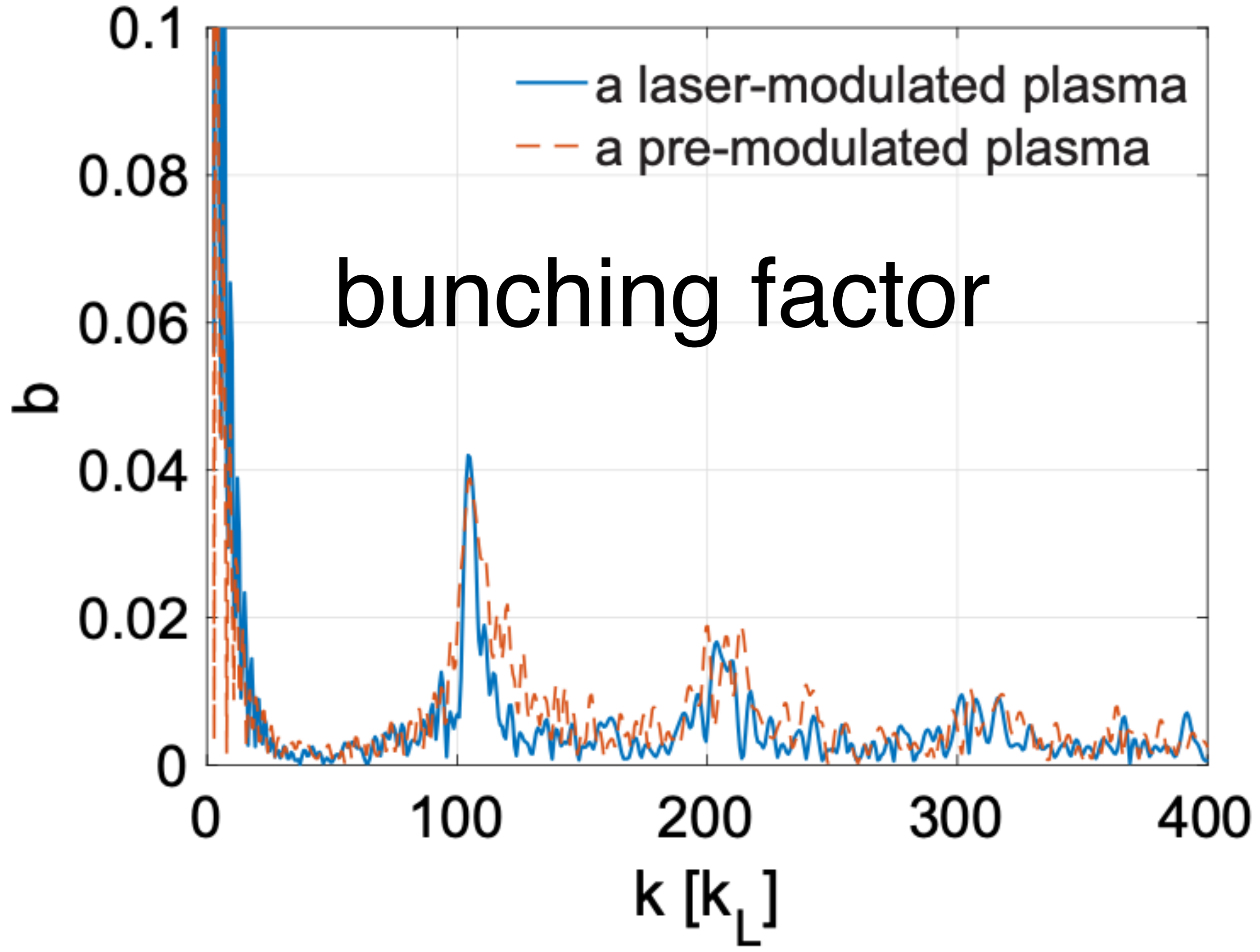


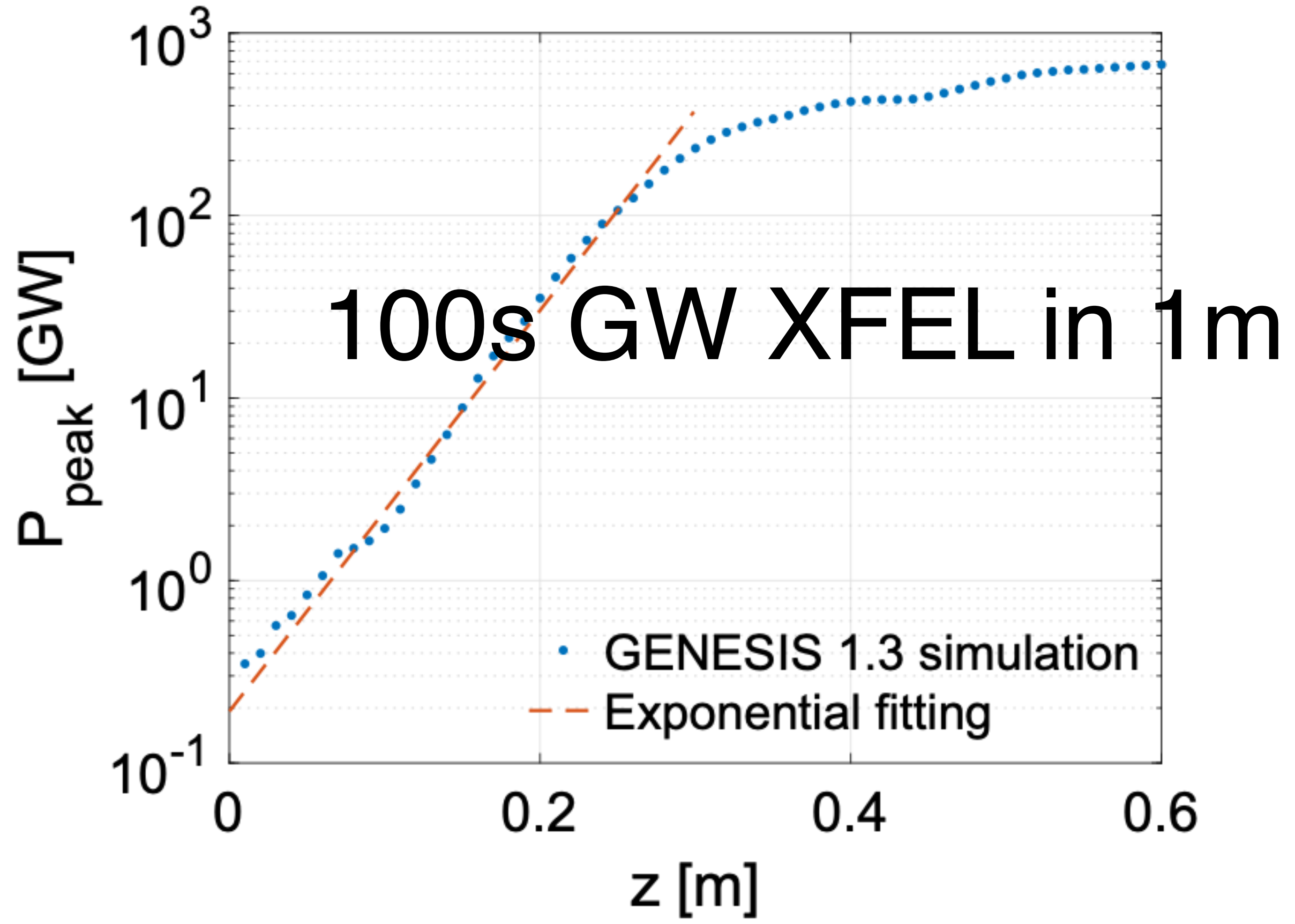
injected beam bunches at X-ray wavelength (~10s nm)



Key questions:

- produce modulated downramp
- measure bunched electrons





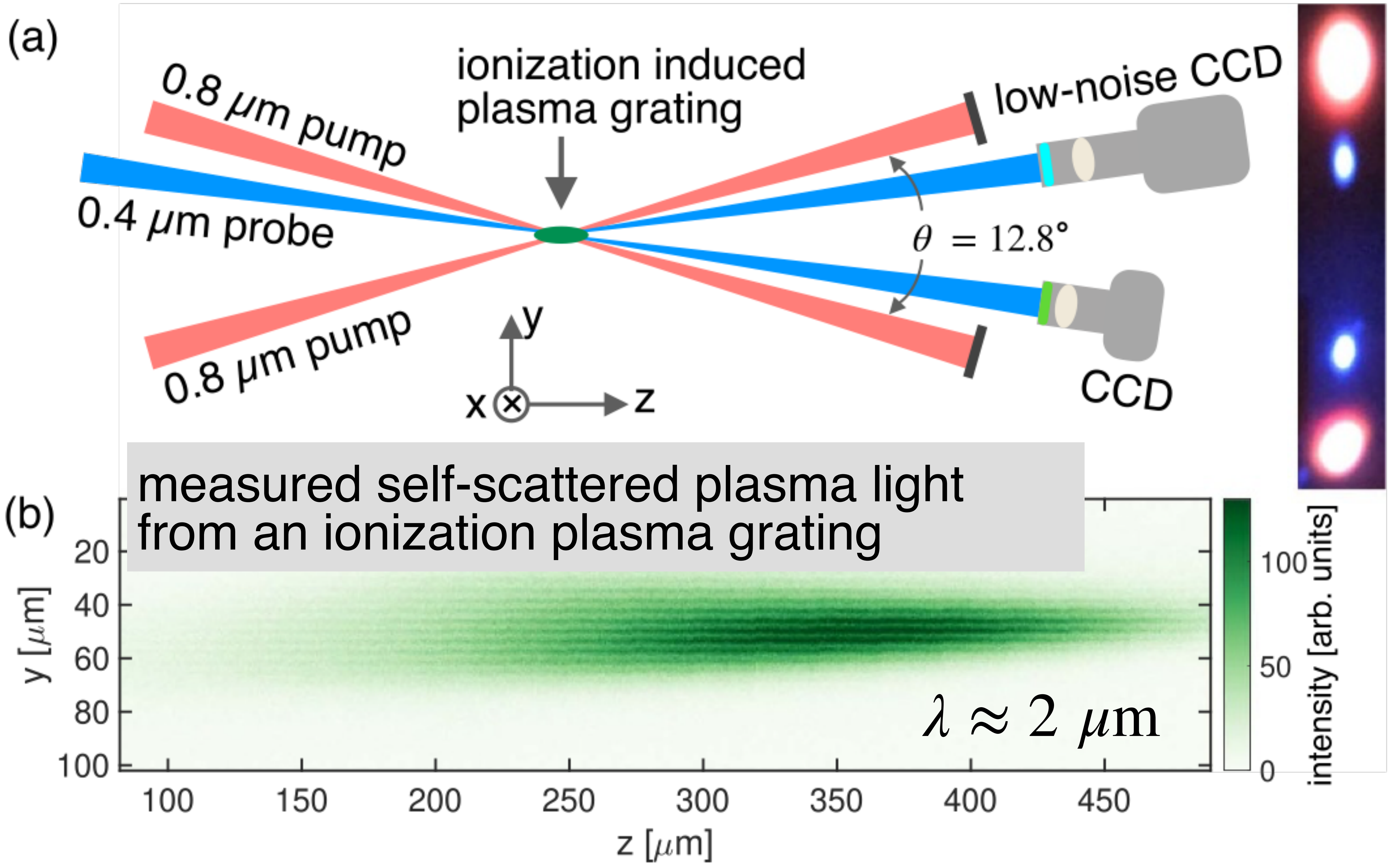
Xinlu Xu et al., Nat. Comm. (2022)

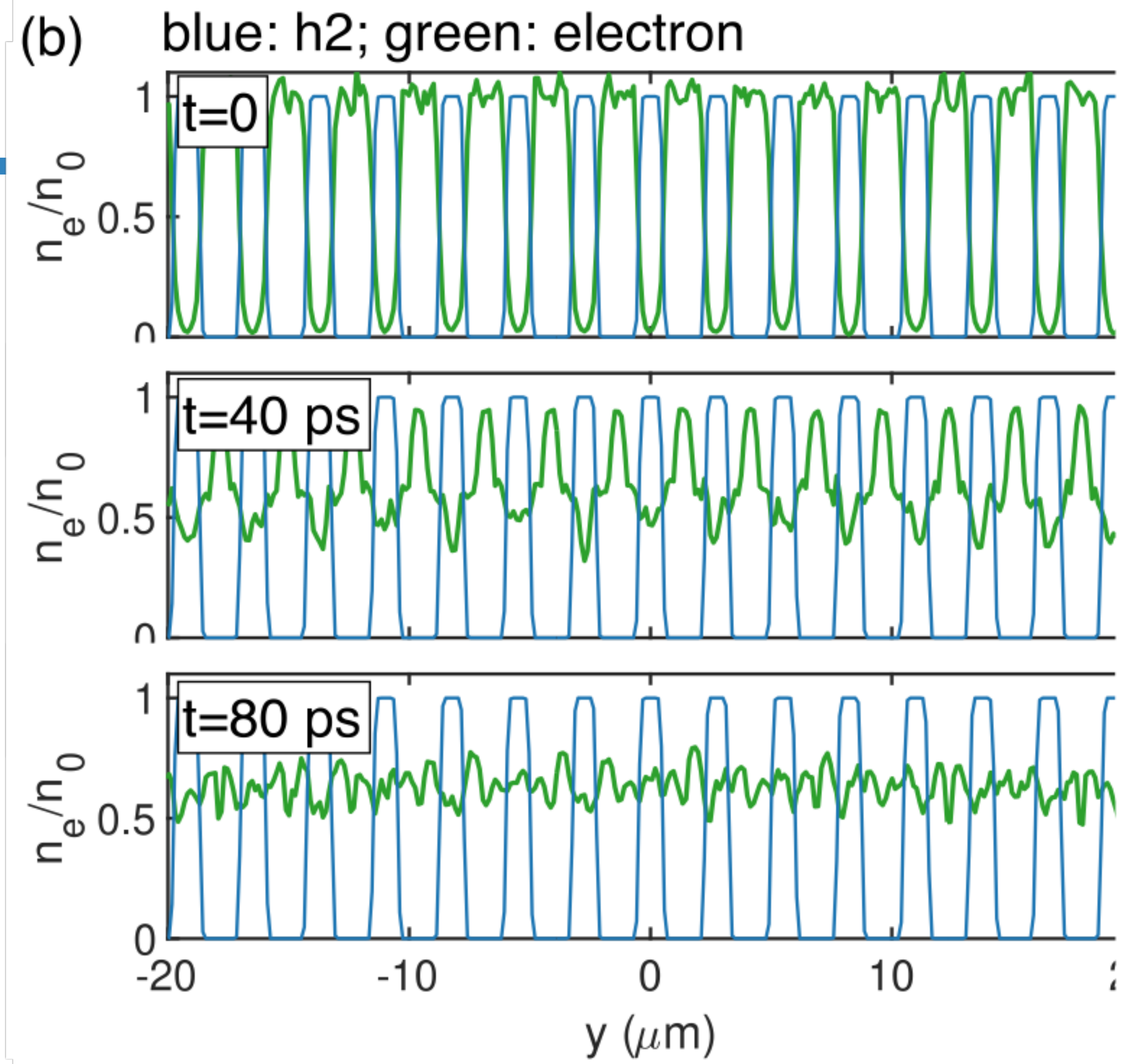
Potential future evolution of the experiment

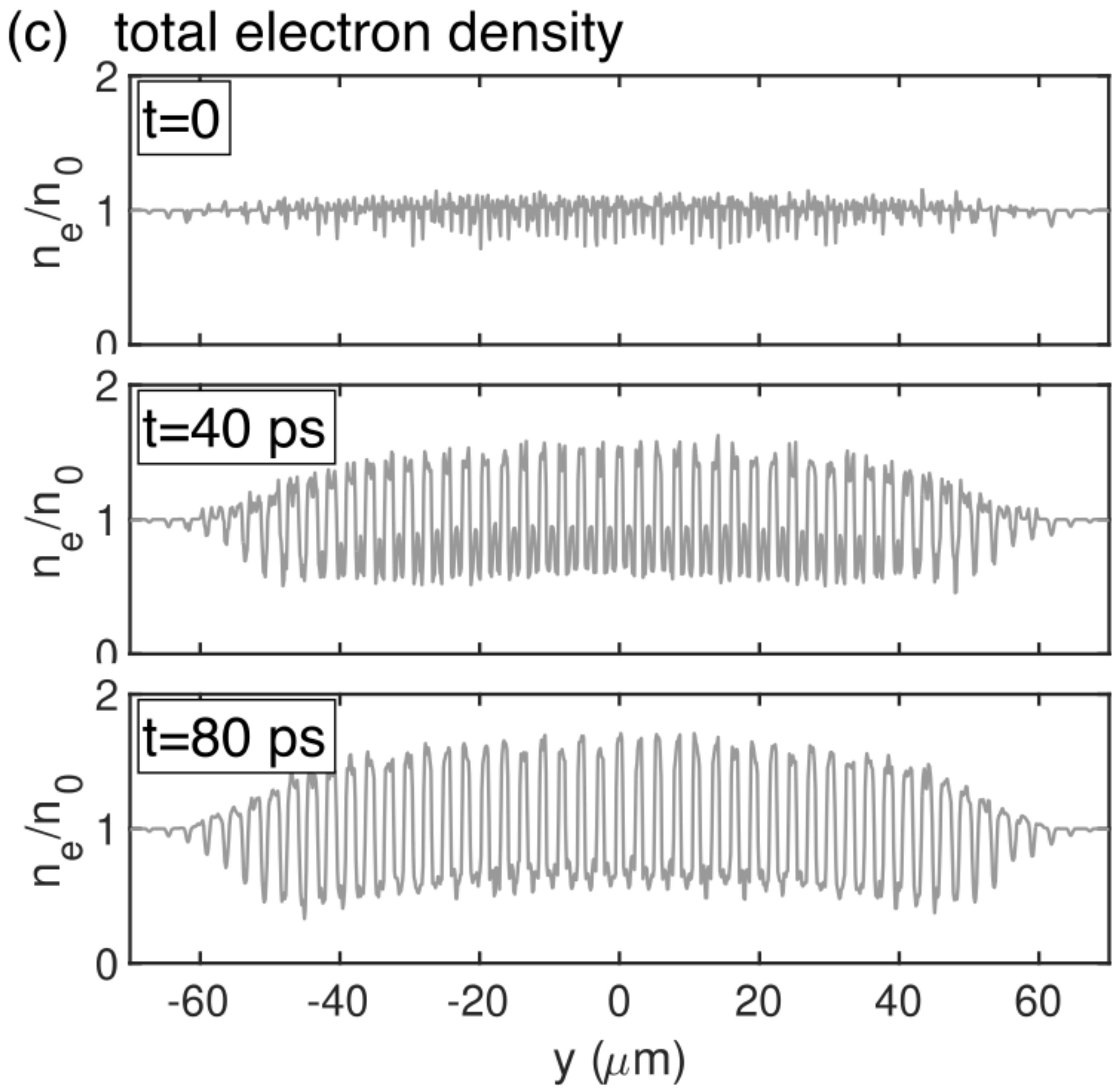
UCLA

Key elements:

- modulate downramp (e.g., ionization plasma grating)
- measure bunched electrons (e.g., using CTR)





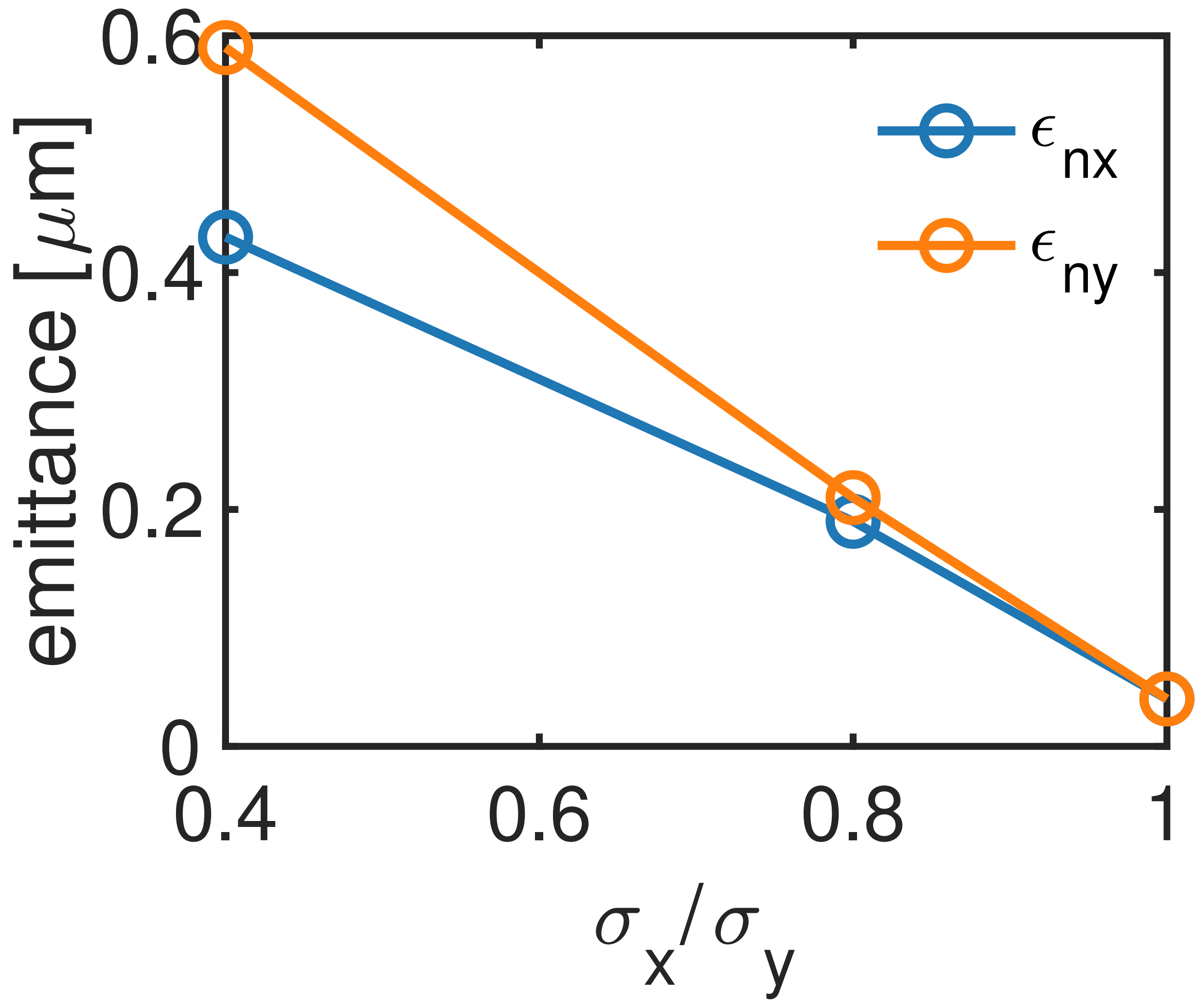


Chaojie Zhang et al., PPCF (2021)

Desired facility upgrades

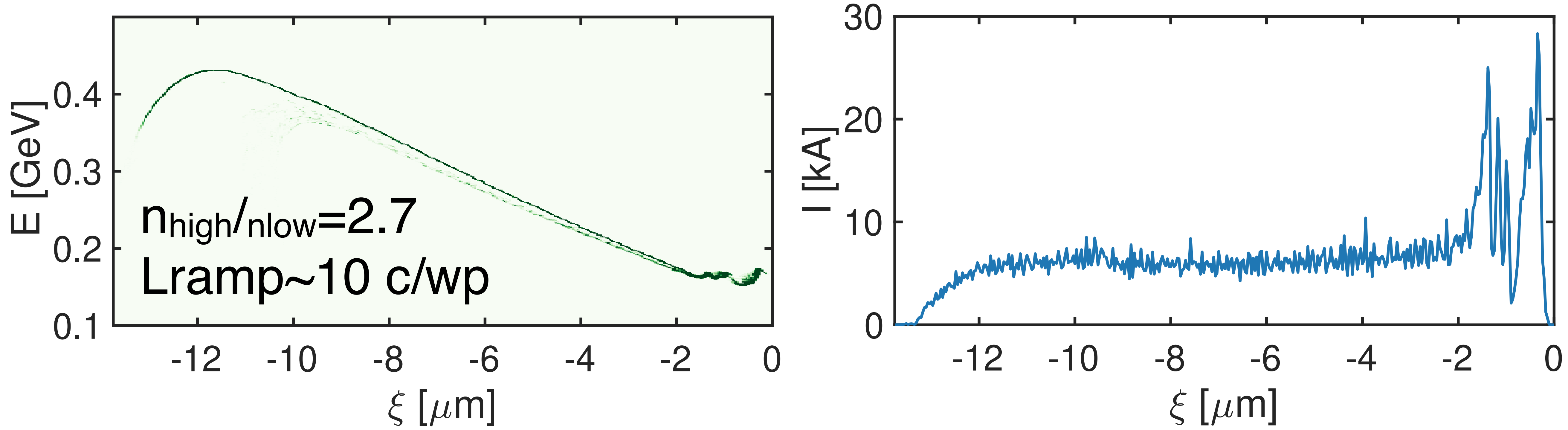
The items listed here do not affect the proposed E304 experimental plan;
But they will provide more controllability and diagnostics for future upgraded experiments;

- Ability to deliver and characterize round beams at IP (critical for generating beams with tens of nm emittance) (year 1 and 2)
- A short undulator after the picnic basket as a emittance diagnostic (year 2 and beyond)
- Downstream deflecting cavity for characterizing the longitudinal phase space of the injected bunch (year 3 and beyond, or use other novel methods)



Asymmetric driver leads to emittance increase

A sharp downramp is capable of generating bunches with large linear chirps.



Collaborations

UCLA — C. Joshi, K. Marsh, W. B. Mori, Y. Wu, Z. Nie, H. Fujii

SLAC — X. Xu, M. Hogan, V. Yakimenko, FACET-II staff

loa — Sebastien Corde's group

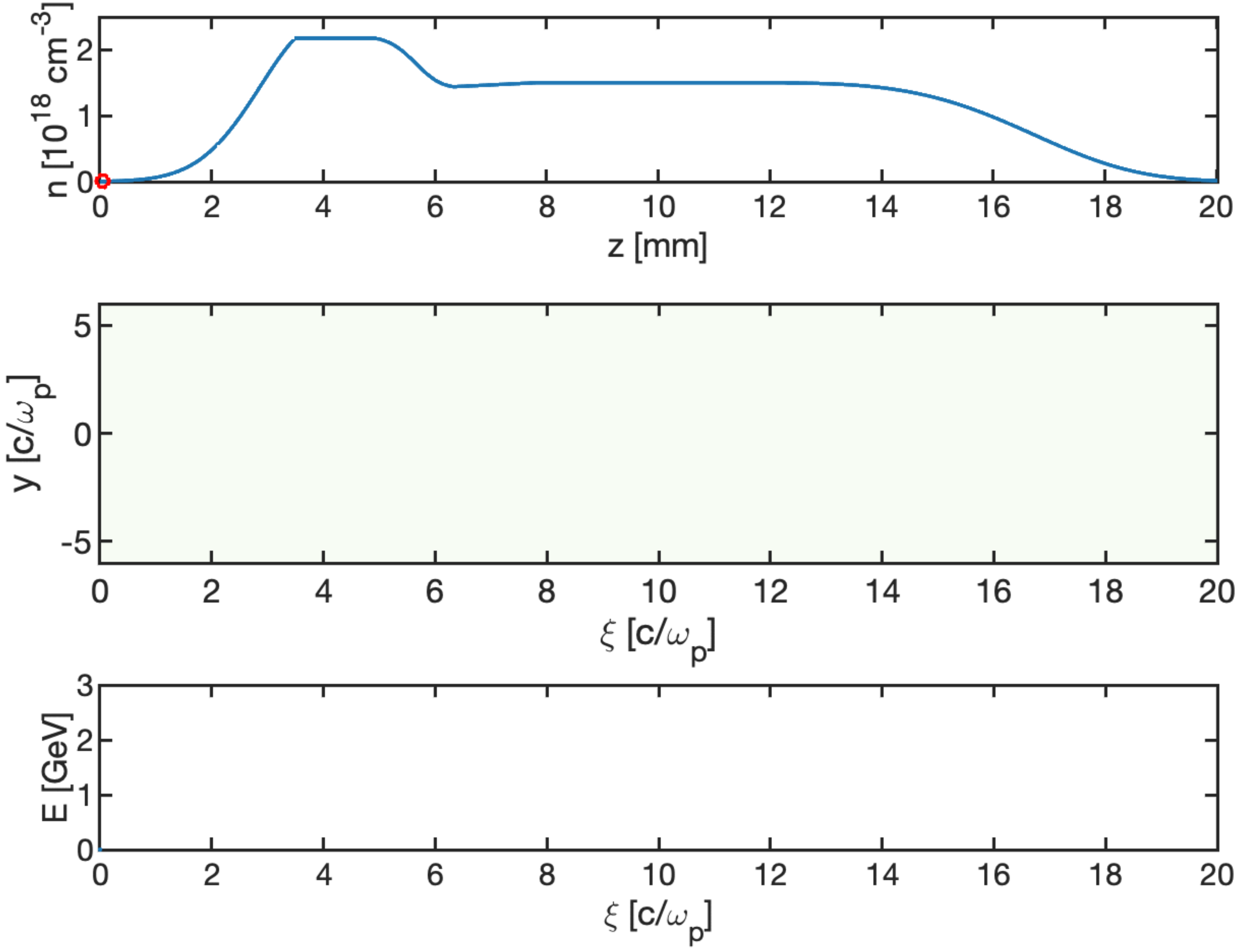
Mike Litos' group

Backup Slides.

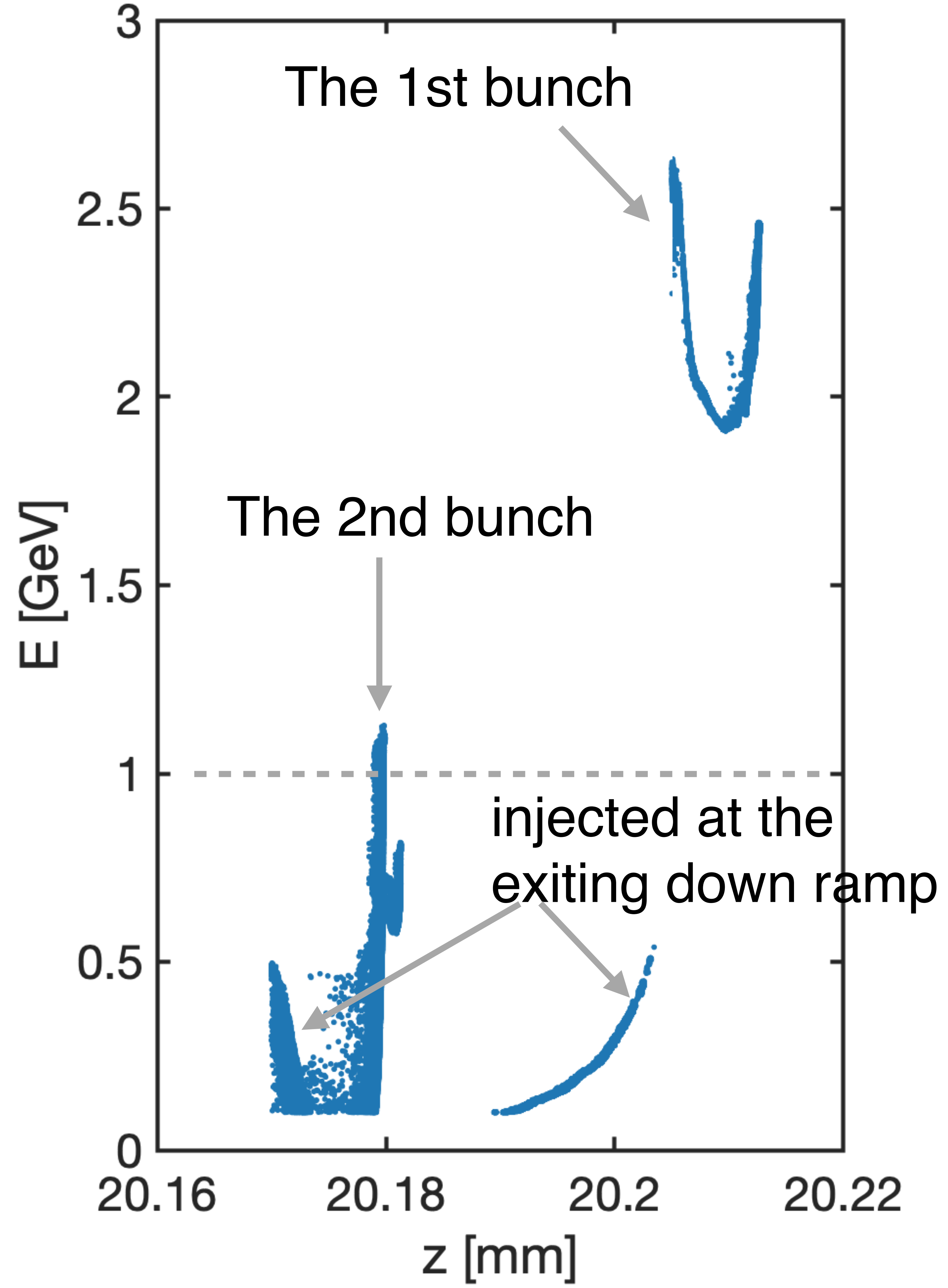
q3D simulation using the max-compressed driver

UCLA

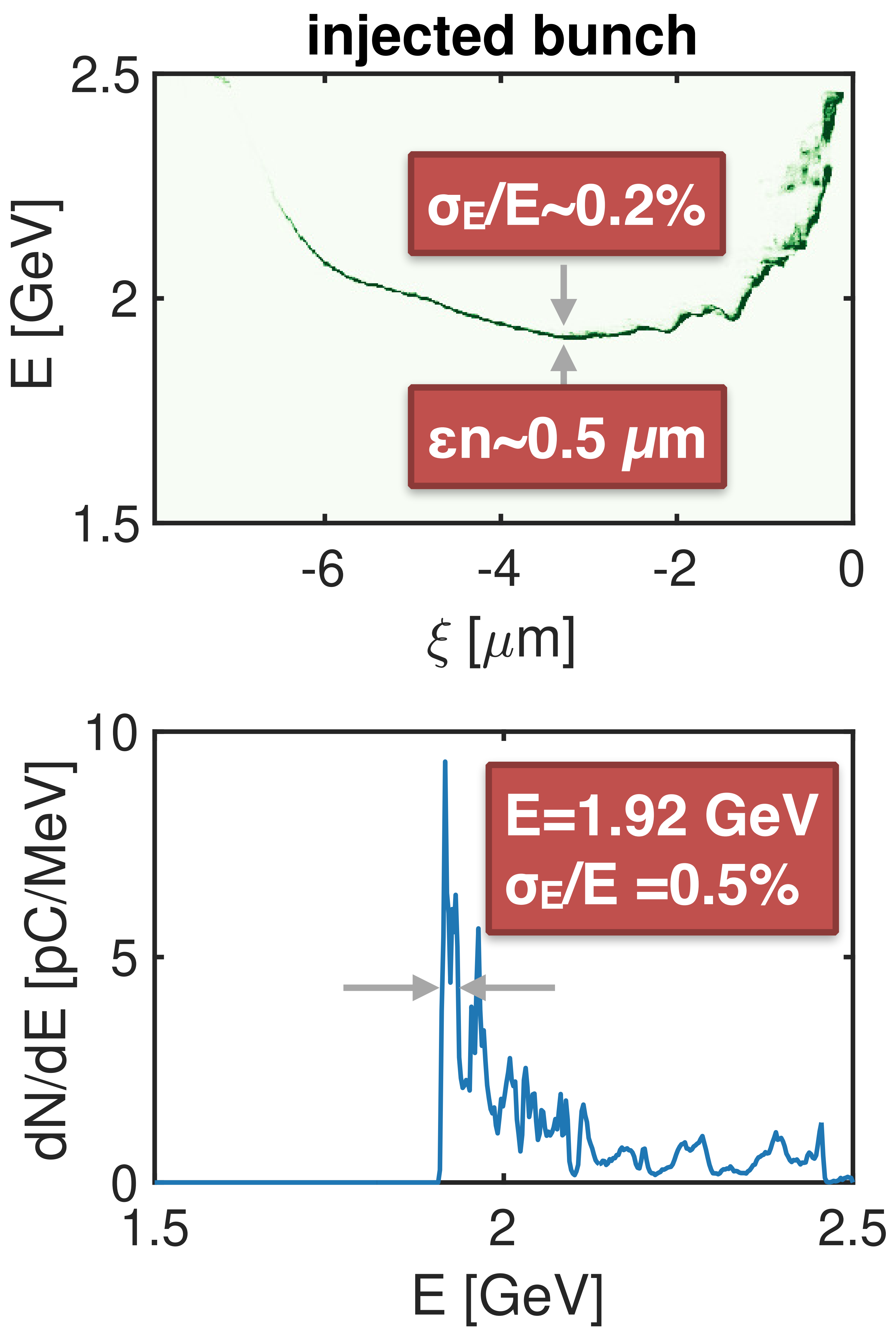
driver: σr=σz=3 μm, εn=3 μm, **Λ=6, Q~1.3 nC** (Q=0.4 nC for sharp downramp)



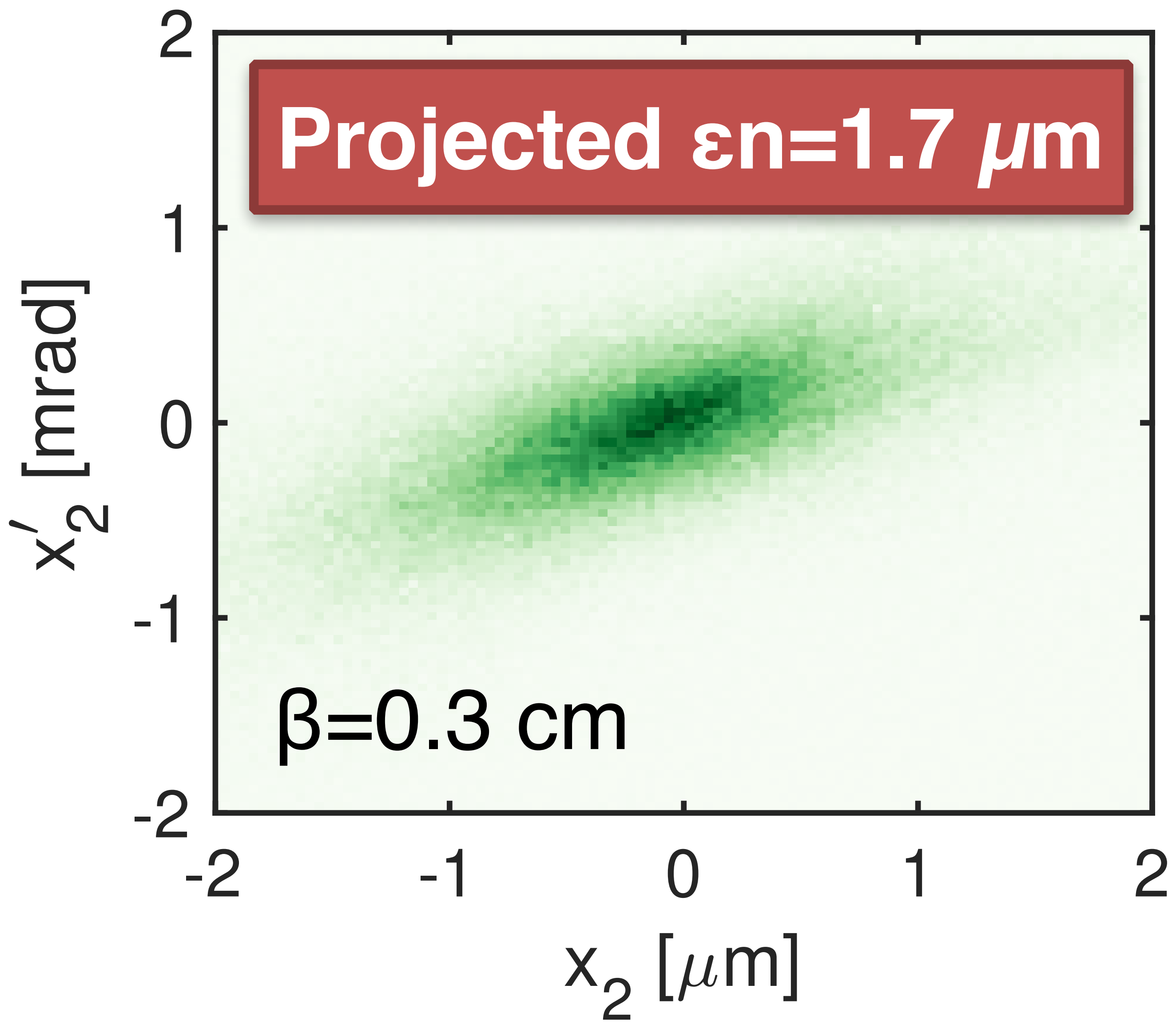
The LPS at the plasma exit:



Injected bunch is accelerated to ~2 GeV in ~1 cm



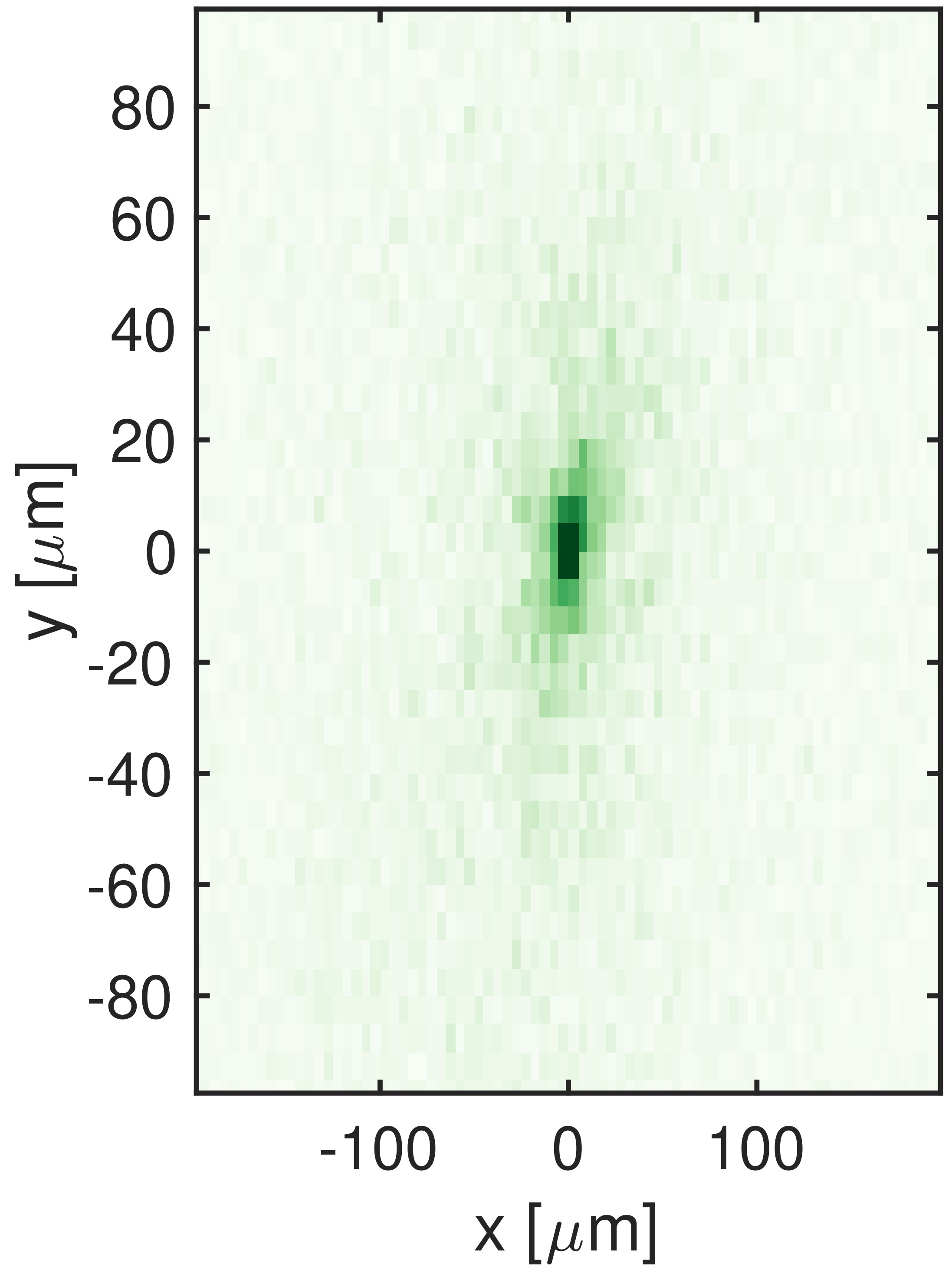
- **Significant energy loss of the driver**
- The energy spectrum of the injected bunch peaks at **1.92 GeV with 0.5%** spread
- **Injected charge: 697 pC**
- **Efficiency: 43%**

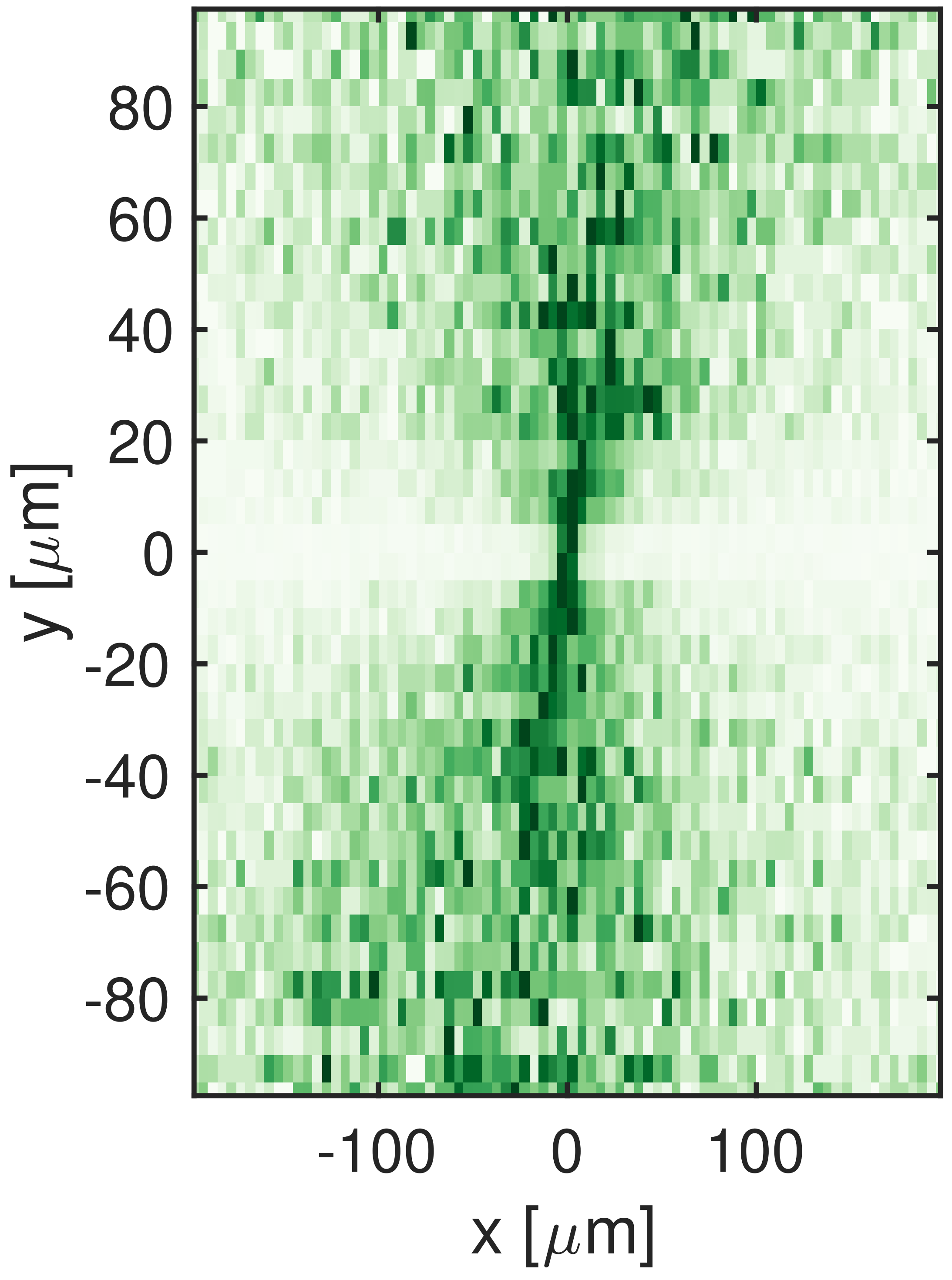


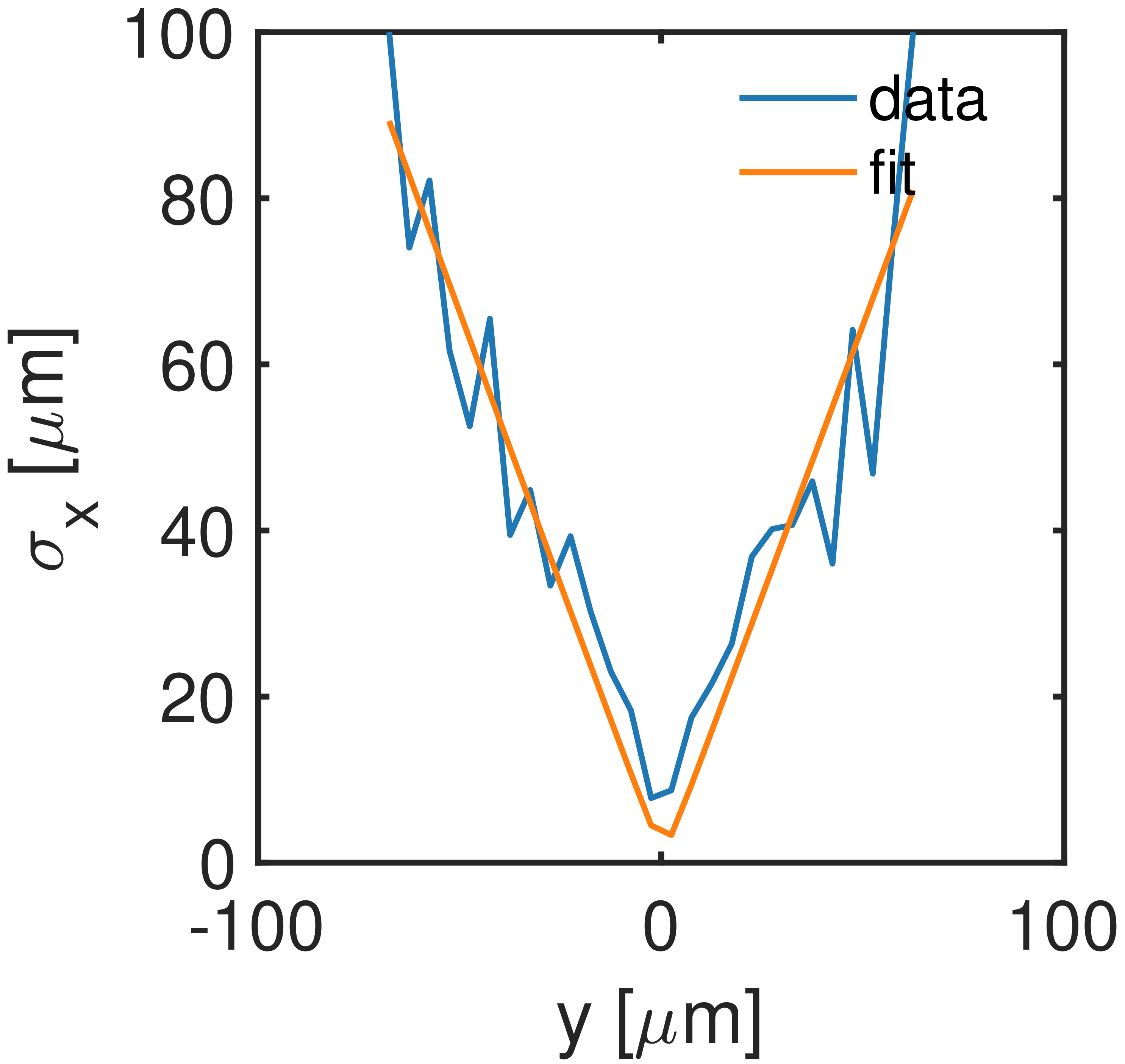
Emittance diagnostic

The injected bunch in the pre-ionized case is tracked from the IP to the dump table (DTOTR1 detector, σ_{reso}~4.5 μm)

Re-imaged beam on DTOTR1 Normalized







Fit: $\varepsilon_n \approx 1.5$ μm

Simulation:
$\varepsilon_n \approx 0.5$ μm (slice)
$\varepsilon_n \approx 1.7$ μm (projected)

- The butterfly technique gives reasonable estimate of the emittance
- The image is noisy due to the limited number of tracked particles (~0.1 M), a realistic bunch with ~700 pC charge will have 4.4 B electrons.

Laser- vs. beam-ionization

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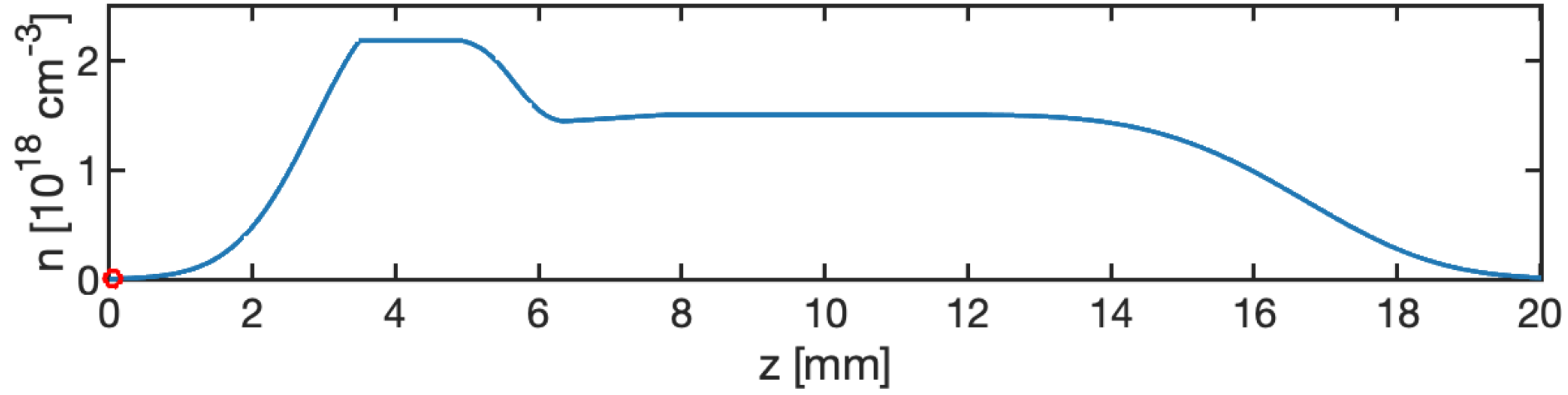
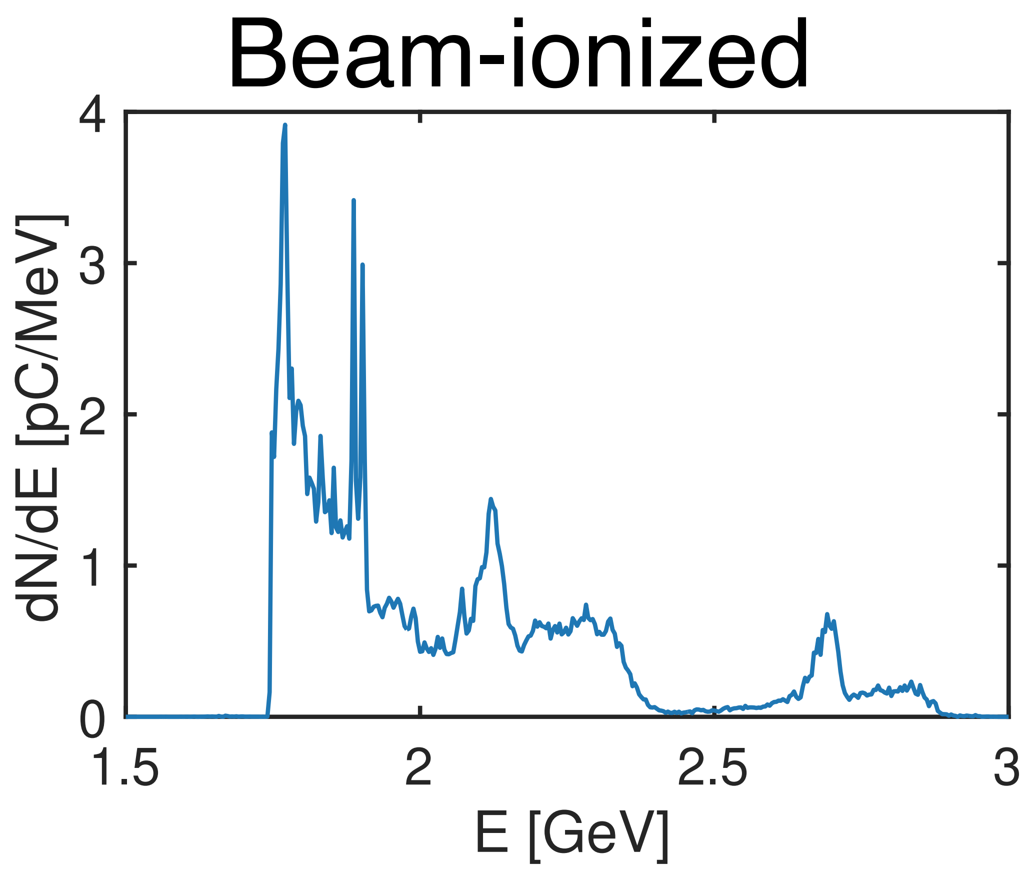
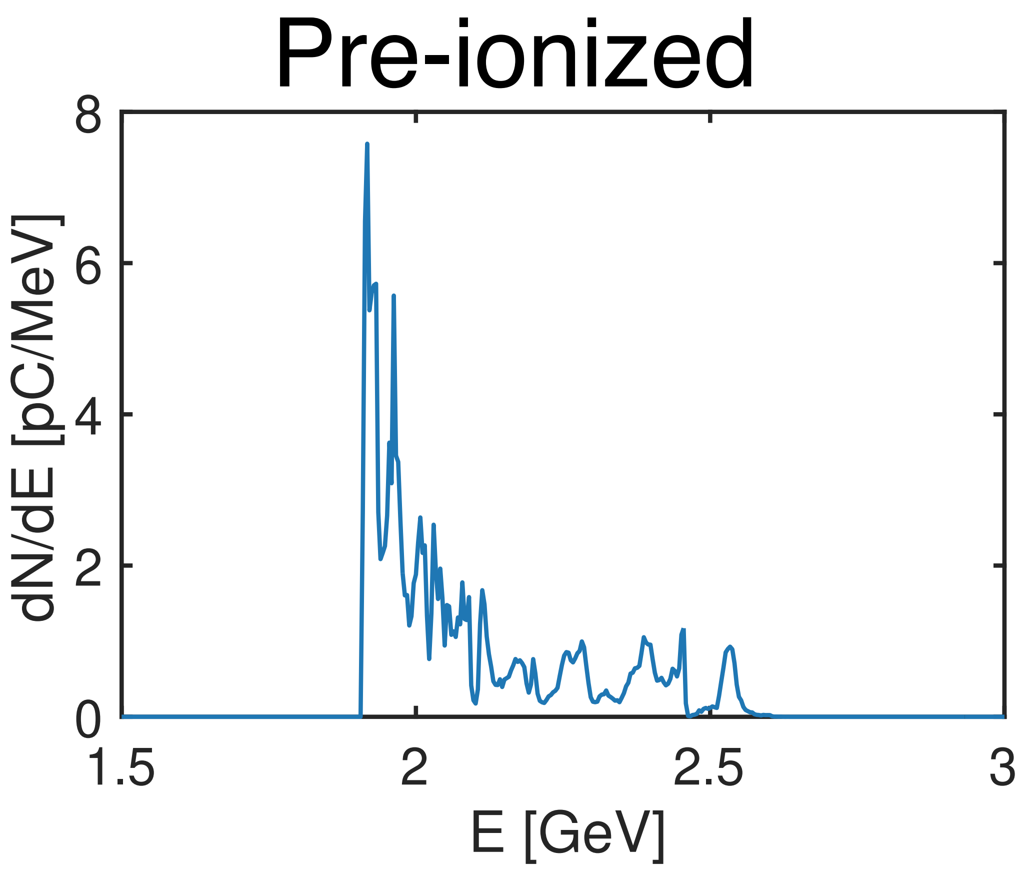
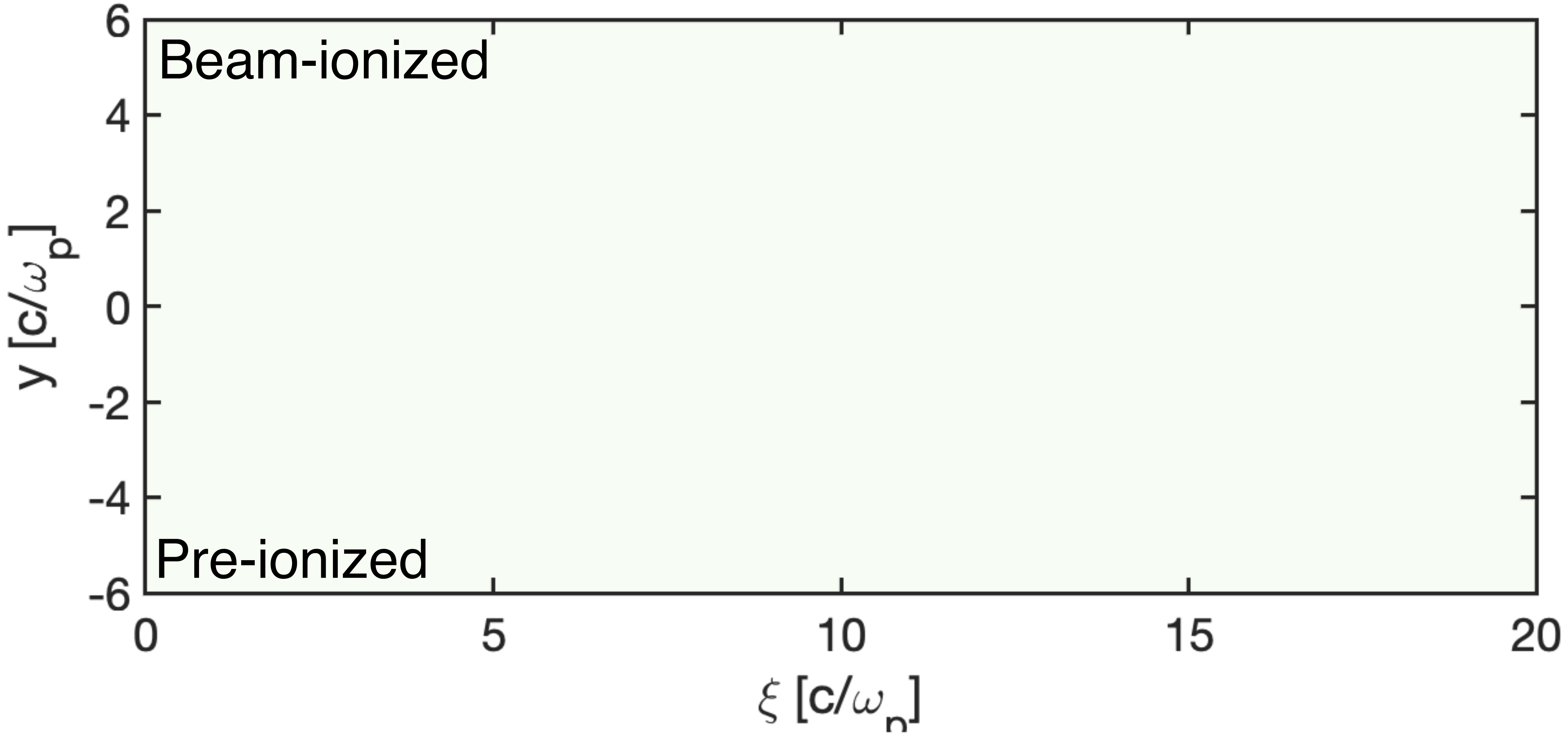








	Beam-ionized	Pre-ionized
E [GeV]	1.77	1.92
σ_E/E [%]	0.7	0.5
Slice ε_n [μm]	2.5	0.5
Q [pC]	670	697

- One important physics that need to be studied is the transverse slowing down of the sheath electrons.
- This can be addressed by comparing the results of pre-ionized vs. beam self-ionized plasma.

Simulation with current available parameters

$\sigma_r = 15\ \mu\text{m}$

$\sigma_z = 10\ \mu\text{m}$

$\varepsilon_n = 20\ \mu\text{m}$

$Q = 2\ \text{nC}$

$n_b \approx 3.5 \times 10^{17}\ \text{cm}^{-3}$

$\Lambda \approx 2.8$

Blowout regime requires:

1) $k_p \sigma_z \gtrsim 0.2$

2) $n_b \gtrsim n_p$ or $k_p \sigma_r \lesssim \sqrt{\Lambda}$

Therefore the plasma density should be in the range:

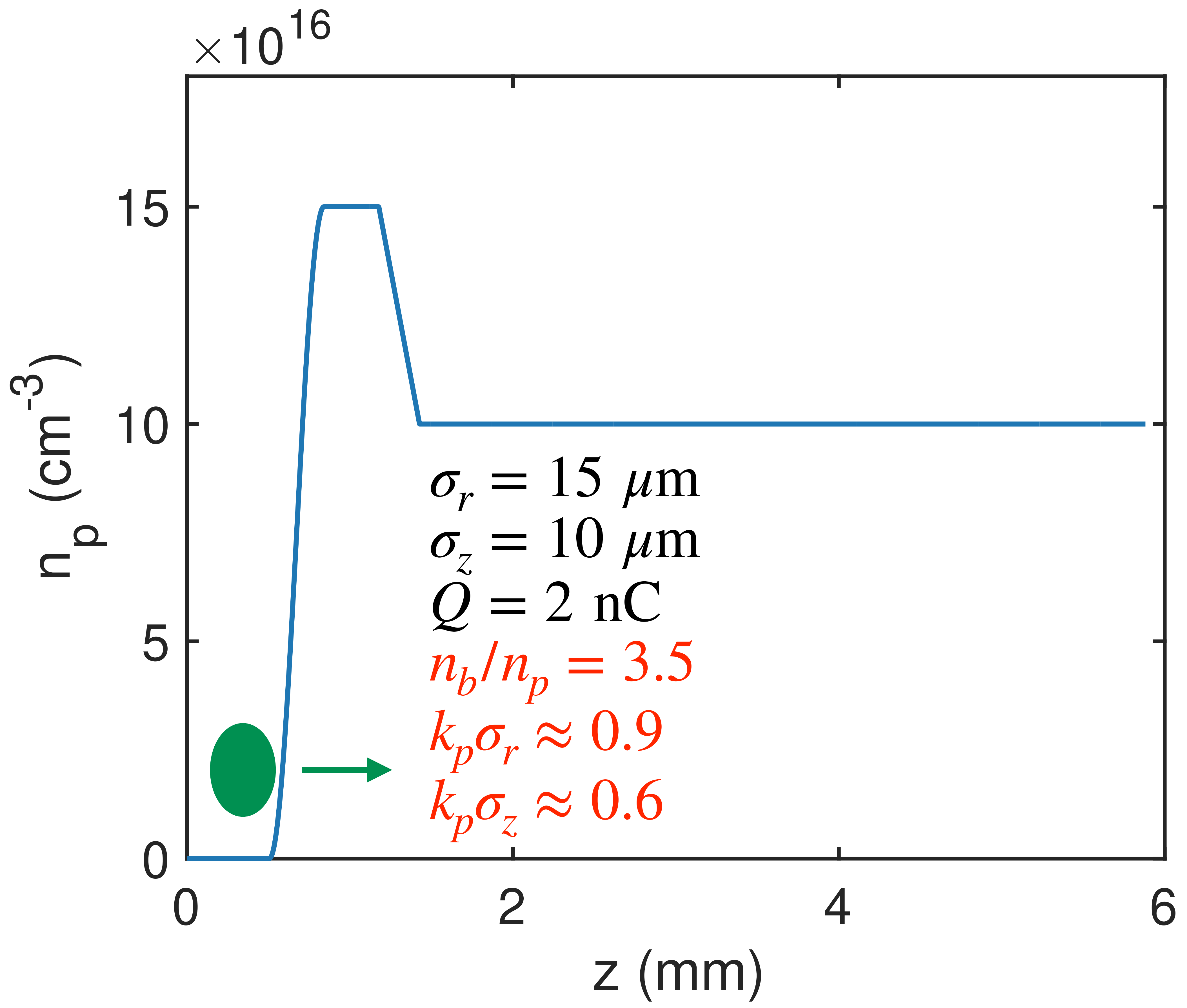
$0.02 < k_p[\mu\text{m}^{-1}] < 0.11$

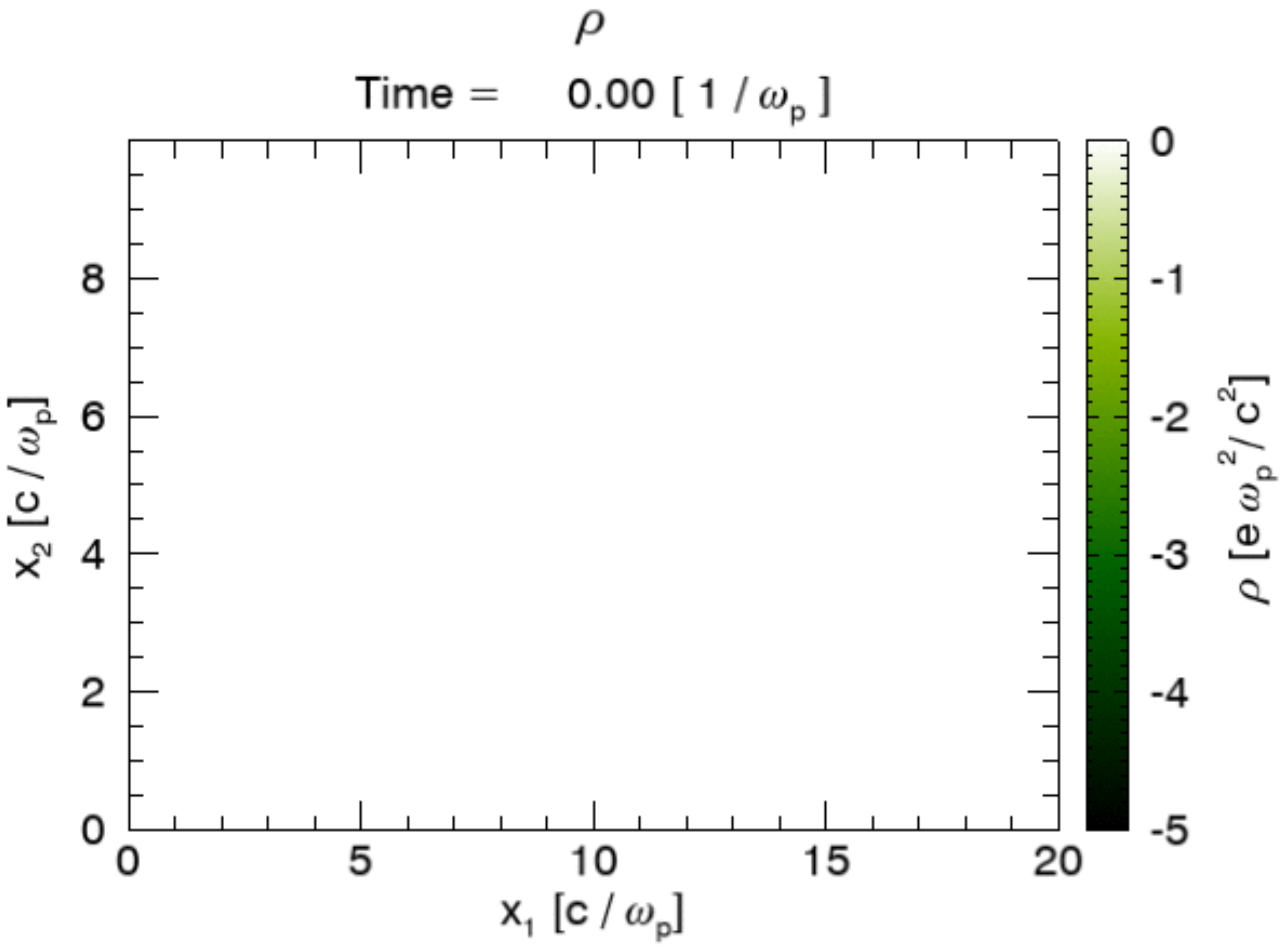
$56 < \lambda_p[\mu\text{m}] < 314$

$1.1 \times 10^{16} < n_p[\text{cm}^{-3}] < 3.5 \times 10^{17}$

Quasi-3D simulation, n_p=10^{17} cm^{-3}

Plasma density profile:





Longitudinal phase space

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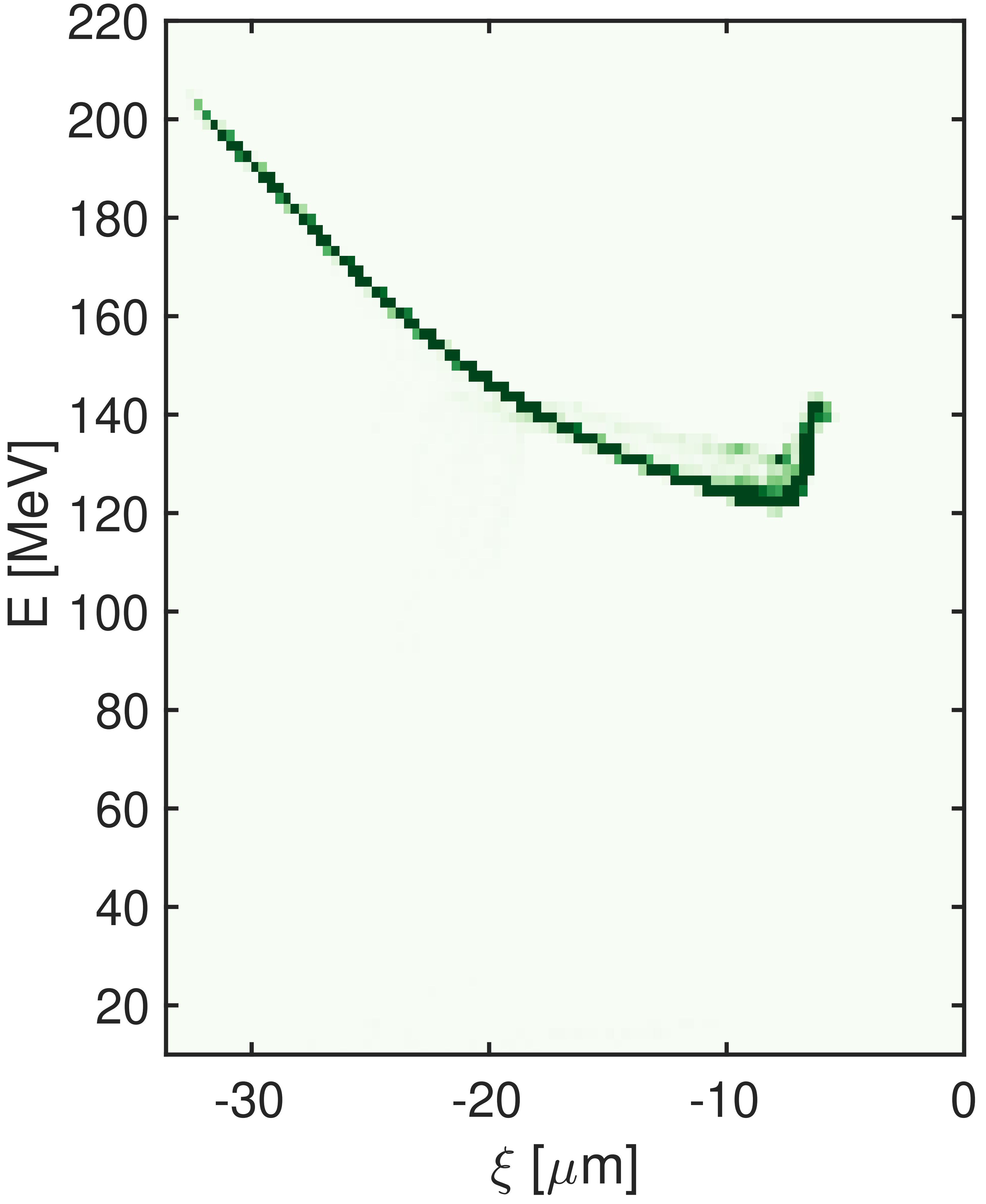
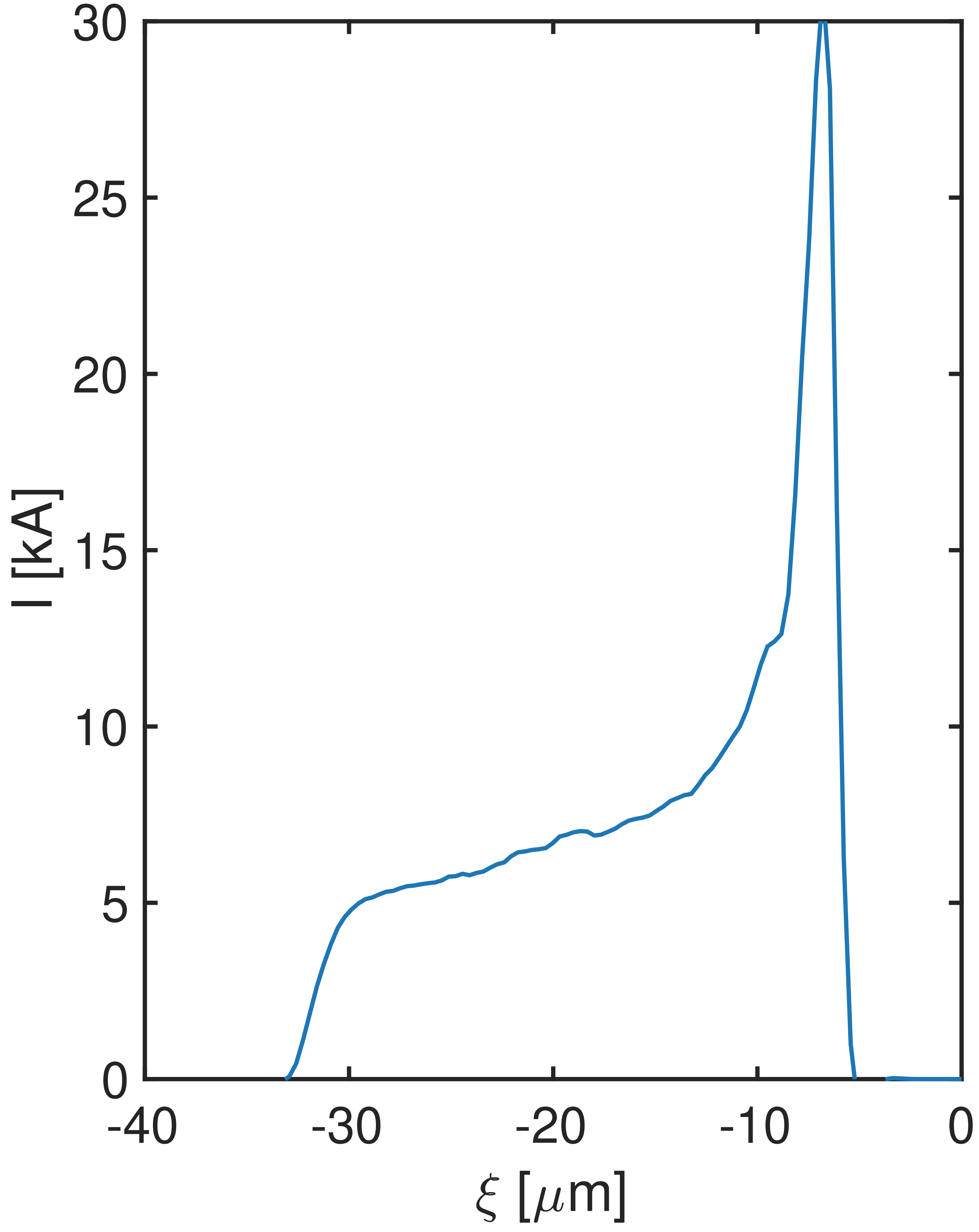
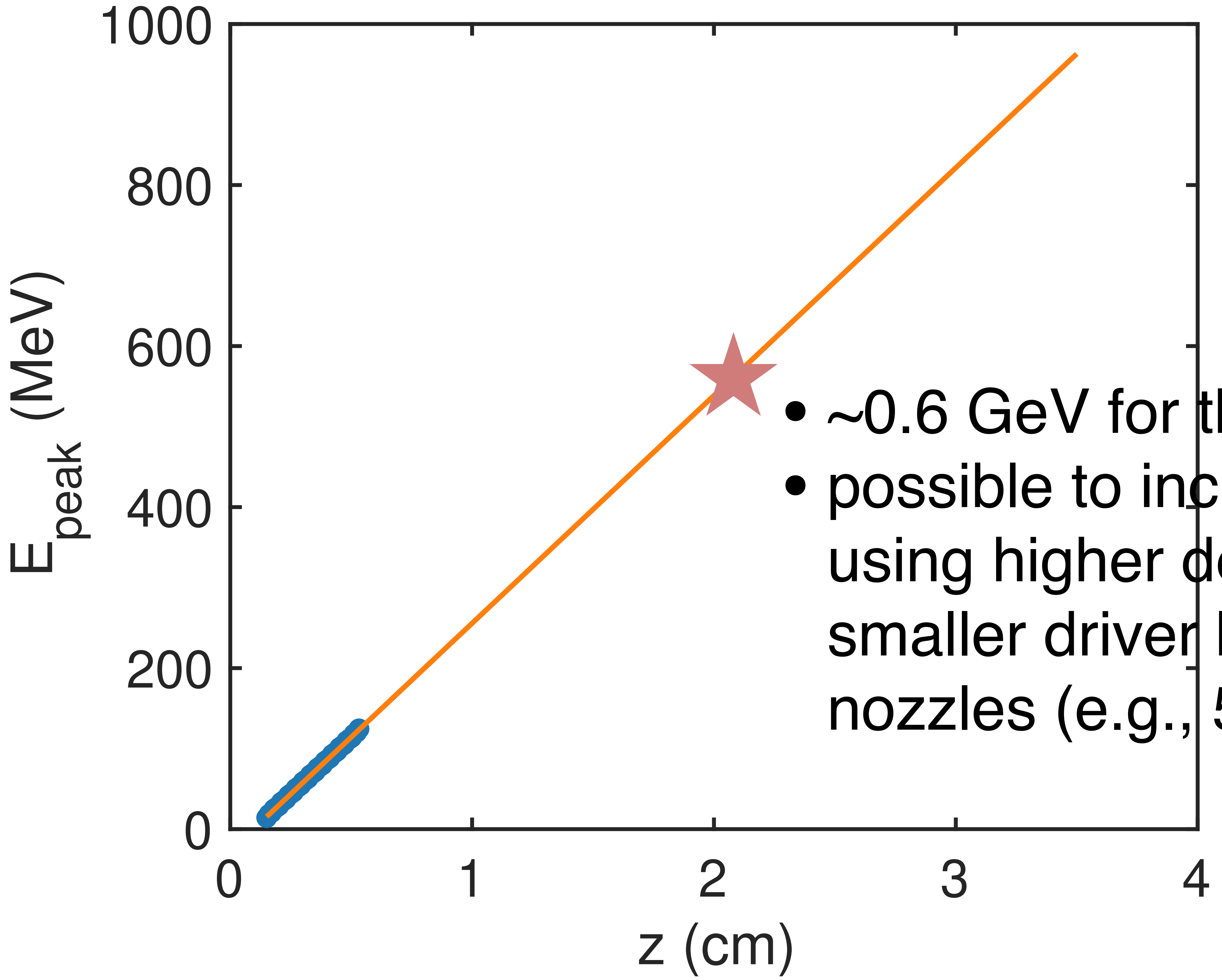
at z=5.3 mm



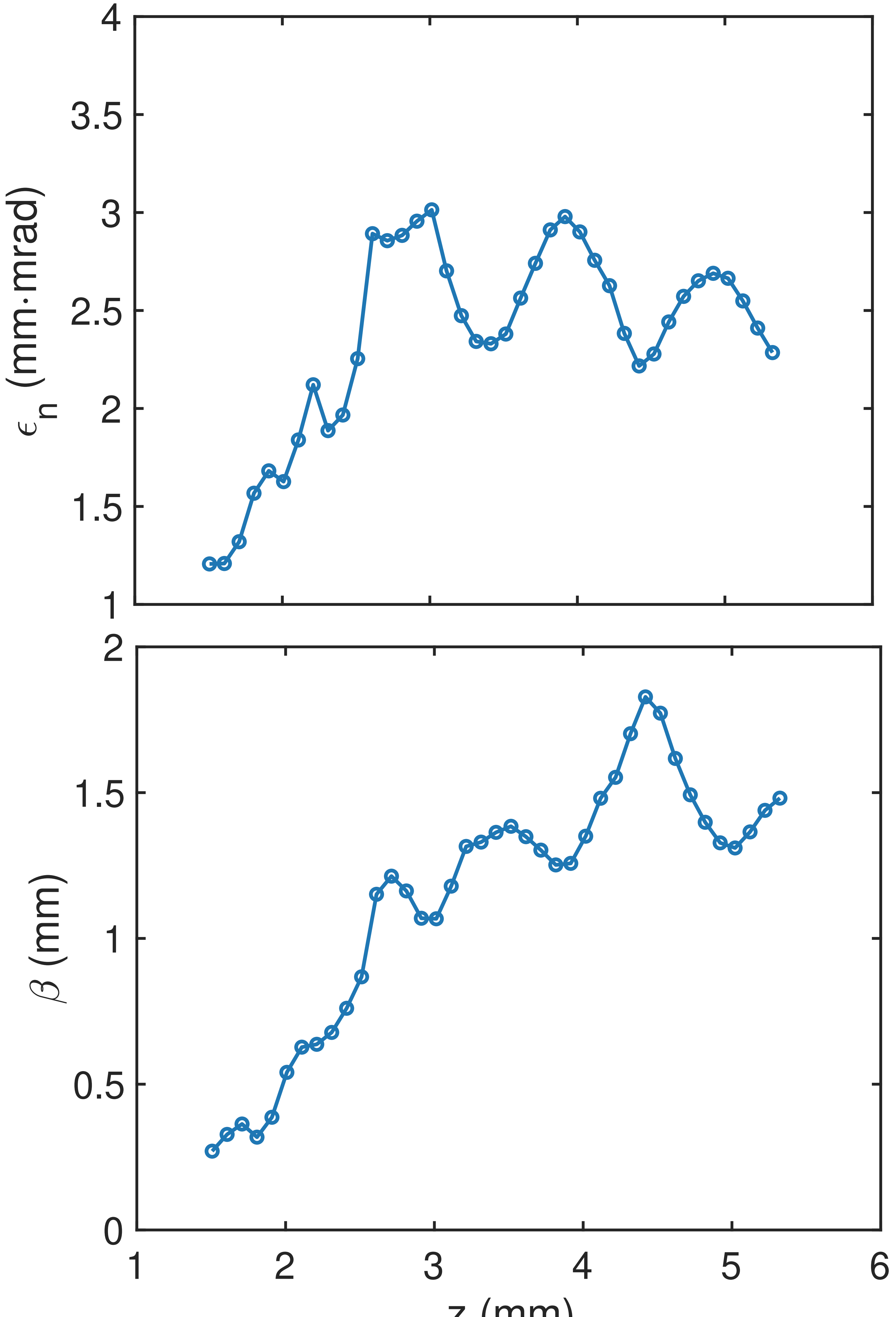


Energy and emittance

Energy vs. acceleration length

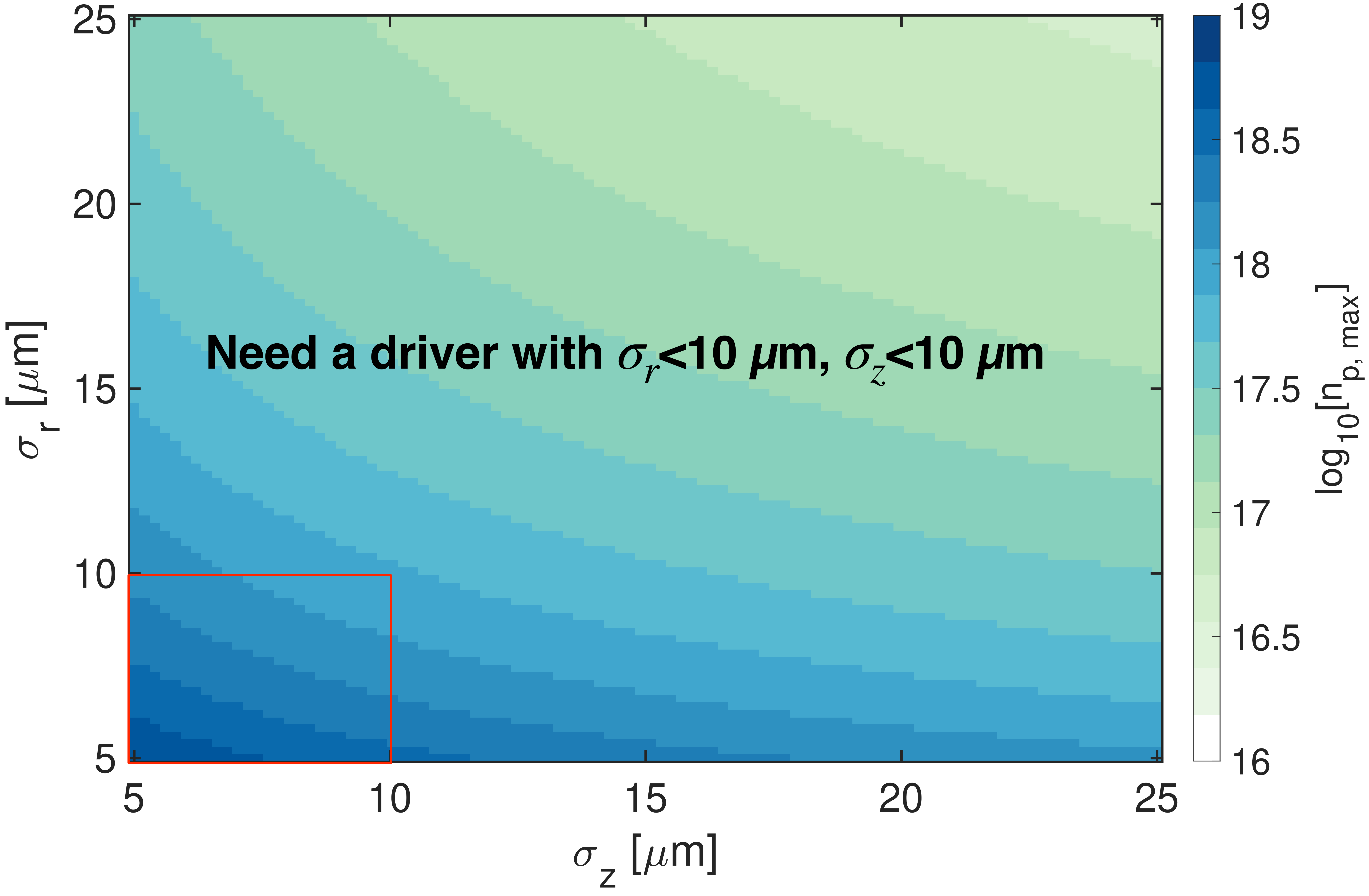


- ~0.6 GeV for the 2-cm nozzle
- possible to increase to ~1 GeV using higher density (requires smaller driver beam)or longer nozzles (e.g., 5-cm, designed)



Required driver beam parameters are achievable using the max-compression config.

UCLA



Single-bunch max compression config:

$Q = 0.6 \sim 2$ nC

$\varepsilon_n \lesssim 40\ \mu$m, $\beta \gtrsim 5$ cm

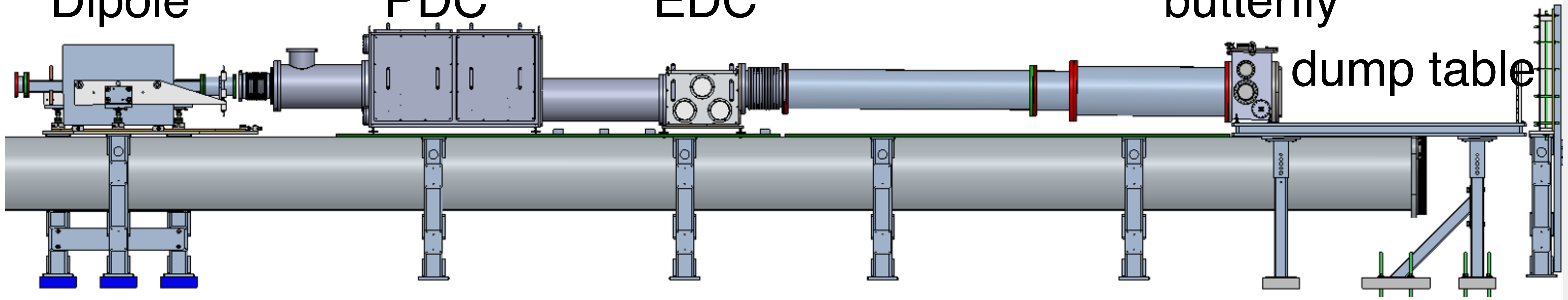
$\sigma_r \approx 10\ \mu$m,

$\sigma_z > 0.25 \sim 100\ \mu$m

$n_b \approx 7.9 \times 10^{17}$ cm^{-3} (for $\sigma_z = 10\ \mu$m)

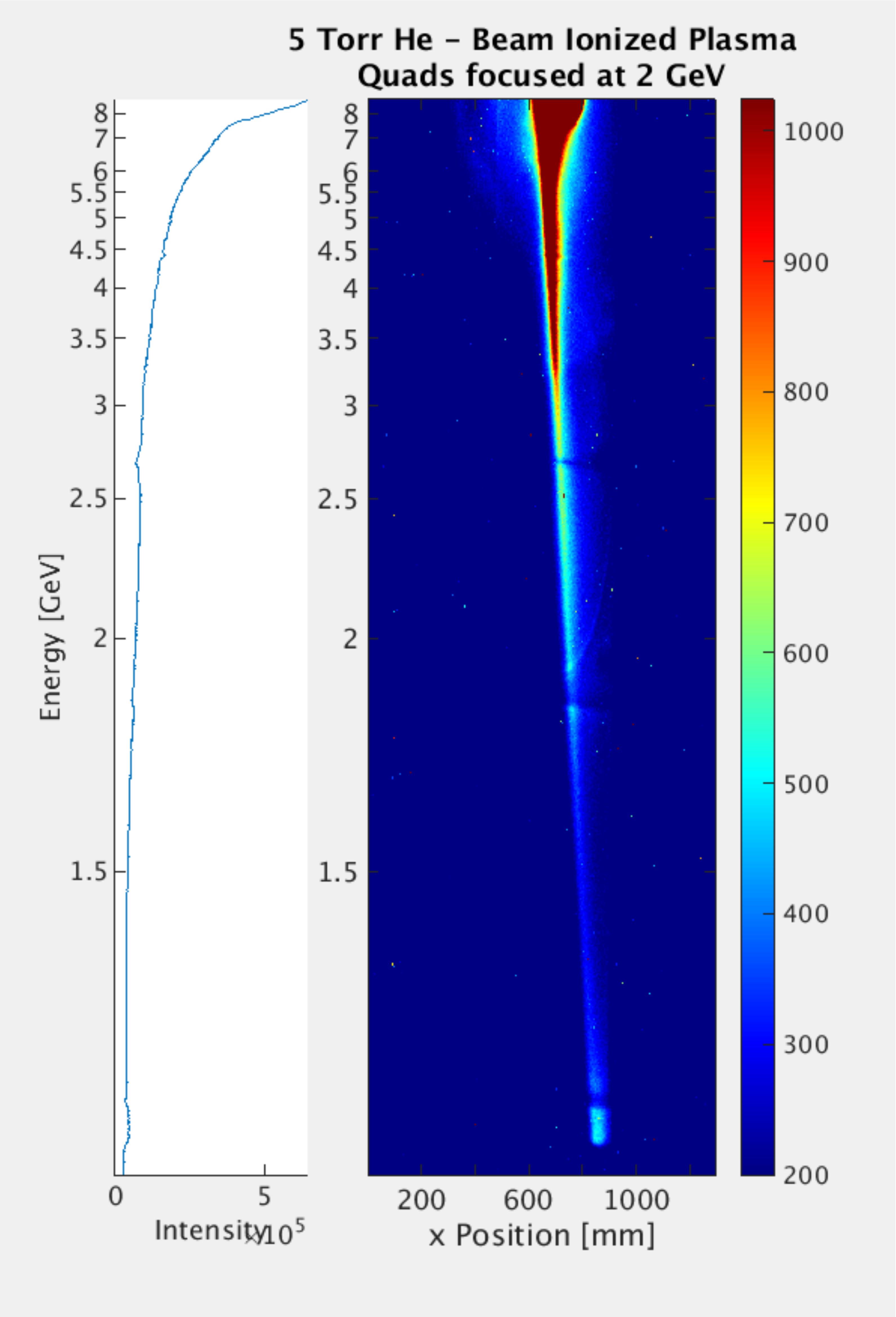
$\Lambda \approx 2.8$

Energy spectrum down to ~1 GeV measured on the dump table



- Energy down to ~1 GeV was measured using the LFOV monitor on the dump table;

- EDC allows measurement of lower energy electrons



Analysis done by Doug Storey

2) Single-Bunch Max-Compression Design Configuration

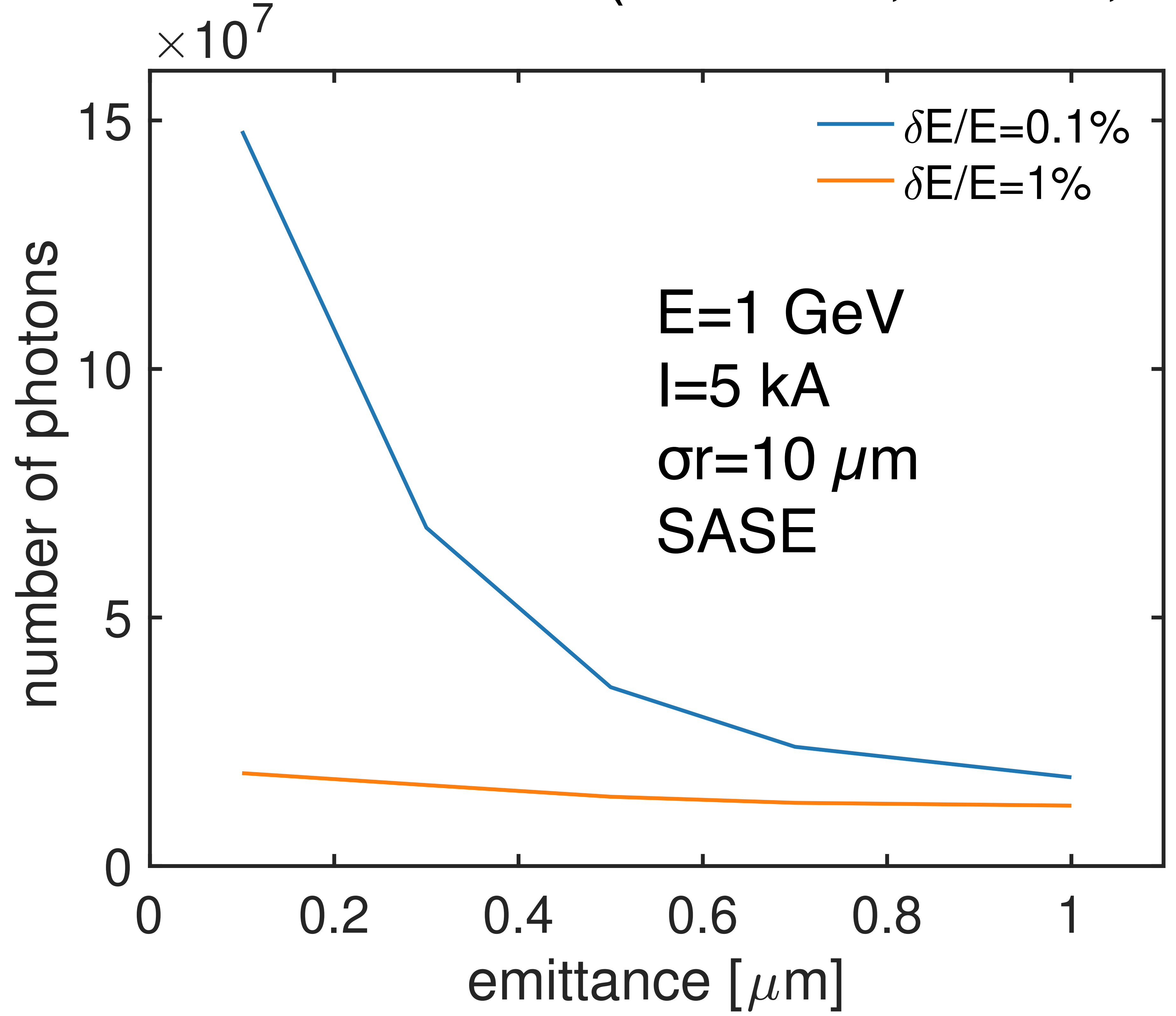
Over-compress bunch in BC14 for high-energy-spread, high-peak current requirements in S20

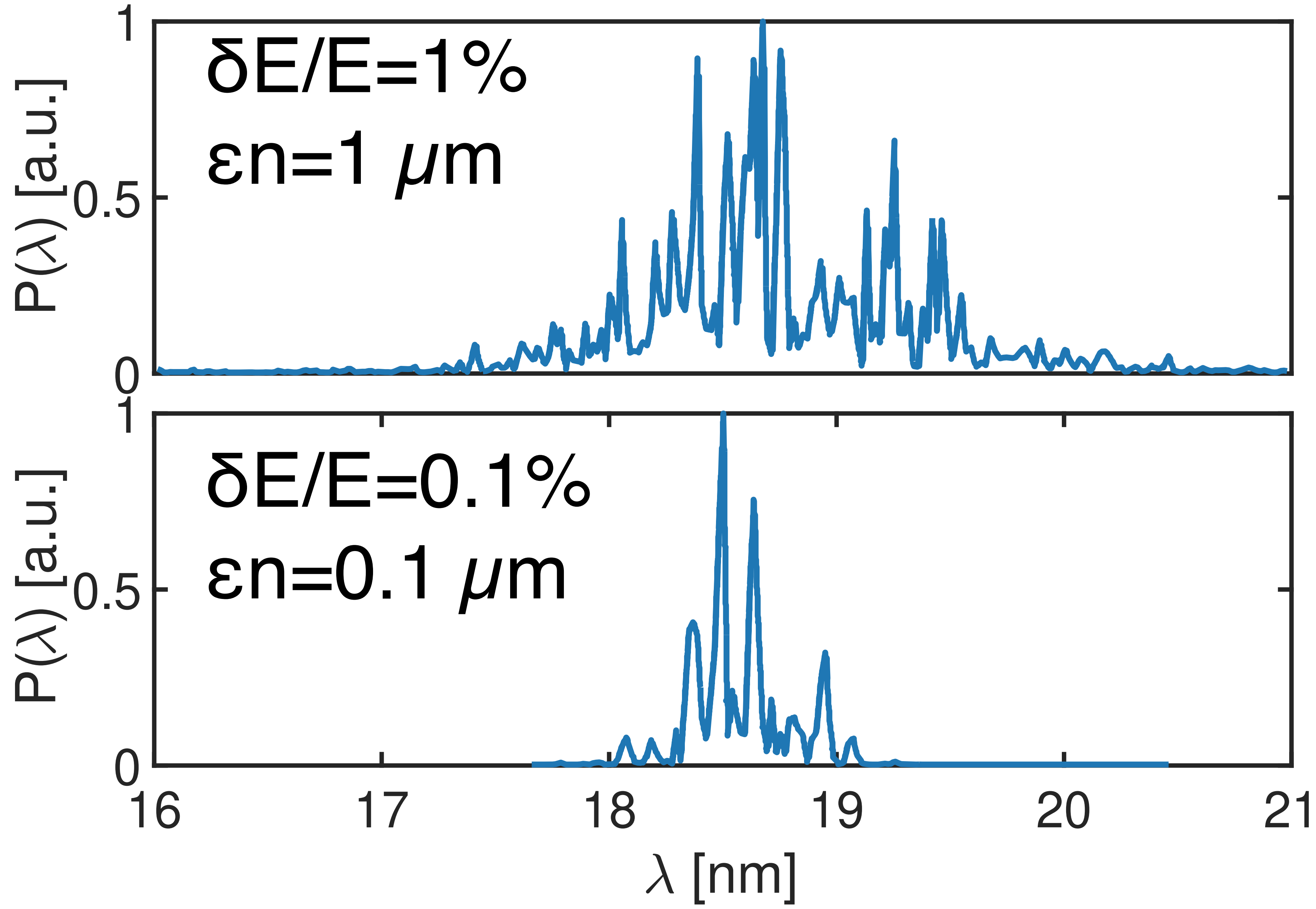
Measure ultralow emittance using undulator emission

A short undulator as a potential diagnostic for ultralow emittance (year 3 and beyond)

Genesis simulation

A short (2 m) undulator as a beam characterization tool (λu=3 cm, K=2.8, N_{period}=66)





- Driver beam radiates at different wavelength (E>7 GeV, εn>5 μm, $\delta E/E \sim 1\%$)