Control and observation of trajectory mixing and wakeless regime in plasma accelerators

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Outline

- Introduction and motivations for the study of trajectory mixing and wakeless regime
- Preliminary results from E-200 and E-300 in beam-ionized helium plasmas
- Experiment goals and project structure
  - Beam-ionized plasma sources and current profile control
  - Advanced shadowgraphy in dark mode for visualisation
  - Physics study of plasma wave damping and wakeless
- Synergies and possible evolution

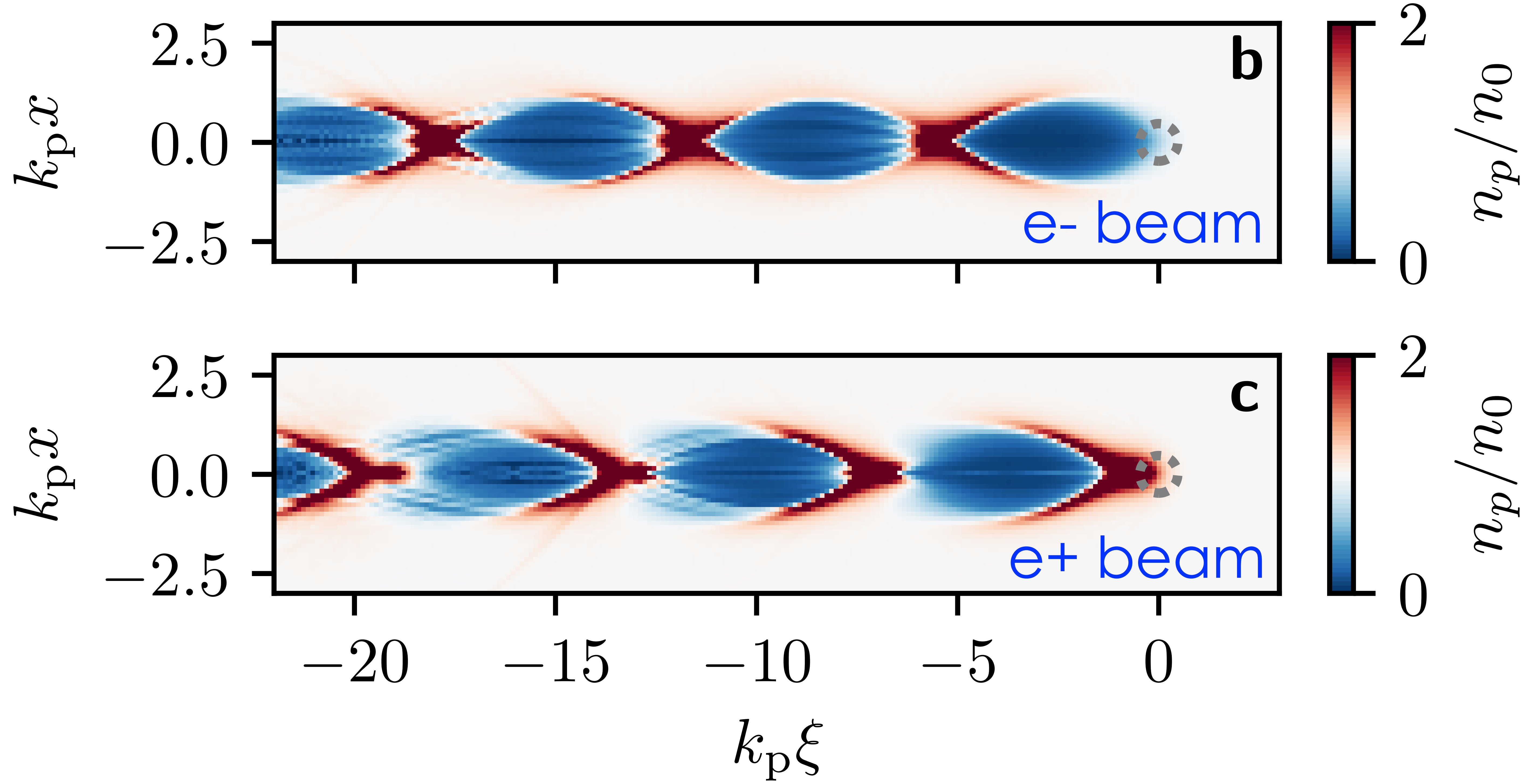
Intro and motivations

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

↓

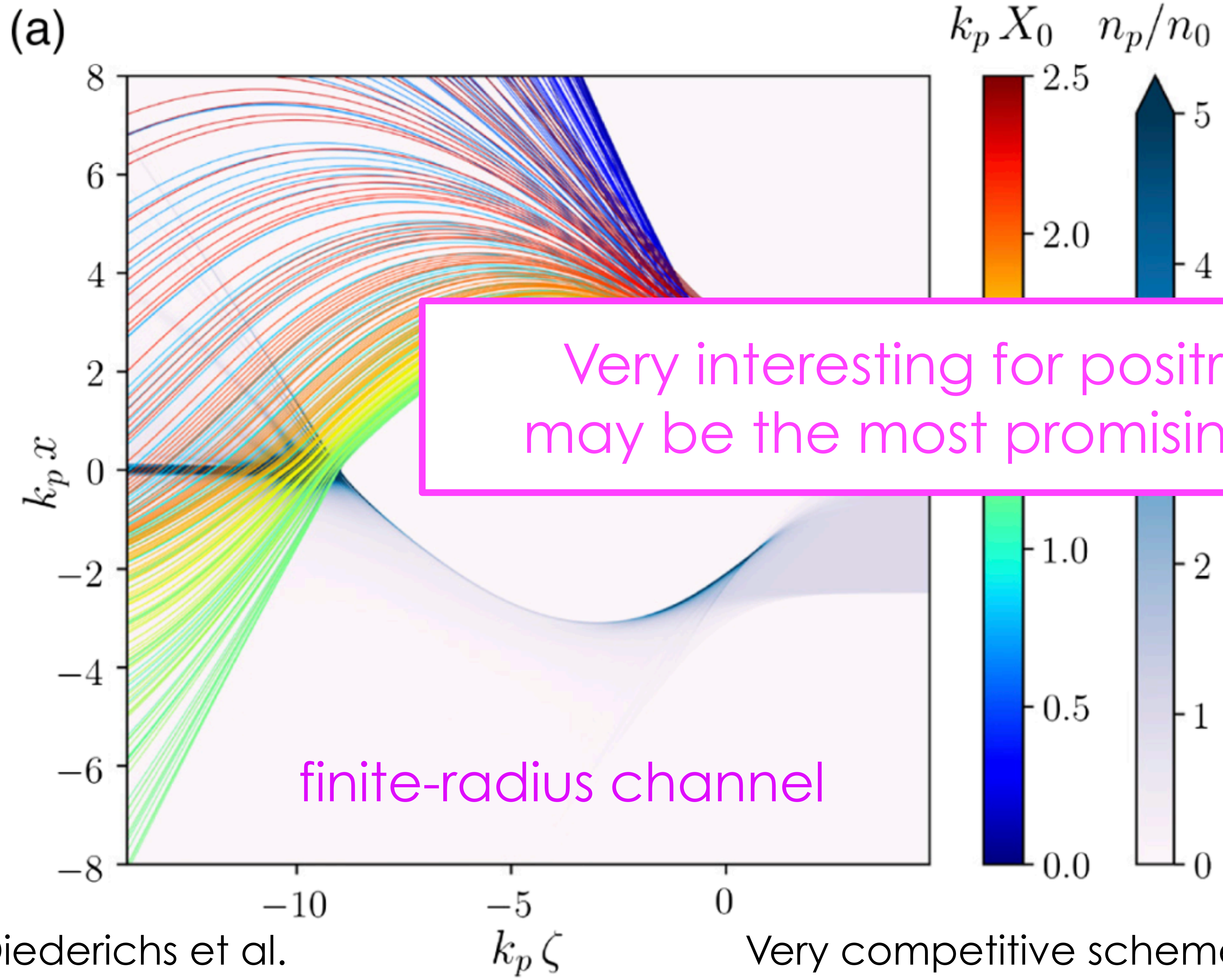
Oscillating Wakefield
in the wake of the beam

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

Finite-width plasma

Synergy with E333 experiment

Finite-radius plasma column scheme for positron acceleration:



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

Very interesting for positron acceleration:
may be the most promising plasma scheme

When blowout radius approximately matches plasma radius

asma electrons return positions are spread longitudinally

extended area focusing and accelerating for e+

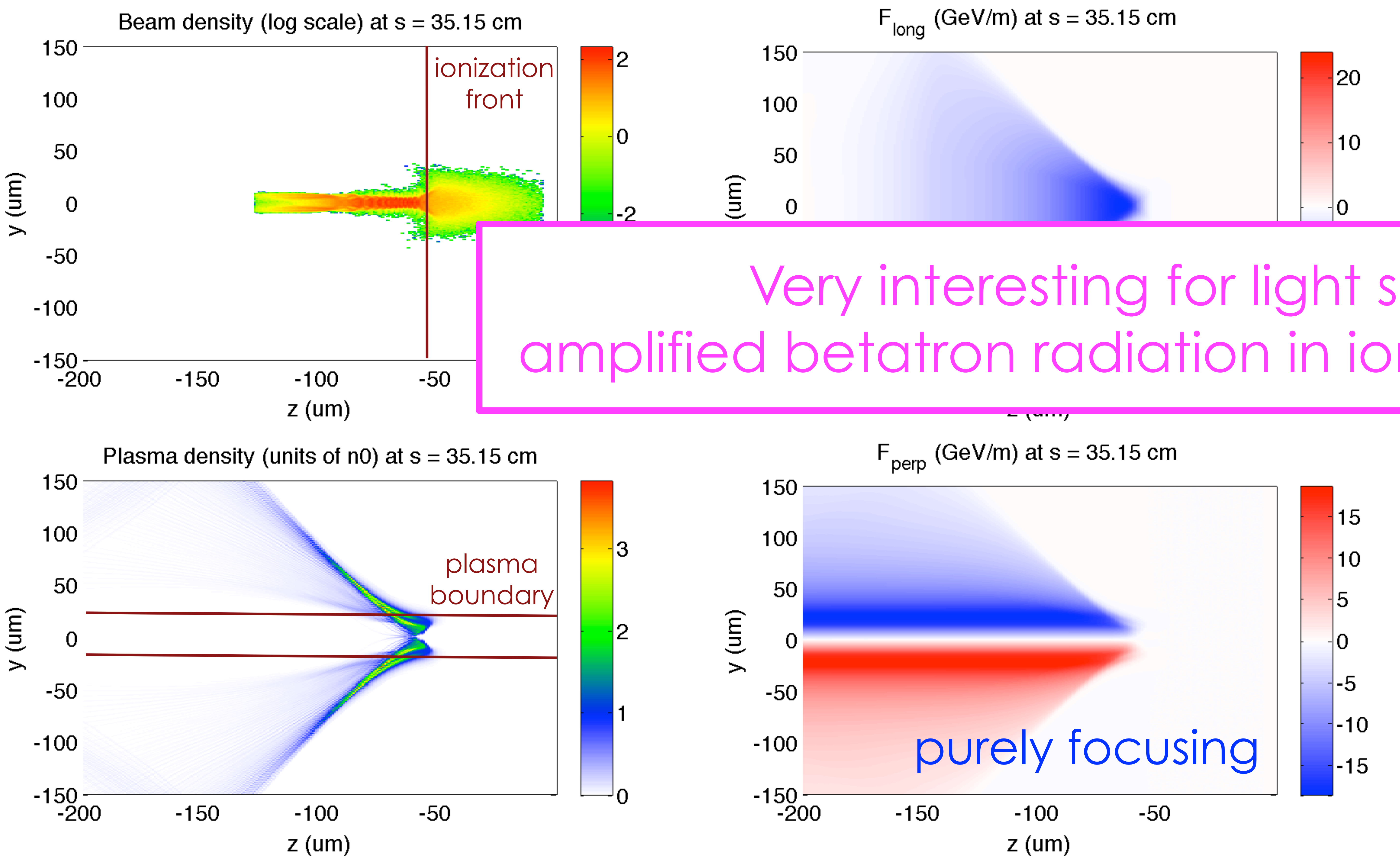
strong trajectory mixing, leading to plasma wave damping

Very competitive scheme,
see G. Cao et al. PRAB 27, 034801 (2024)

Finite-width plasma

Synergy with E306 experiment

Example of beam-ionized plasma:



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

If blowout radius greater than plasma radius

↓

Blown-out plasma electrons return to axis

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

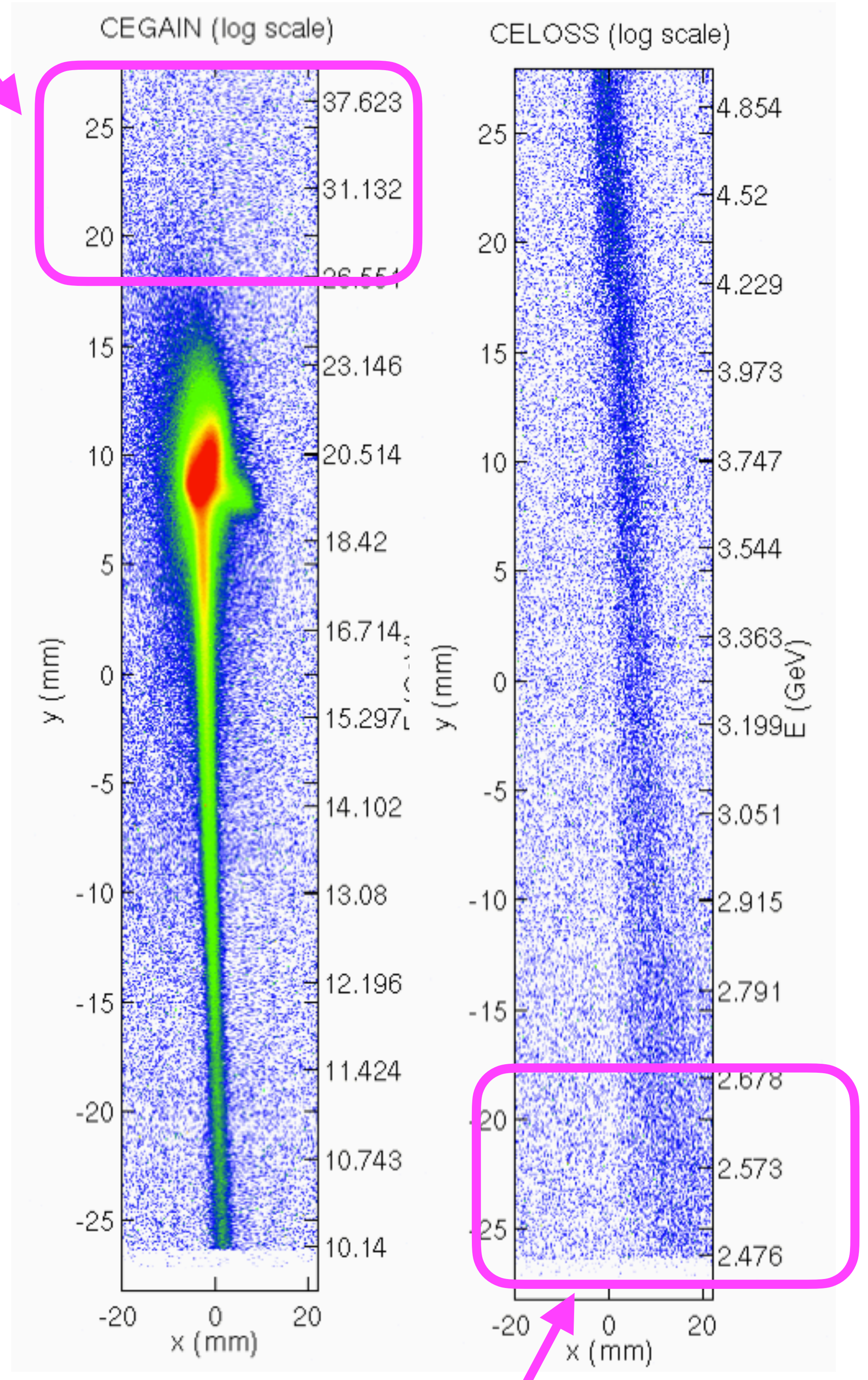
here referred as wakeless regime

E-200 and E-300 preliminary results on wakeless

E-200 results: helium vs argon beam-ionised plasma sources

He up to 64 Torr — from wakeless to standard PWFA regime → **Ar 16 Torr**

No acceleration



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

E-200 observations:

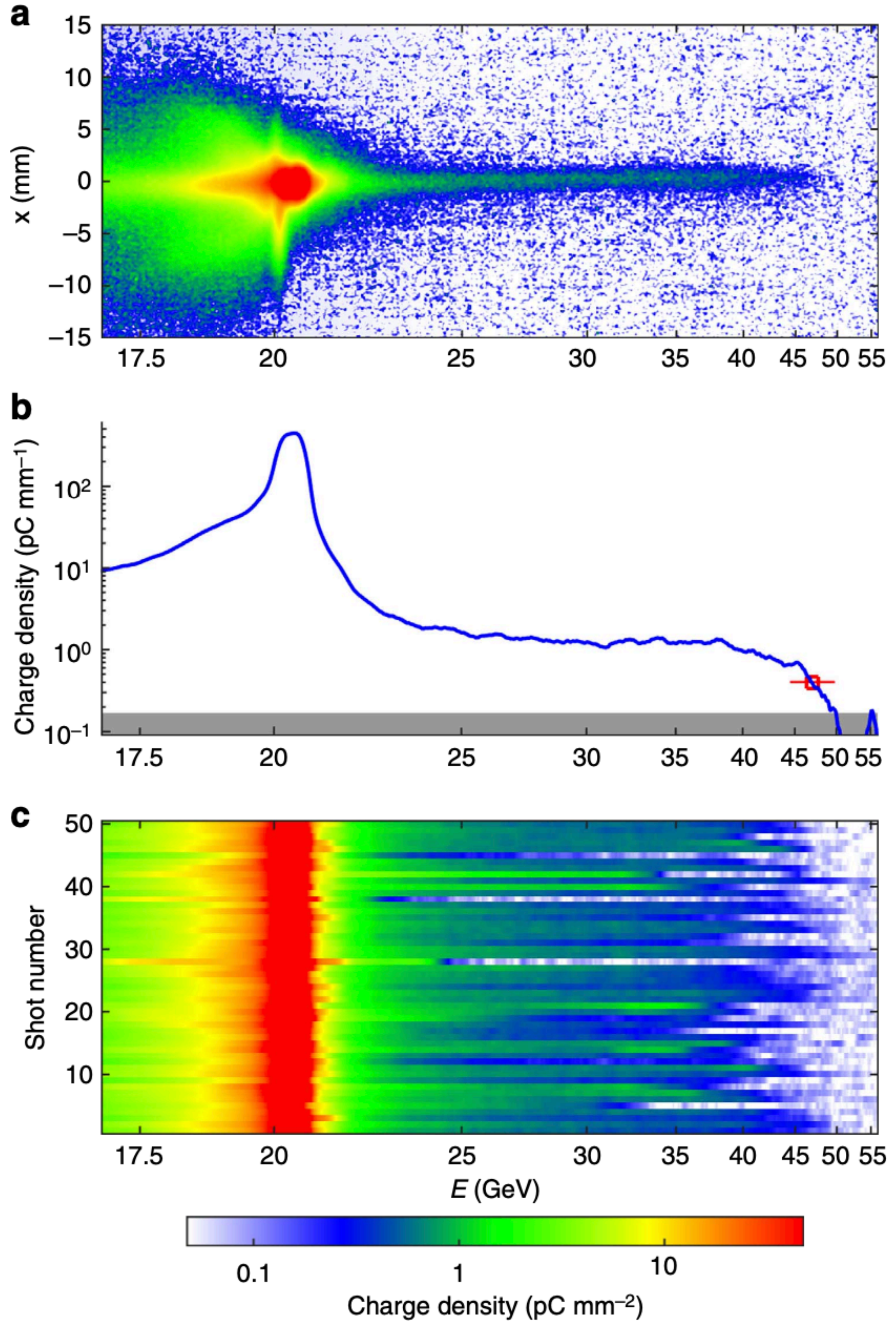
- Pure He: never observed any acceleration despite full energy loss, tested up to 64 Torr
- He-Ar mixture at 32 Torr: acceleration observed above 40% Ar

…ation

No acceleration up to 64 Torr, corresponding to:

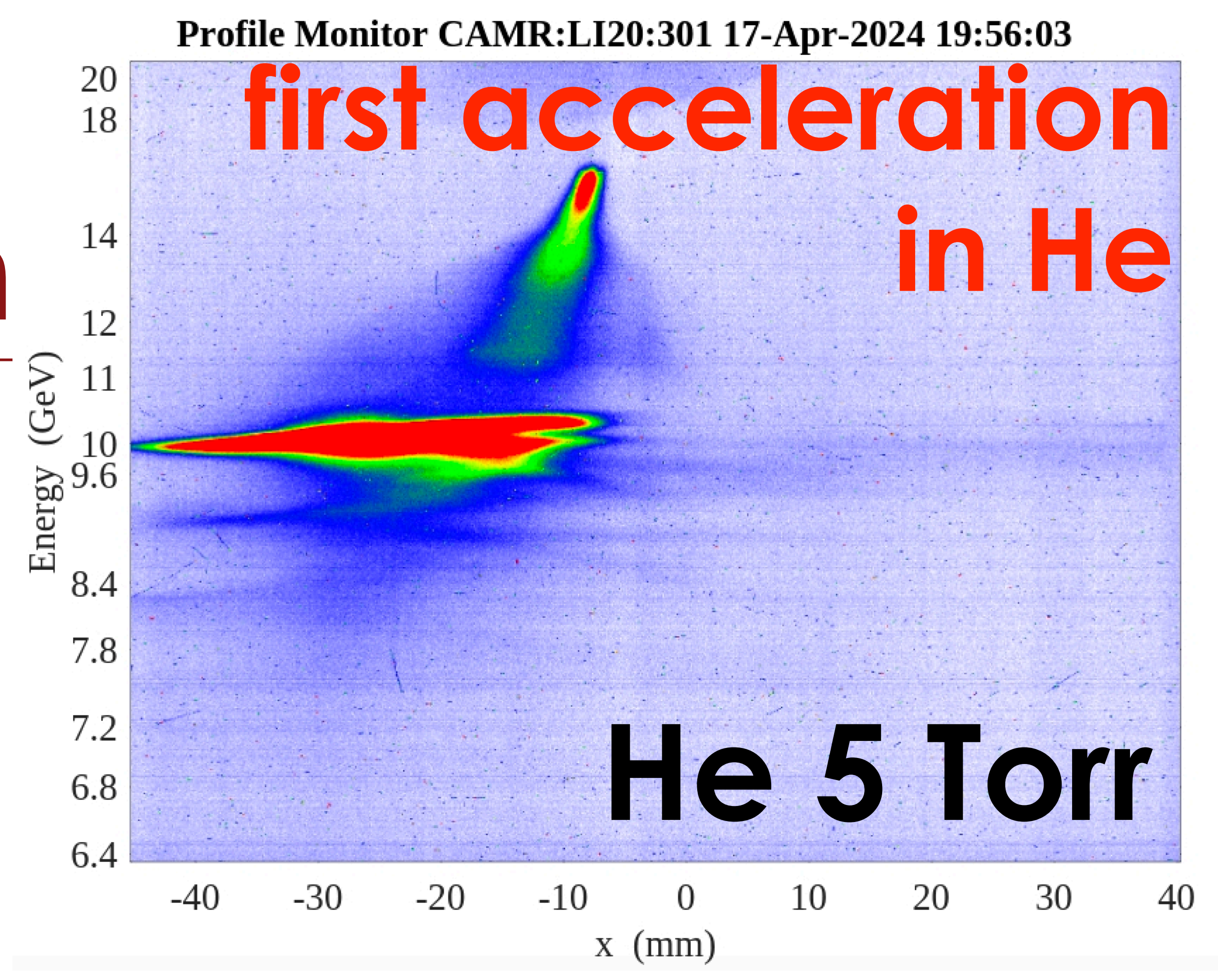
$n_p \simeq 3 \times 10^{18}\ \mathrm{cm}^{-3}$ and $\lambda_p \simeq 20\ \mu m$

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



Nature Commun. 7, 11898 (2016)

E-300 results: compression scan in beam-ionised helium



- Experimental set-up for compression scan
  - Laser heater configuration to enhance ionization/interaction
  - 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

Experiment goals and project structure

Goals and project structure

High level goal: control and observe trajectory mixing/plasma wave damping and transition from standard PWFA to wakeless.

How?

- Develop and use advanced tools

control

Part A
Controlling drive current profile and beam-ionised plasma sources

Part B
Advanced shadowgraphy in dark mode for direct visualisation

observe

- To explore physics

Part C
Plasma wave damping and wakeless

physics

Part A — current profile and beam-ionised plasma sources

How

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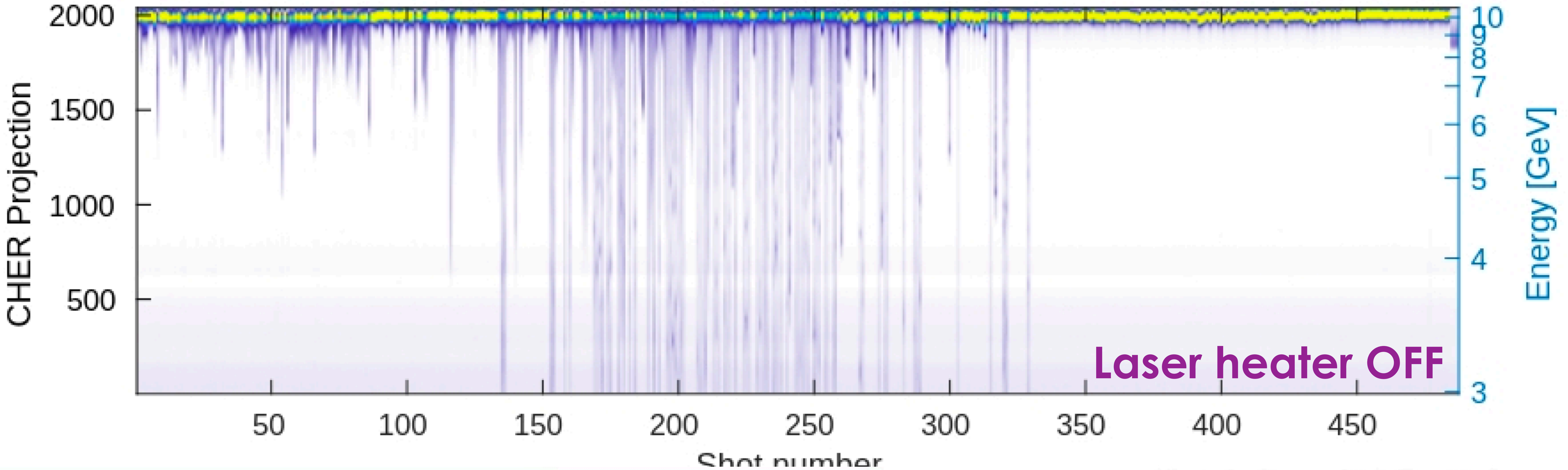
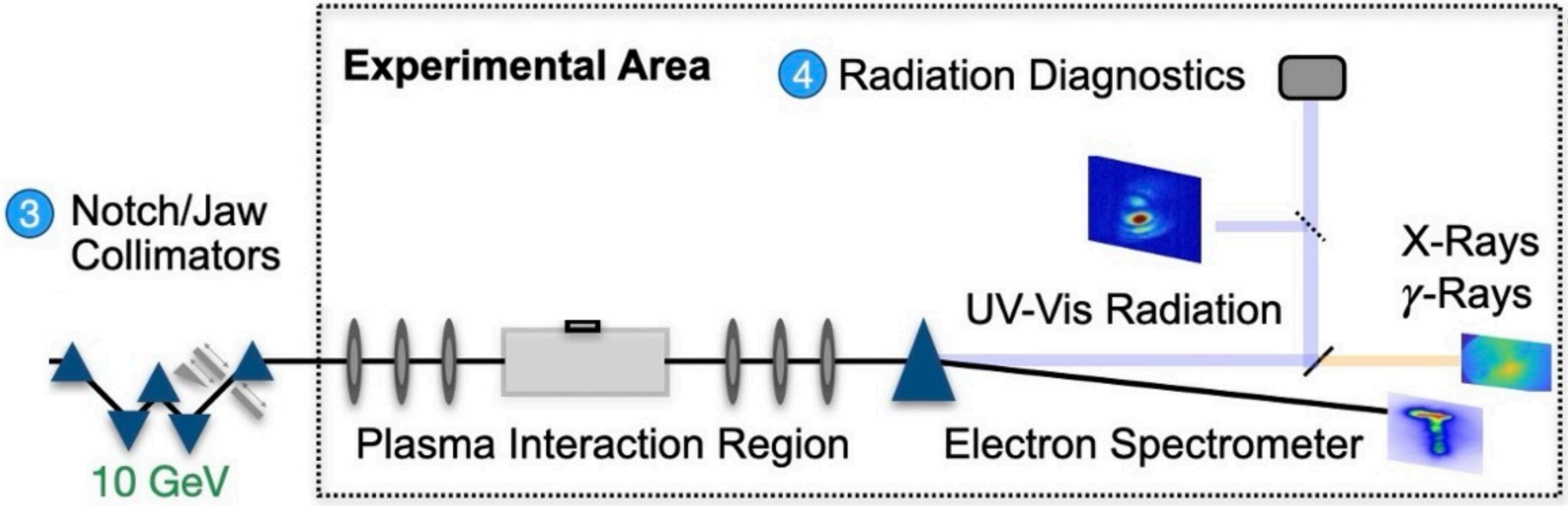
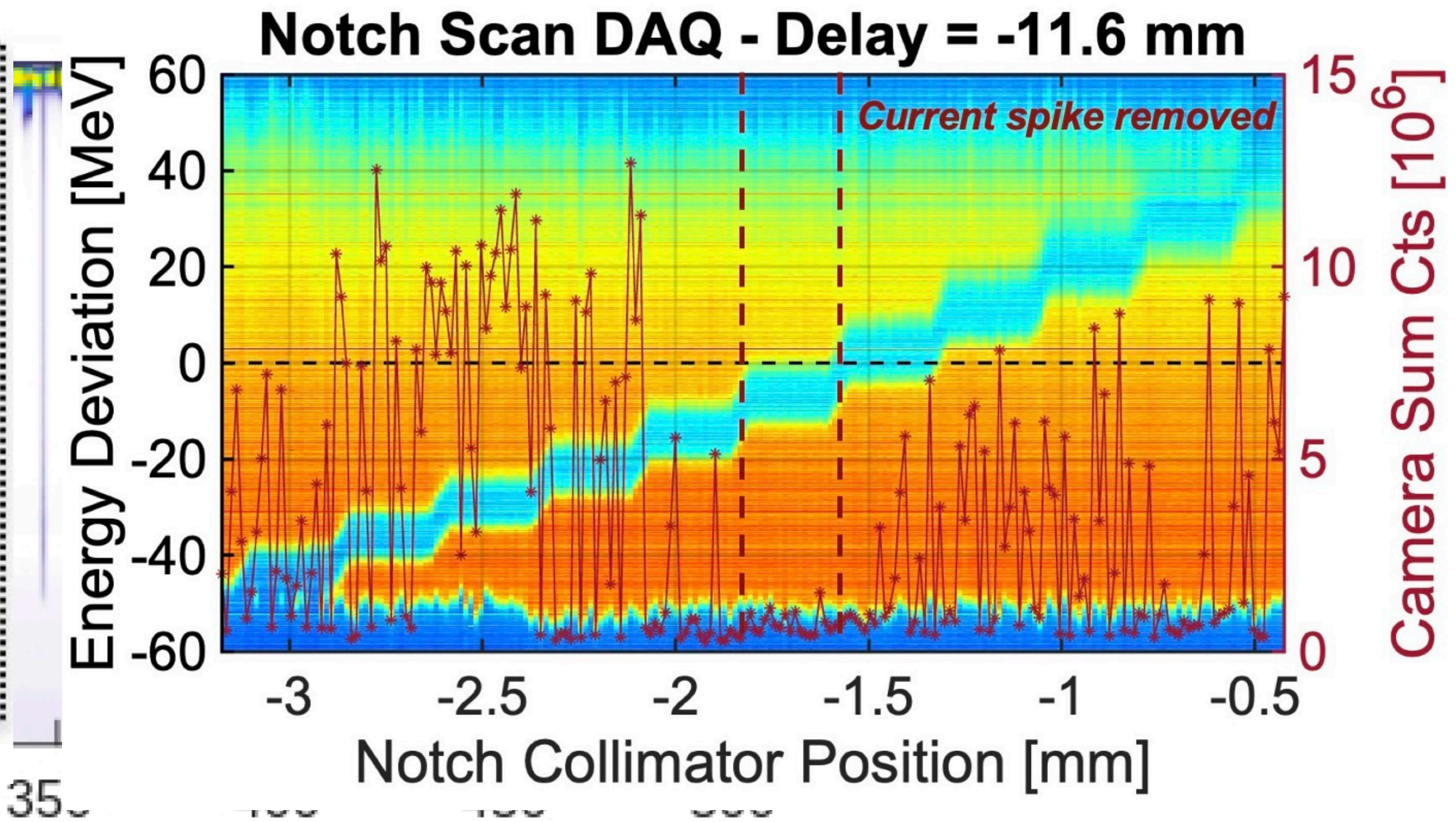
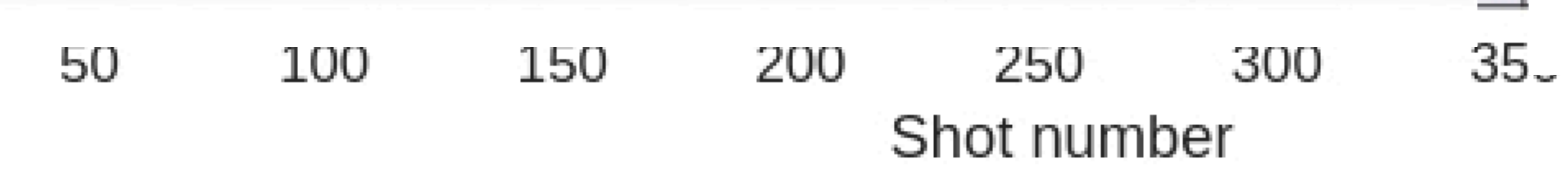




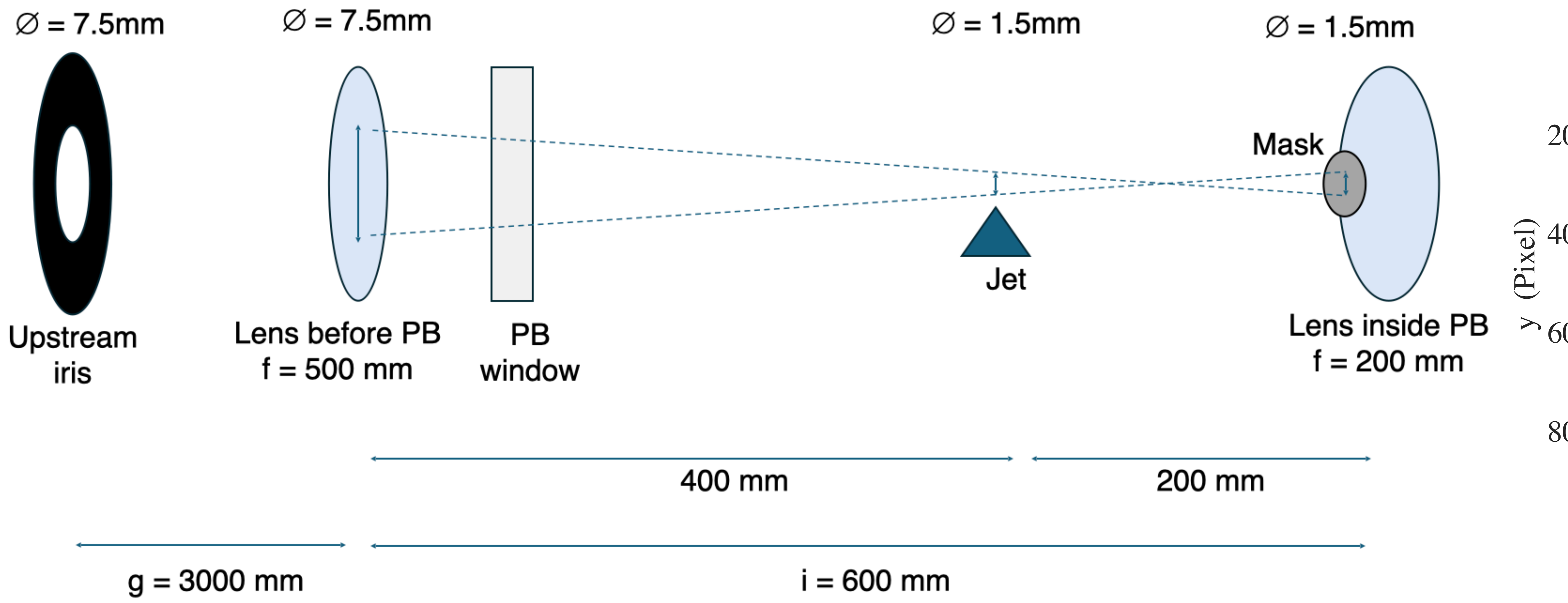




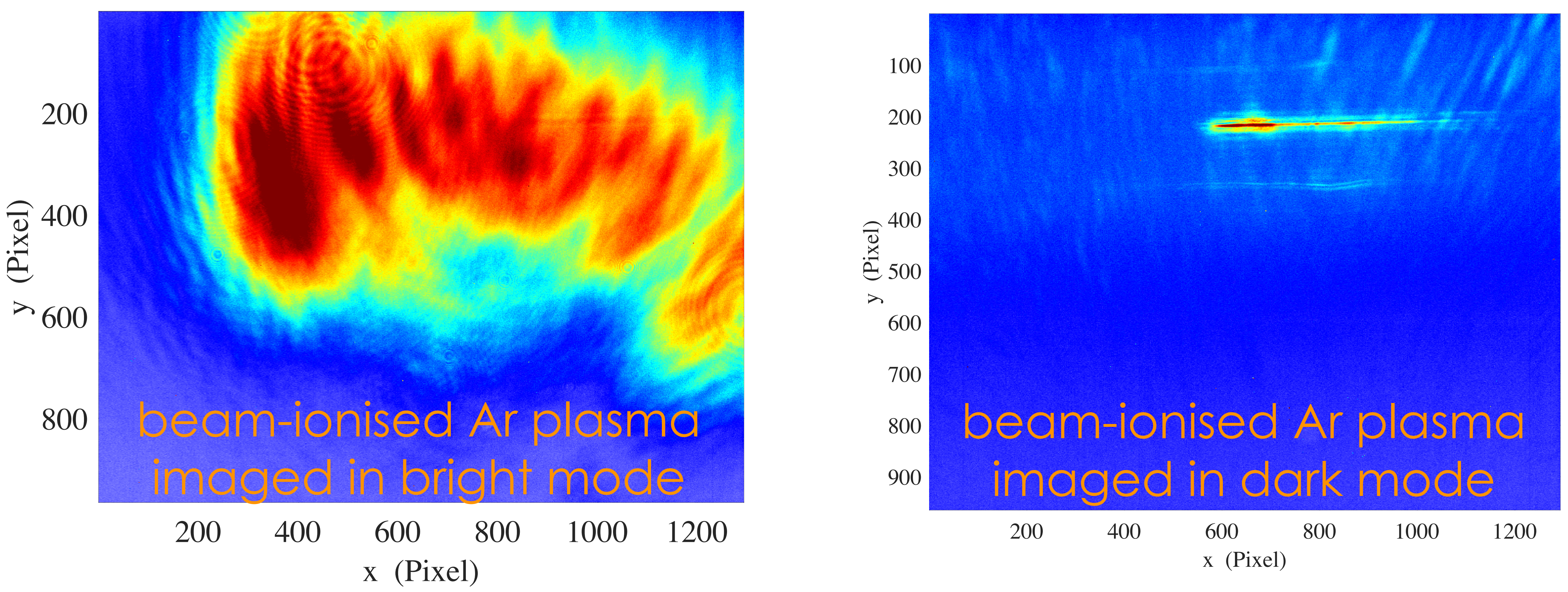
Part B — advanced shadowgraphy in dark mode

How to observe?

- Dark-field shadowgraphy under development for E305 at plasma densities above 10^{18} cm^{-3}, aim to reuse and adapt for densities below 10^{18} cm^{-3}.



Ar plasma density ~10^{18} cm^{-3}



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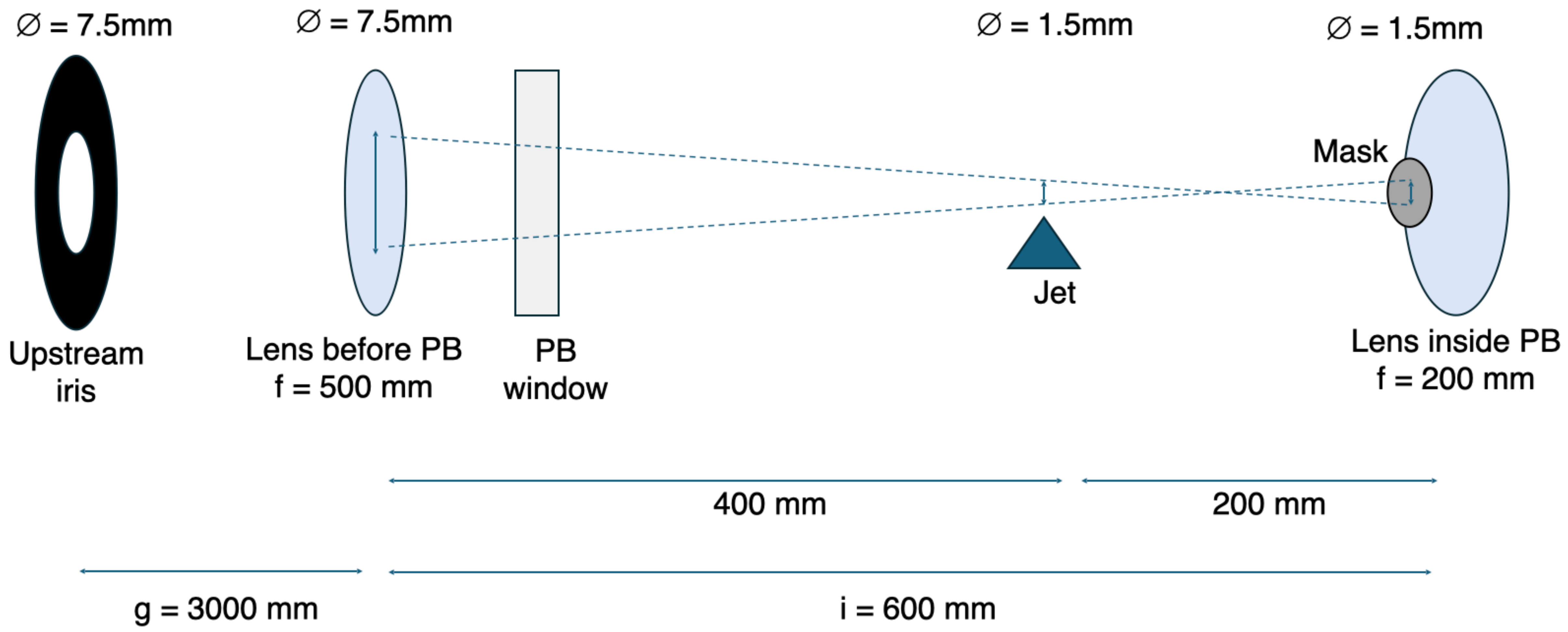
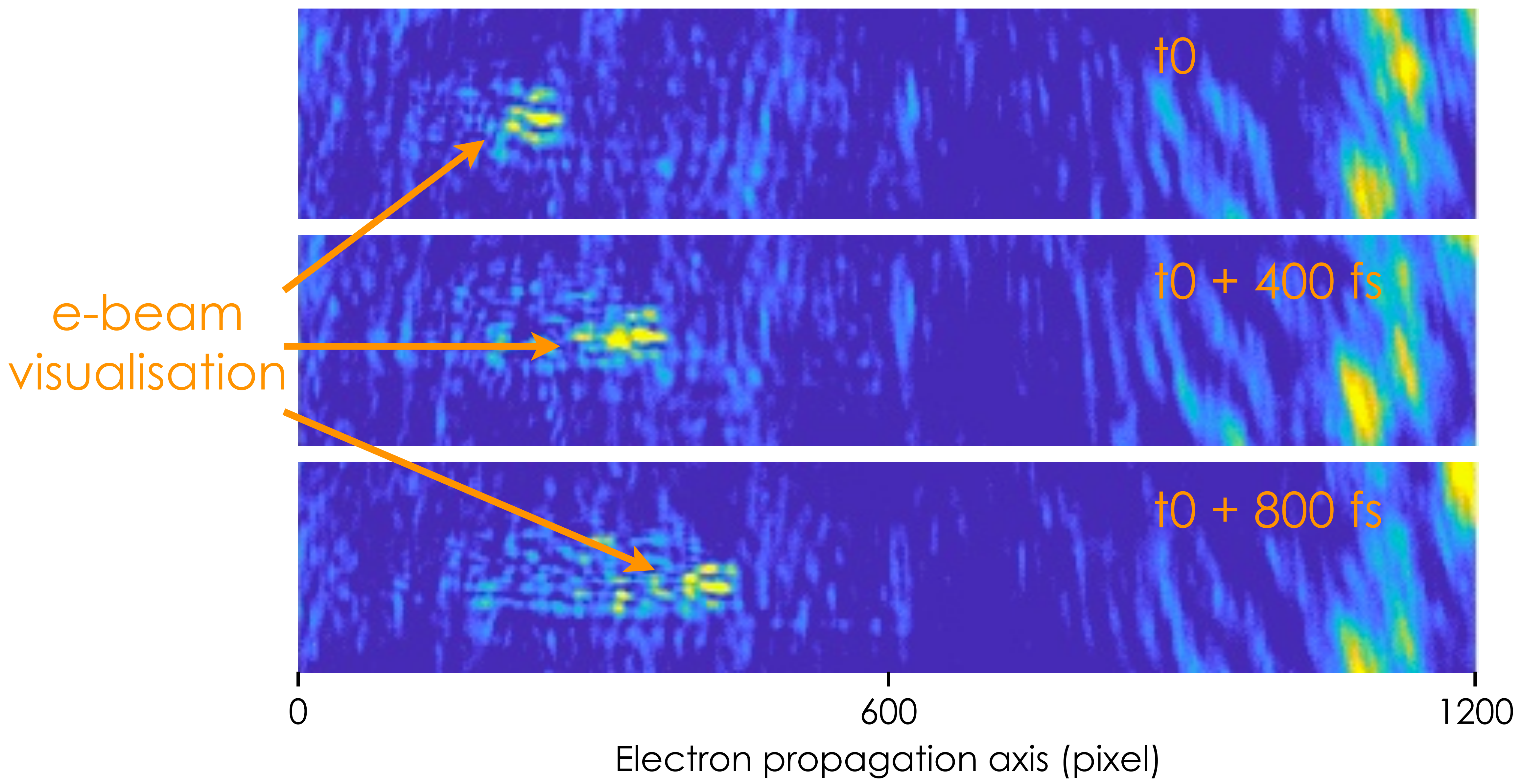


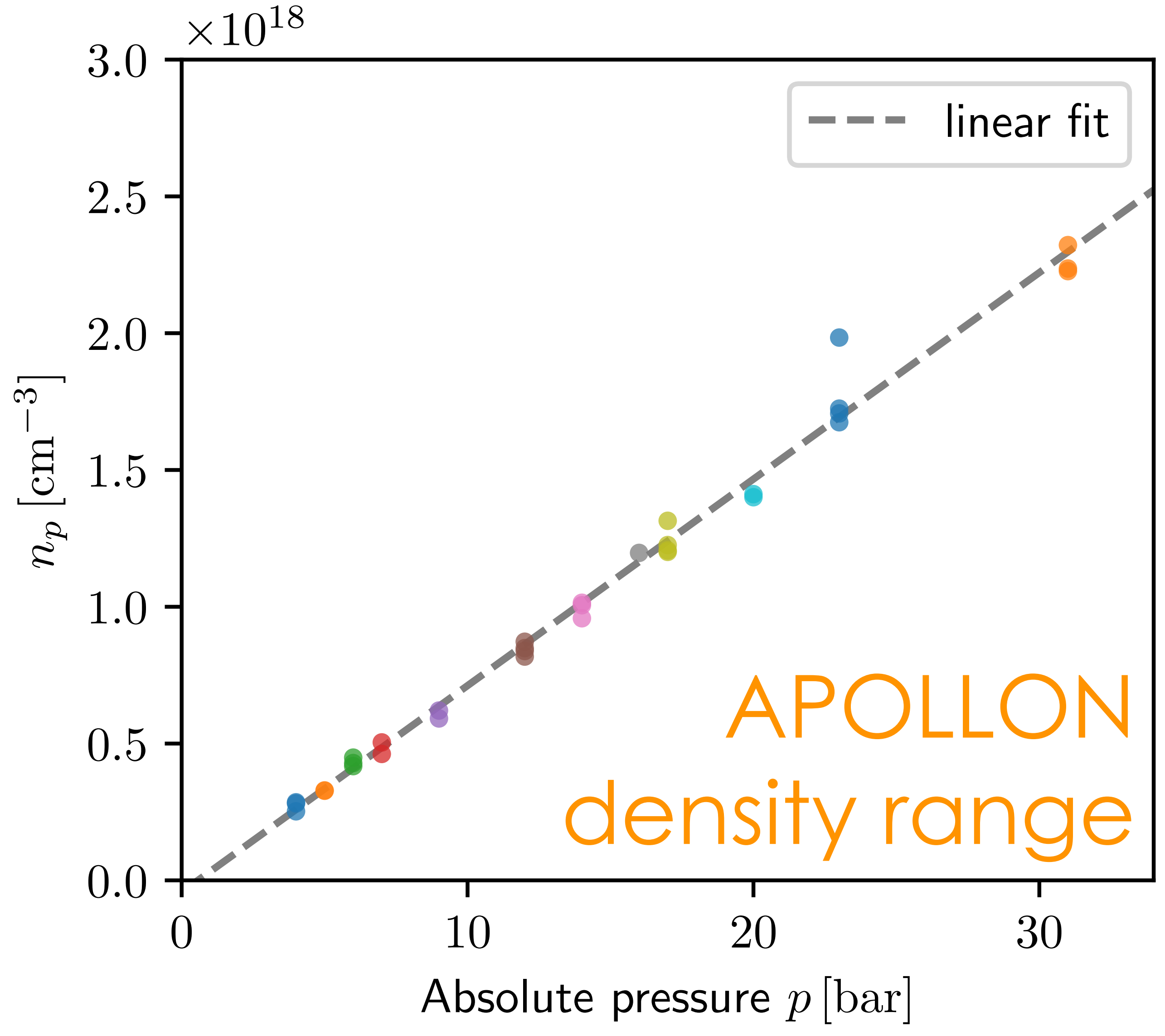
Timed with respect to other lasers/ebeam in He 8 Torr during oven cooldown on Monday 11/18

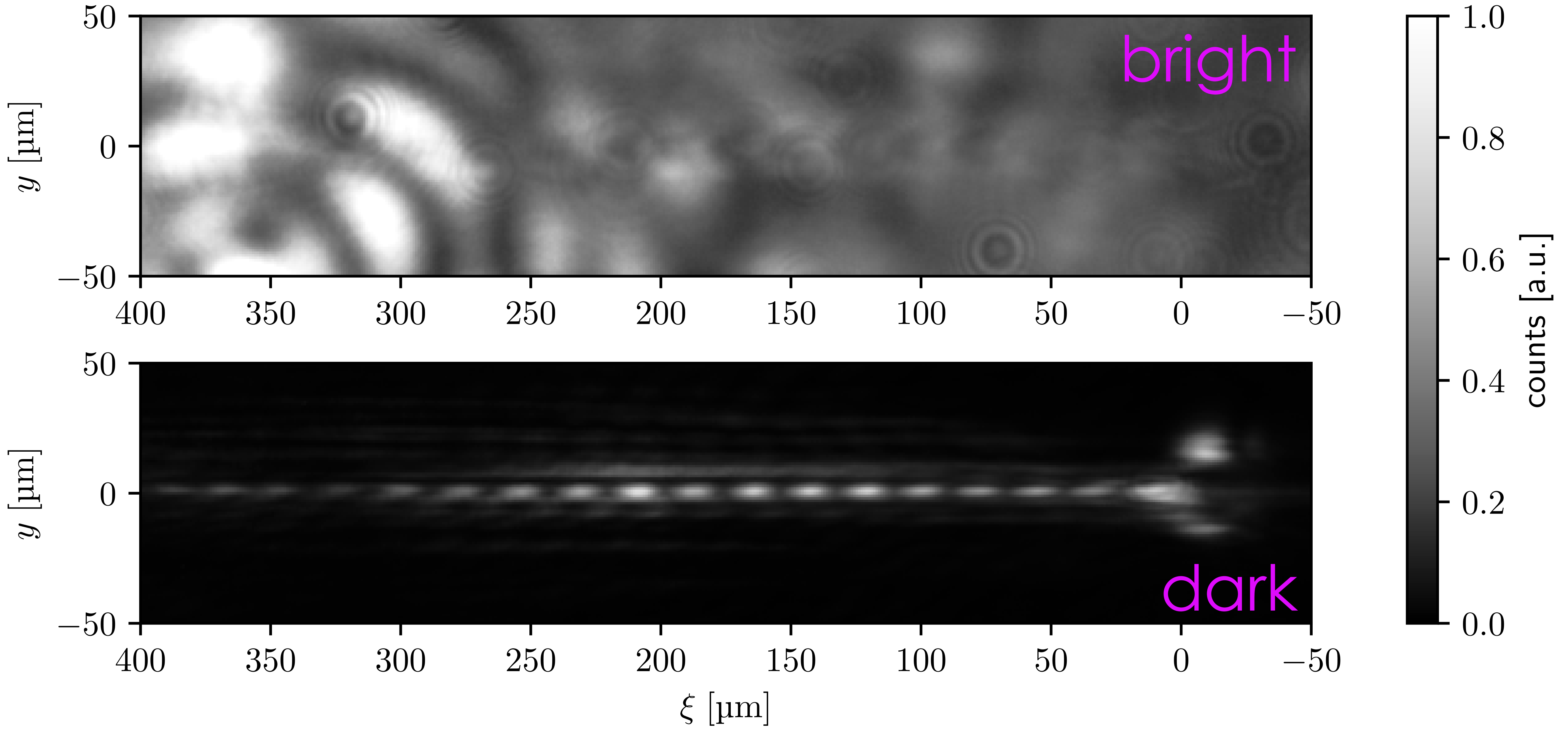


Part B — advanced shadowgraphy in dark mode

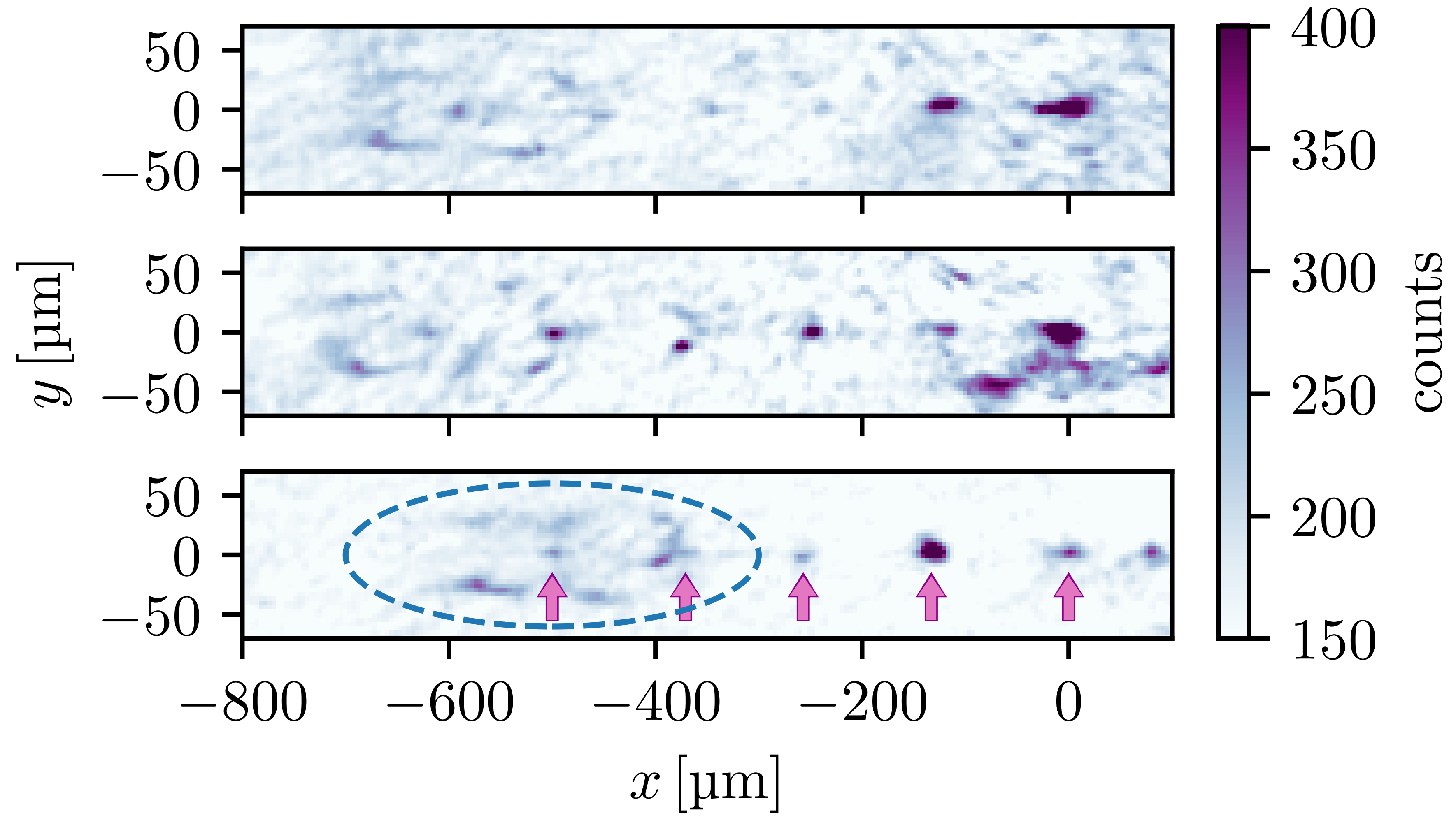
How to observe?

- Plasma wave snapshots in dark mode demonstrated at LWFA facilities (LOA, APOLLON) down to the 10^{17} cm^{-3} range.





laser-driven plasma wave

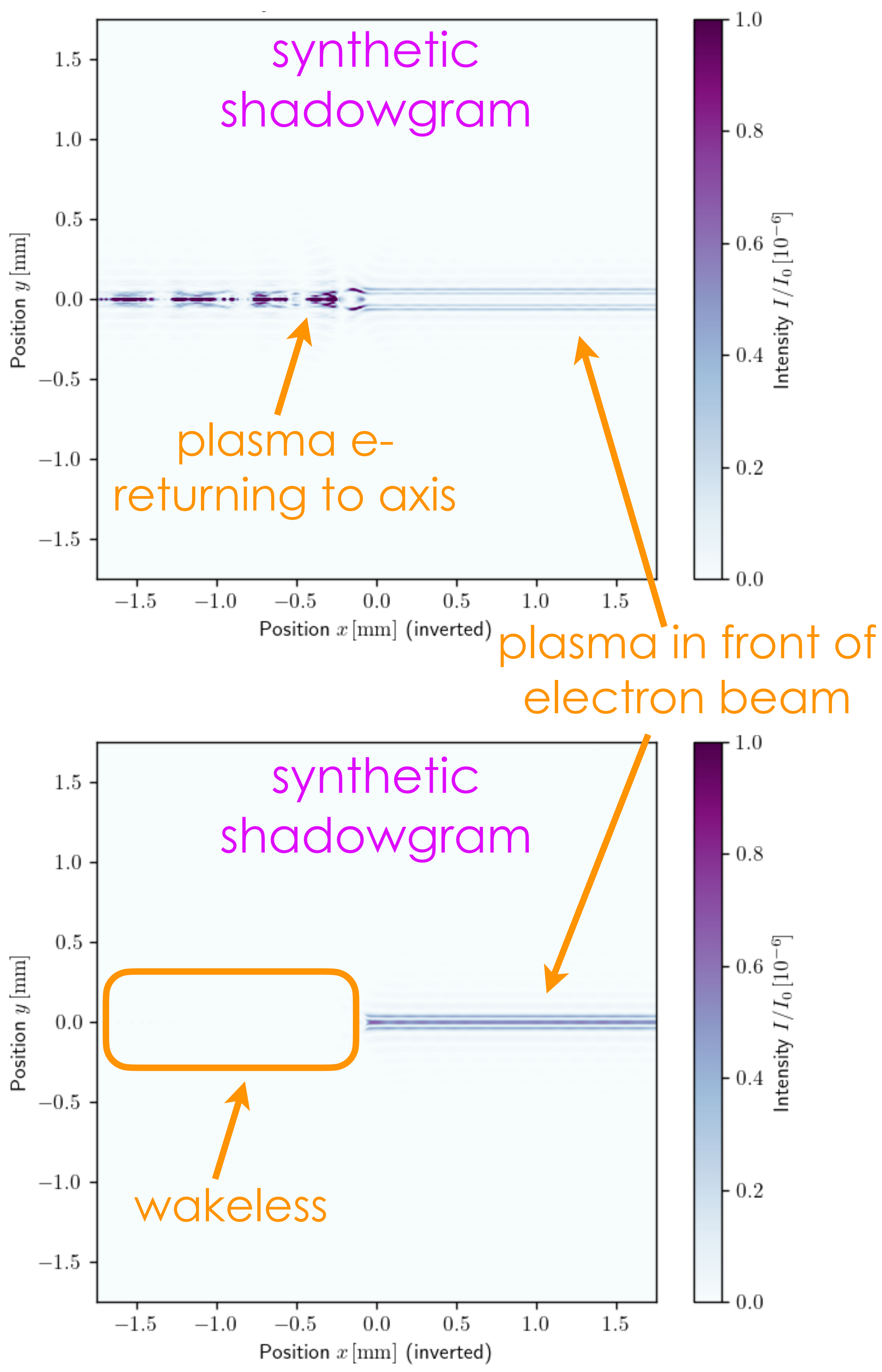


plasma wave driven by LWFA electrons in low-density gas jet, observed plasma density of 6-8 10^{16} cm^{-3}

Part C — physics study of plasma wave damping and wakeless

- Trajectory mixing: take snapshots of weakly and strongly damped plasma waves when varying current profile and plasma radius.

- Wakeless: take snapshots showing disappearance of plasma oscillation and providing direct visualisation of waveless wake.



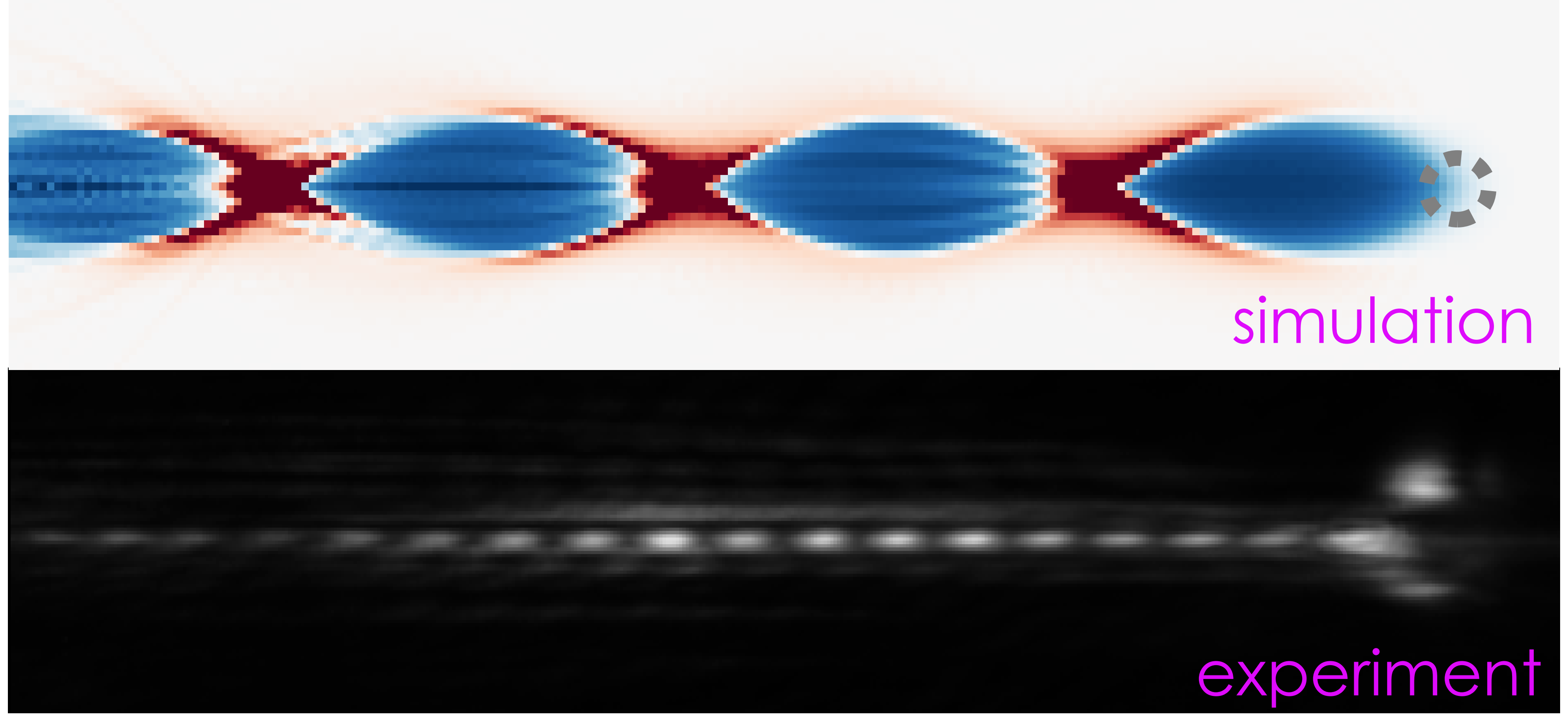
Synergies and possible evolution

Synergies and possible evolution

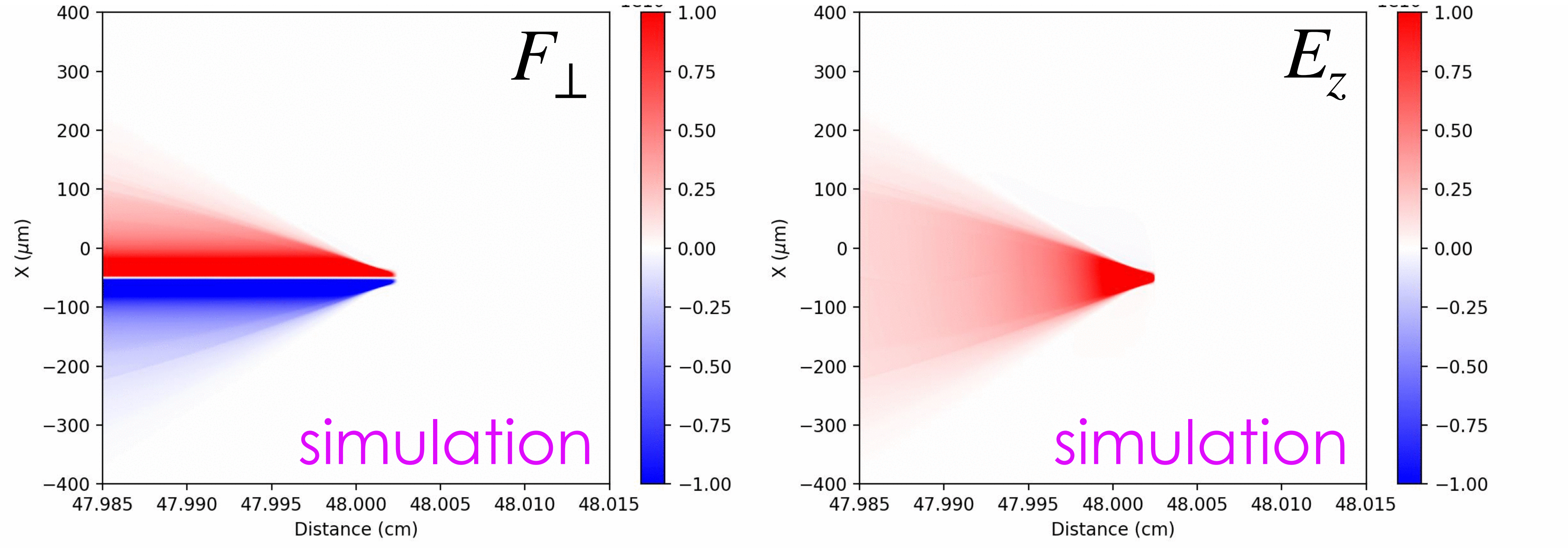
- Provide new tools that can be leveraged by E306 (ion channel laser) and E333 (positron acceleration in finite-radius plasmas)
- Advanced shadowgraphy in dark mode: provide a straightforward way to verify and adjust conditions to be in the right regime
- Beam-ionised plasma sources with current-profile control can be used for early physics insights, even if performance is not optimised.
- Possible evolution (high risk/high gain): controlled current spike at the beam front could make beam-ionised plasma sources very competitive, free of overlap shot-to-shot fluctuations.

Thank you for your attention

standard plasma wave



wakeless



experimental shadowgram ???