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Modulation of dense electron beams in nanostructures: A simulation study in preparation of the FACET-II E-336 experiment

Alexander Knetsch on behalf of FACET-II E-336 collaboration

especially M. Gilljohann, Y. Mankovska, P. San Miguel Claveria
X. Davoine, who performed the presented simulations

Principal Investigators: Sébastien Corde and Toshiki Tajima

Motivation and goals: With small structures come high fields

The wave-breaking field

$$E[\mathrm{GV/m}] = m_e \omega_p c / e \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}$$

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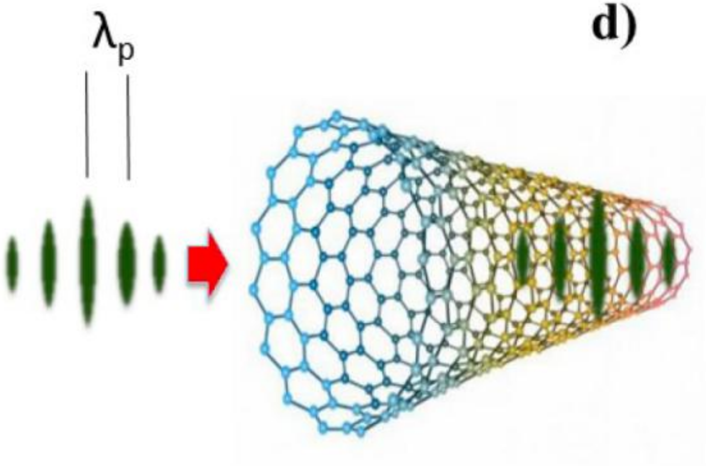
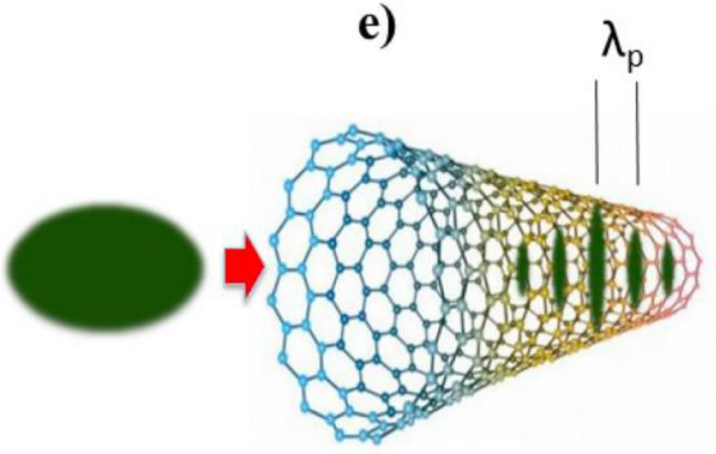
- To reach TV/m accelerating fields, we need solid density plasmas (10^{24} cm^{-3})
- Electron-electron collisions are a hazard to beam quality and transport
- Beam-guiding nano-structured targets such as crystals or nanotubes

Motivation and goals: With small structures come high fields

Modulated beam in nanotube structure

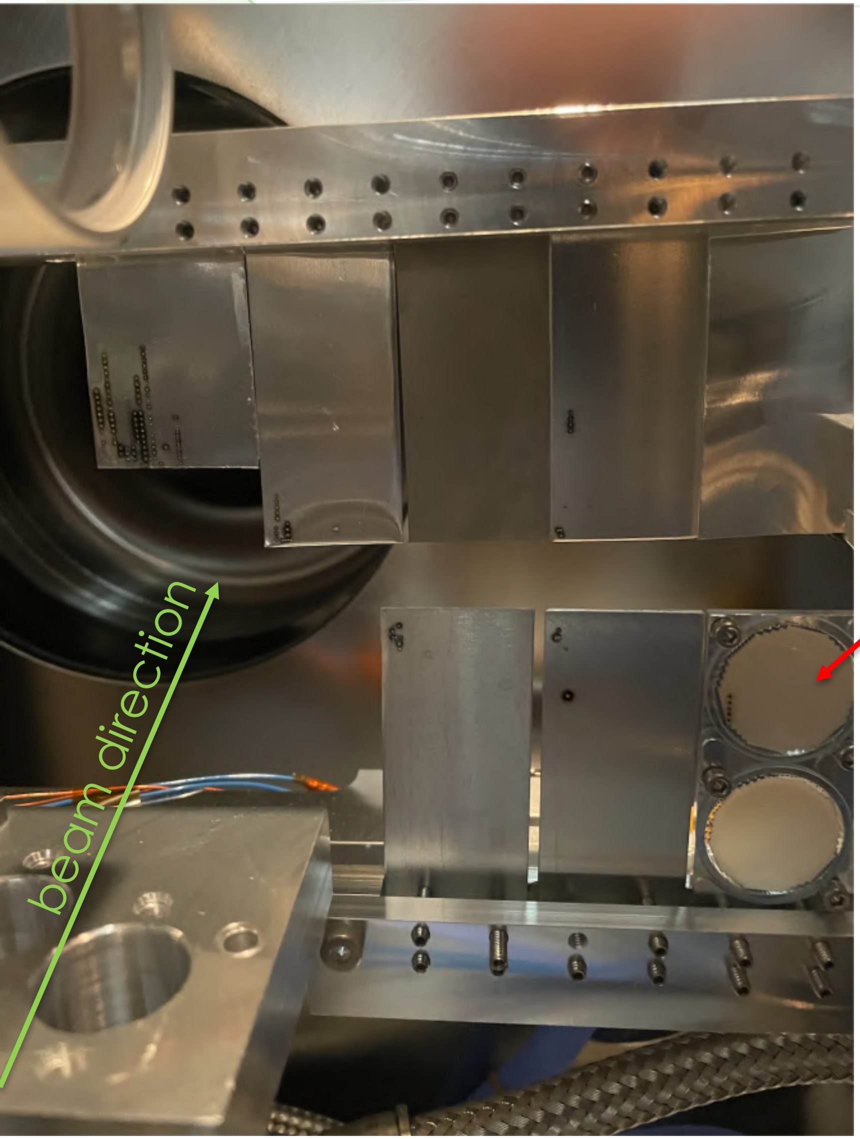


Self-modulation in nanotubes

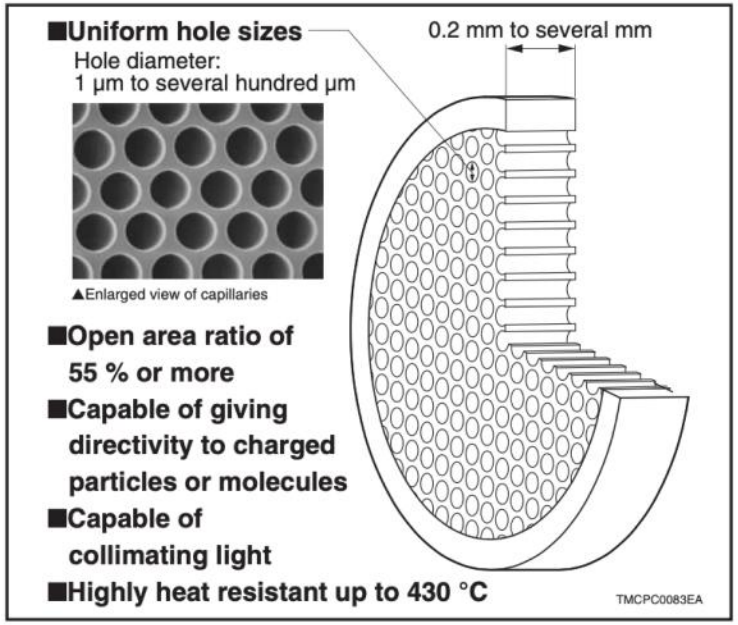


R. Ariniello, et al. "Channeling Acceleration in Crystals and Nanostructures and Studies of Solid Plasmas: New Opportunities." *arXiv preprint arXiv:2203.07459* (2022).

The target installed at FACET-II



Nano tubes

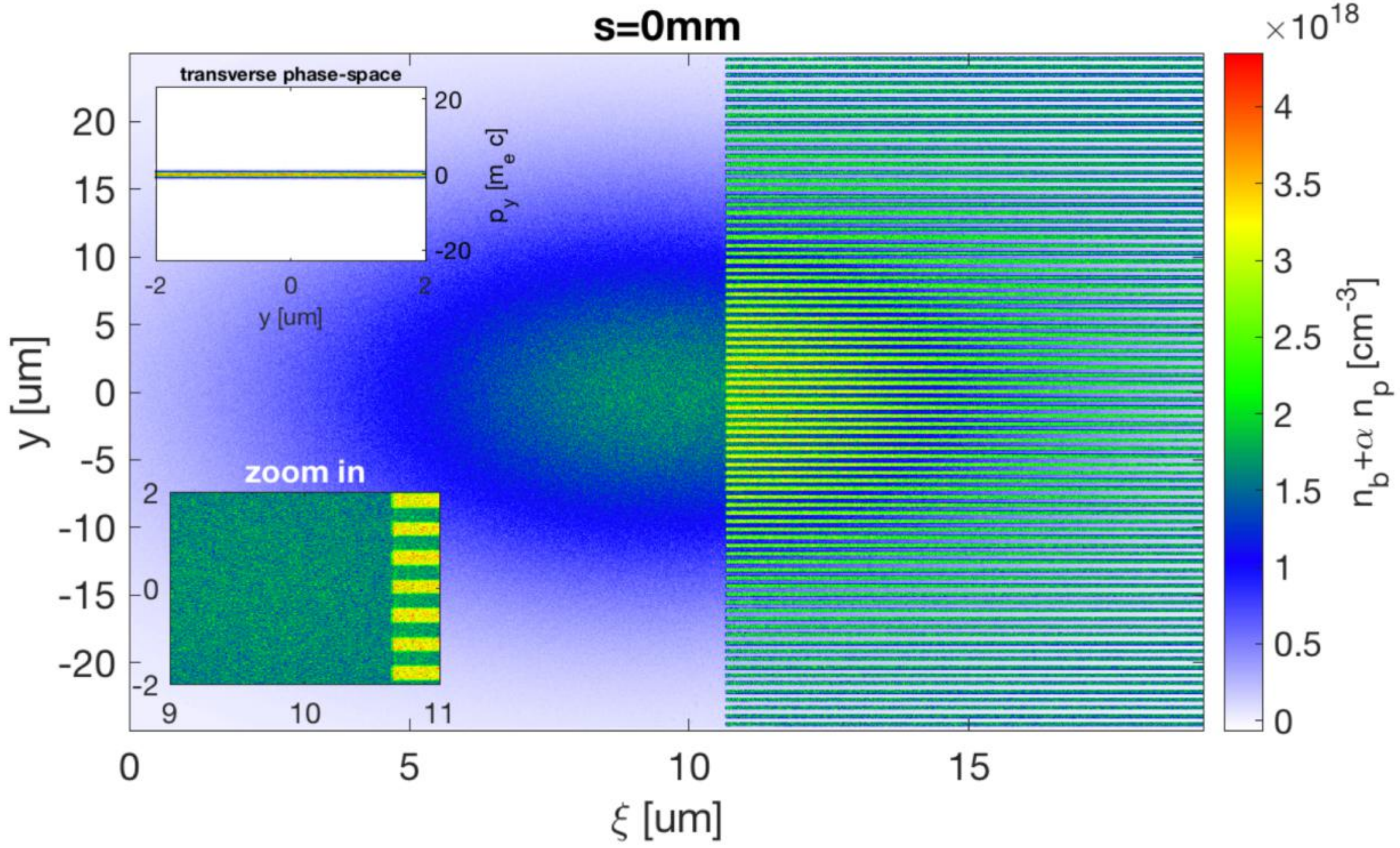


- Installed sample: 1-mm thick, 6 micron-diameter nanotubes made in lead glass
- Typical electron beam parameters:
  - Several kA current
  - Ca. 10 micrometer spot size

Science goals of E-336

- Demonstrate feasibility of the study of beam-nanotarget interaction and of beam-induced wakefields in nanotargets
- Observation of electron beam nano-modulation
- Observation of betatron X-ray radiation
- Confirmation of simulation models

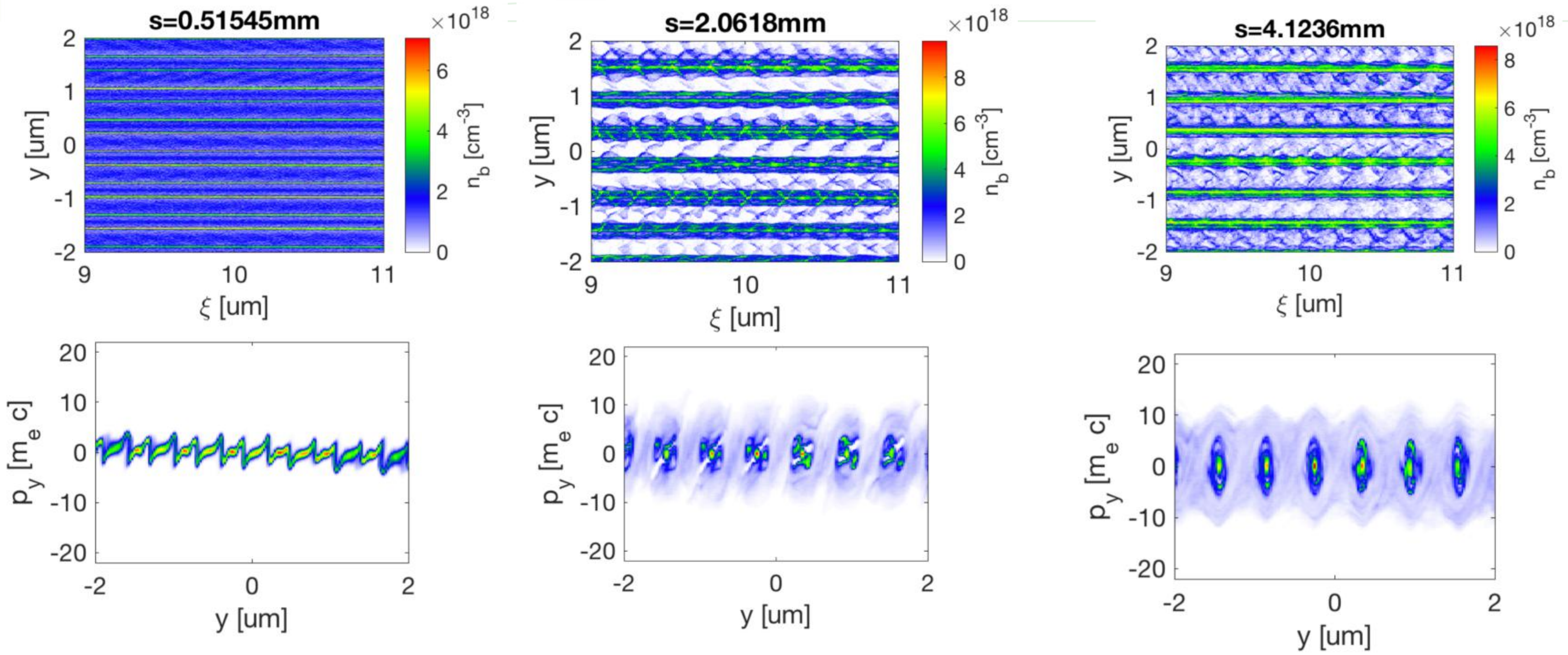
Pre-ionized nanotubes at FACET-II



Beam parameters
2 nC
10 GeV
10 μm rms $\sigma_{\parallel}$
$d = 300$ nm
$n_p = 10^{24}$ cm^{-3}

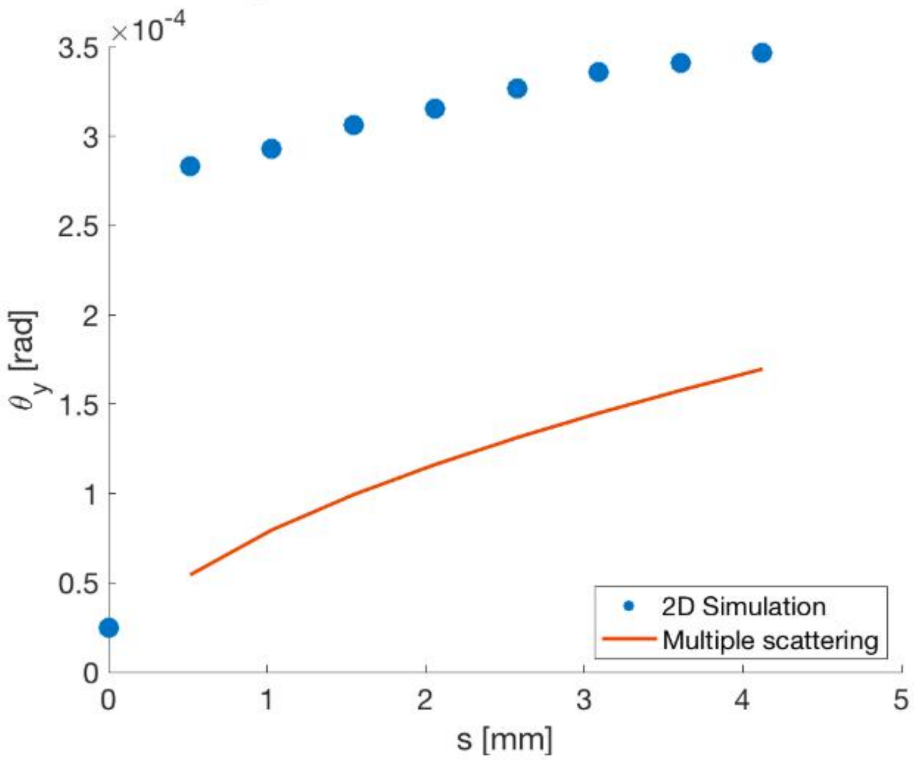
- Simulation study with achievable beam parameters
- Electron beam overfills nanotube array

Pre-ionized nanotubes



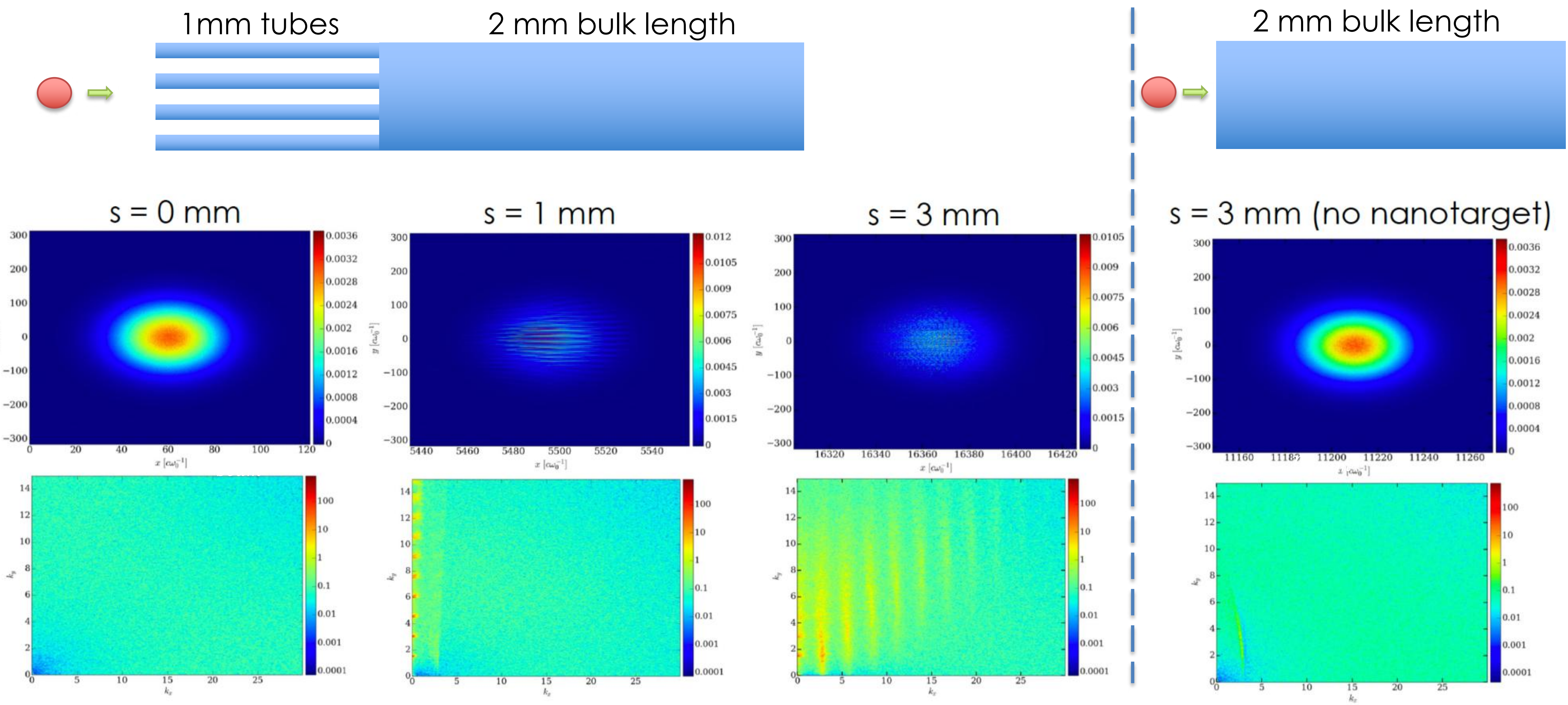
- Strong transverse modulation in charge density High-resolution
- Transverse ‘microbunching’ in the vacuum gaps.

Pre-ionized nanotubes



- Divergence factor 3-5 higher than expected from only multiple scattering
- Ideal as experimental observable

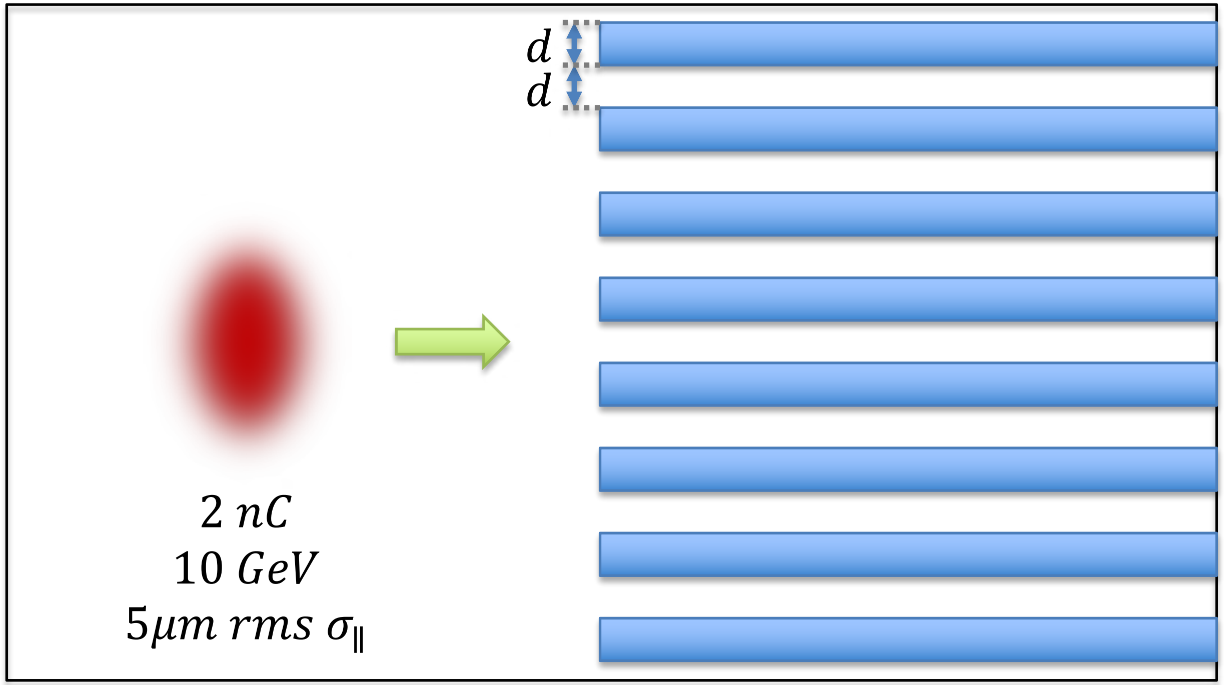
Simulation of tubes in pre-ionized Alumina



Simulation of tubes in Alumina and Silica with ionization

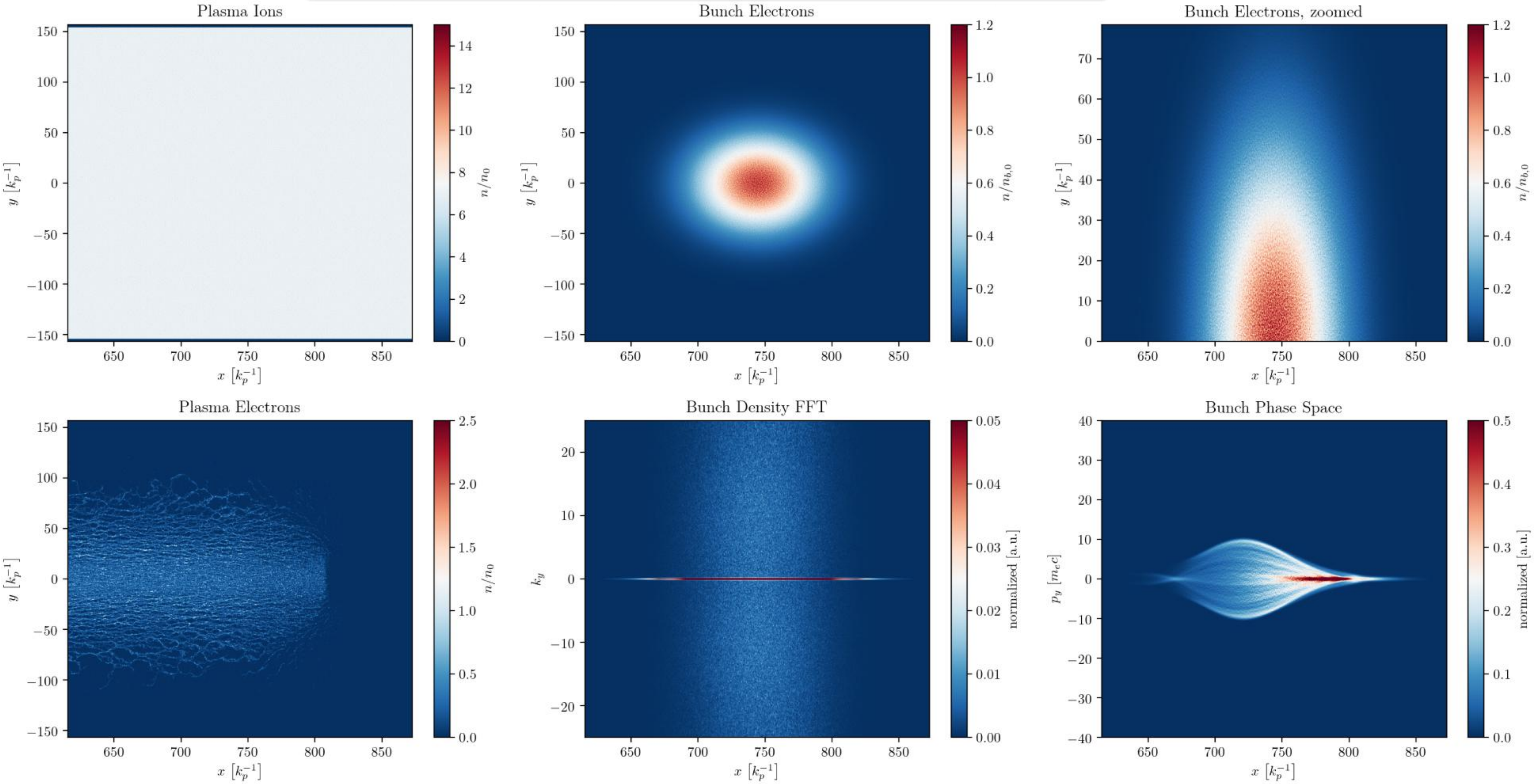
2D simulations parameters

- Bunch radius
  - $\mathbf{5\ \mu m}$
- Nanotube diameter
  - $\mathbf{2000\ nm}$
  - $\mathbf{200\ nm}$
  - $\mathbf{20\ nm}$ (beam clipped)
- Nanotube material
  - **Silica**
    - $11.7\ eV$,
    - $\lambda_p = 270\ nm$ and
    - $k_p^{-1} \approx 40\ nm$ for full 1st ionization
  - **Alumina**
    - $10.5\ eV$
    - $\lambda_p = 180\ nm$ and
    - $k_p^{-1} \approx 30\ nm$ for full 1st ionization

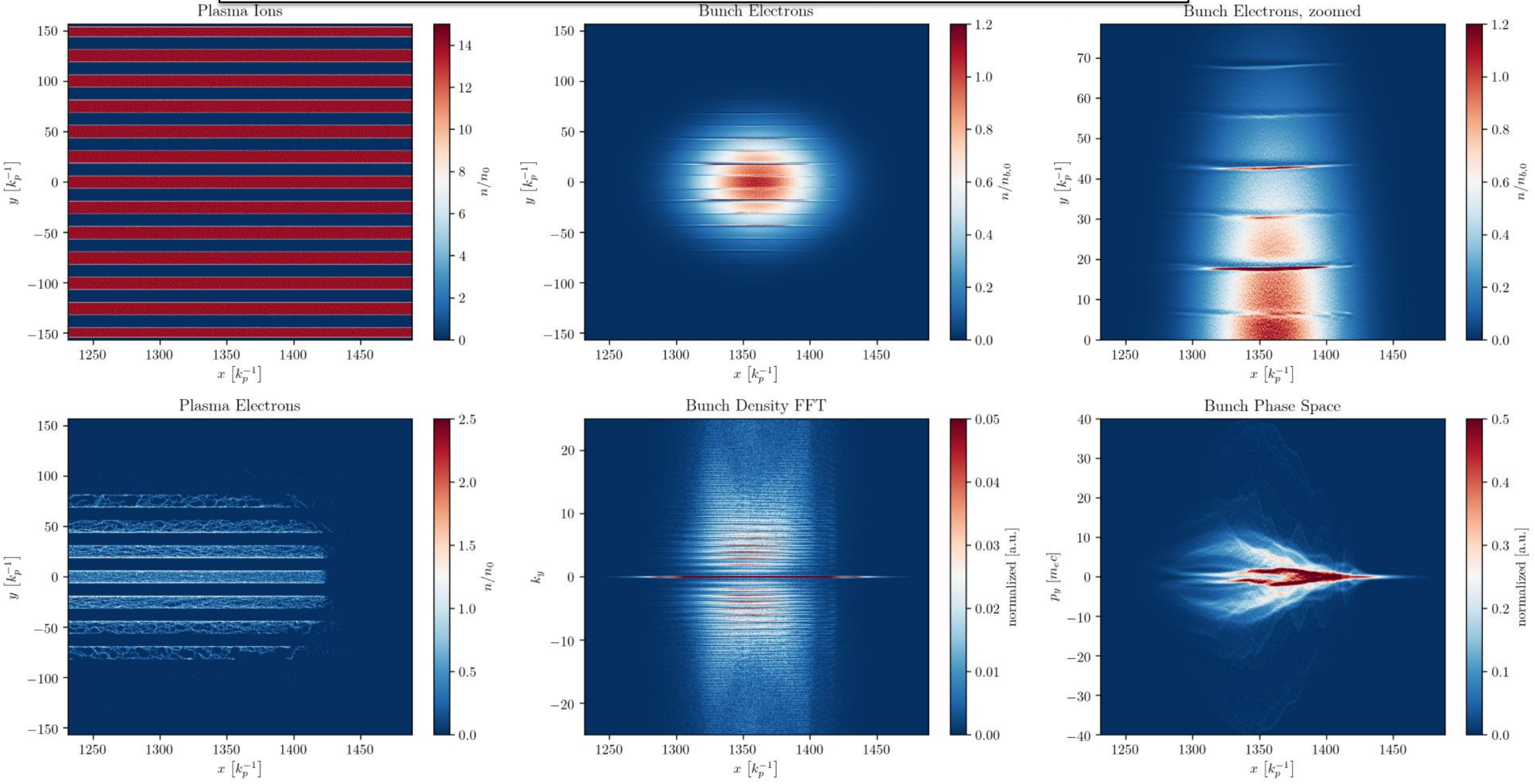


Transverse cell size:
- $4\ nm$ ($20\ nm$ sim)
- $40\ nm$ ($200\ nm, 2000\ nm$)

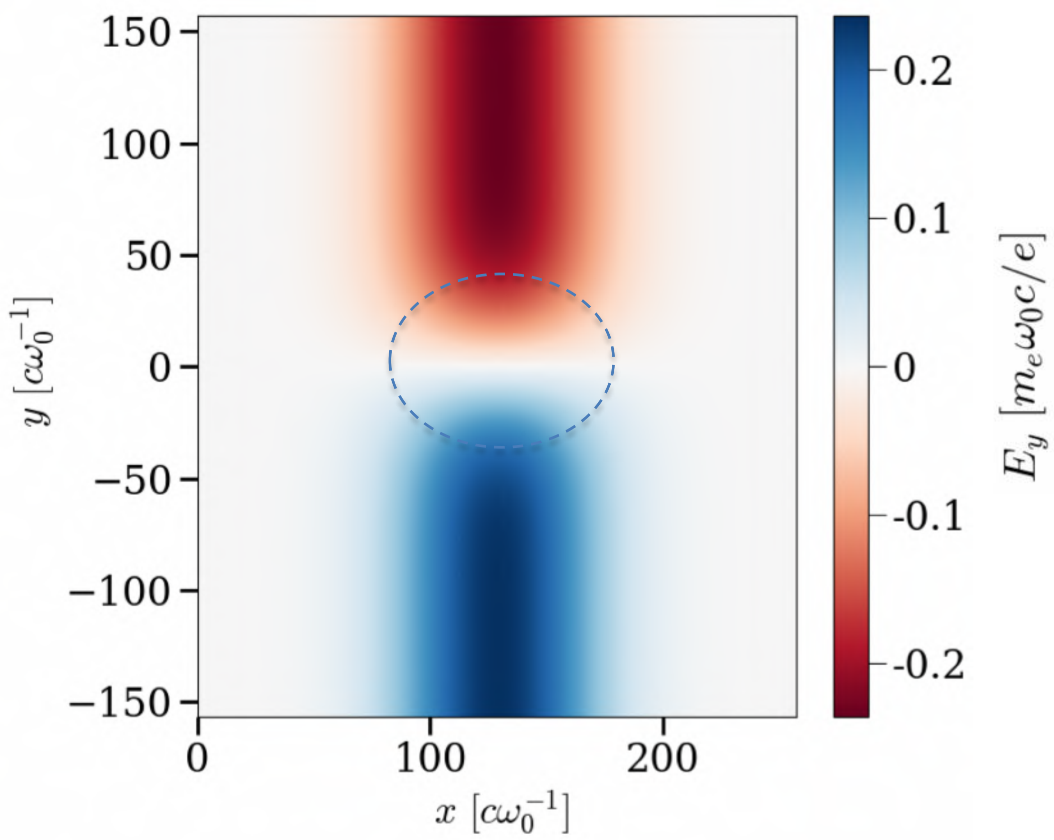
Alumina Bulk σ_b=5 um z ~ 140 um

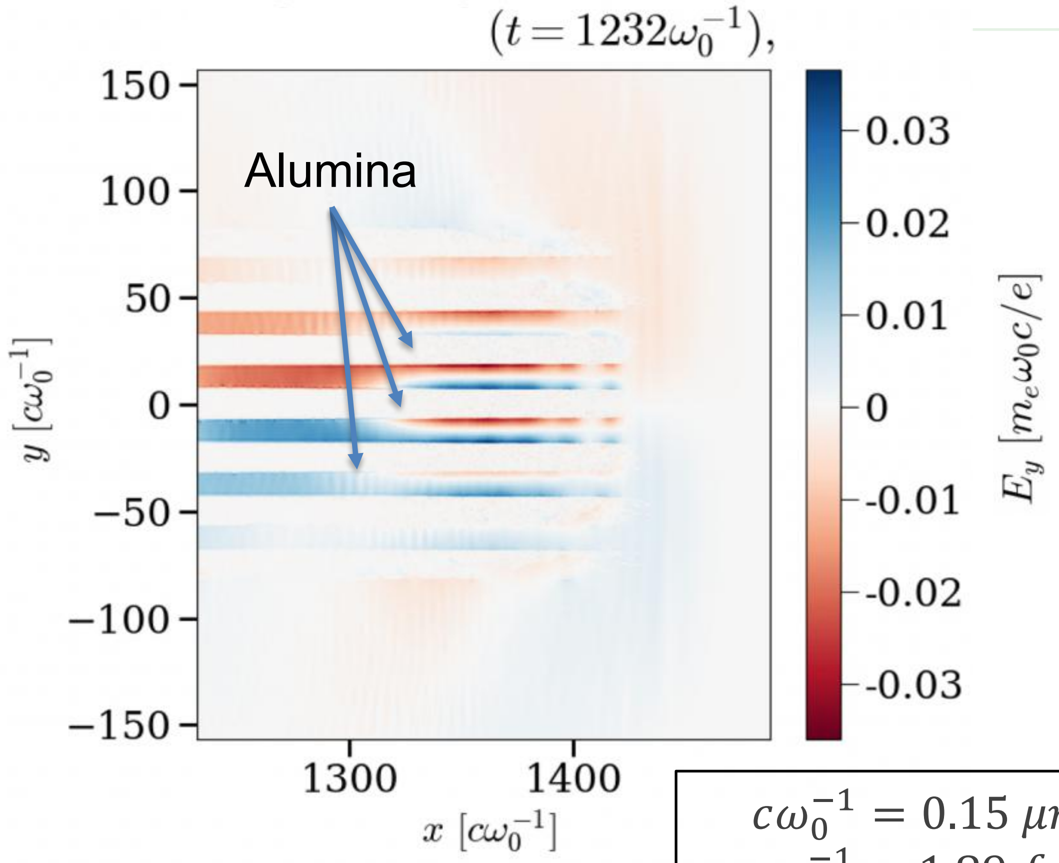


Alumina d=2000nm σ_b=5 µm z ~ 240 µm



Alumina 2000nm σ_b=5μm

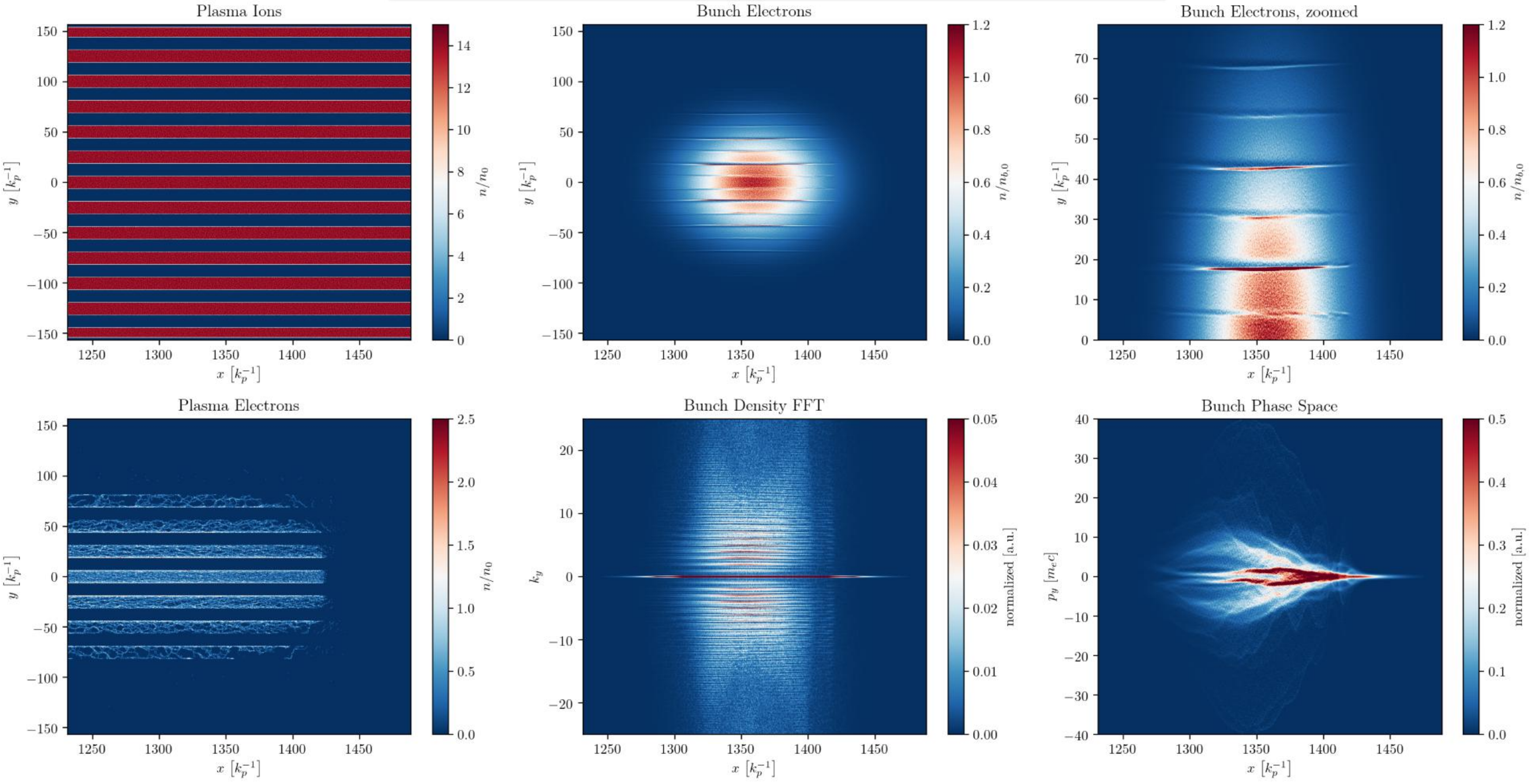




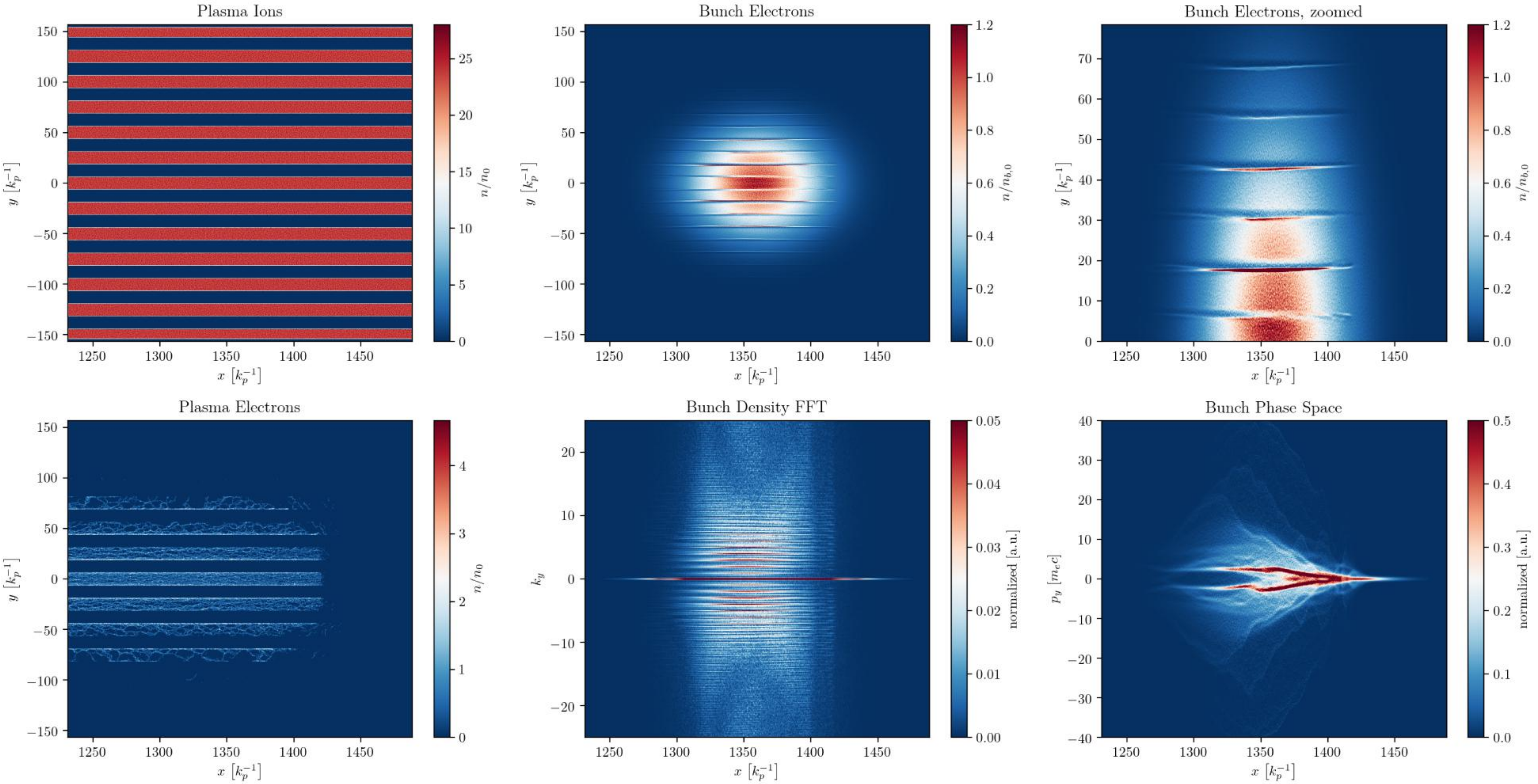
$$c\omega_0^{-1} = 0.15\ \mu m$$
$$\omega_0^{-1} = 1.89\ fs$$
$$\frac{m_e\omega_0 c}{e} = 3.2\ TV/m$$

- Beam self field ionizes the solid-density material
- Propagation of self-fields into the bulk shielded by ionized surface plasma

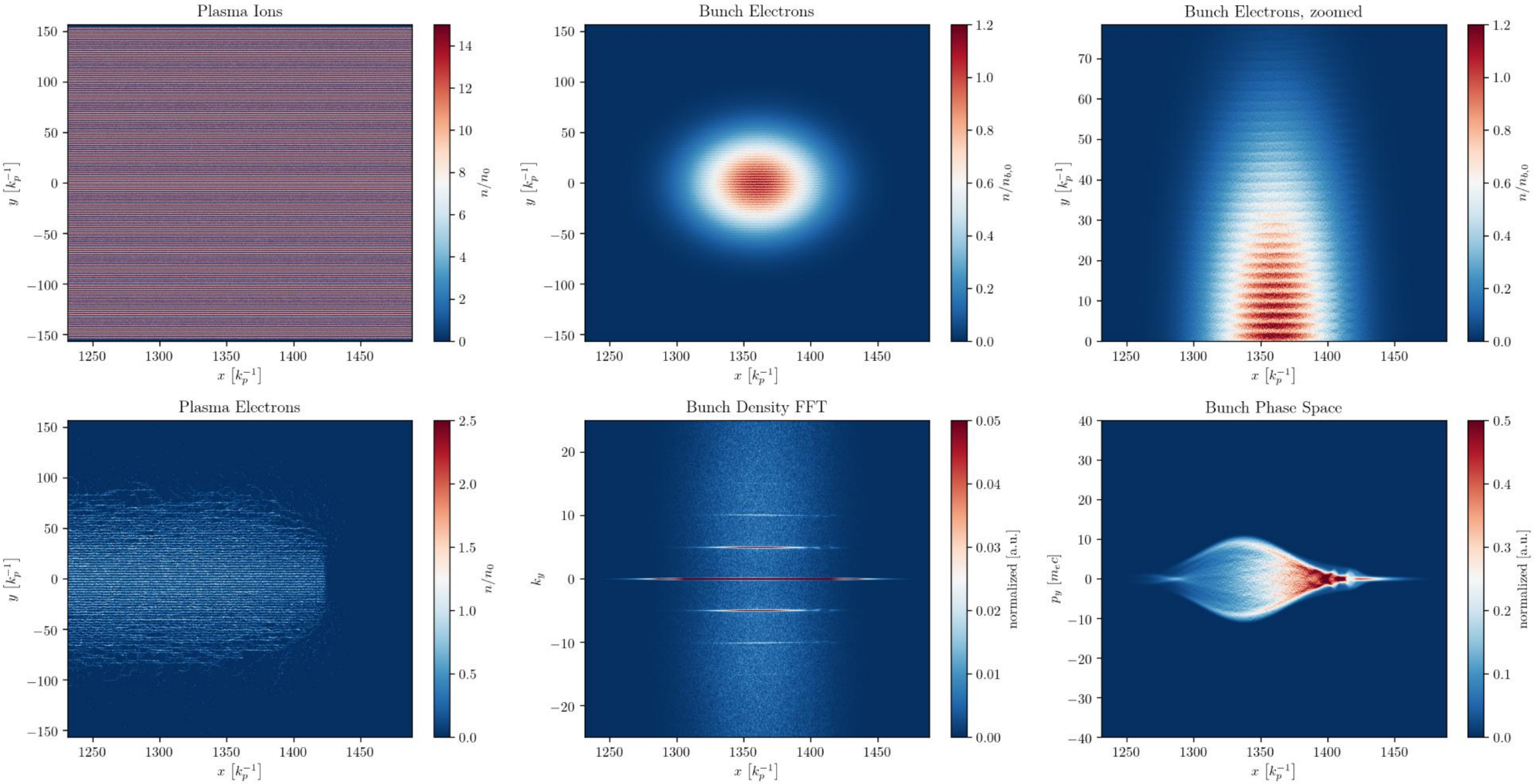
Alumina 2000nm σ_b=5 μm z ~ 230 μm



Silica 2000nm σ_b=5 μm z ~ 230 μm



Alumina 200nm σ_b=5 μm z ~ 230 μm



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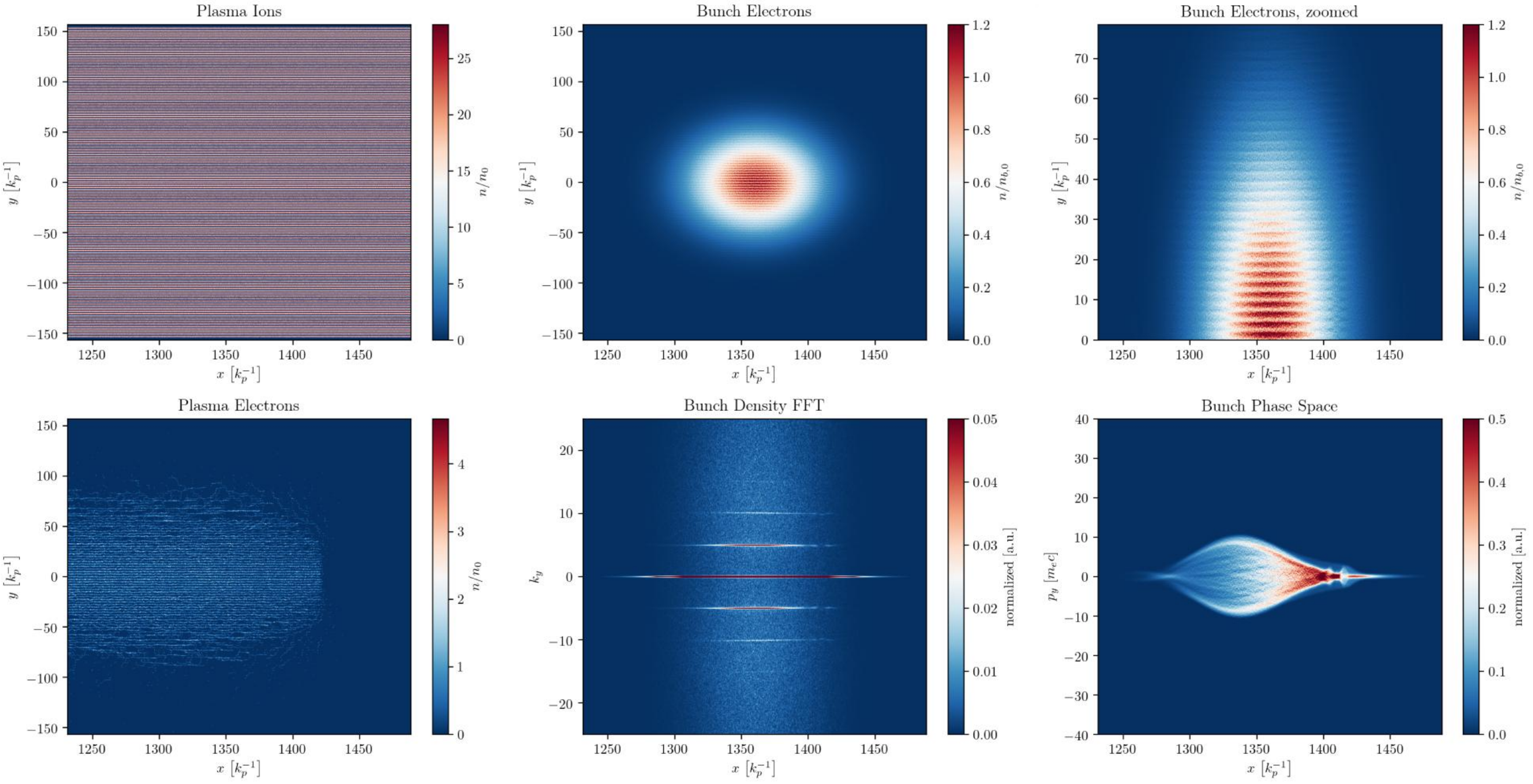

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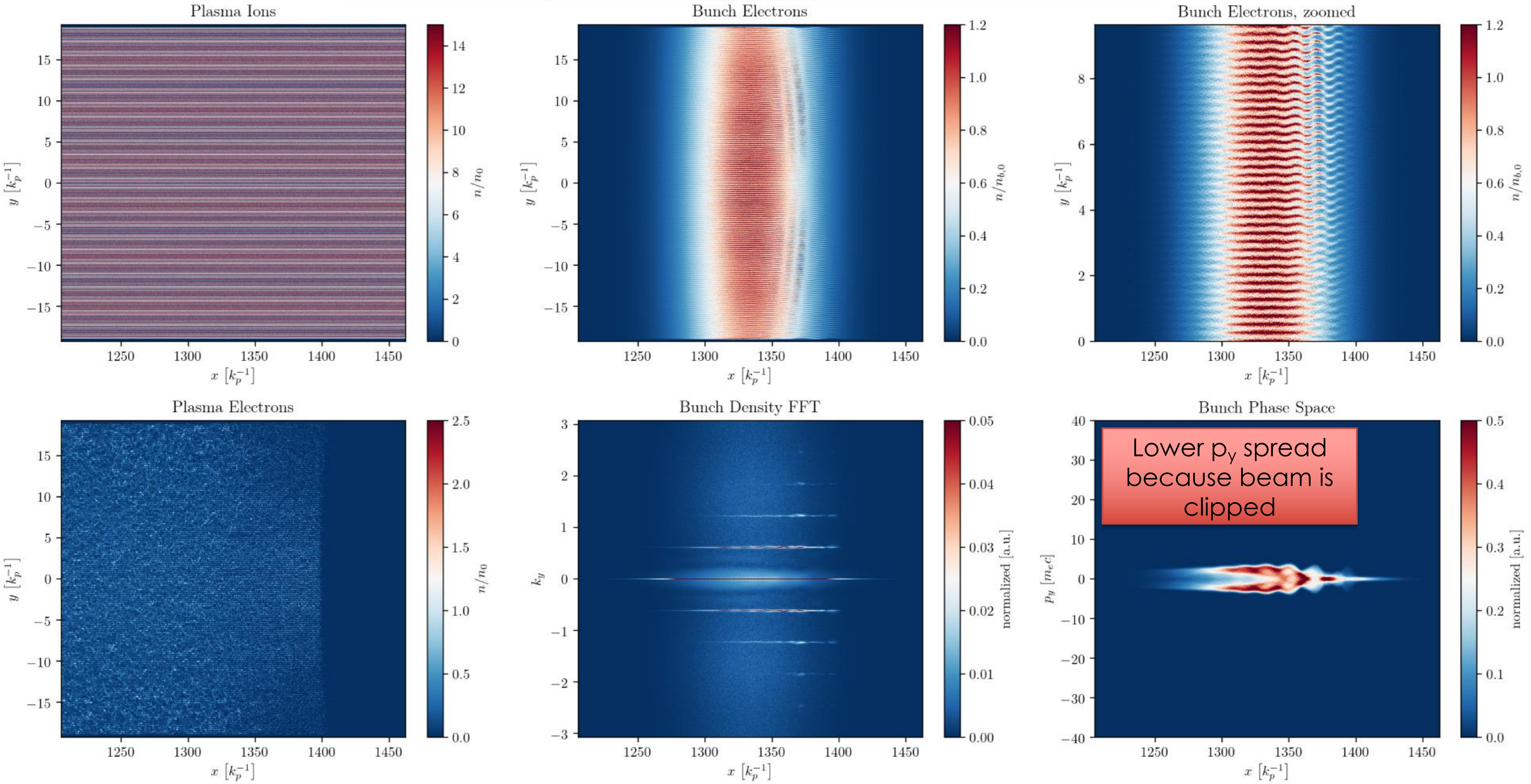
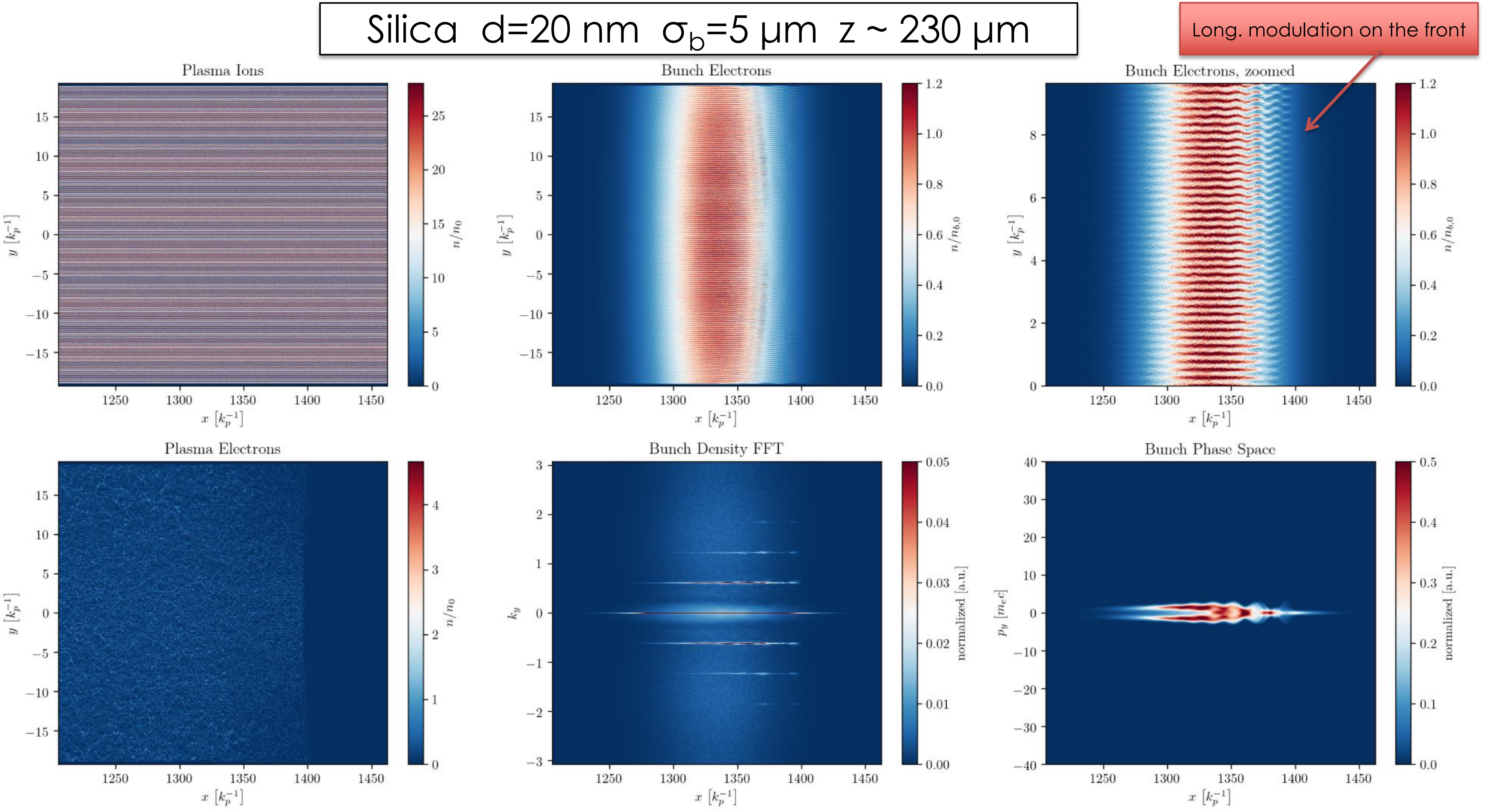


Silica d=20 nm σ_b=5 µm z ~ 230 µm



Longitudinal modulation in $d = 20\ \mathrm{nm}$ case

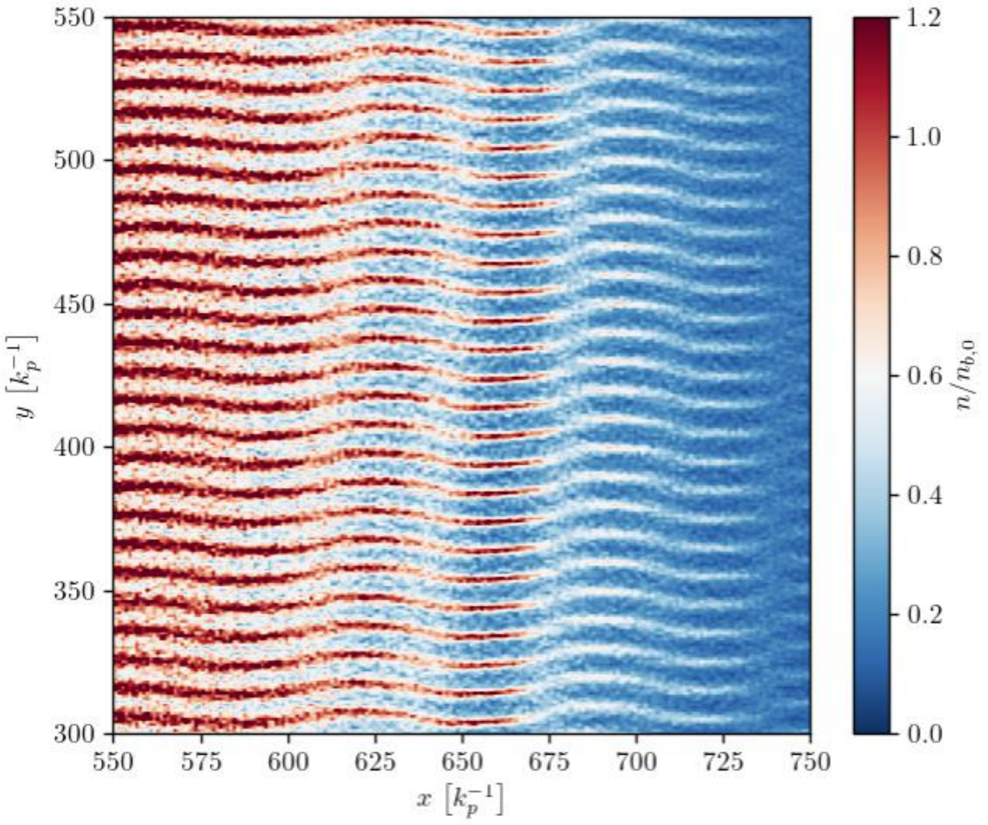
Long. modulation from wakefields?

Modulation has $\lambda_{mod} \approx 11\ \mu\mathrm{m}$.
For fully ionized first level of bulk $\lambda_{bulk} = 175\ \mathrm{nm}$

However, Al only partially ionized with $\mathrm{n} = 8.5e^{-3}\ n_{Al}$

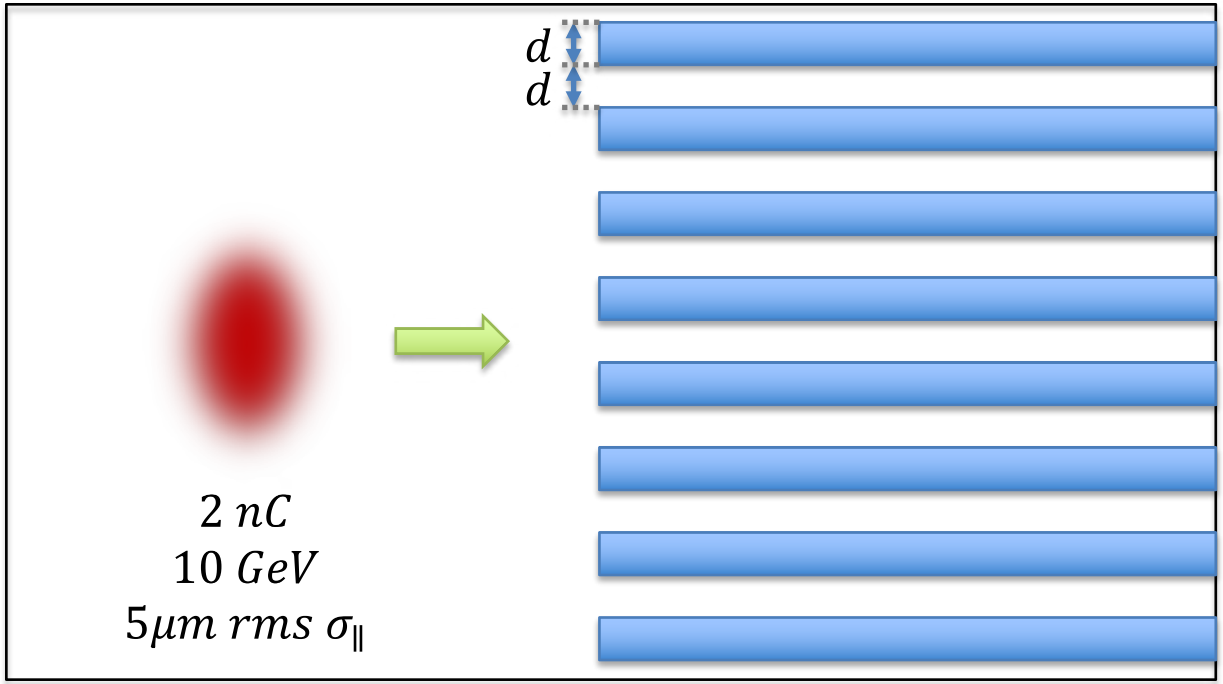
- Corresponds to $\lambda = 1.8\ \mu\mathrm{m}$

Observed modulation does not correspond to the plasma frequency of the ionized plasma.



Comparison pre-ionized vs. neutral alumina

- Bunch radius
  - $\mathbf{5\ \mu m}$
- Nanotube diameter
  - $\mathbf{2000\ nm}$
  - $\mathbf{1000\ nm}$
  - $\mathbf{500\ nm}$
  - $\mathbf{200\ nm}$
  - $\mathbf{100\ nm}$
- Nanotube material
  - **Alumina (neutral)**
    - $10.5\ eV$
    - $\lambda_p = 180\ nm$ for full ionization
  - **Alumina (pre-ionized)**
    - 1st level fully ionized



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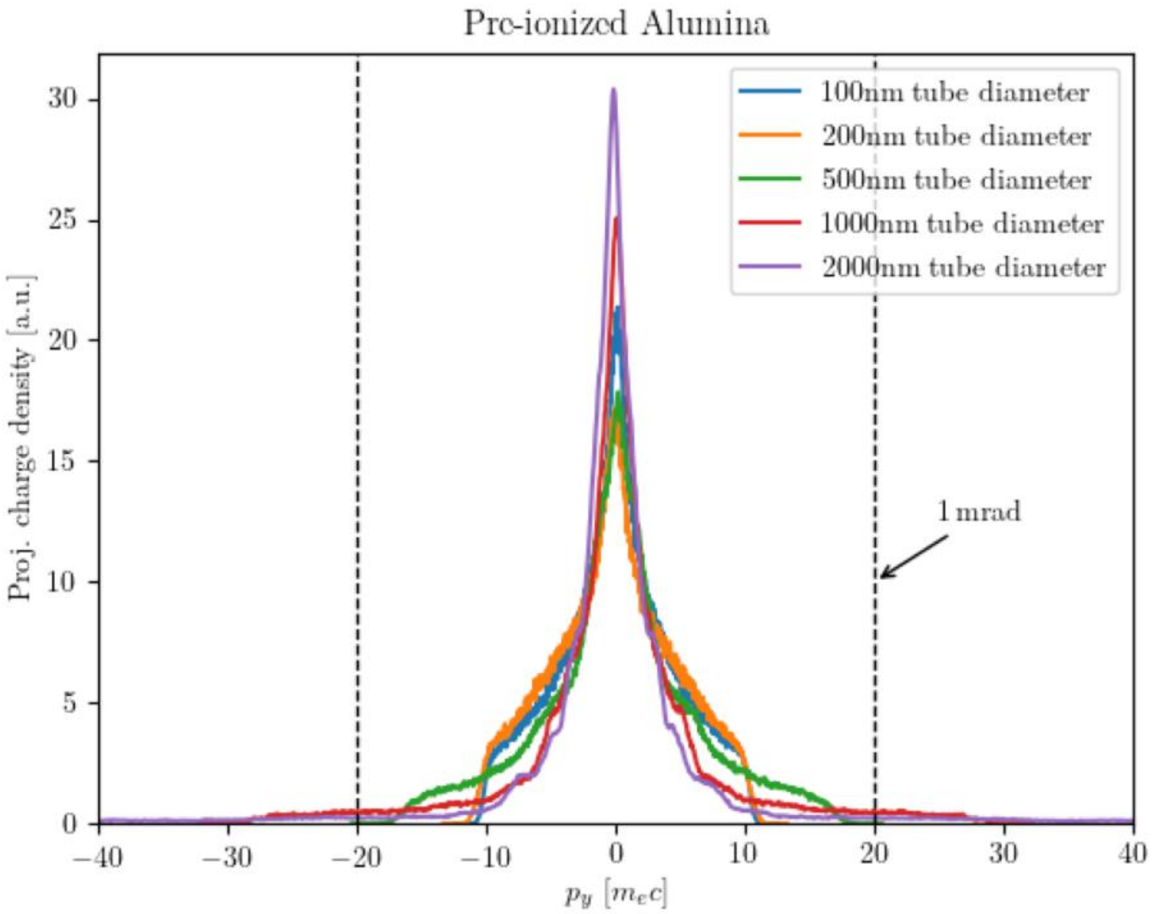
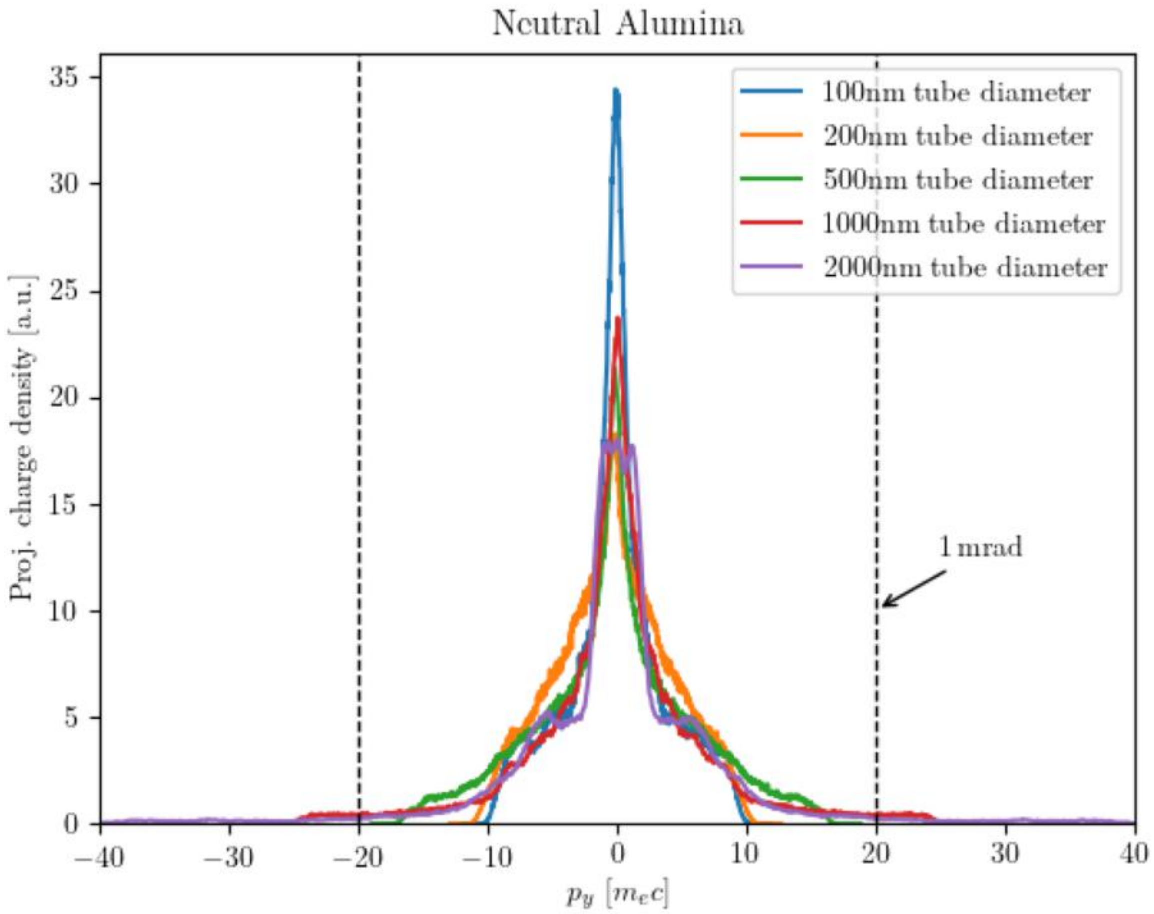
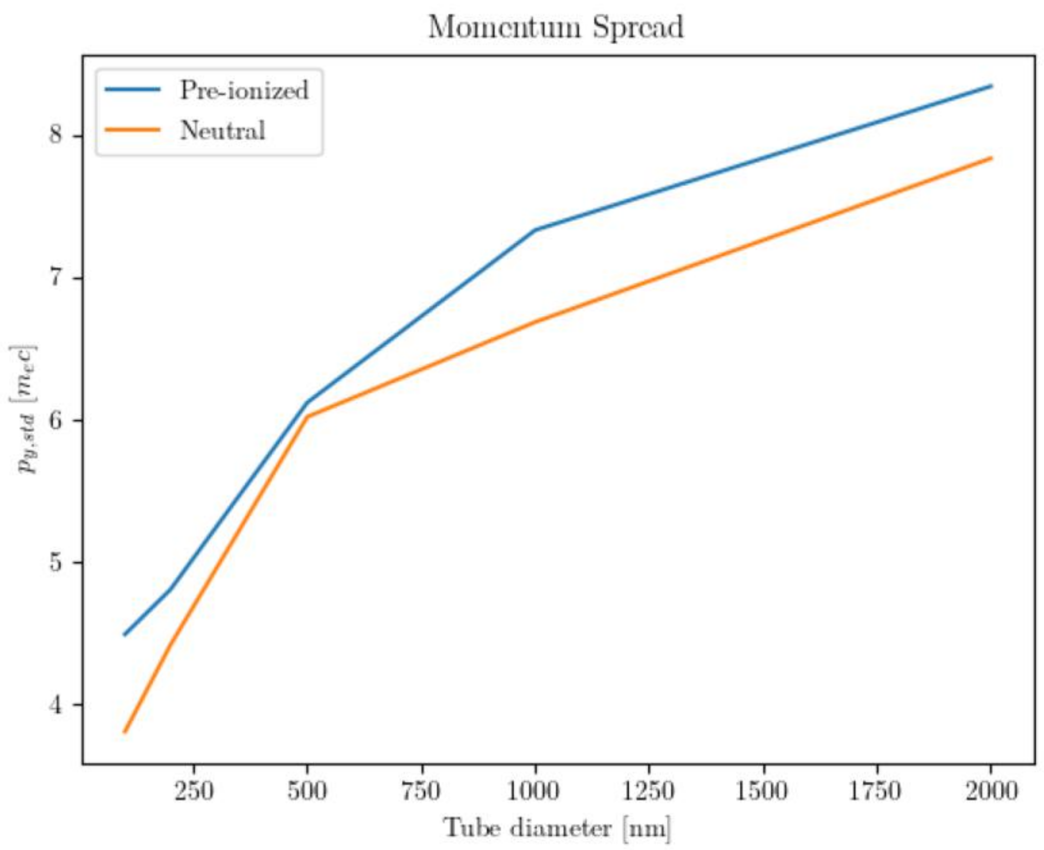




Larger diameter tubes lead to

- higher transverse momentum but less particles are affected
- Less effect on the core of the beam

Comparison pre-ionized vs. neutral alumina



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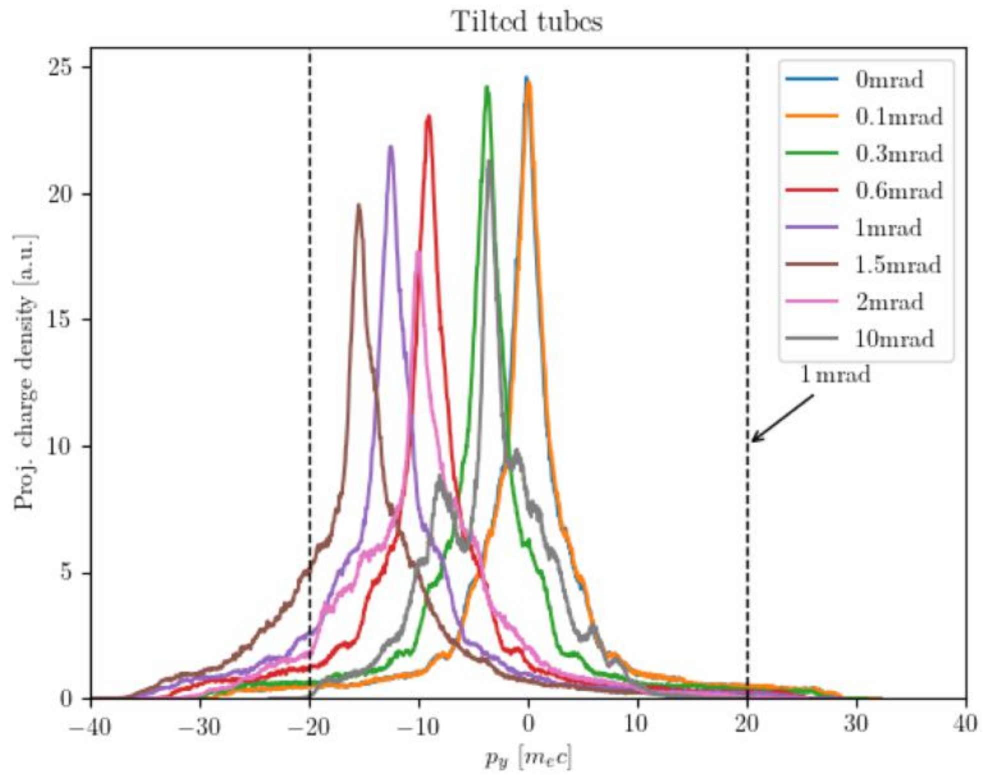
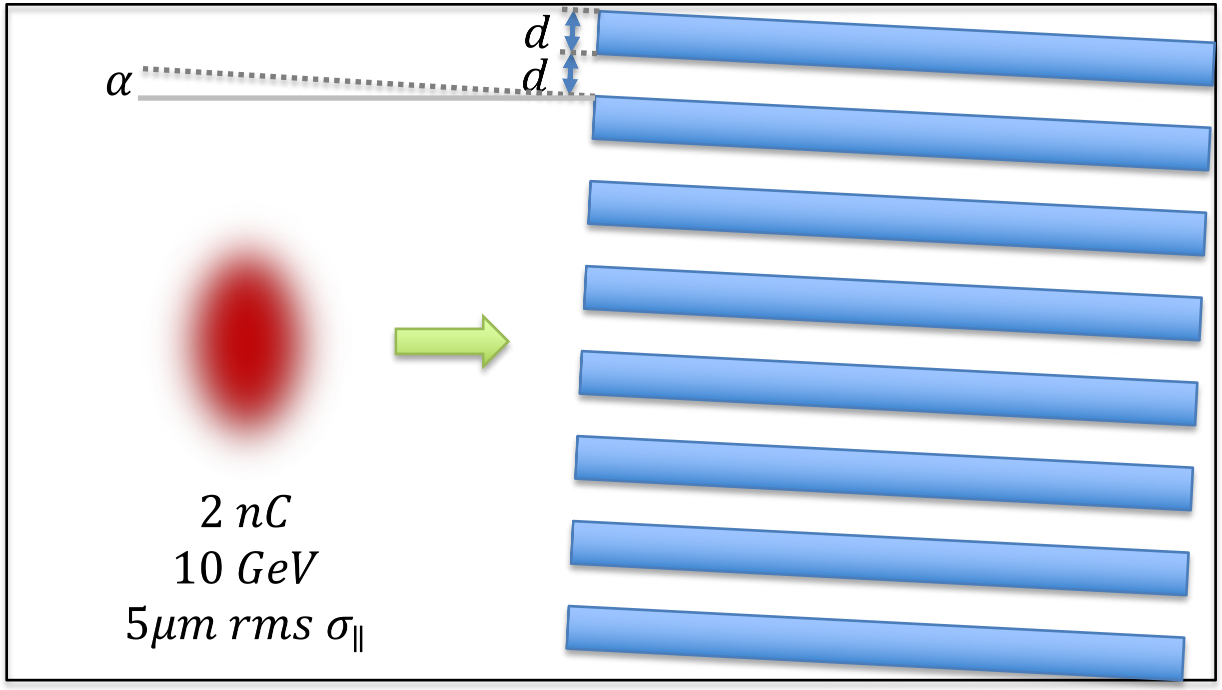
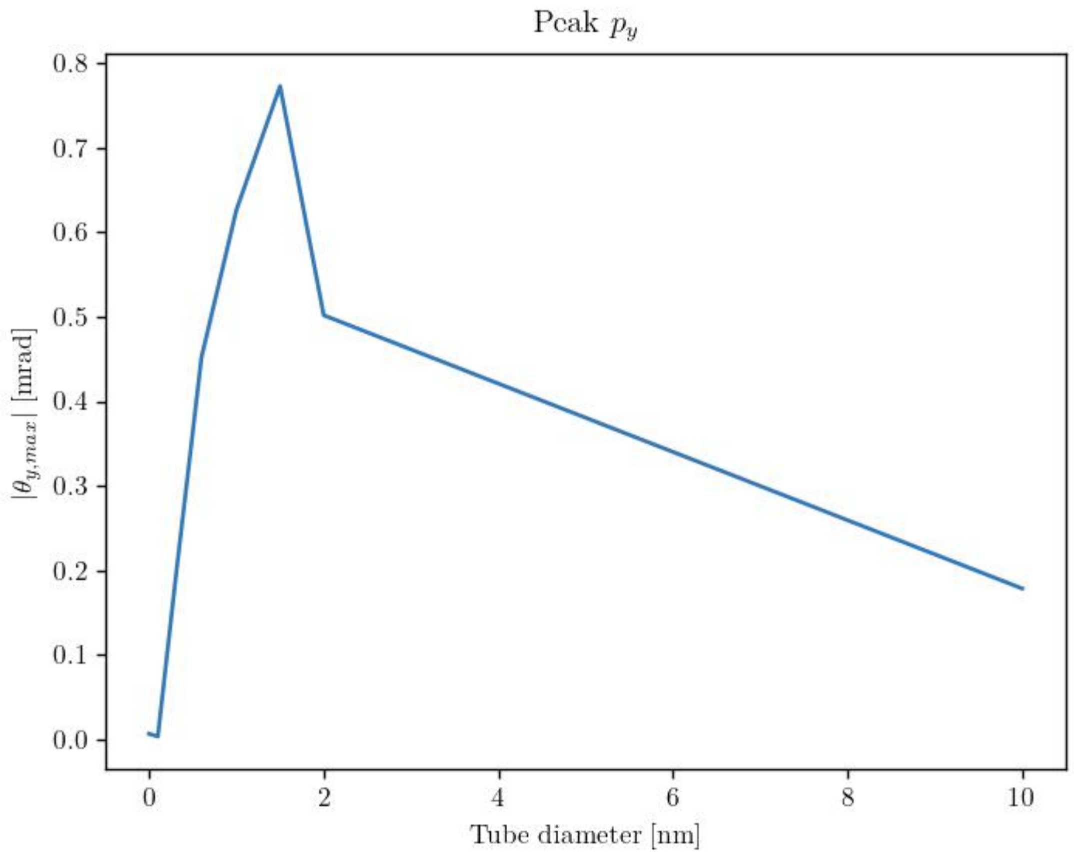
Tilted tubes

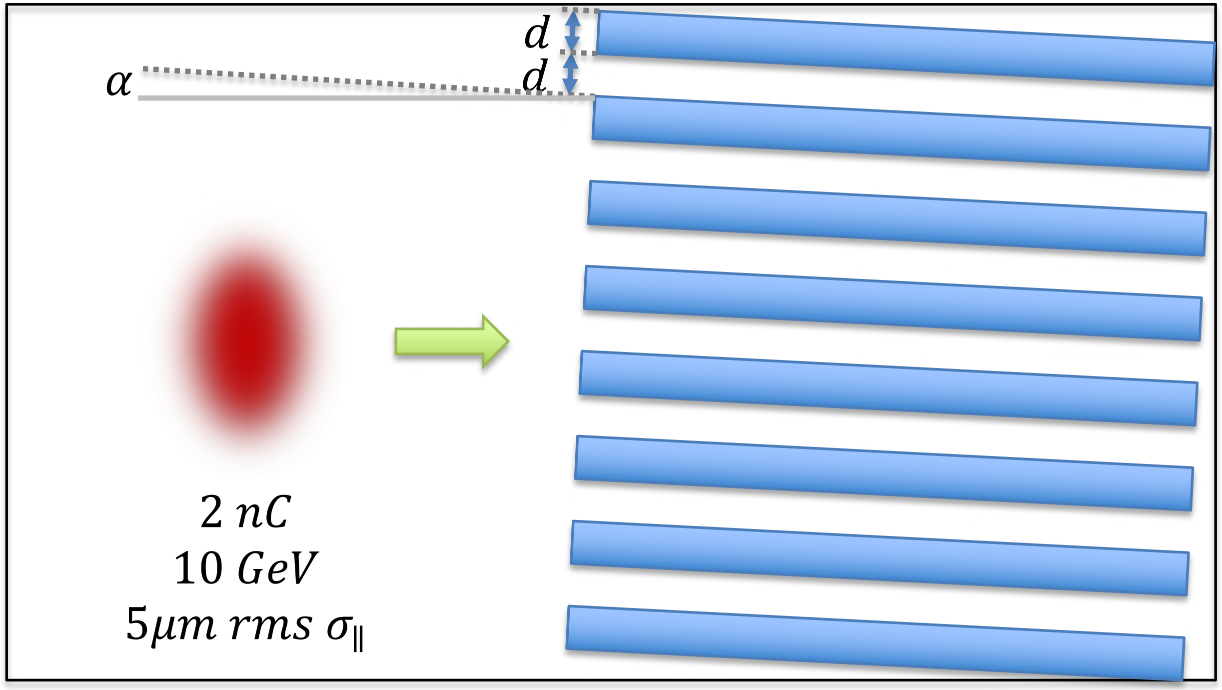




Tilting the target leads to a general kick of the beam

Tilted tubes





Kicks are easy to observe on electron spectrometer as well as x-ray diagnostics

Summary

- First simulation study performed to guide experimental observables of the E-336 experiment
    - Beam-divergence
    - Beam-deflection
    - Transverse nano-modulation
    - X-ray radiation
- More effects such as collisions will need to be implemented
- Explanation of observed longitudinal modulation
- Experimental data coming soon… stay tuned

Thank you for your attention