The Role of Ion Motion in Resonantly-Driven Accelerators

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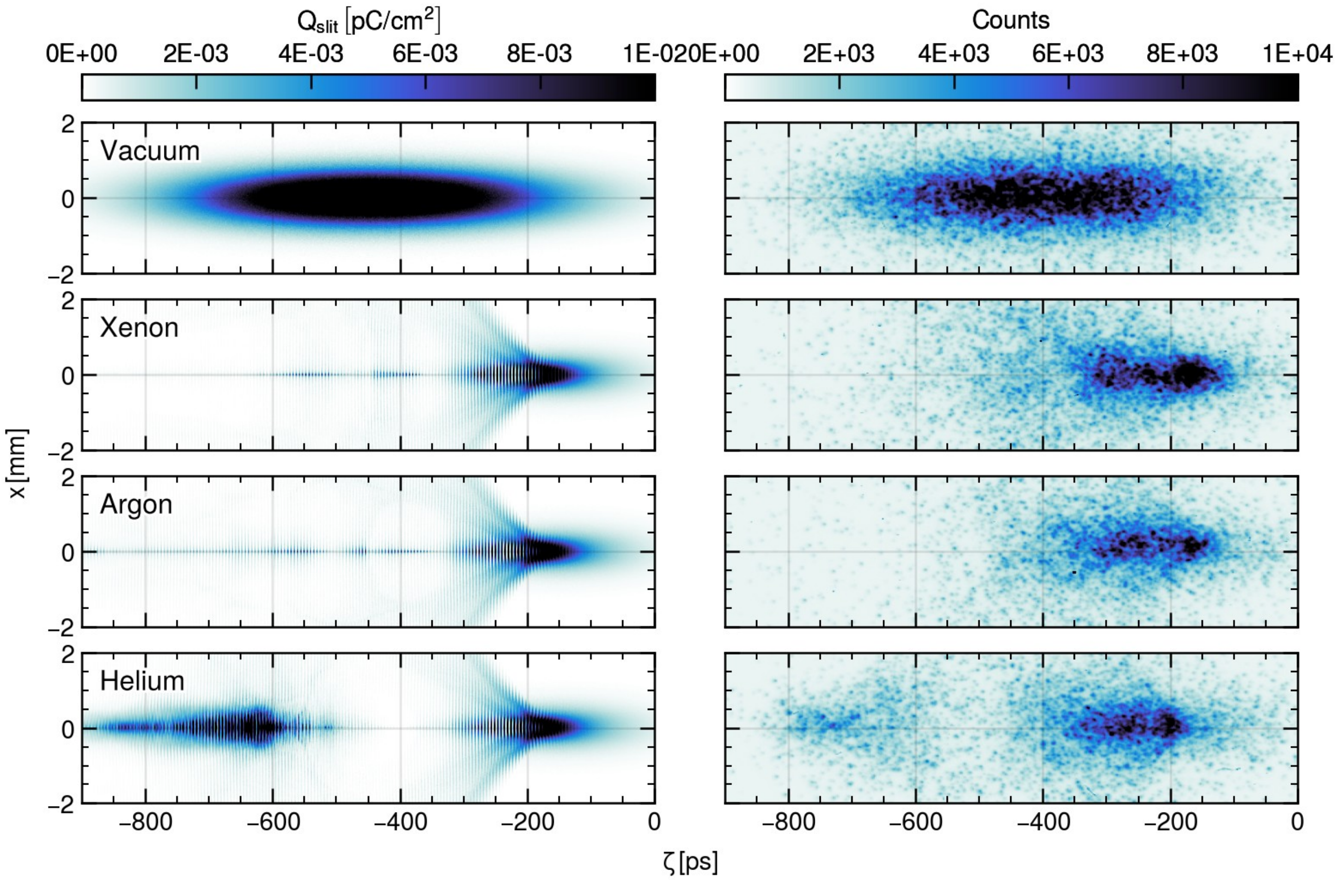
Motivation

Experimental and simulation results have shown in good qualitative agreemment that ion motion decreases the wakefield strength and stops the development of the self-modulation instability (SMI) towards the beam tail.

What is the dominant mechanism?

Simulation

Experiment by M. Turner, P.Muggli (AWAKE collaboration)

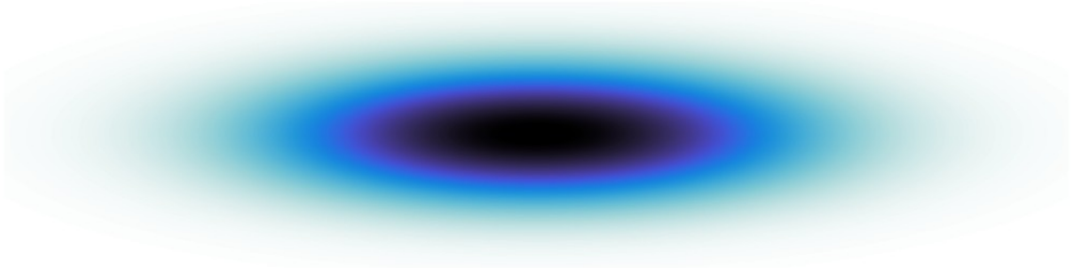


Motivation

Two Relevant Regimes

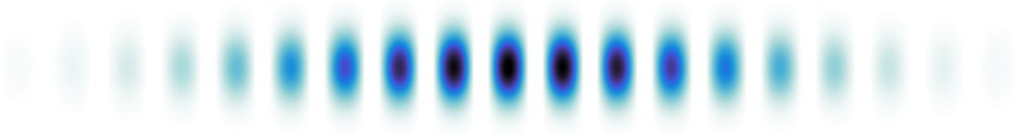
Chain of causality difficult to follow → Models help to deepen understanding

Long beam



- Prior to SMI
- Wakefield grows from a seed
- Model: Short driver

Self-modulated beam



- After SMI
- Wakefield resonantly driven by microbunches
- Model: Premodulated beam

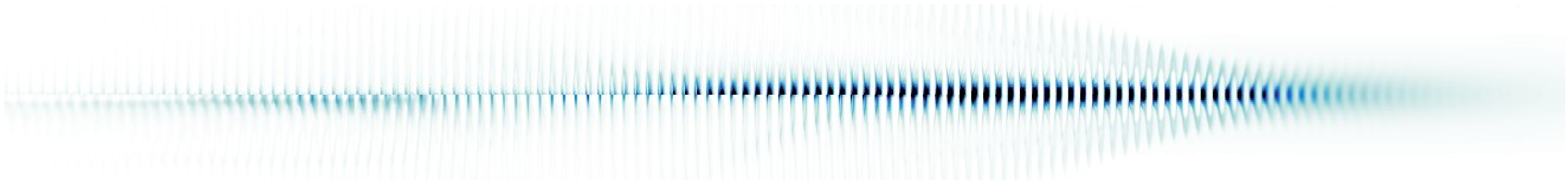
Structure

Motivation

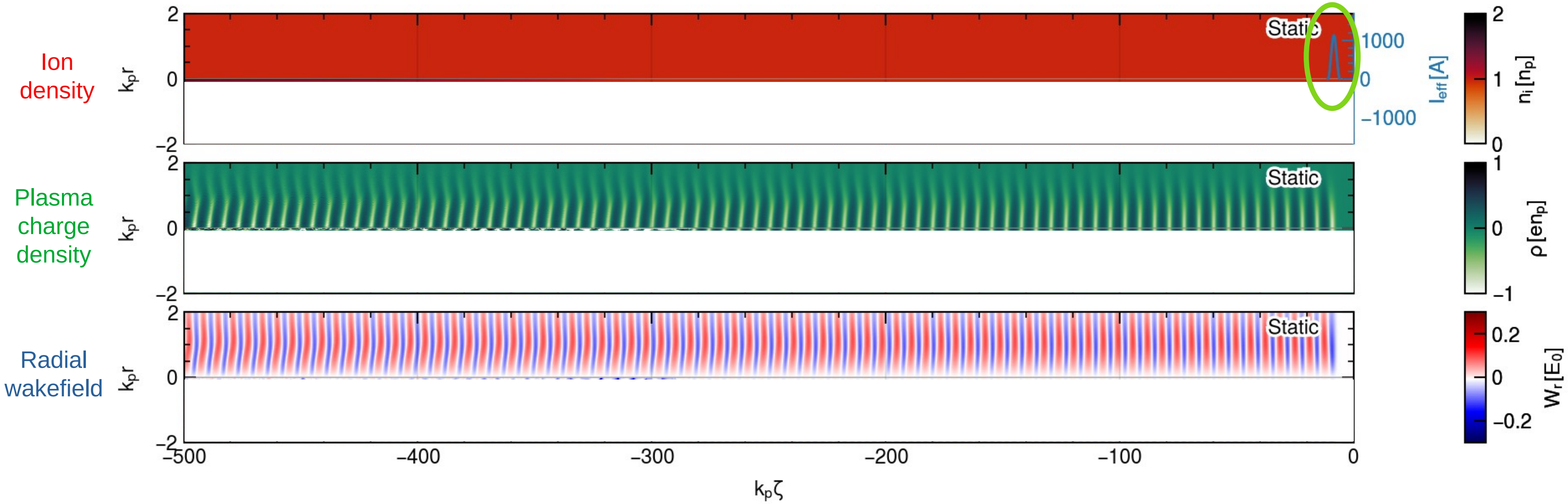
Dominant effect of ion motion for a …

- Short driver
- Premodulated driver
- Self-modulated driver

Conclusion

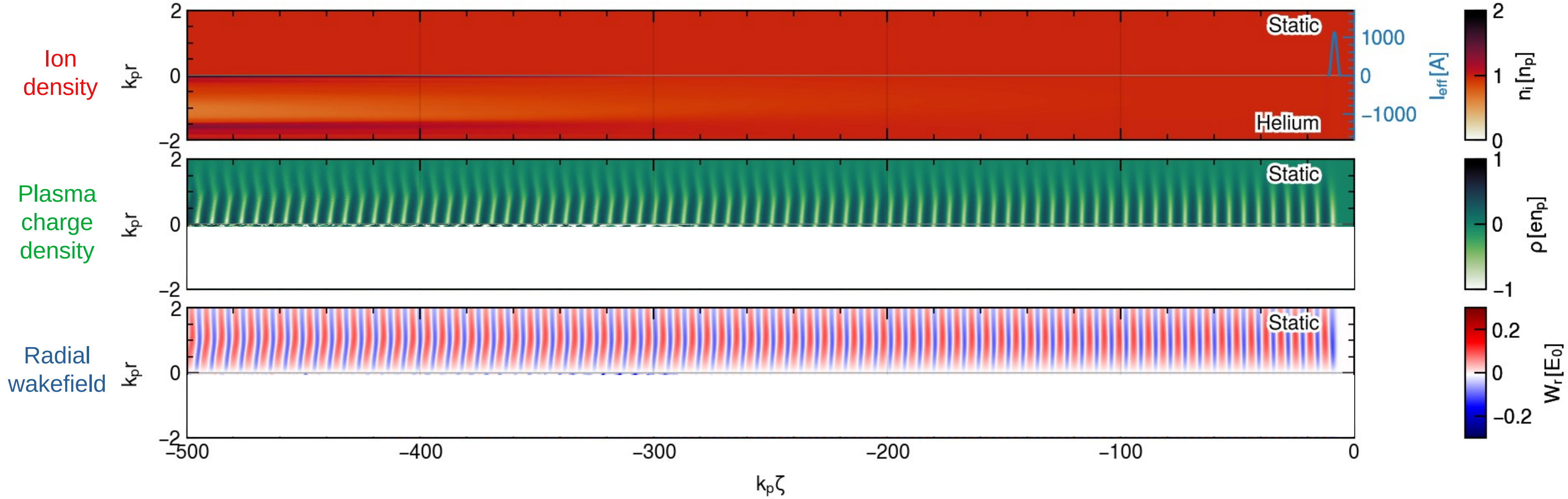


Short Driver



- Short, dense beam drives weakly relativistic electrostatic plasma response

Short Driver



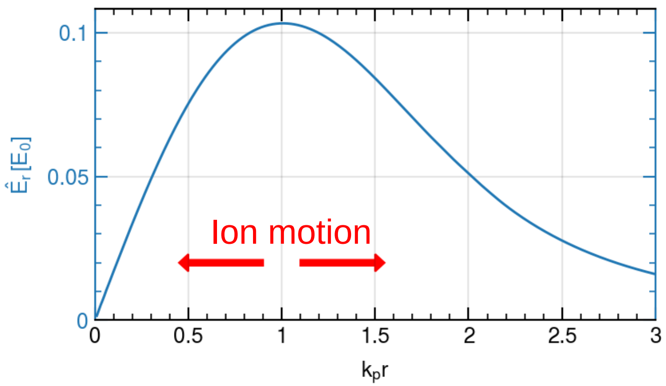
- Short, dense beam drives weakly relativistic electrostatic plasma response
- Plasma ions experience ponderomotive force of wakefields amplitude

Short Driver - Ponderomotive Force

Net motion of ions driven by radial gradient in wakefield components (F. Chen, 2018)

$$\boldsymbol{F}_p = -\frac{e^2}{4m_e\omega_p^2}\nabla_r\hat{\boldsymbol{E}}^2$$

Envelope of radial electric field



Ions with $k_pr<1$ pushed towards axis
Ions with $k_pr>1$ pushed outwards

Short Driver - Ponderomotive Force

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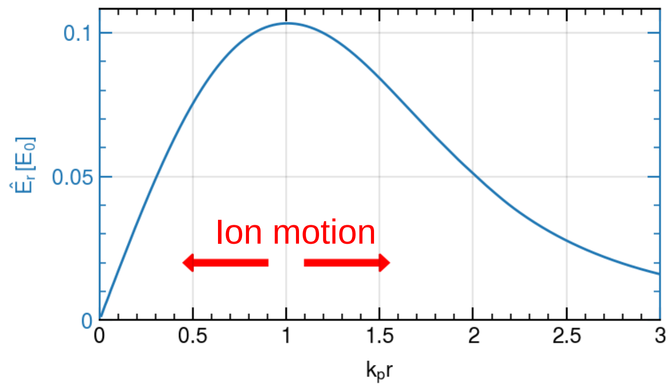

Ions with $k_p r<1$ pushed towards axis

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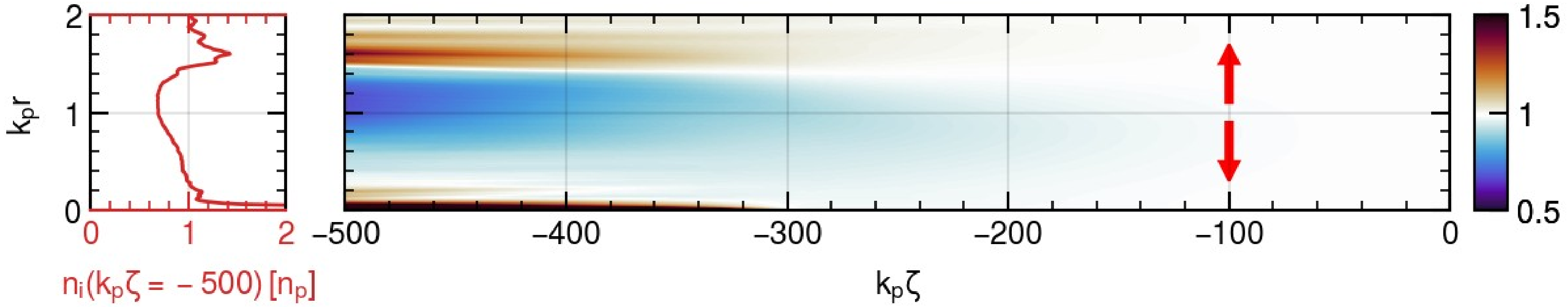
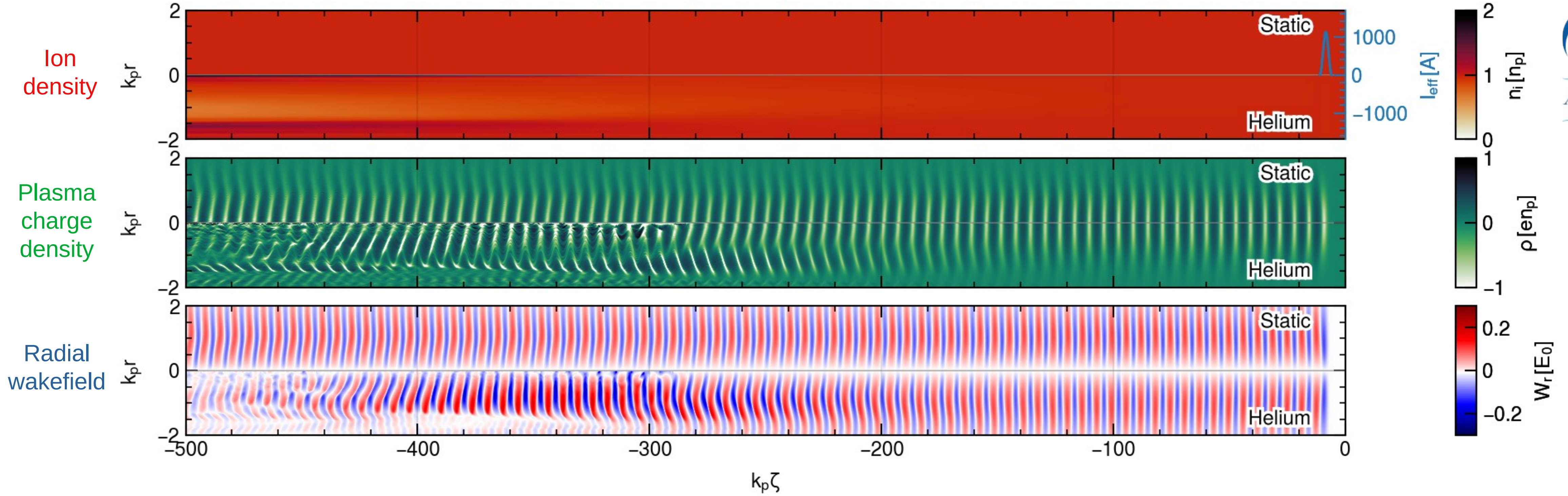


Ion density

Short Driver

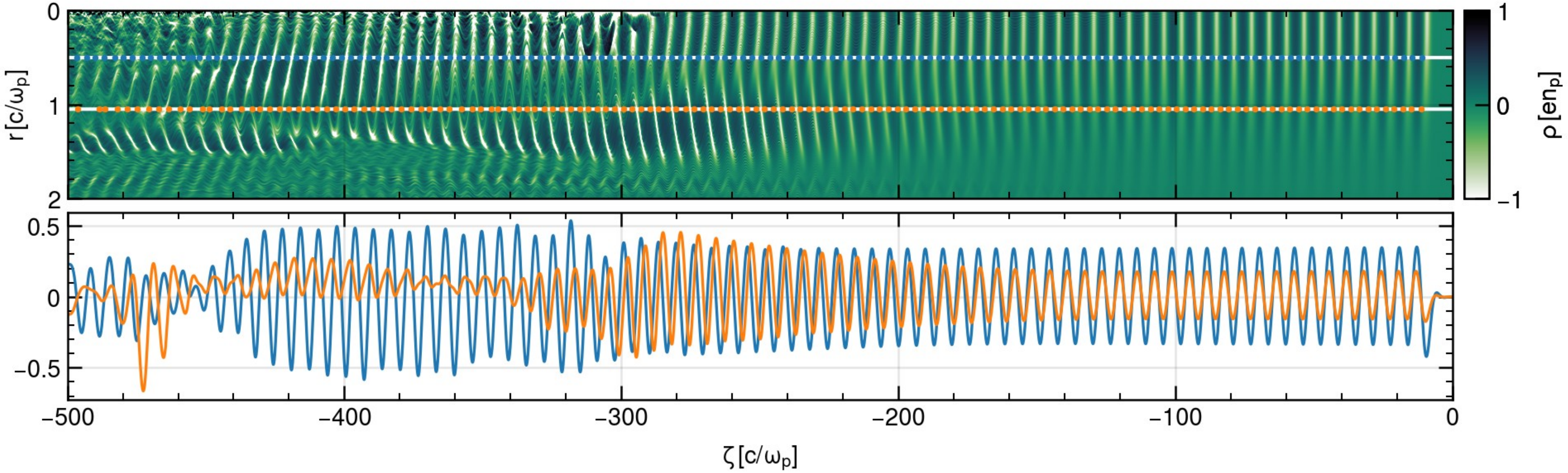


- Local variation of the restoring force results in local plasma wavelength changes
- Plasma wave dephases between different radii
- Radial wakefield (~radial integral of plasma charge density) reduces due to **phase mixing**

Short Driver - Phase Mixing

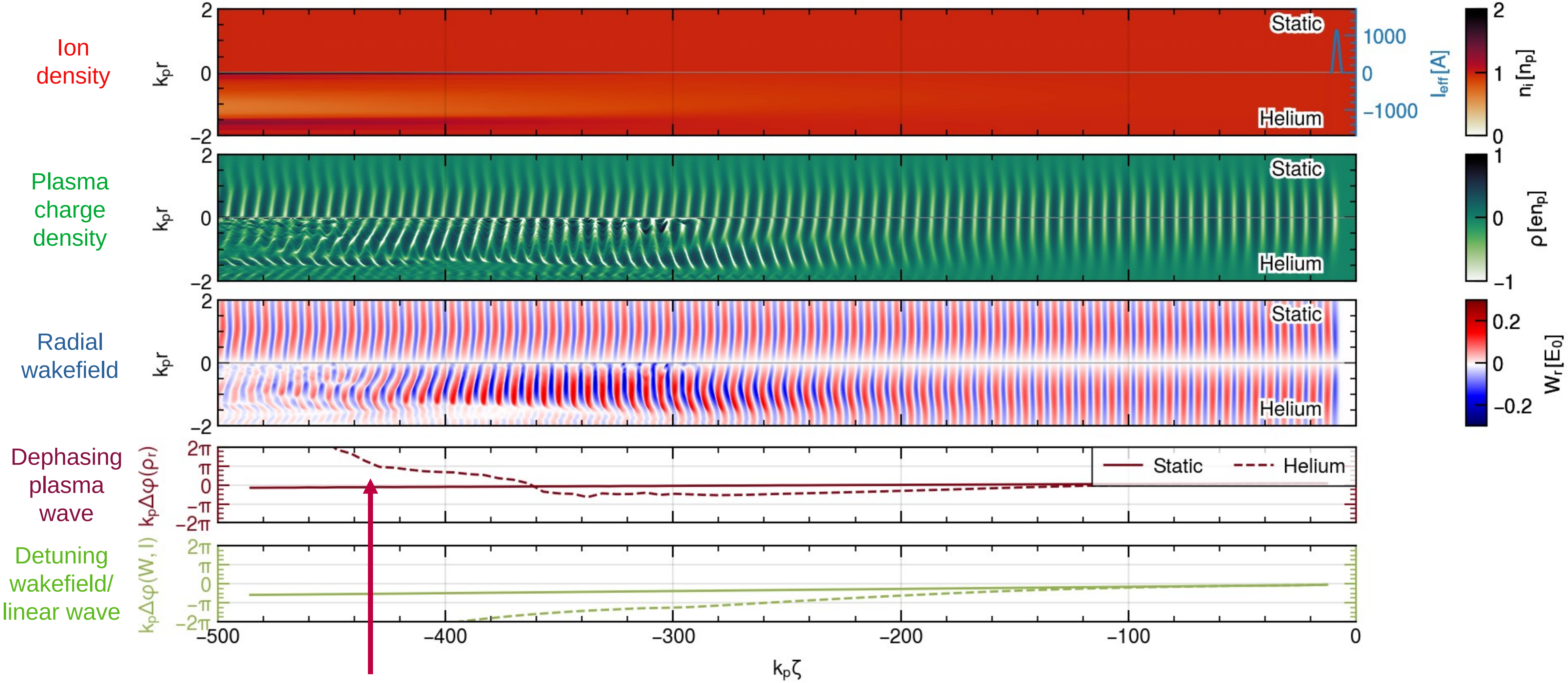
Plasma charge density

25th & 75th lineout



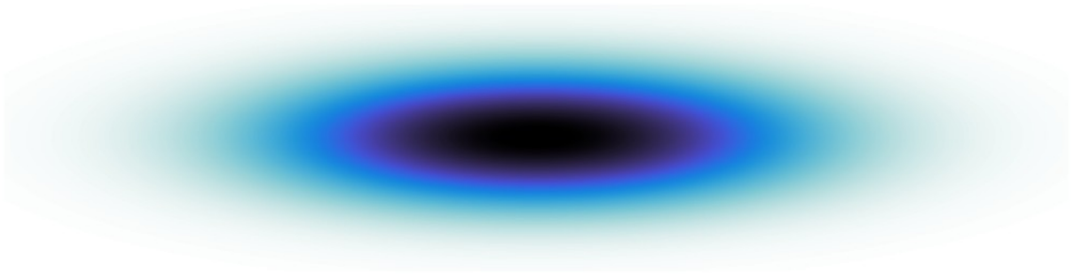
- Phase of plasma wave shifts between different radii
  Here: *25th* and *75th* percentile of initial radial beam distribution
- Transverse plasma electron oscillation becomes decoherent

Short Driver



Wakefield greatly reduces when plasma wave dephases in the order of π/k_p

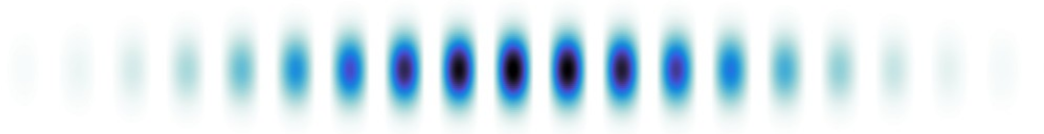
Long beam



Dominant effect: Phase mixing

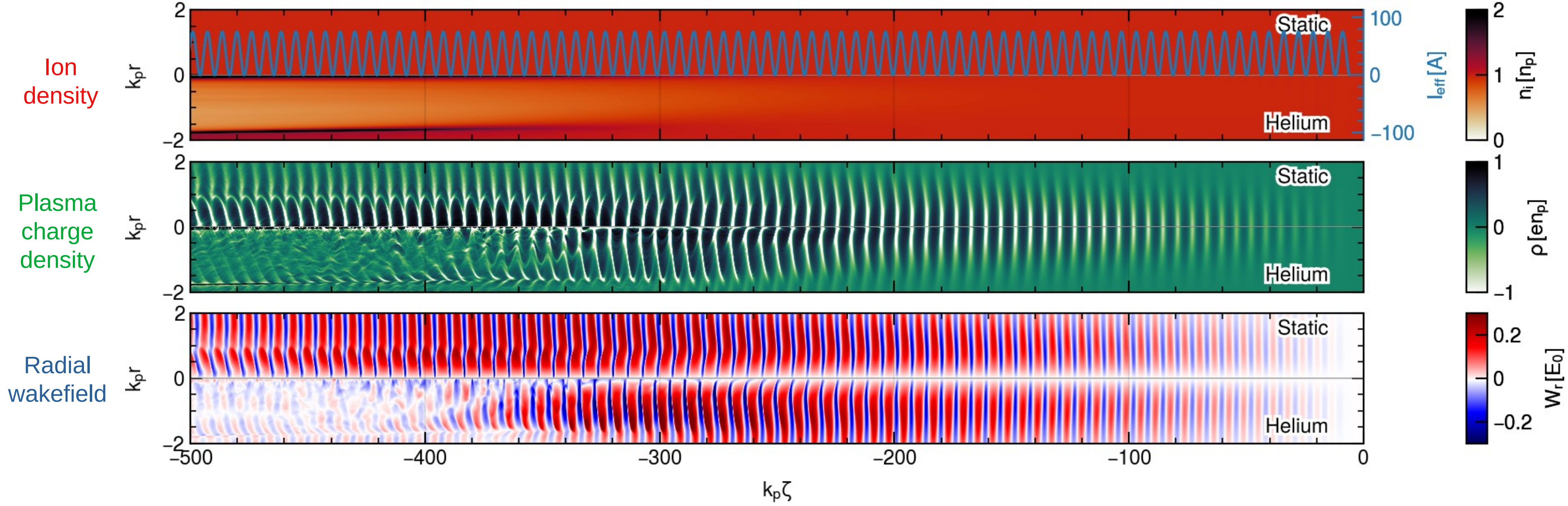
✓

Self-modulated beam



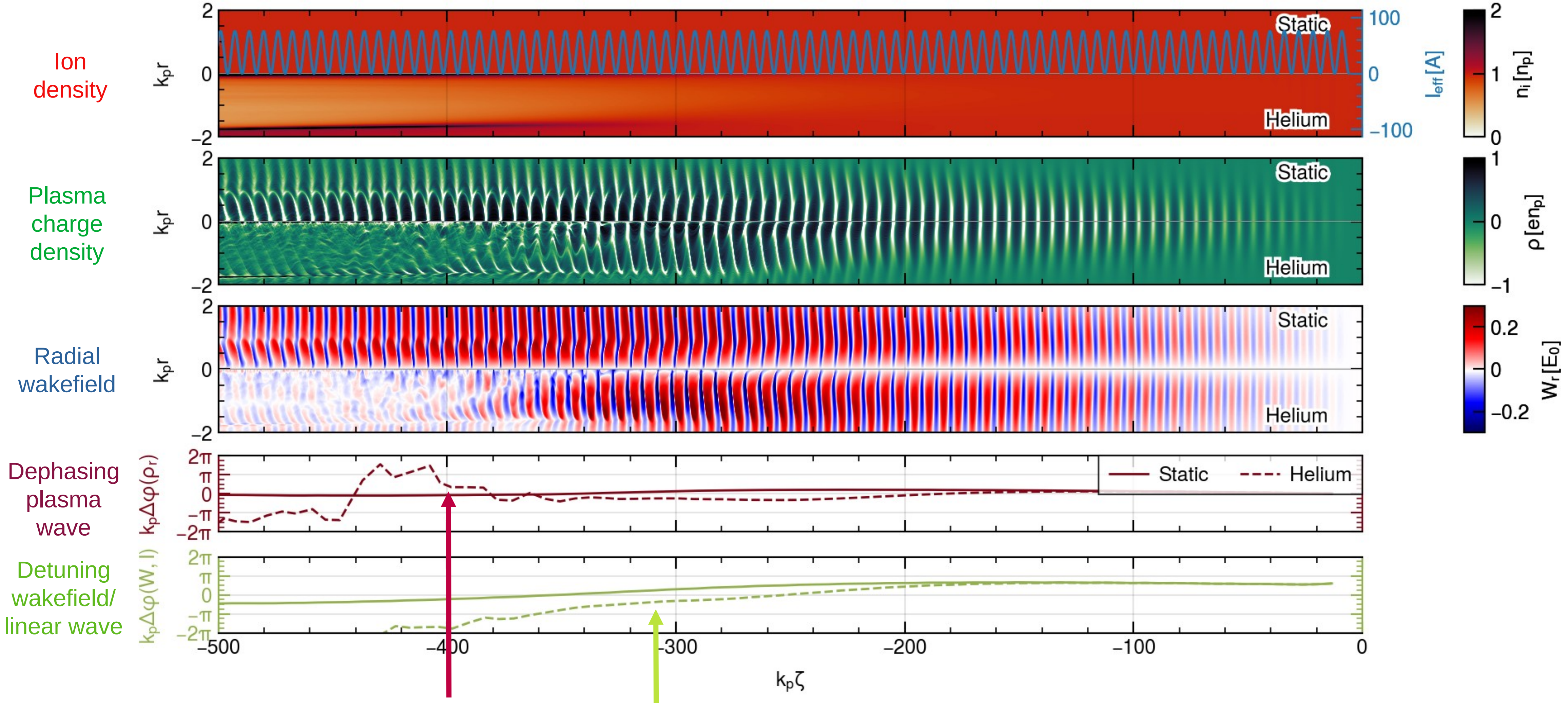
?

Premodulated Driver



- Microbunches initially correct for radial phase mixing
- **Detuning** of plasma response to a linear wave ($\omega=\omega_{p0}$) result in saturation and reduction of wakefield

Premodulated Driver



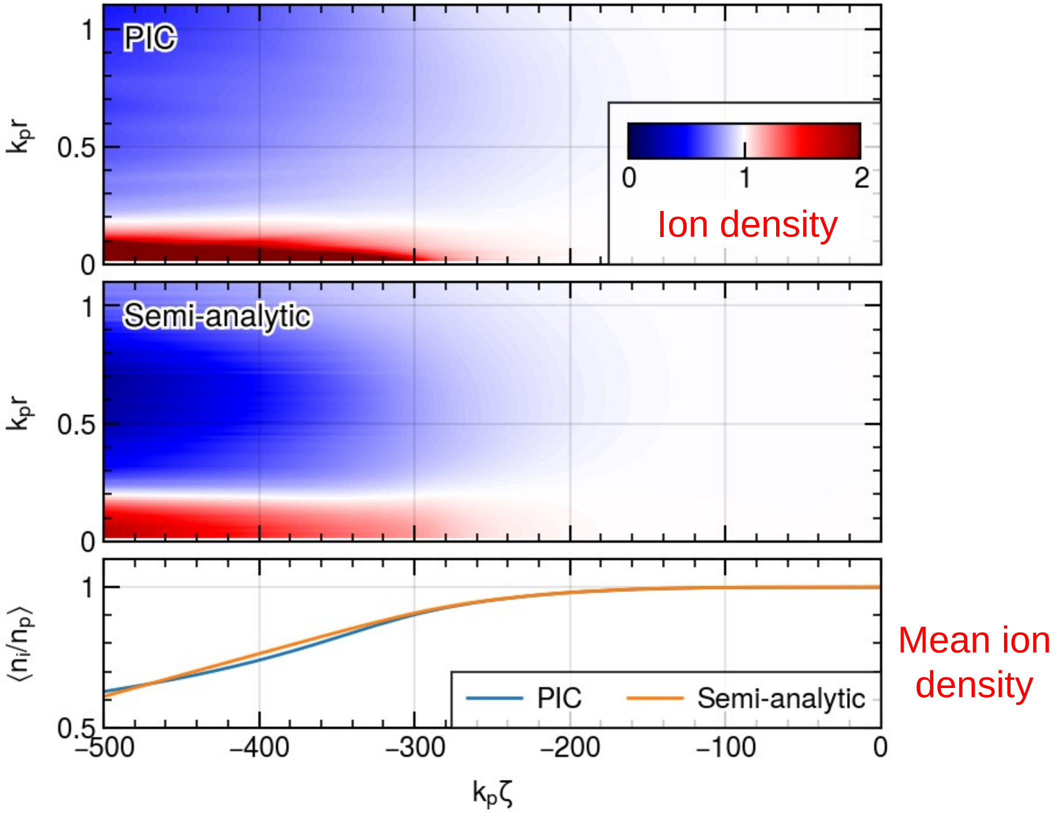
Dephasing of plasma response between different radii occurs after wakefield reduced

Wakefield reduces when detuning reaches order of $\pi/2 \ 1/k_p$

Premodulated Driver - Linear Theory

Ion density change well described in linear theory (J. Vieira, 2012)

$$\partial_\zeta^2 \delta n_i / n_p = -\frac{1}{4 m_i / m_e} \nabla_r^2 \hat{\boldsymbol{E}}^2 / E_0$$



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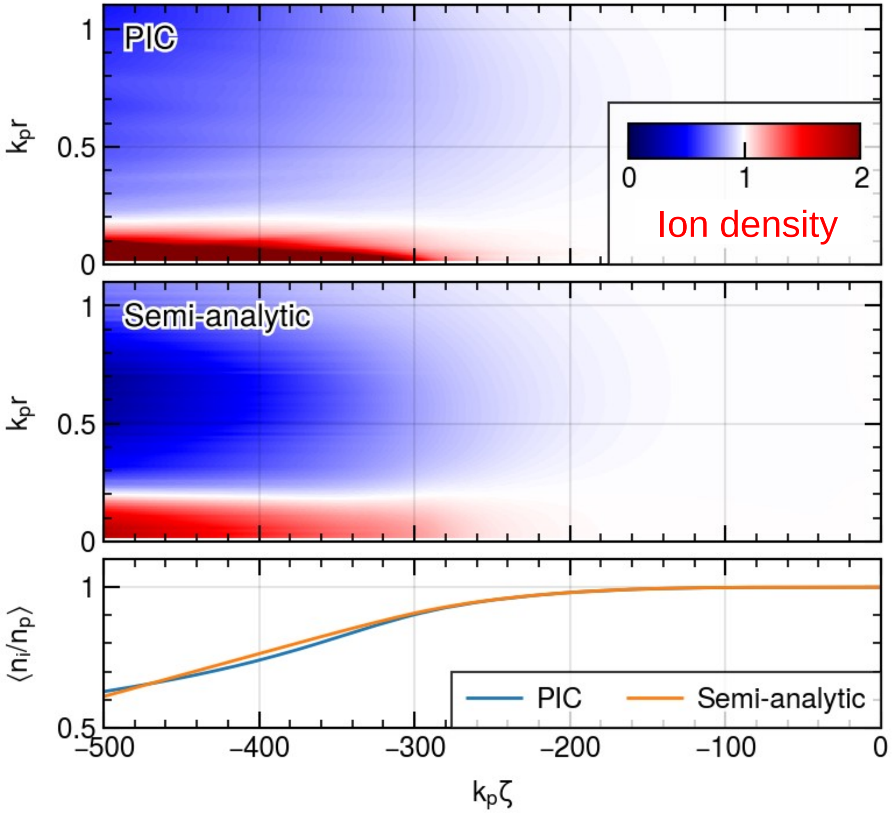


Mean ion density

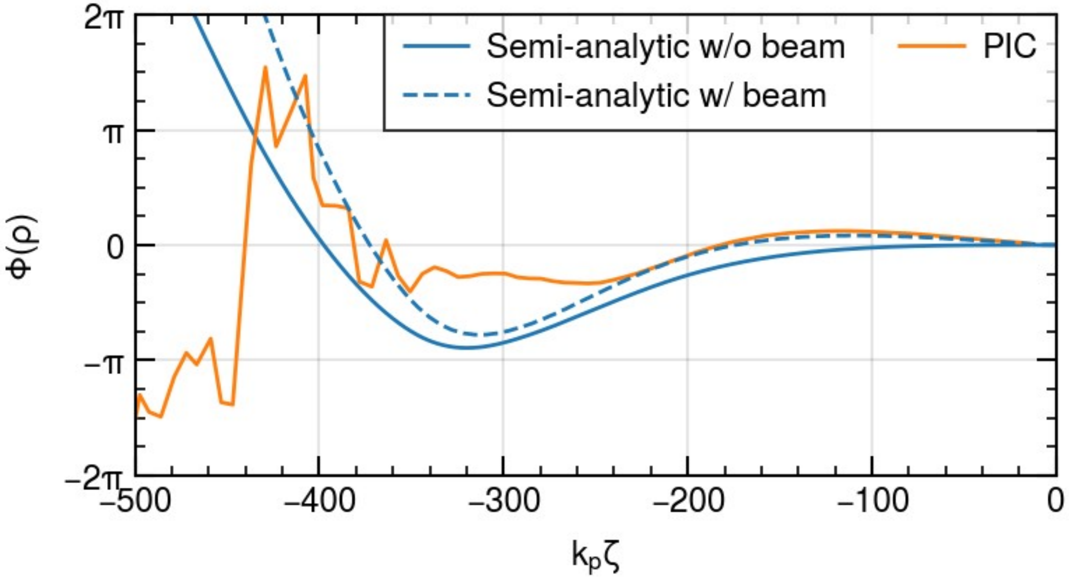
Dephasing in plasma response due to ion density variation and microbunch correction reflected by

$$k_p = k_{p0} \frac{\sqrt{(n_i + n_b)/n_0}}{1 + \alpha E_z^2 / E_0^2}$$

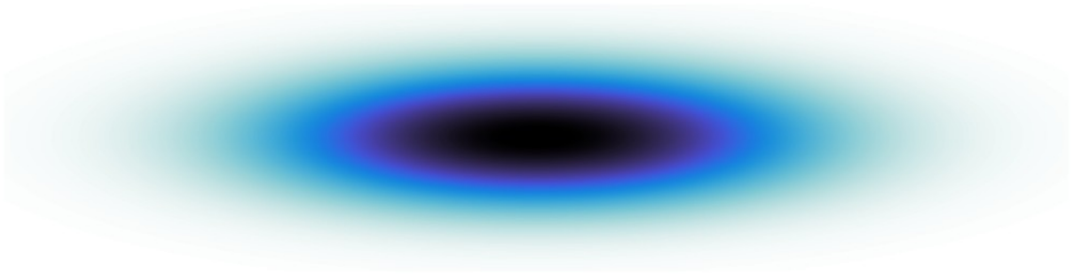
from PIC

Adapted and edited from
K. Lotov, 2013
P.I. Morales Guzman, 2021

Dephasing in plasma wave



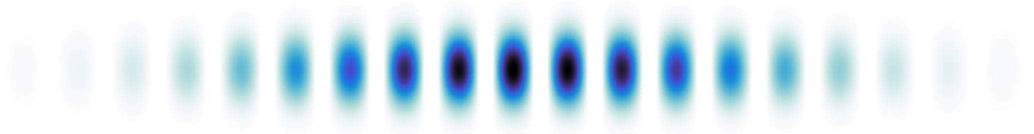
Long beam



Dominant effect: Phase mixing

✓

Self-modulated beam

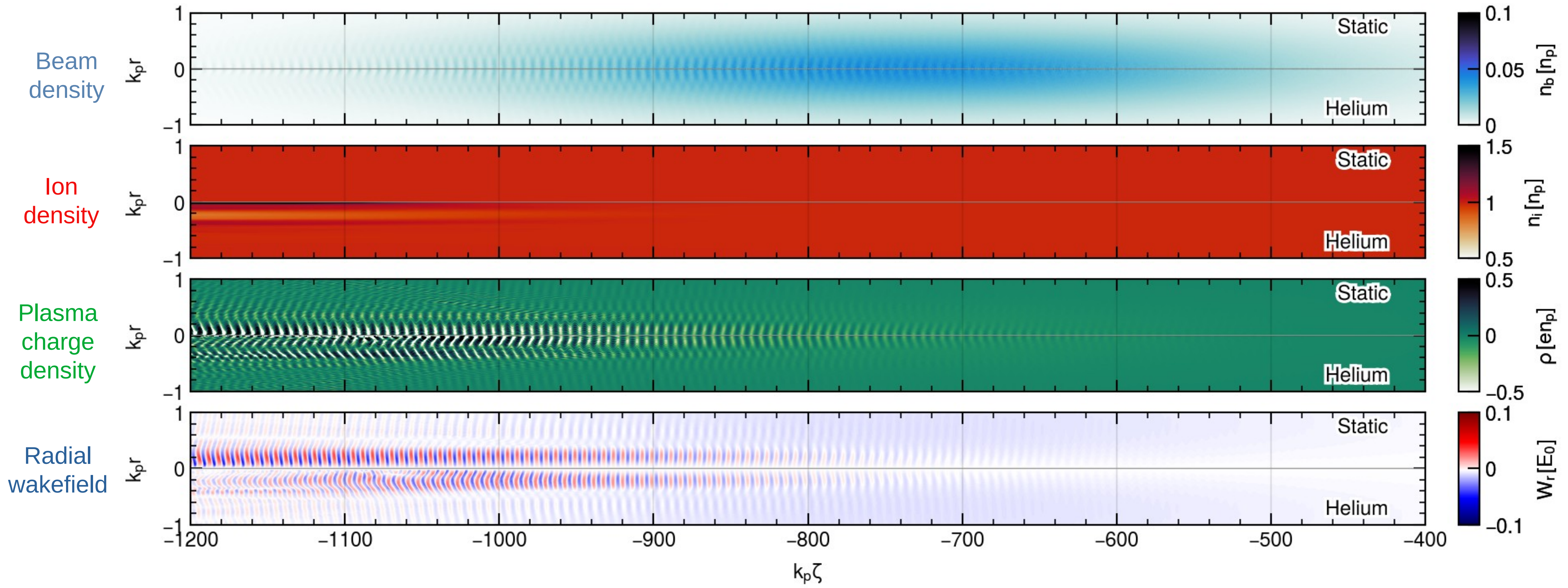


Increased detuning combines with phase mixing

✓

Does this apply the same way for a self-modulating beam?

Self-Modulated Driver @ 1.5m



- Wakefield radially peaks at lower radii, which results in a lower extend of ion motion
- Wakefield dominantly reduces due to phase shift of the plasma response radially

Self-Modulated Driver @ 1.5m

Beam density

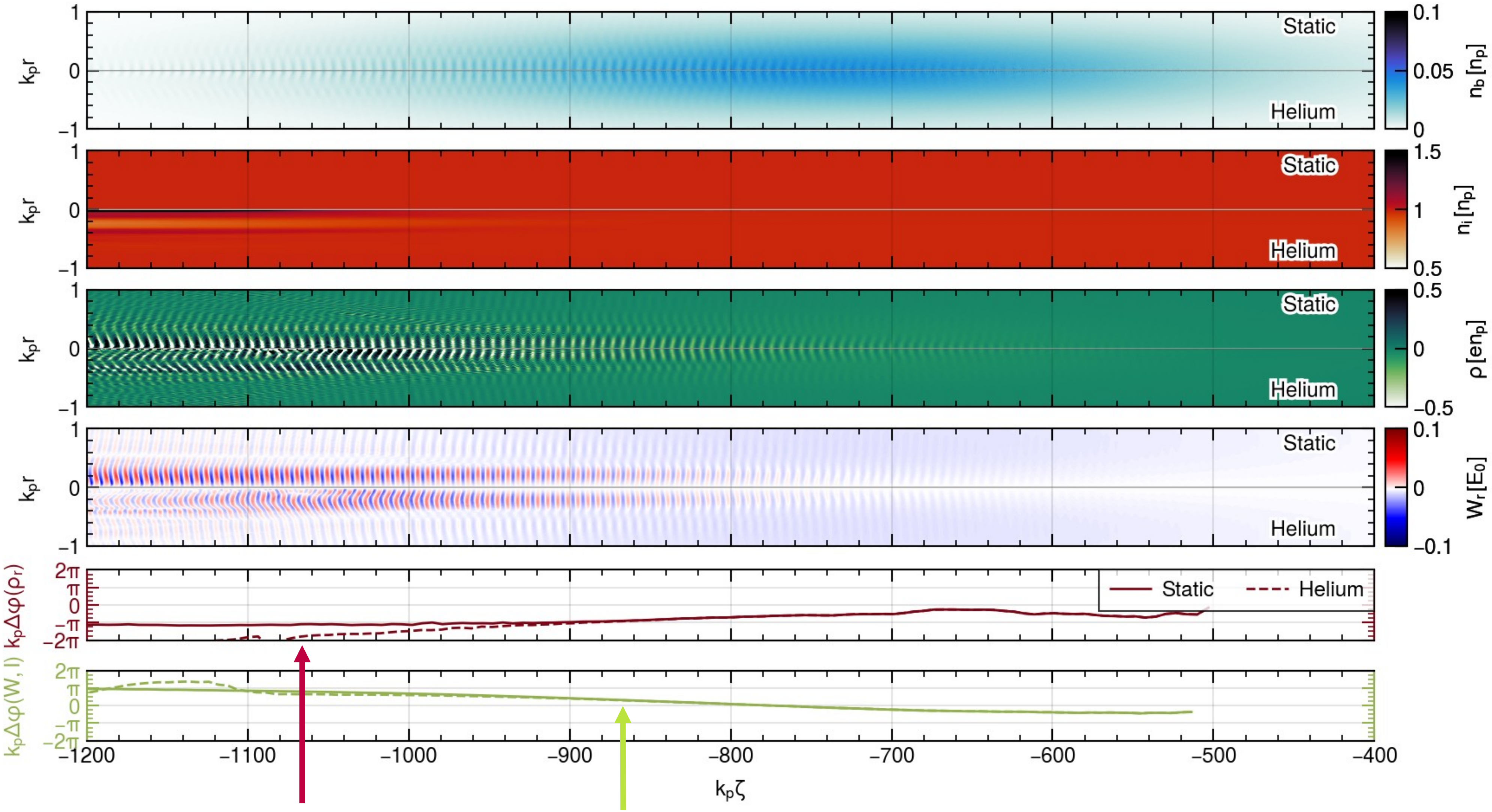
Ion density

Plasma charge density

Radial wakefield

Dephasing plasma wave

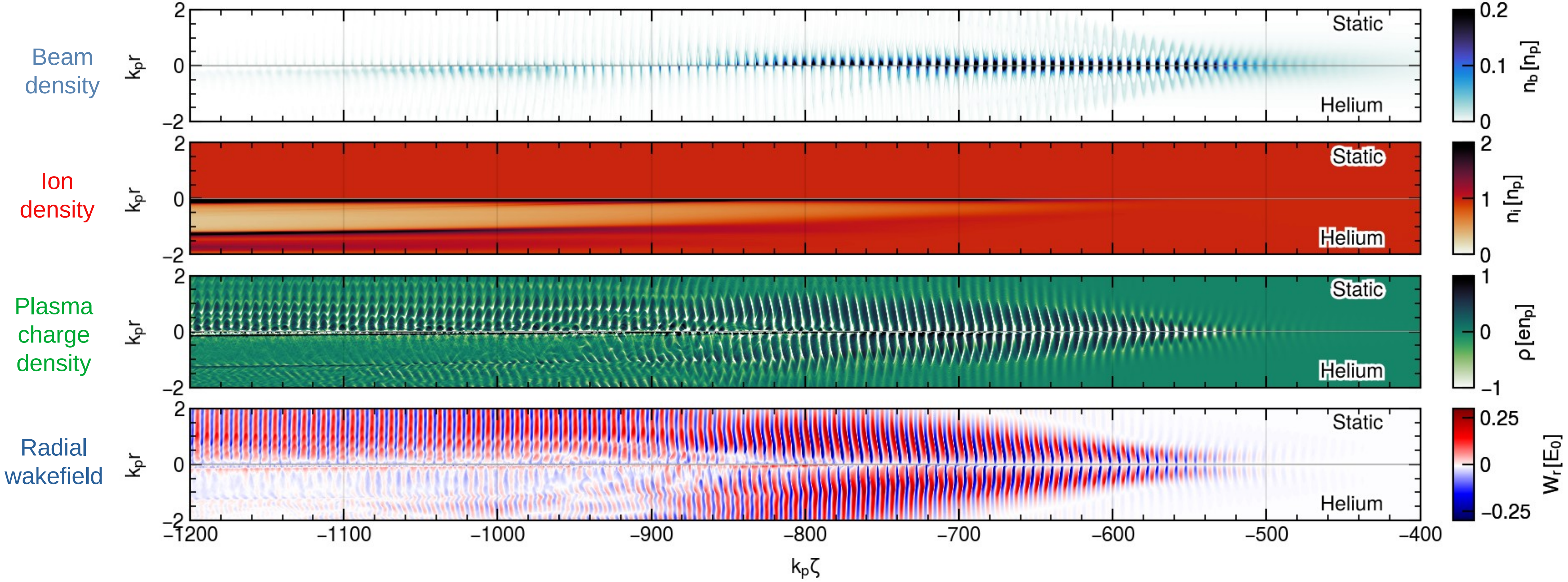
Detuning wakefield/ linear wave



Wakefield reduces when dephasing differs by π/k_p from SMI induced phase shift

No relevant dephasing → Microbunch spacing comparable to static ion

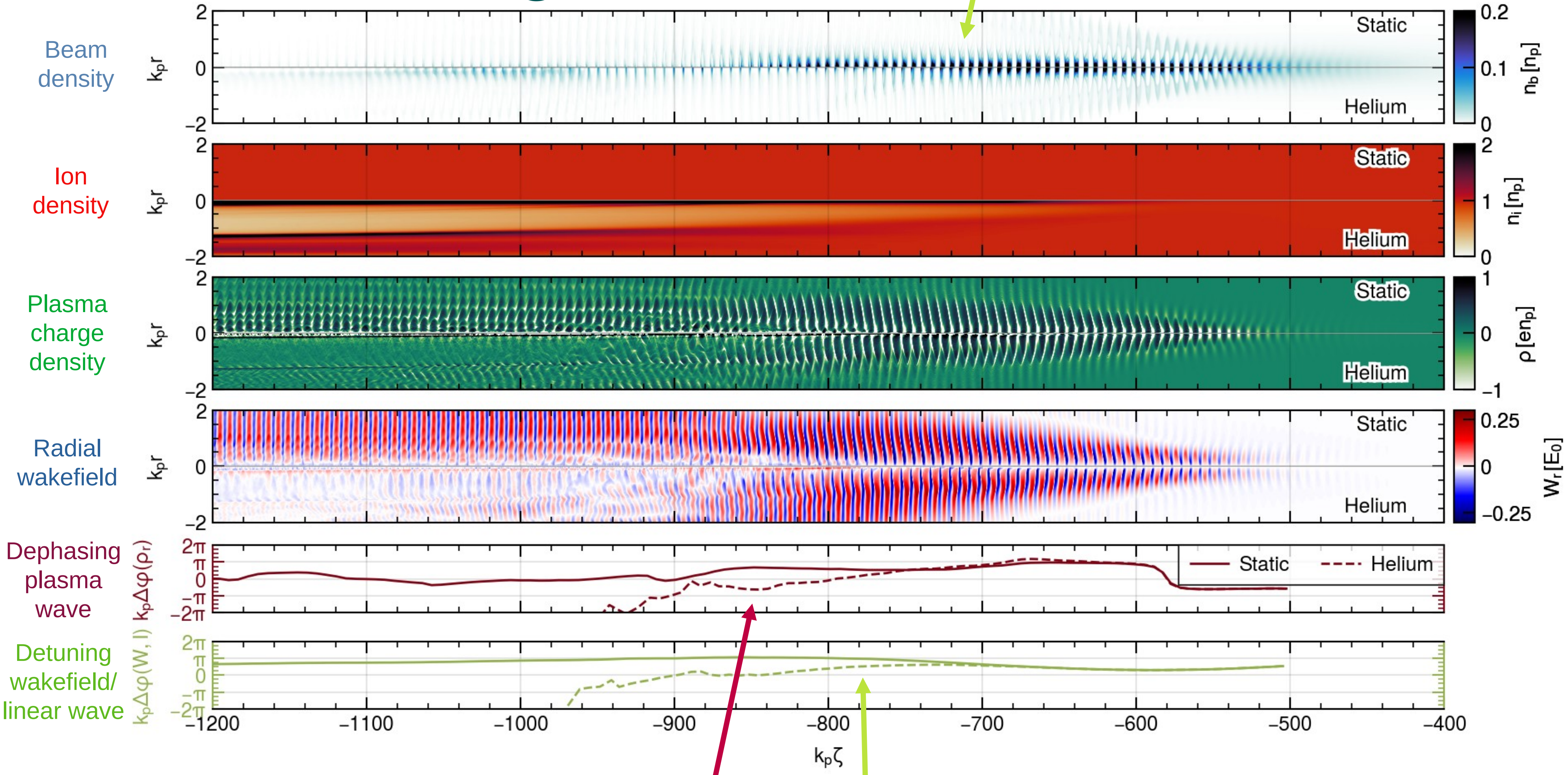
Self-Modulated Driver @ 5m



- After SMI microbunches compensate phase shift in plasma response
- Microbunches deteriorate faster at comparable wakefield amplitude…

Self-Modulated Driver @ 5m

Detuning aligns with shorter microbunches



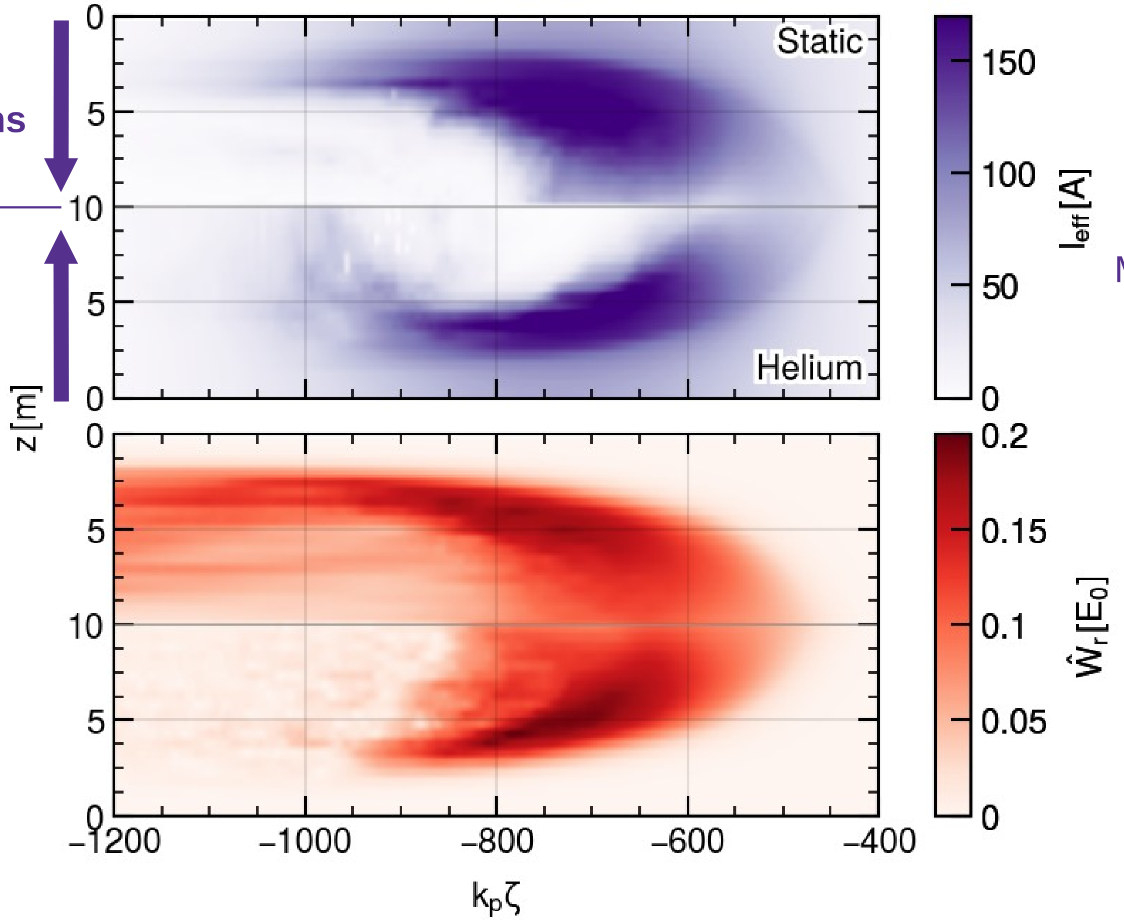
Combination of phase mixing and detuning reduces wakefield

Self-Modulated Driver

Beam and Wakefield Evolution

Beam propagating in plasma with **static ions**

Beam propagating in **Helium**



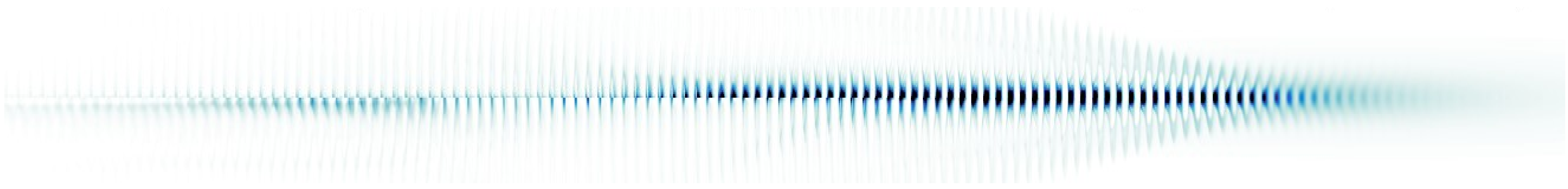
Beam effective current ~ Microbunch current

Radial wakefield envelope

- Effective current of beam head reduces faster in Helium due to increased detuning between radial wakefield and microbunches at comparable wakefield amplitude.
- Beam tail survives in Helium as radial wakefield is greatly reduced during and after SMI.

Conclusion

- Experimental and simulation data showed that development of SMI stops due to ion motion.
- We used PIC simulations to understand the dominant effect of ion motion.
- At early propagation distances, the plasma response dephases at different radii due to local plasma wavelength variation, which reduces the radial wakefield due to phase mixing. This effect lets the beam tail survive.
- Once SMI develops, the wakefield reduces as the wakefield detunes from the linear wave and due to phase mixing. The microbunches deteriorate faster due to detuning.



Thank you for your attention

For questions please contact me: erwin.walter@cern.de

Literature

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Motivation

Breakdown of SMI