Positron transport and acceleration in beam-driven plasma accelerators using a plasma column

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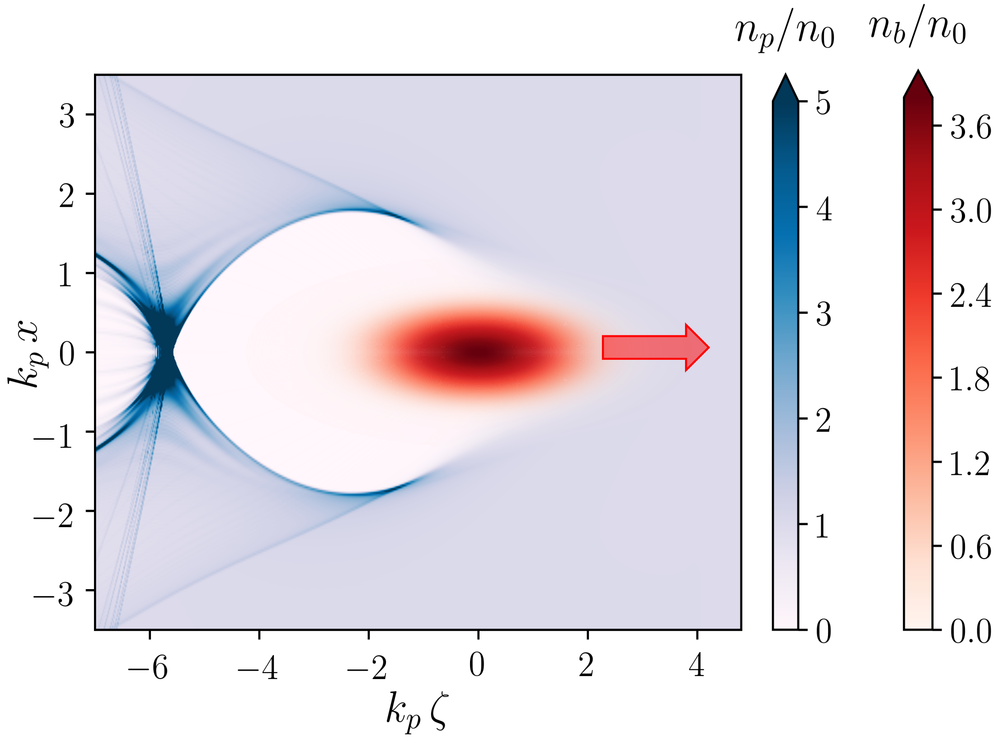
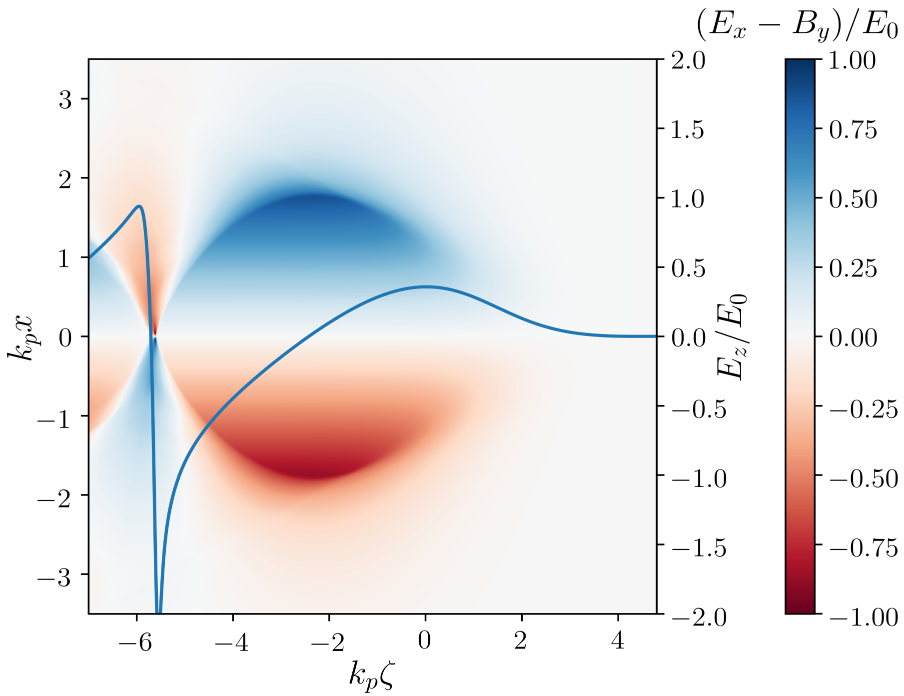
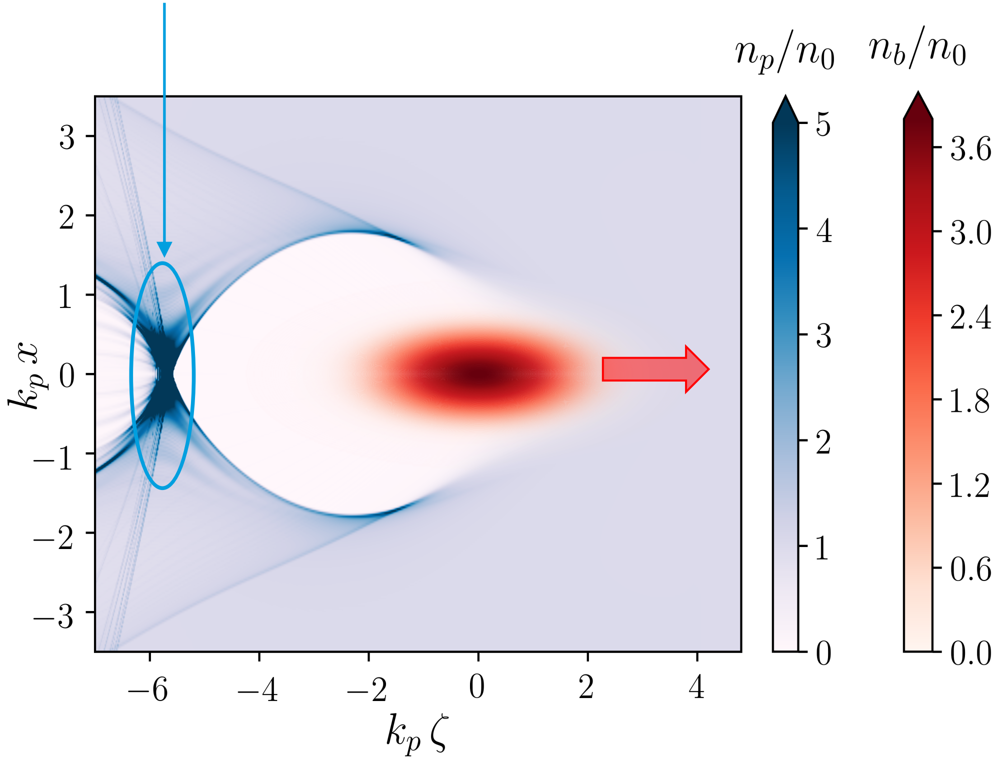
Positron acceleration is a challenge



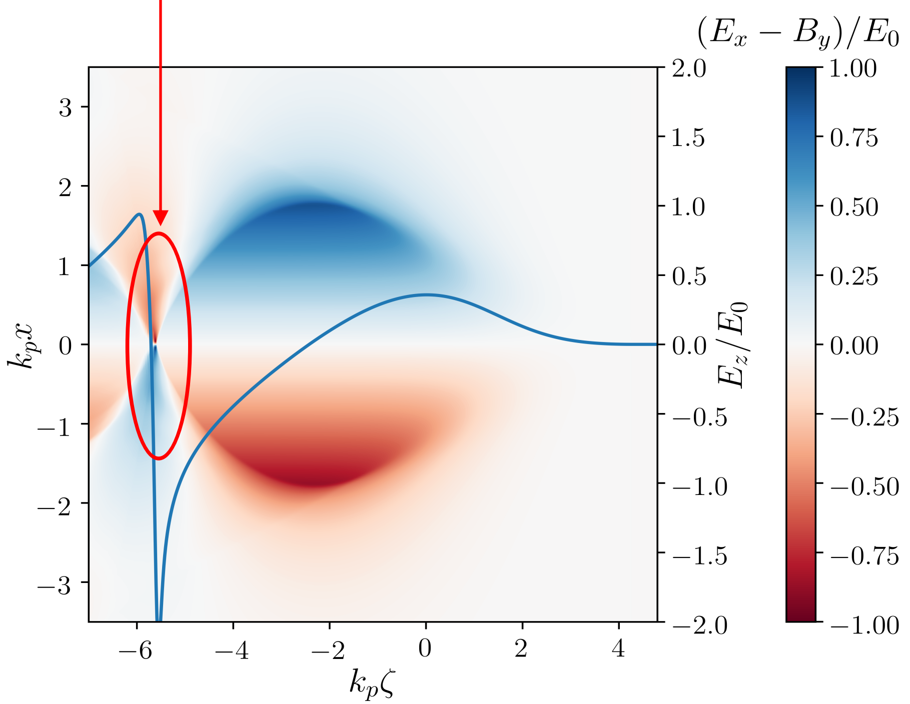


Positron acceleration is a challenge

High density electron cusp



Focusing field for positrons



No efficient and stable concept available!

Wakefield generation in plasma columns

with regard to positron acceleration

Modeling tools

- 2D axisymmetric
- PIC or fluid for plasma
- Quasi-static modality
- Dynamic time step adjustment + subcycling

C. Benedetti at al., AAC2010, AAC2012, ICAP2012, AAC2016, PPCF2017

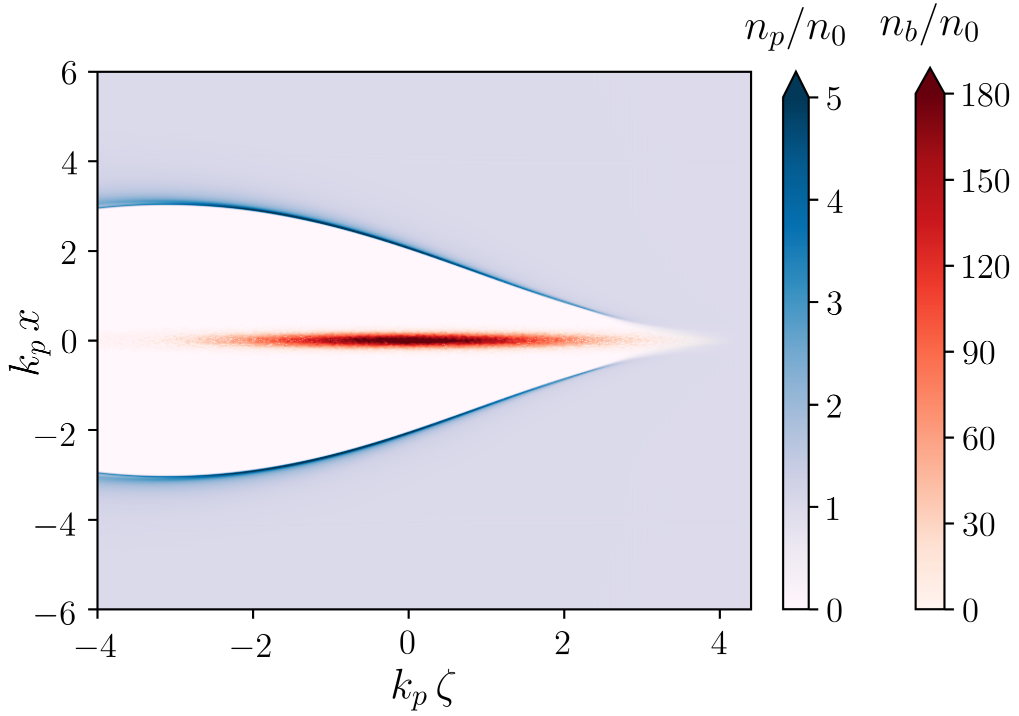
- 3D Cartesian
- Quasi-static PIC
- Dynamic time step adjustment + subcycling
- High resolution subgrid in “dynamically interesting” domains
- Parallelized with MPI

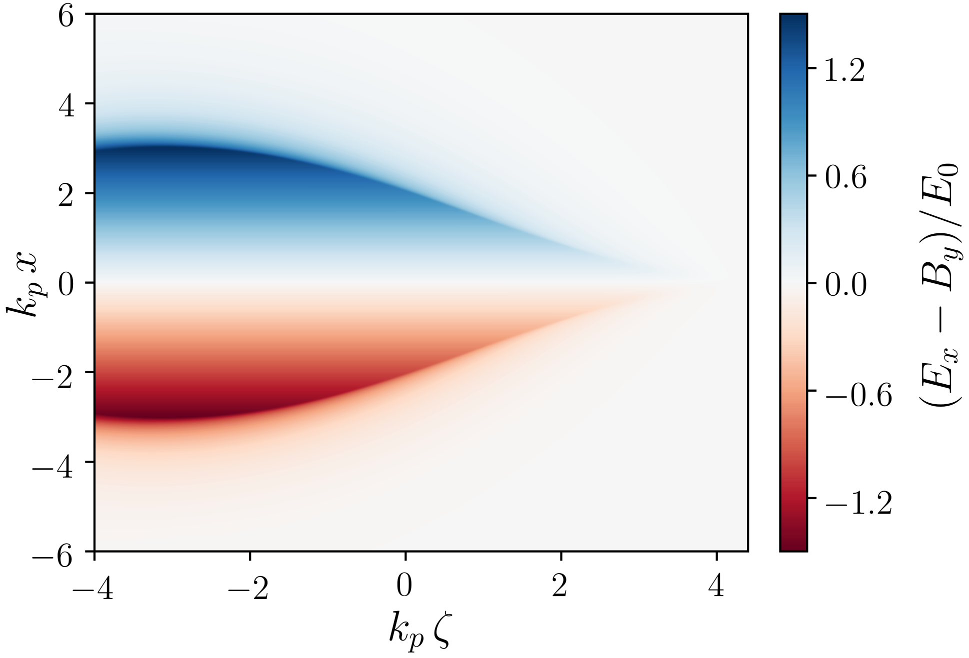
T.J. Mehrling et al., PPCF2014, AAC2018

Wakefield generation in plasma columns

in pre-ionized plasma columns

In the homogeneous, infinite plasma case:





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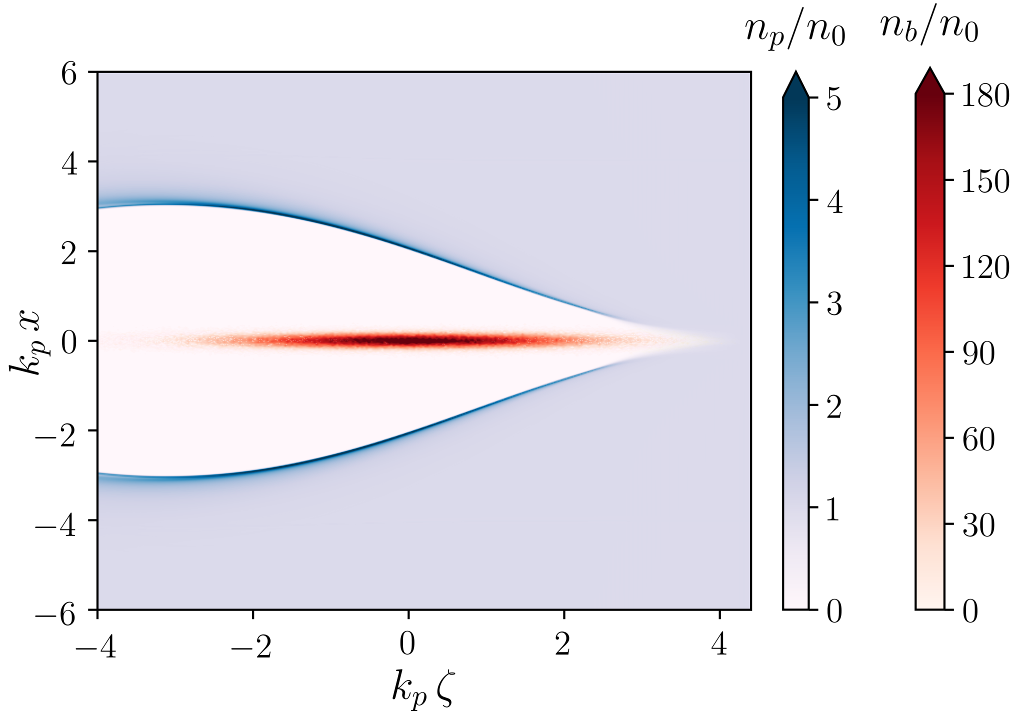
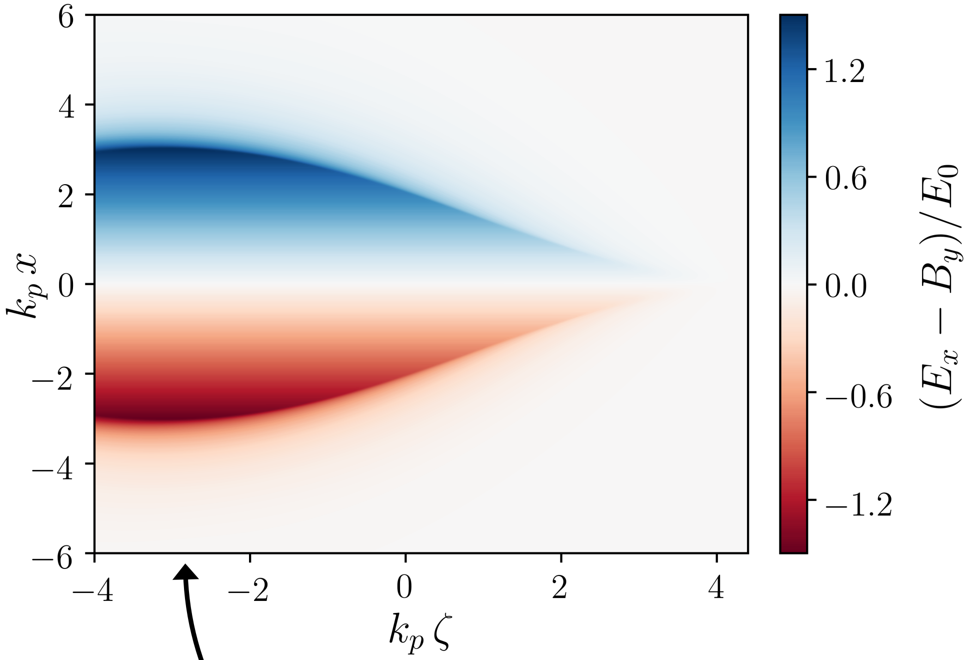
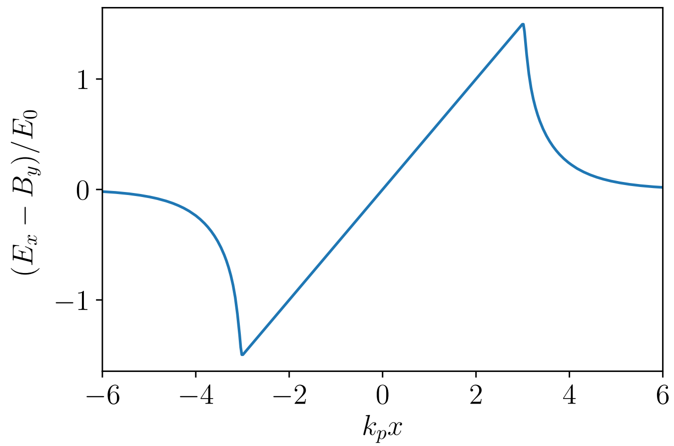




Line-out
at ζ = -3.0



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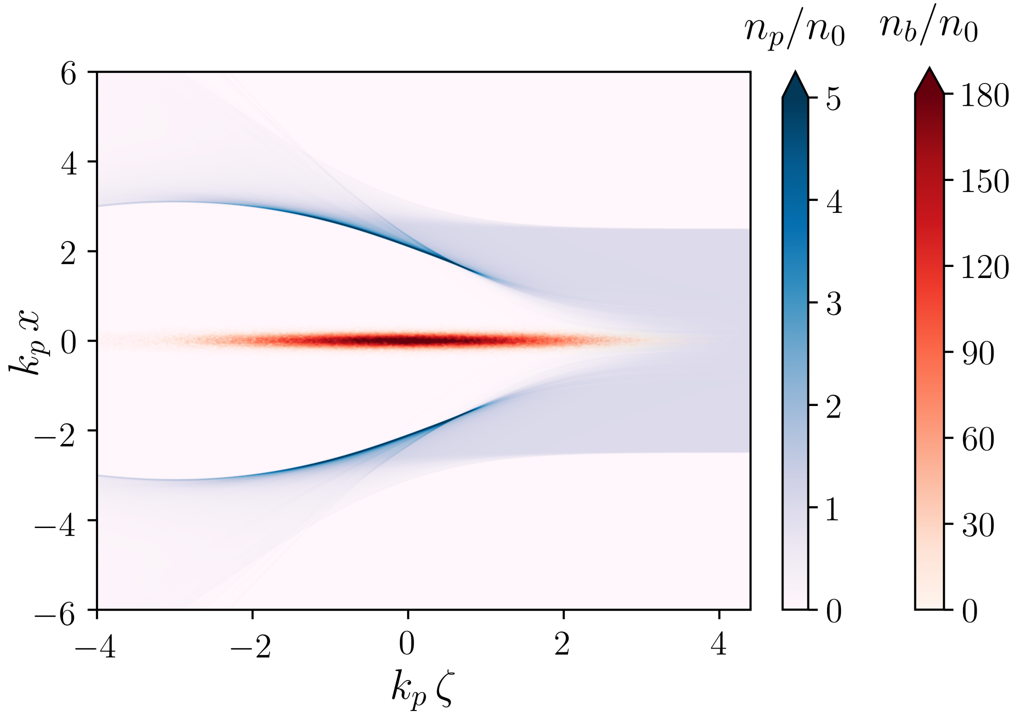

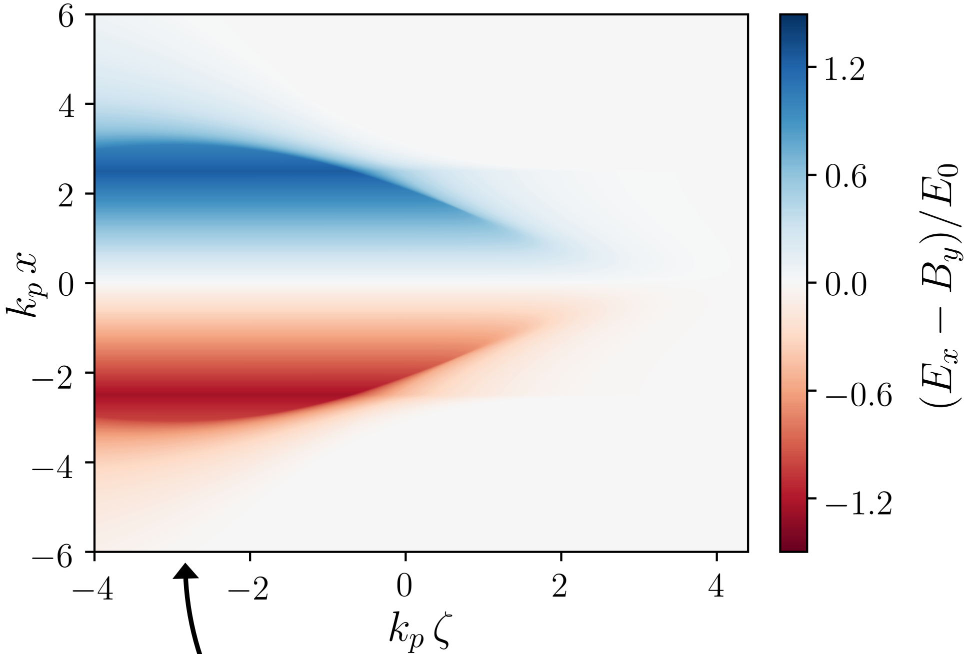

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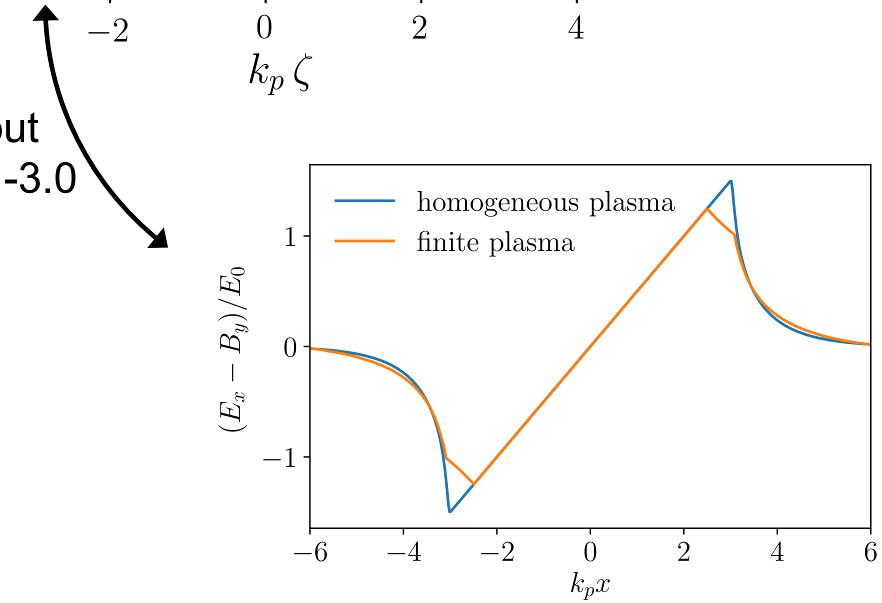

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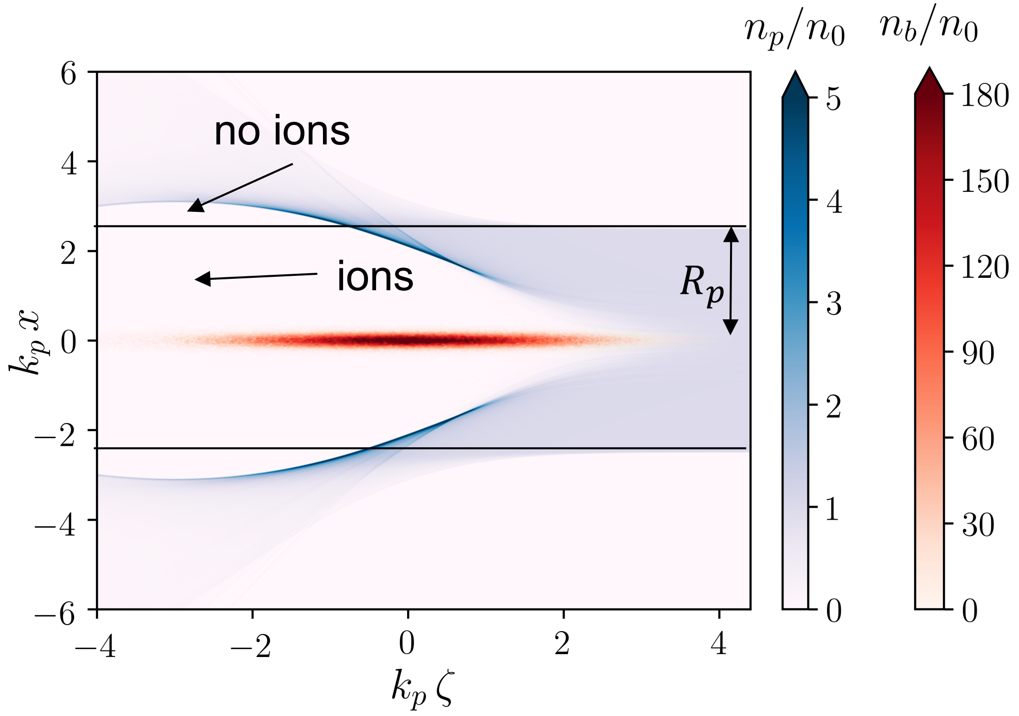
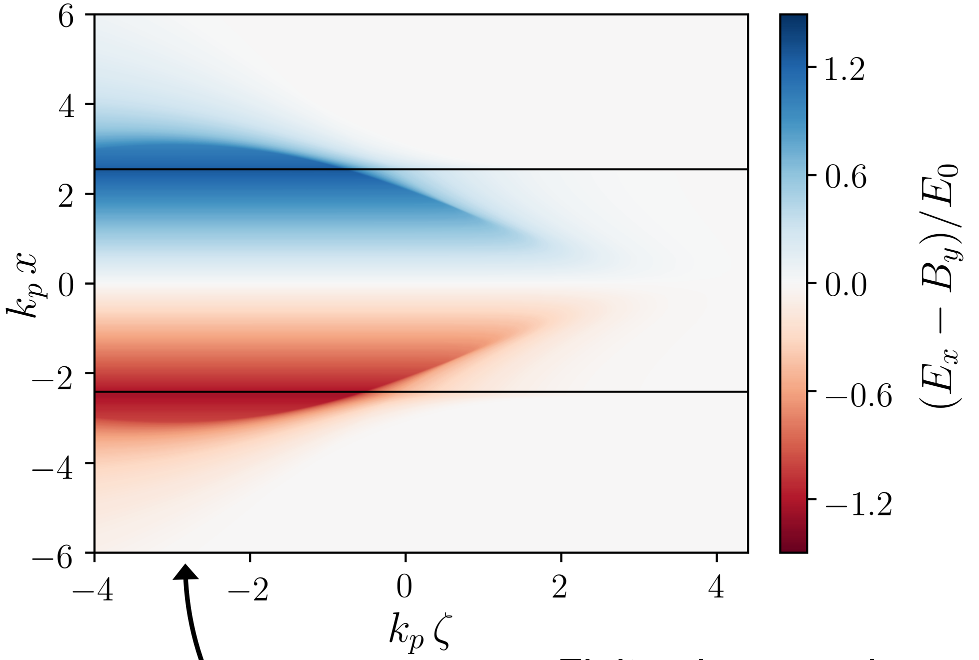
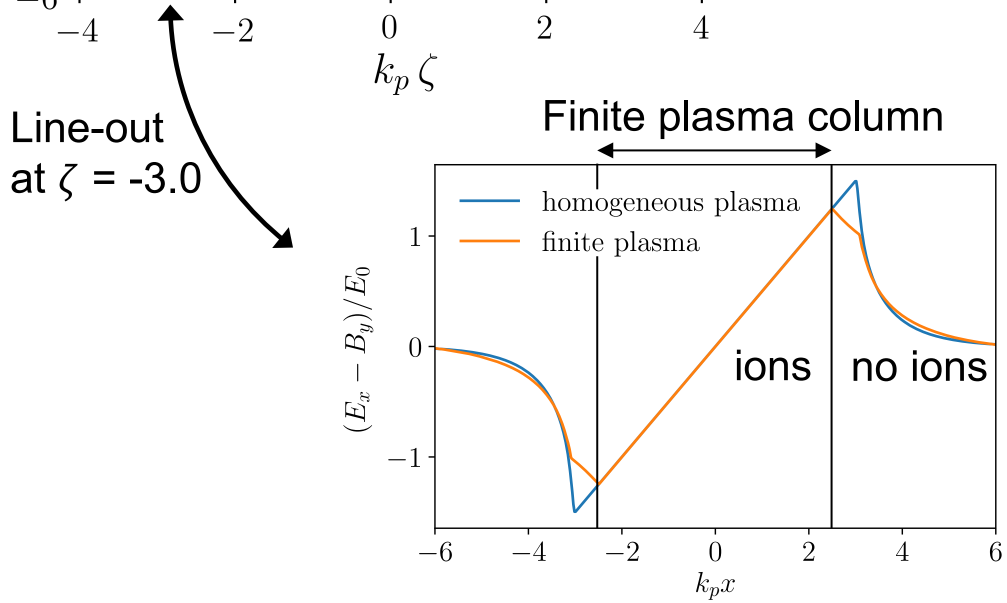


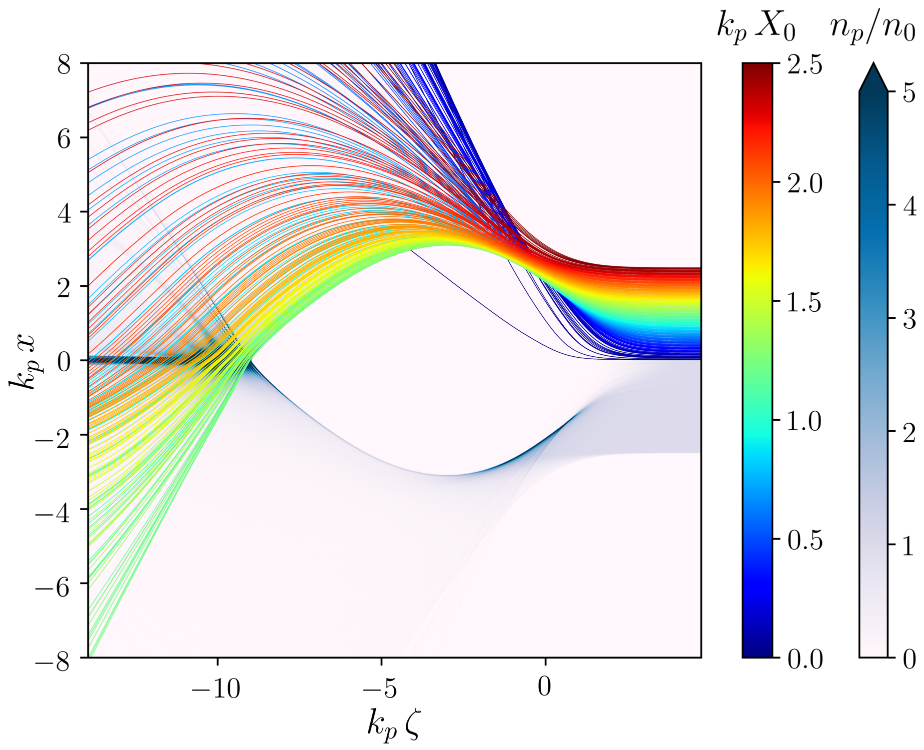


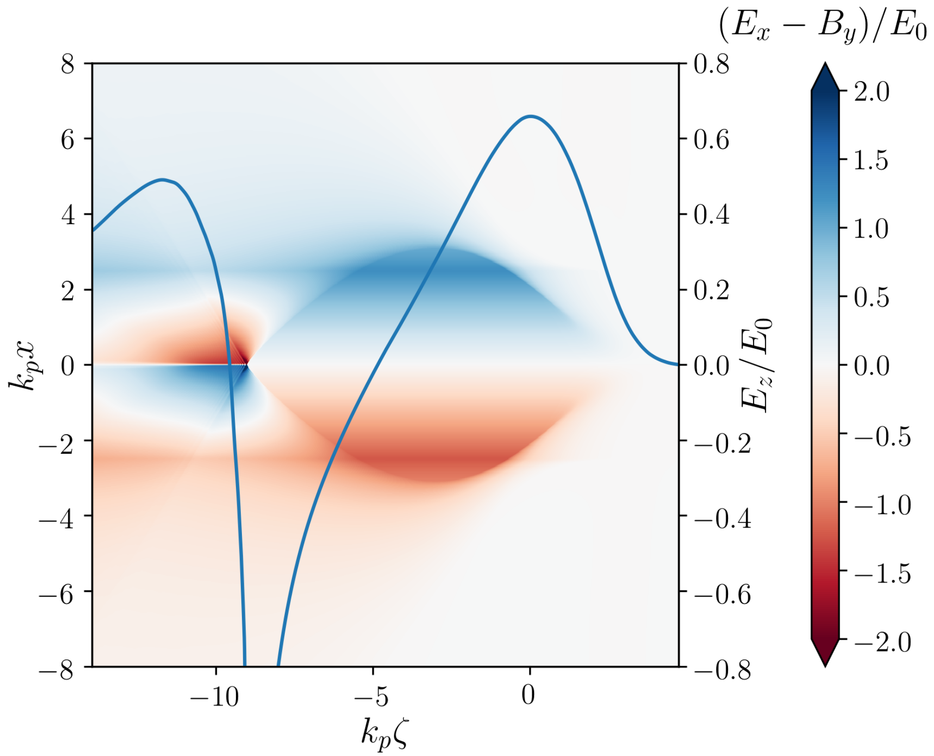


Lack of ions due to finite plasma column leads to a **modified transverse wakefield**

Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns





Elongated plasma electron trajectories induce positron acc. field

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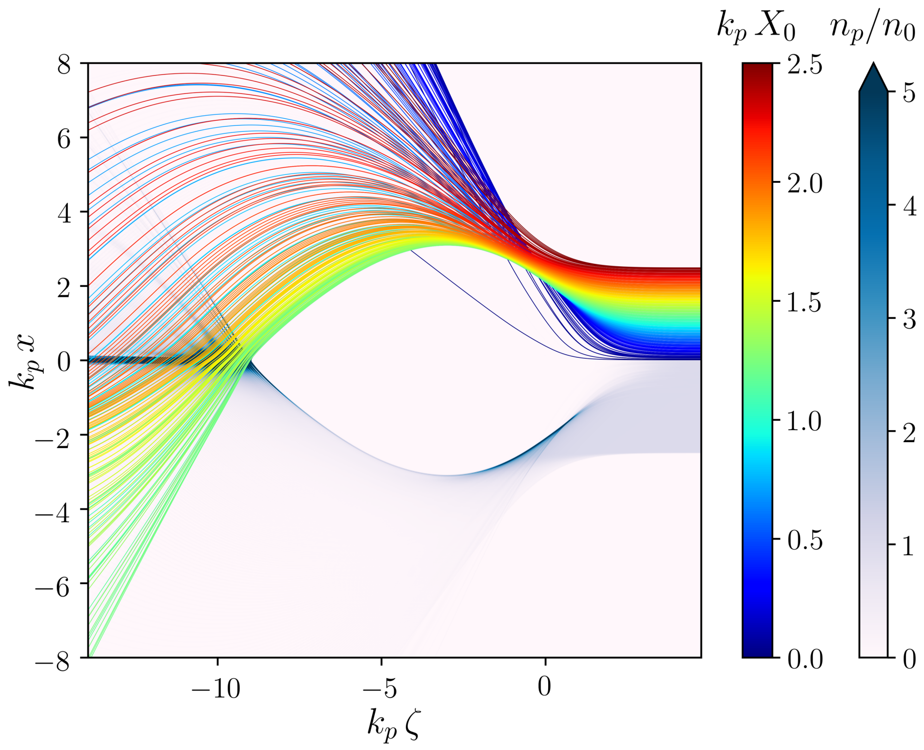
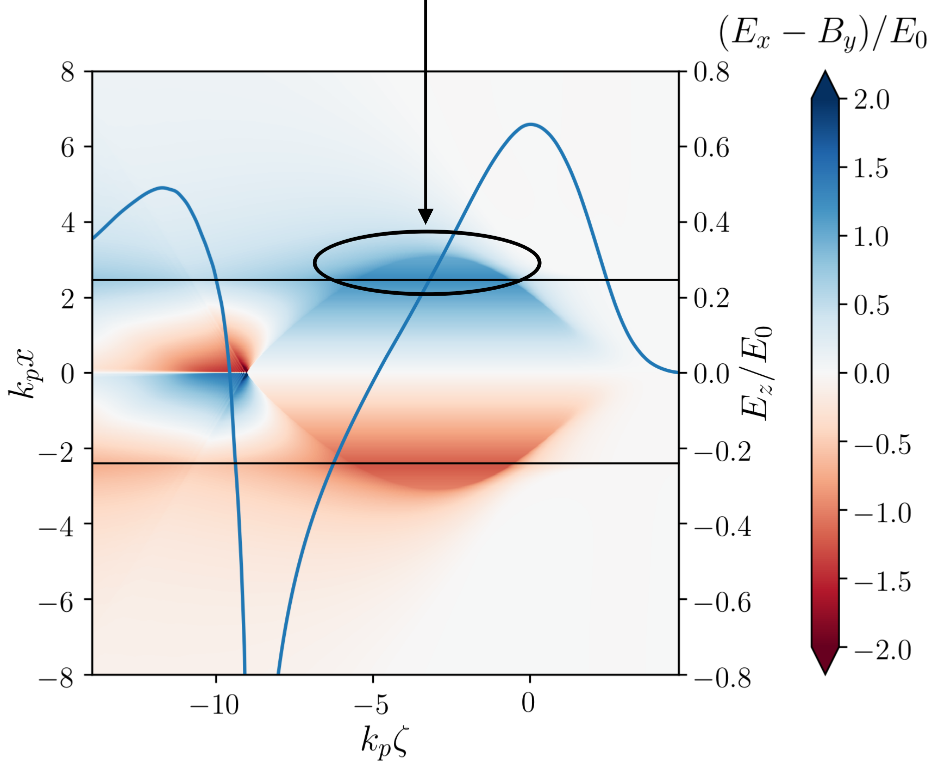


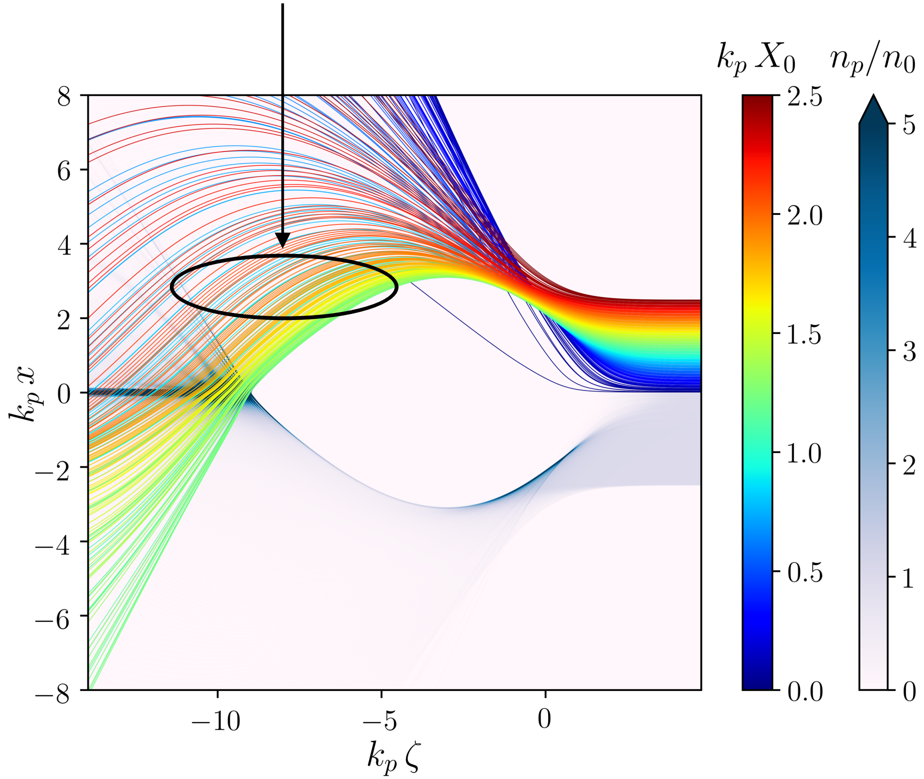
1. Modified transverse wakefield



Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns

2. Elongated electron trajectories



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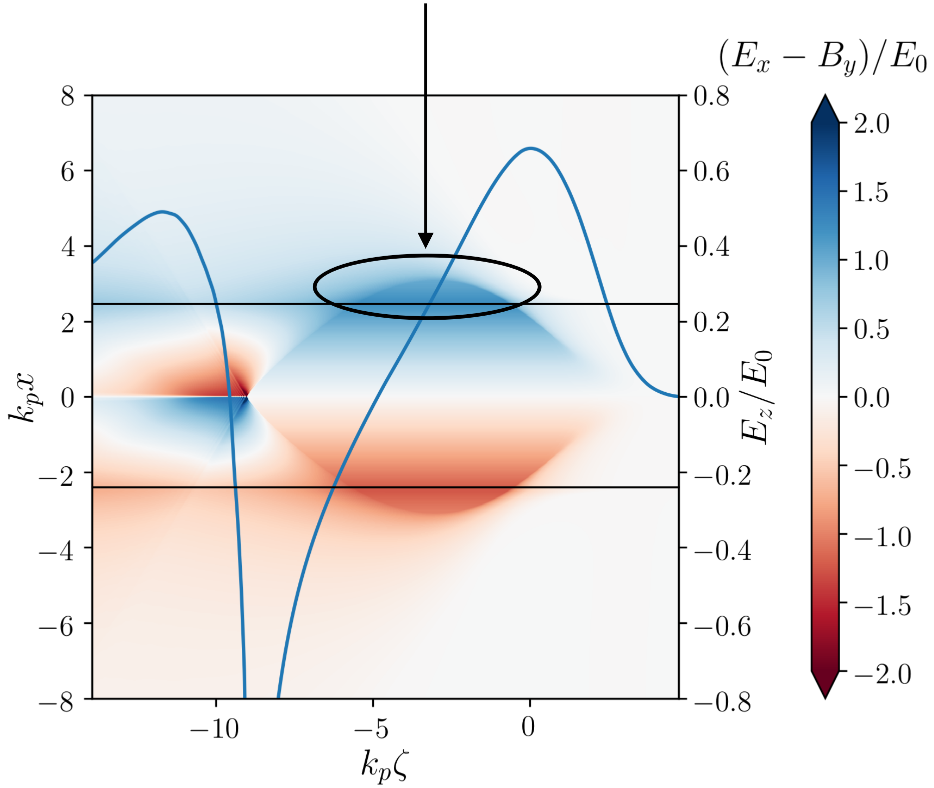

Elongated plasma electron trajectories induce positron acc. field

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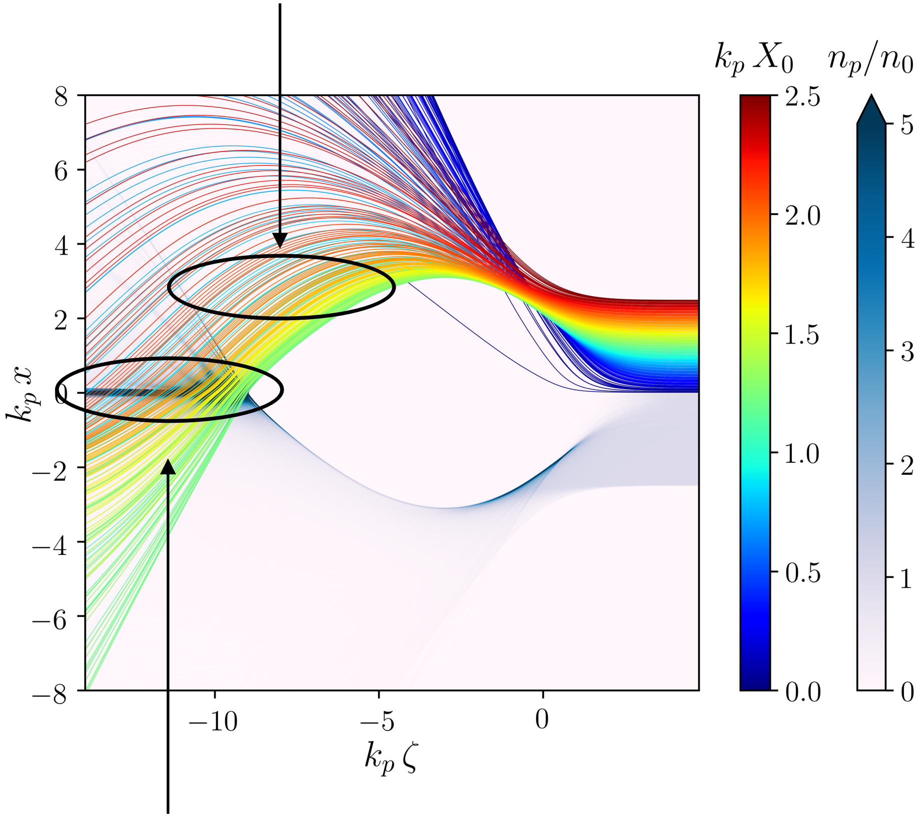
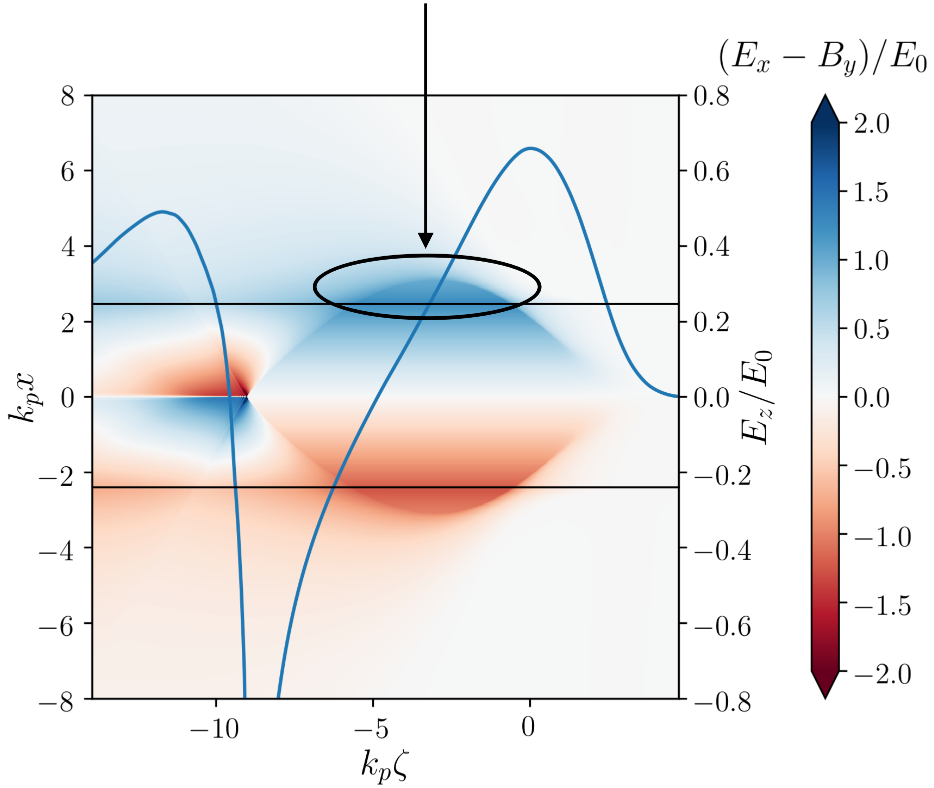


3. Long, high-density electron filament

1. Modified transverse wakefield



Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns

2. Elongated electron trajectories

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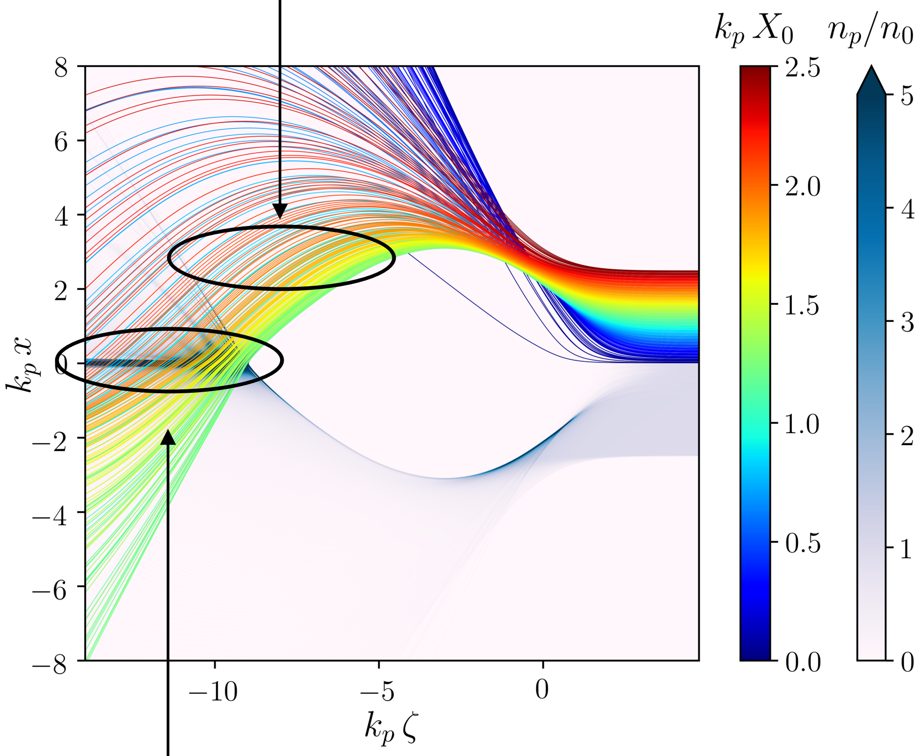
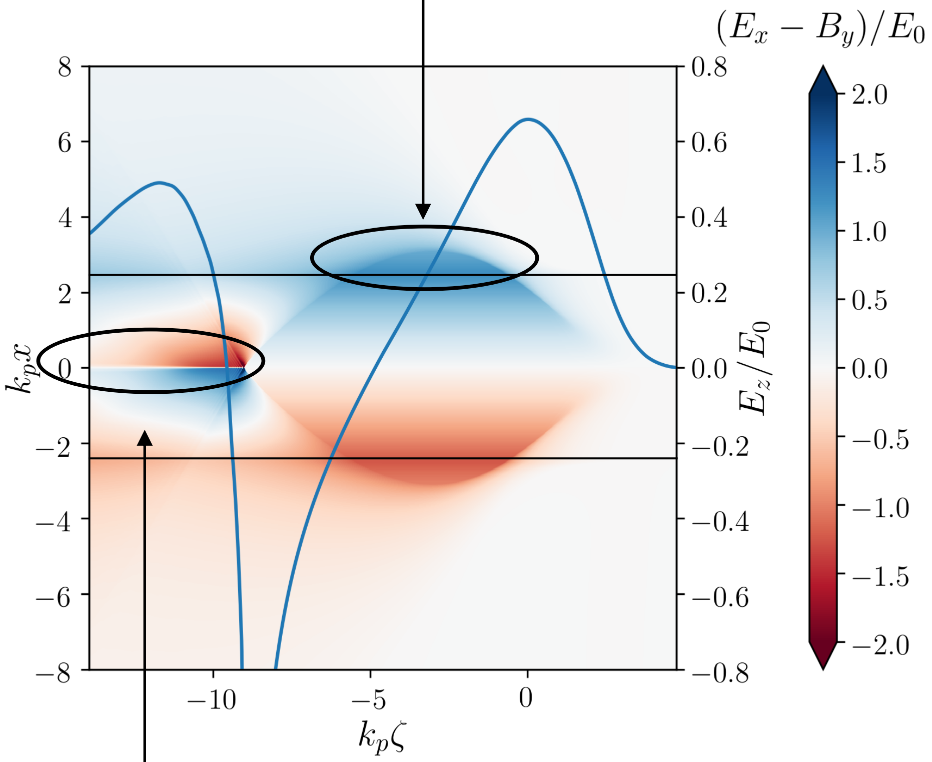


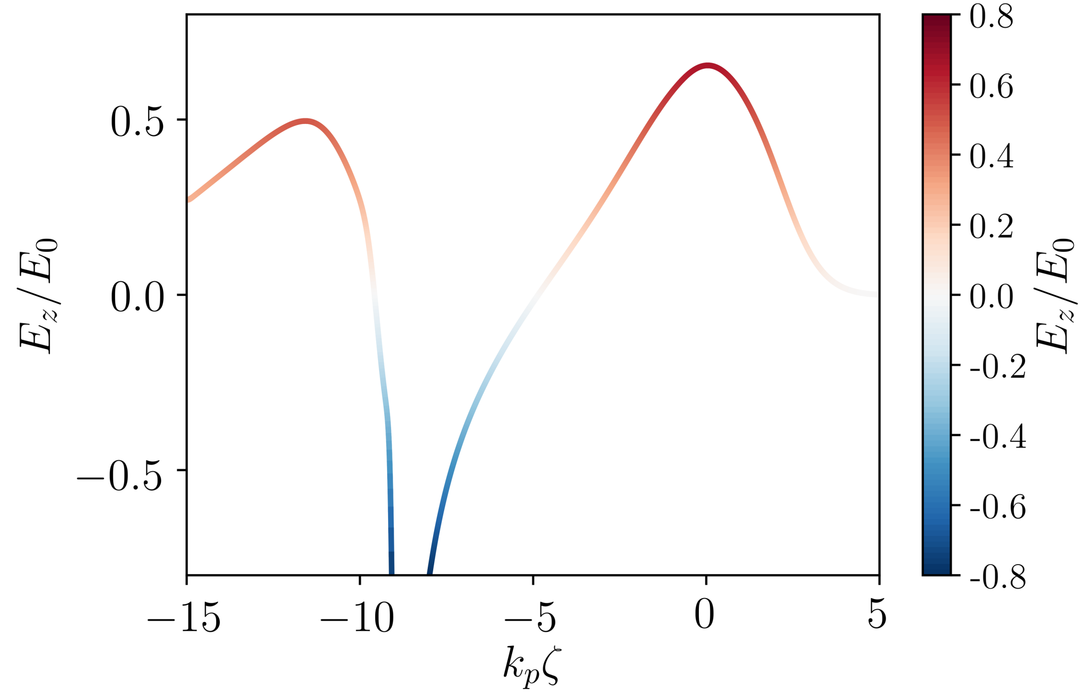


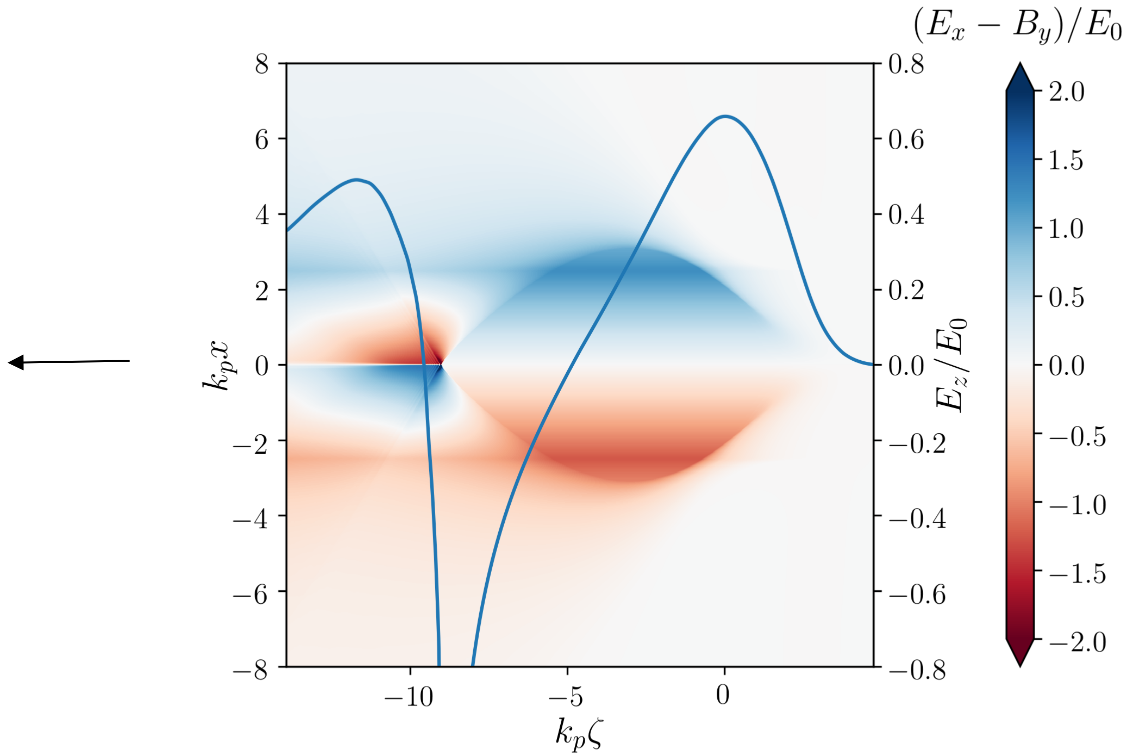
3. Long, high-density electron filament

4. Accelerating and focusing fields for positrons

Plasma radius can be optimized w.r.t. efficient positron acc.

in pre-ionized plasma columns





Plasma radius can be optimized w.r.t. efficient positron acc.

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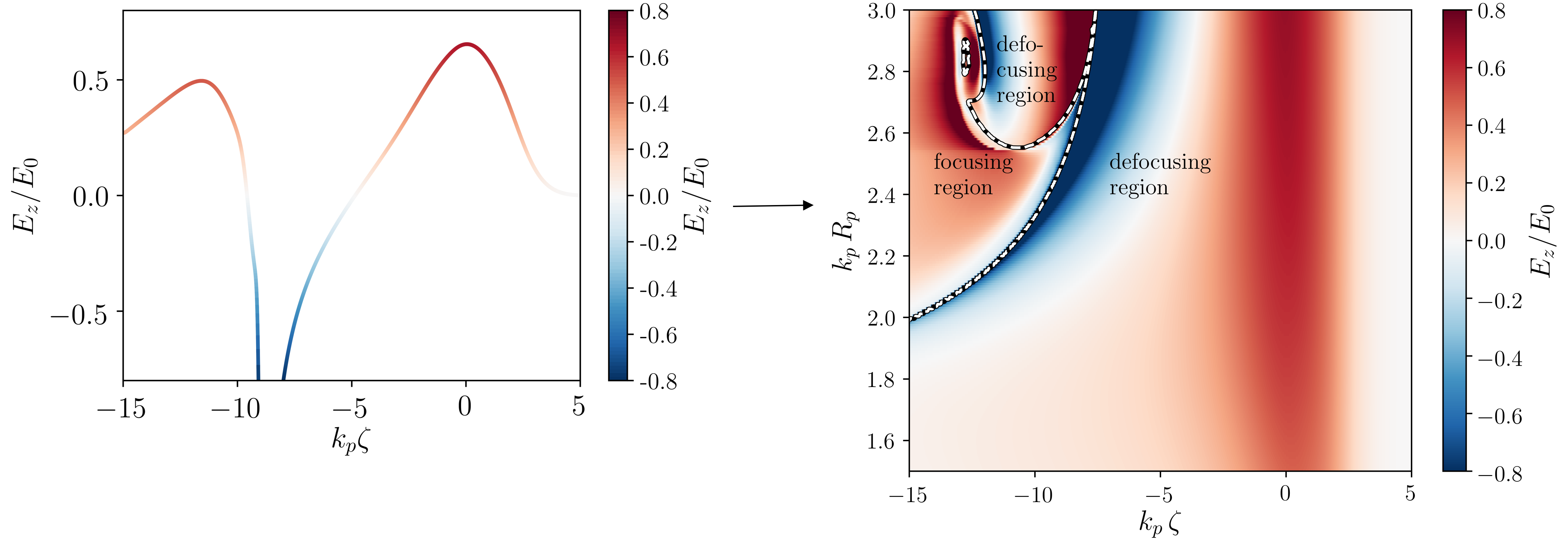
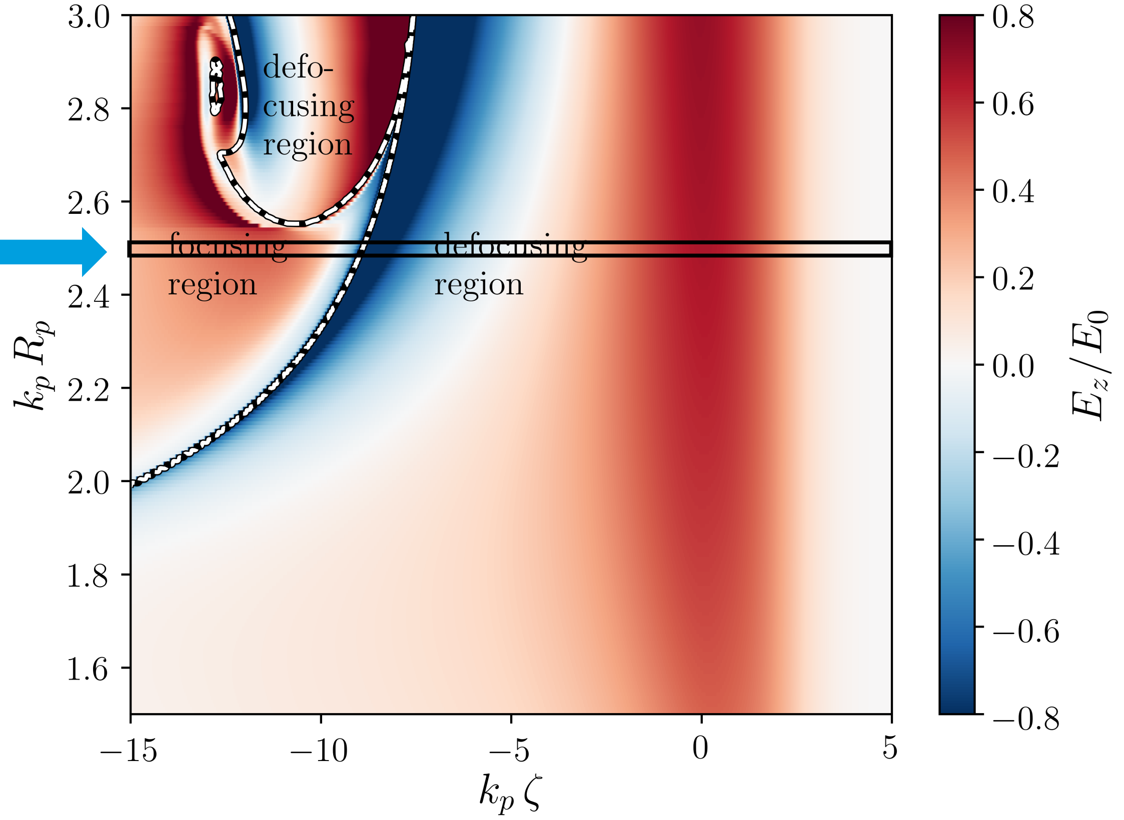


Plasma radius can be optimized w.r.t. efficient positron acc.

in pre-ionized plasma columns

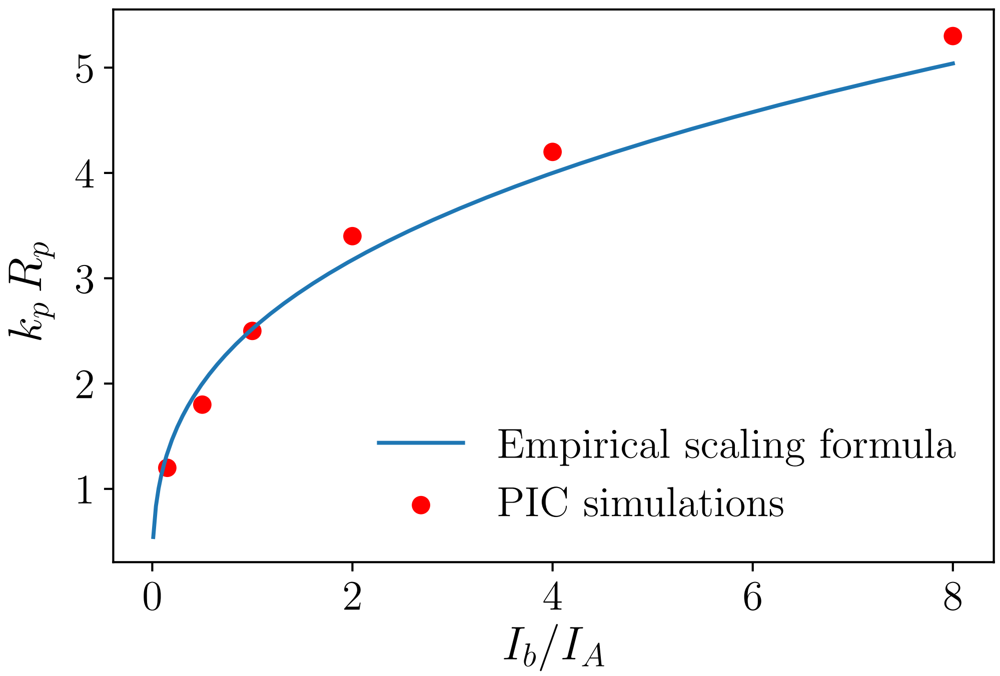
Optimal plasma radius $R_p \approx 2.5\, k_p^{-1}$

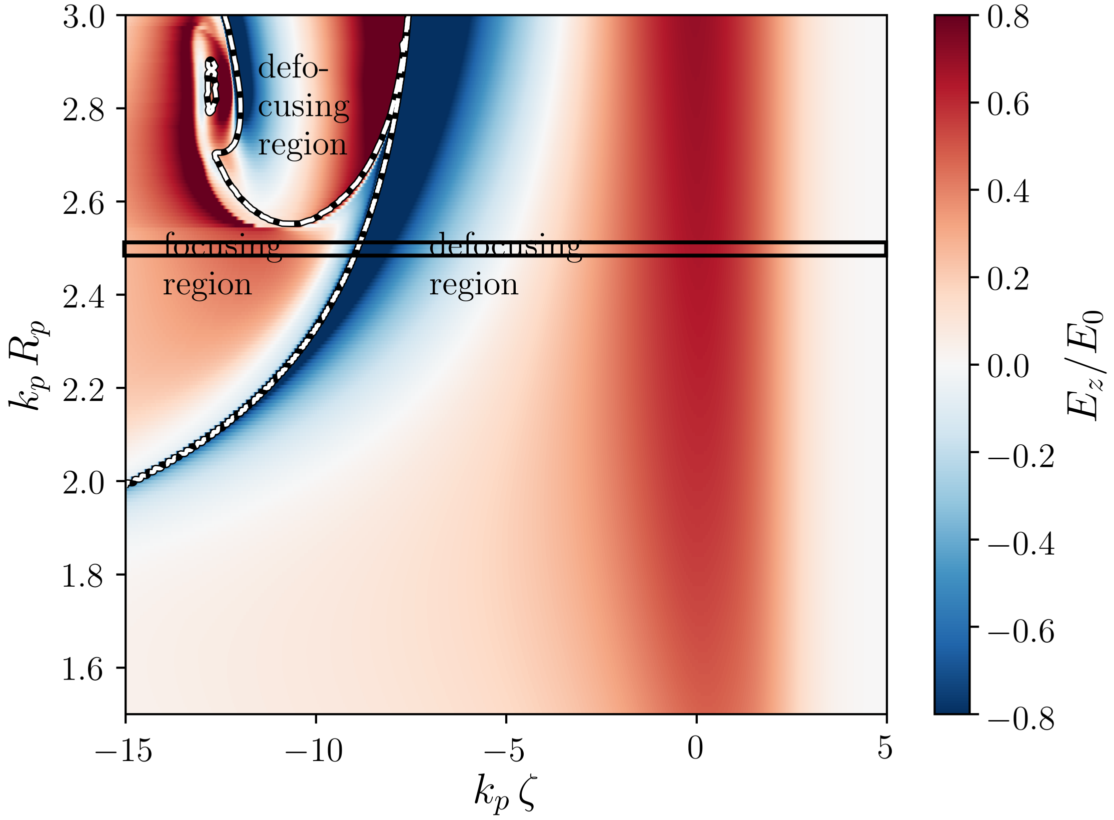


Drive beam parameters: $k_p\sigma_x = 0.3, k_p\sigma_z = \sqrt{2}, I_b/I_A = 1$

Plasma radius can be optimized w.r.t. efficient positron acc.

in pre-ionized plasma columns





Optimal plasma column radius (numerical fit):

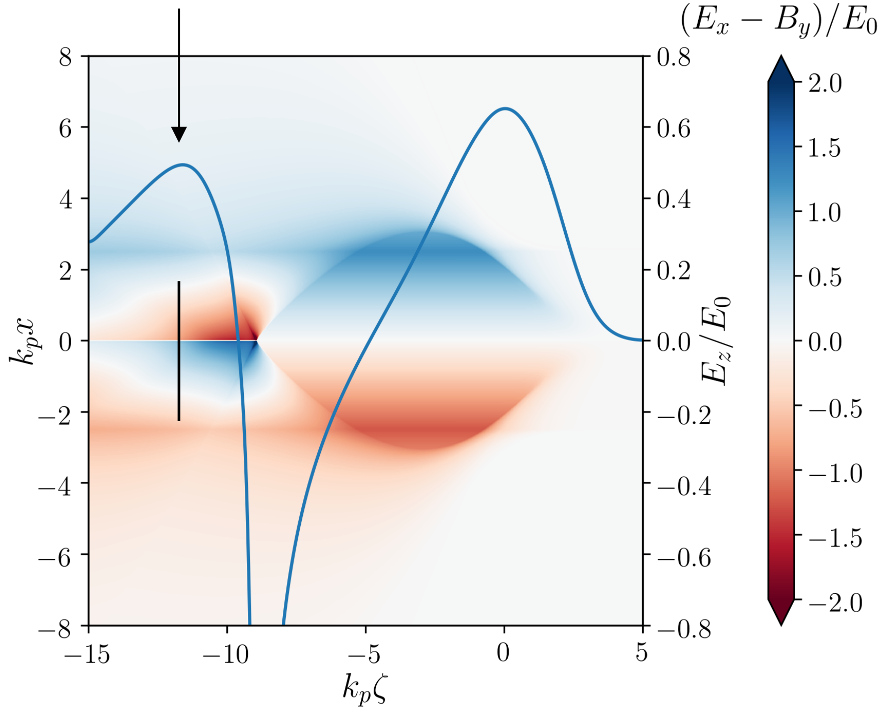
$k_p R_p \approx 2\sqrt[3]{2 I_b/I_A}$

Drive beam parameters: $k_p\sigma_x = 0.3, k_p\sigma_z = \sqrt{2}, I_b/I_A = 1$

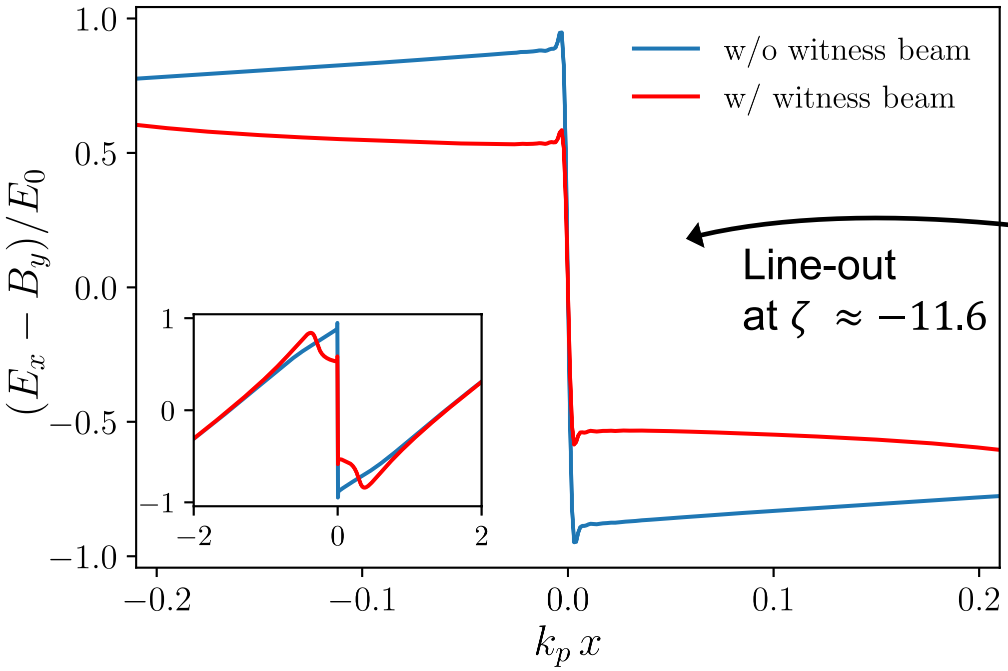
Positron transport and acceleration in plasma columns

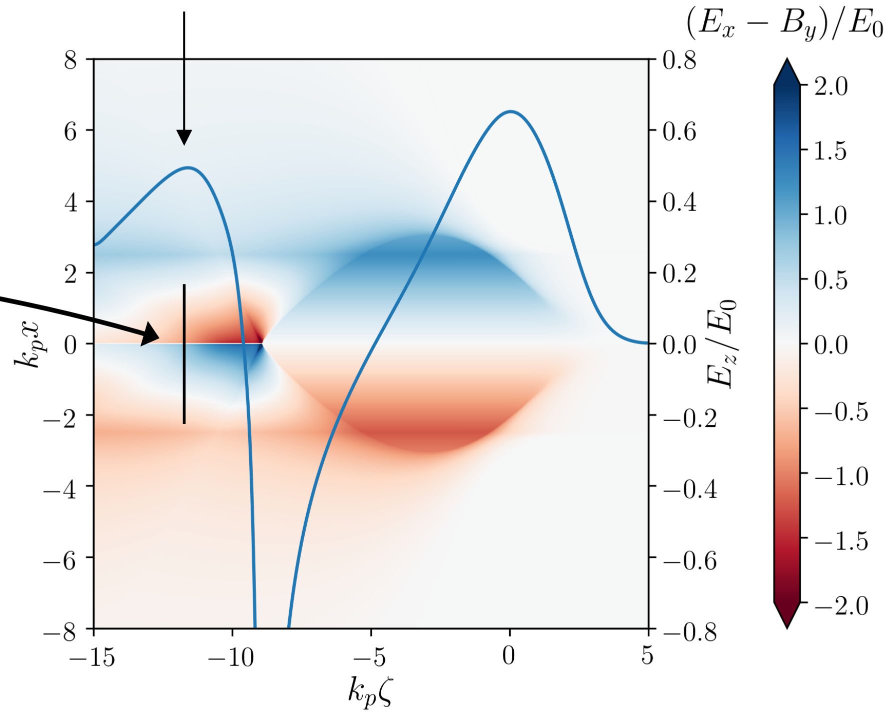
Emittance preservation achievable with matched beams

Optimal positron
witness bunch position



Emittance preservation achievable with matched beams



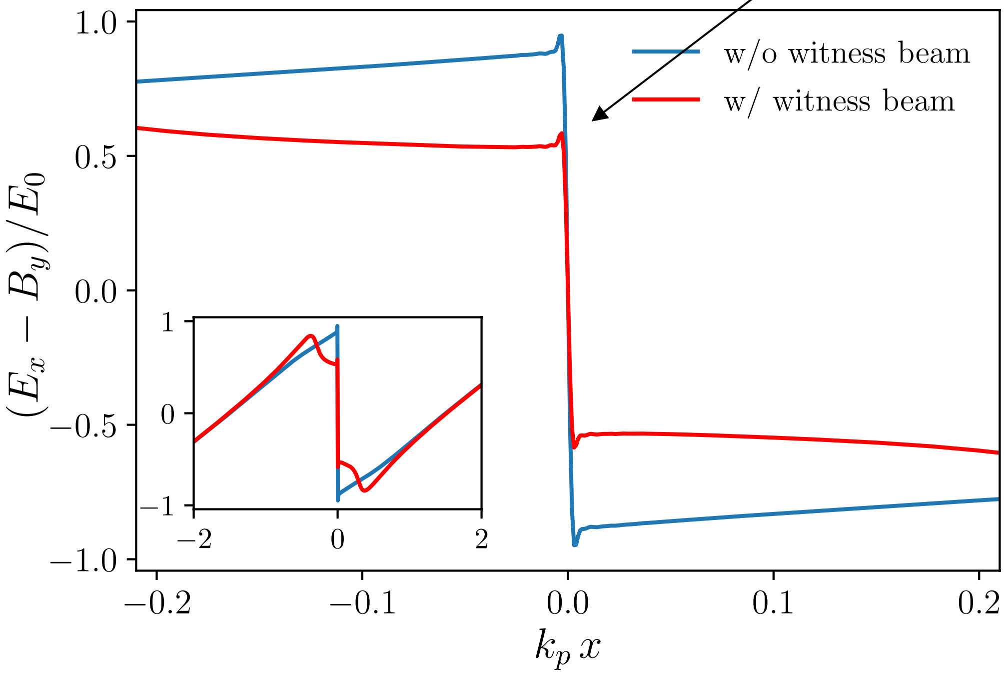


Witness beam parameters:

$k_p\sigma_x = 0.025,\ k_p\sigma_z = 0.5,\ \mathrm{n_b}/n_0 = 500$

Emittance preservation achievable with matched beams

$$\frac{E_x - B_y}{E_0} \approx -\alpha\, \mathrm{sgn}(x)$$



Quasi-matching condition for positron bunch with Gaussian transverse phase-space distribution

$$\sigma_x^3 \simeq 1.72\, \frac{\epsilon_x^2}{\alpha\, \gamma}$$

→ 2% rms emittance growth

Matching depends on longitudinal bunch position since $\alpha = \alpha(\zeta)$

Witness beam parameters:

$k_p\sigma_x = 0.025,\ k_p\sigma_z = 0.5,\ \mathrm{n_b}/n_0 = 500$

C. Benedetti et al., PRAB 2017
S. Diederichs et al., PRAB 2019

Demonstration of emittance-preserving positron acceleration

Comparison to PIC simulation

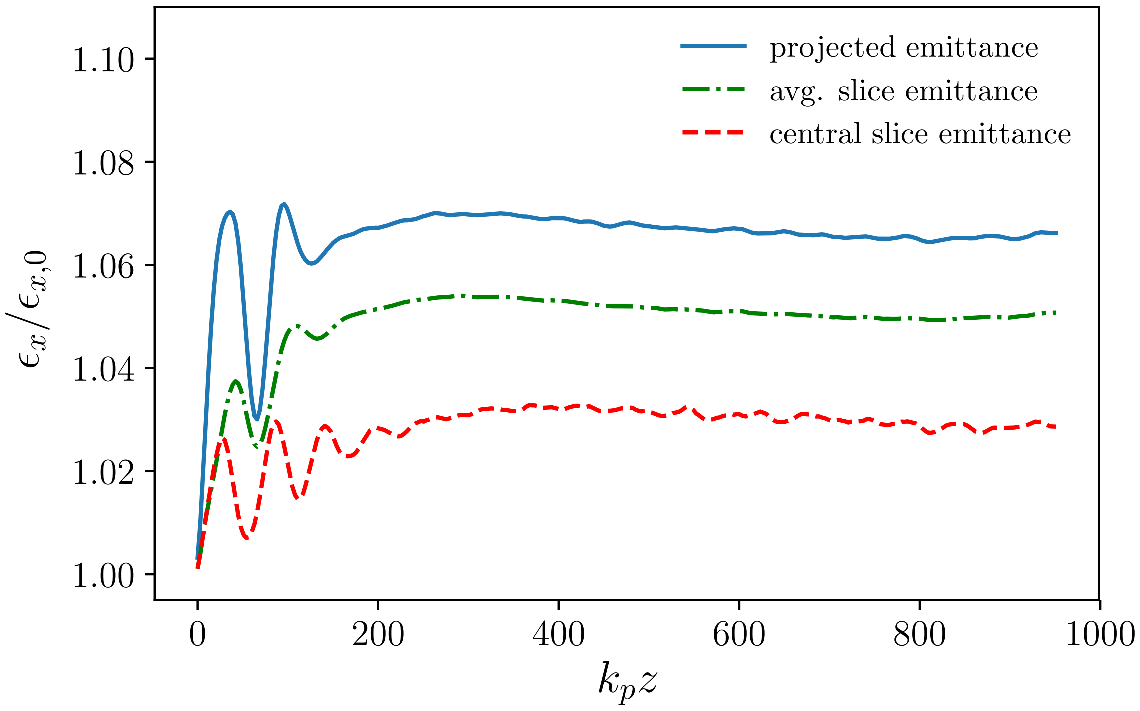
Plasma column: $n_0 = 5{\times}10^{17}\text{cm}^{-3}$, $\mathrm{R_p} \approx 20\mu\text{m}$

Driver beam parameters (Gaussian, non evolving):
$\sigma_x = 2.3\mu\text{m}$, $\sigma_z = 10.6\mu\text{m}$, $I_b/I_A = 1$, $Q_b = 1.5\text{nC}$

Witness beam parameters (Gaussian):
$\sigma_x = 0.19\mu\text{m}$, $\sigma_z = 3.75\mu\text{m}$, $Q_b = 84\text{p}C$, $\epsilon_x = 0.75\mu\text{m}$

→ 30 GeV/m accelerating gradient

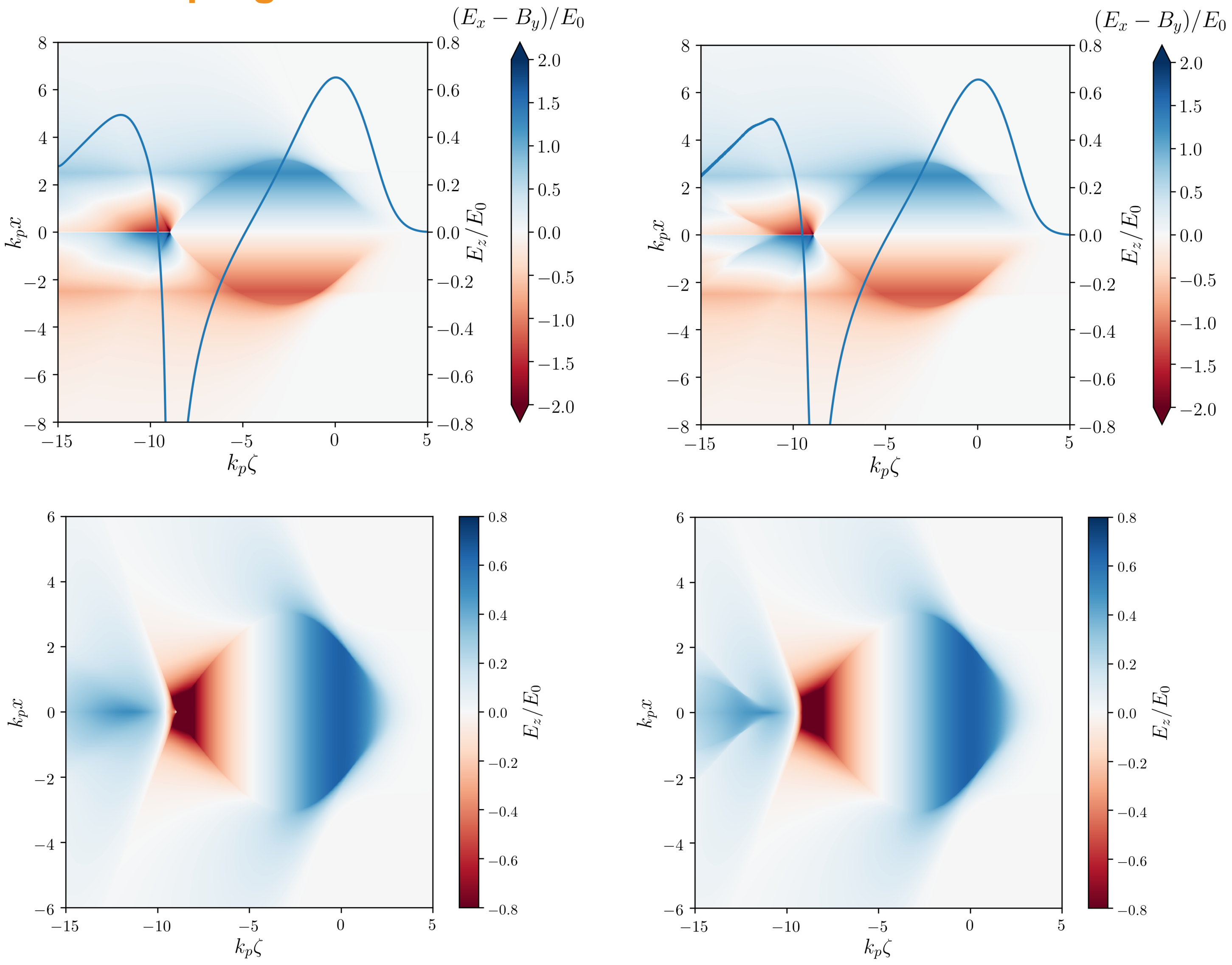
Positron beam emittance evolution

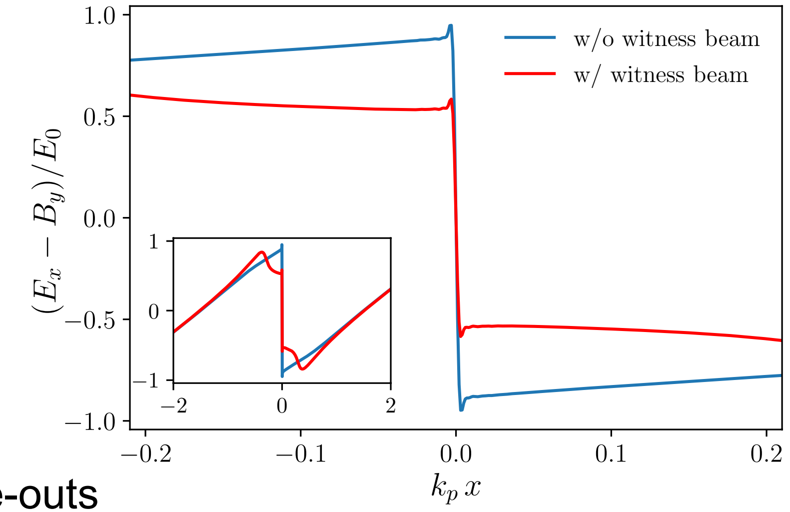


Emittance growth from simulation:
→ quasi-matched central slice: ≈ 3%
→ total (projected) bunch: ≈ 7%

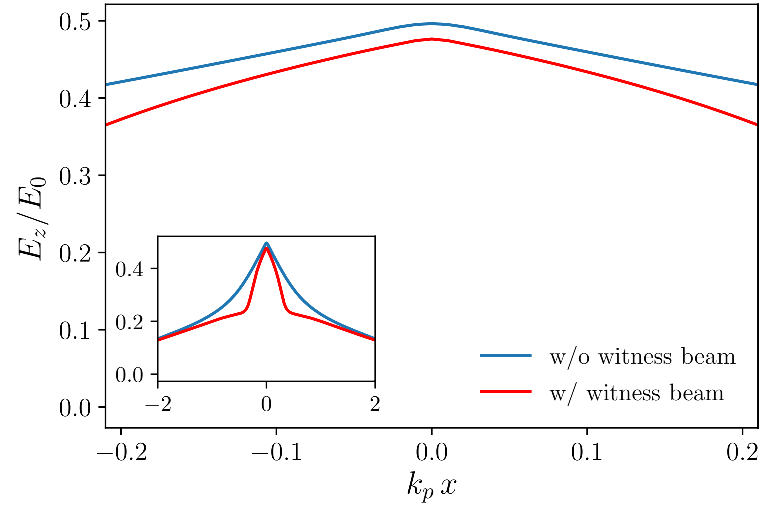
Energy spread can be controlled by beam loading

Work in progress

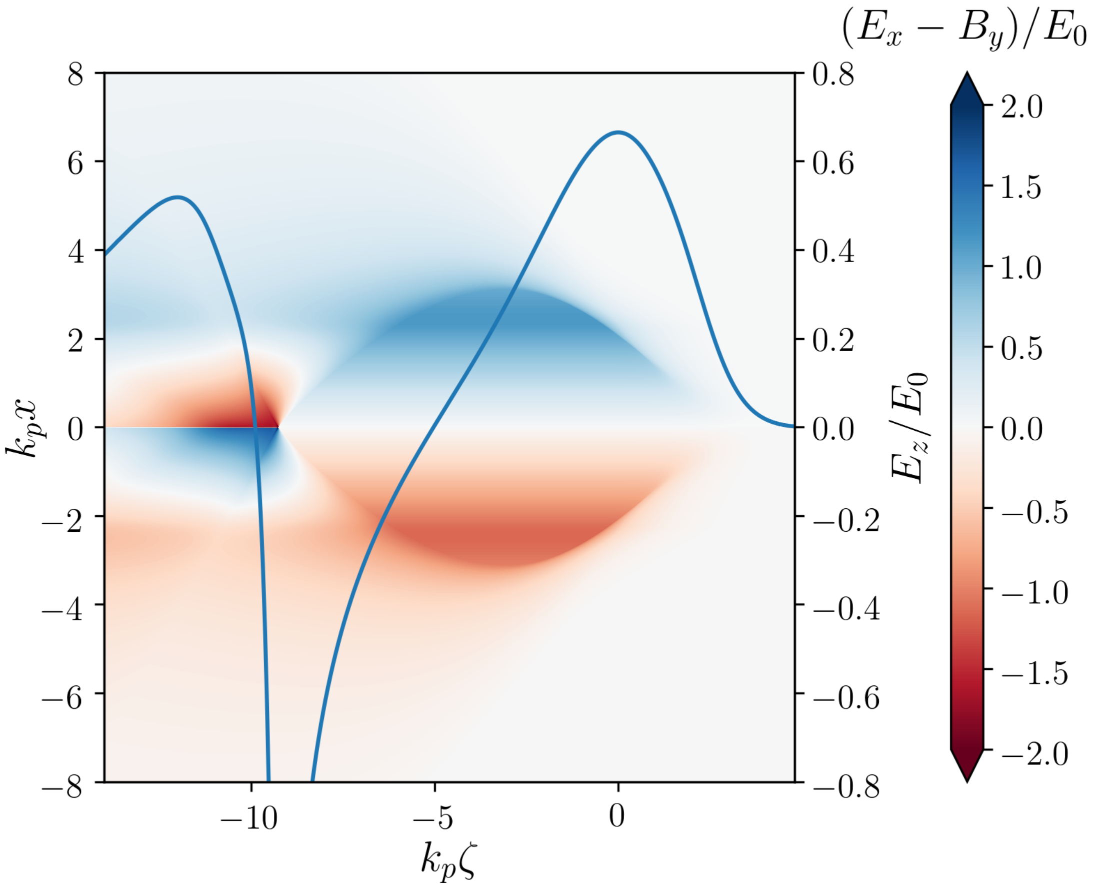


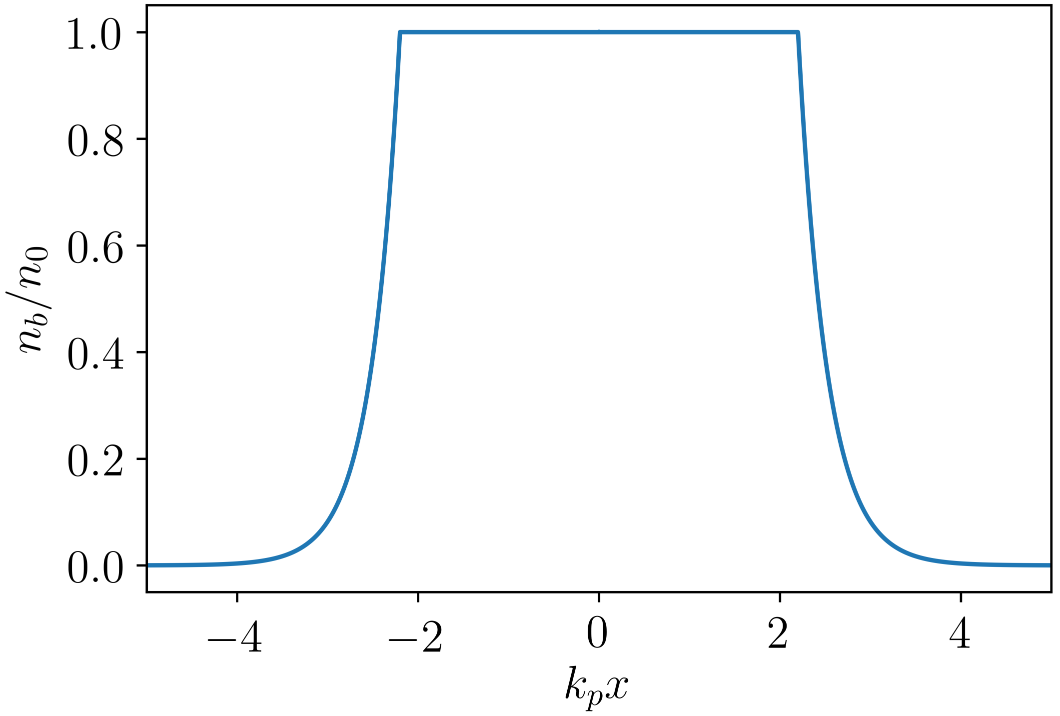


Line-outs
at $\zeta \approx -11.6$



Concept has tolerance on shape of plasma column



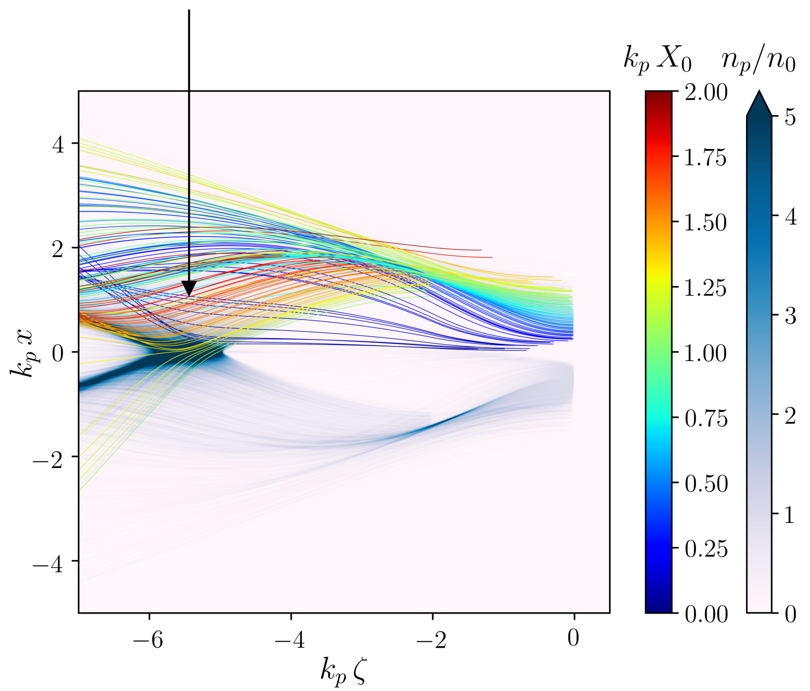


$k_p R_p = 2.2,\ k_p \sigma_{R_p} = 0.32$

Plasma column can be generated by beam-field-ionization

Work in progress

Expanded region of high electron density



Self-inherent alignment between
drive beam and plasma column

Plasma column can be generated by beam-field-ionization

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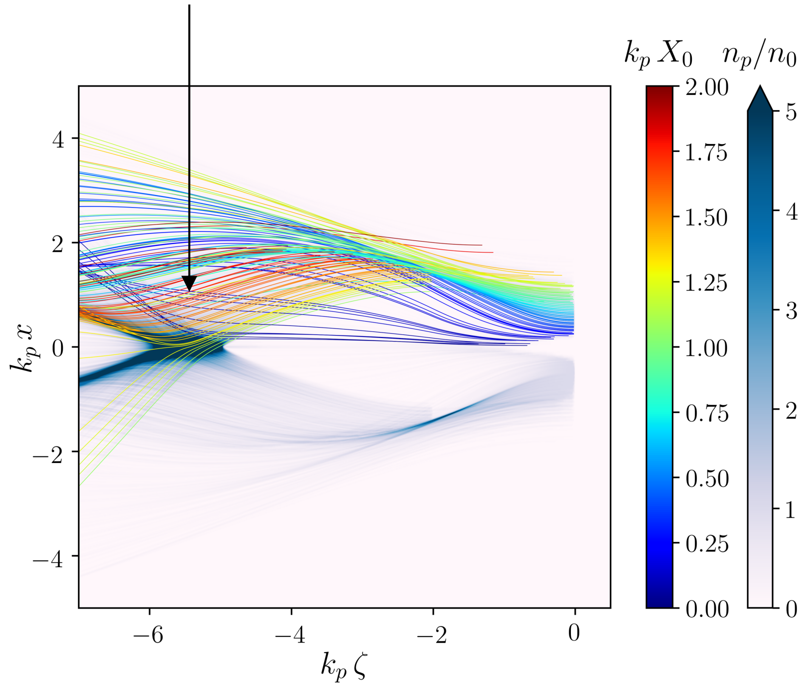
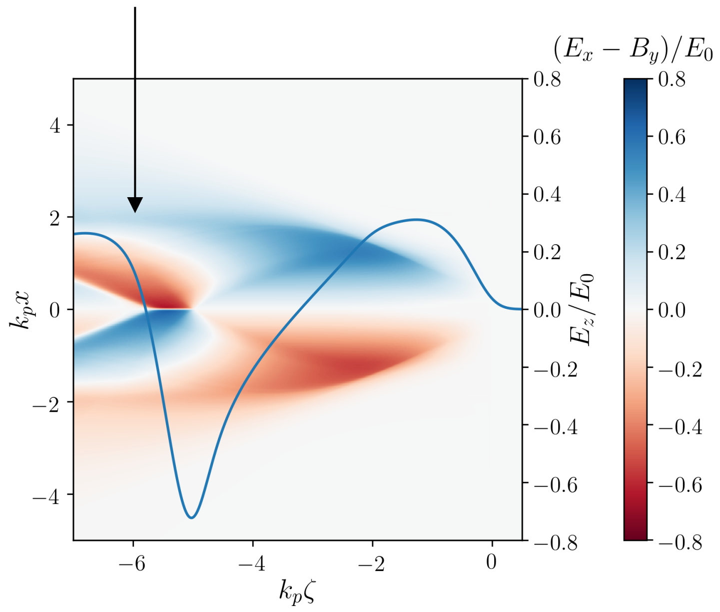


Positron accelerating and focusing field don‘t match

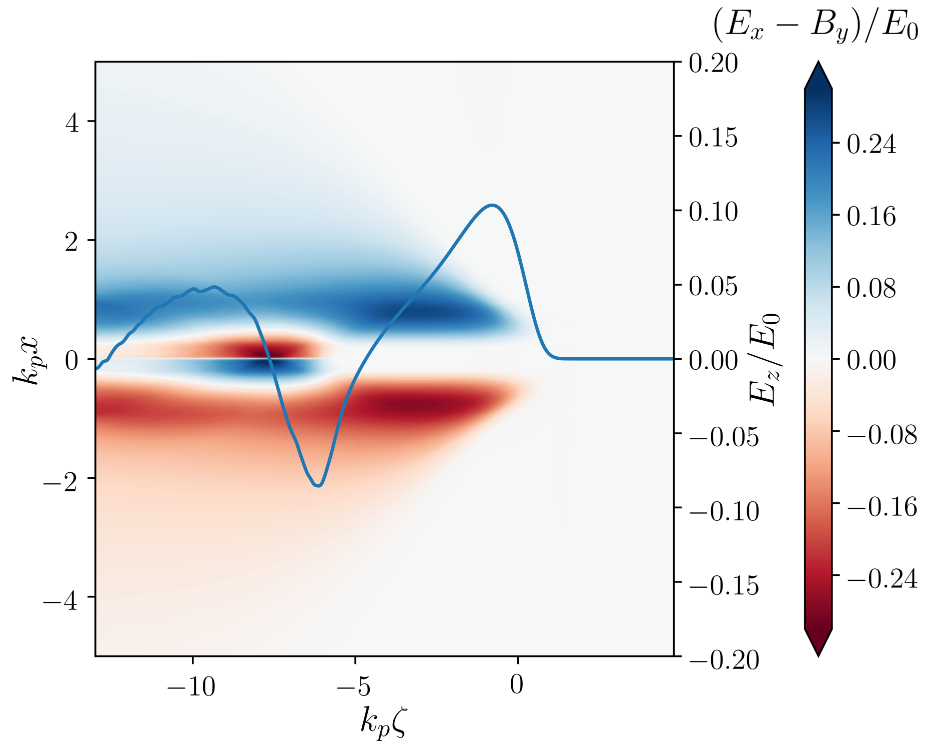


Self-inherent alignment between
drive beam and plasma column

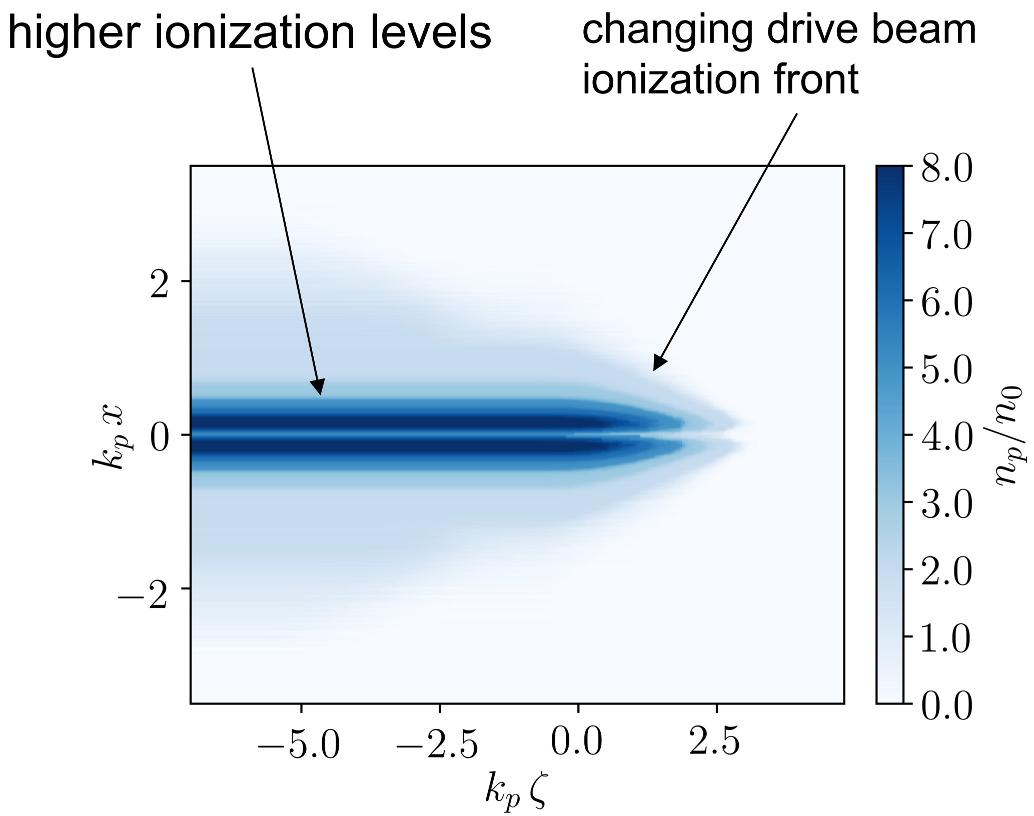
Solvable by parameter optimization!

Coupled plasma column generation limits accelerating fields

Work in progress



$k_p\sigma_x = 0.3, k_p\sigma_z = \sqrt{2}, n_b/n_0 = 2.9$
$n_0 = 1.25{\times}10^{18}\text{cm}^{-3}$



Solvable by full beam parameter,
gas density & species optimization!

Summary

- Finite radius plasma columns have been proposed as structures suitable for positron transport and acceleration in a PWFA;
- The wakefield produced in these structures has been studied and optimized with respect to positron acceleration (an expression for the optimal radius has been obtained);
- Quasi-matching condition for a positron bunch has been obtained;
- PIC simulations show that by using plasma columns acceleration of positron beams with substantial charge while preserving the emittance is possible.

For more details, see our publication: **Diederichs *et al*., Phys. Rev. Accel. Beams 22, 081301 (2019)**

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