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

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18.09.19

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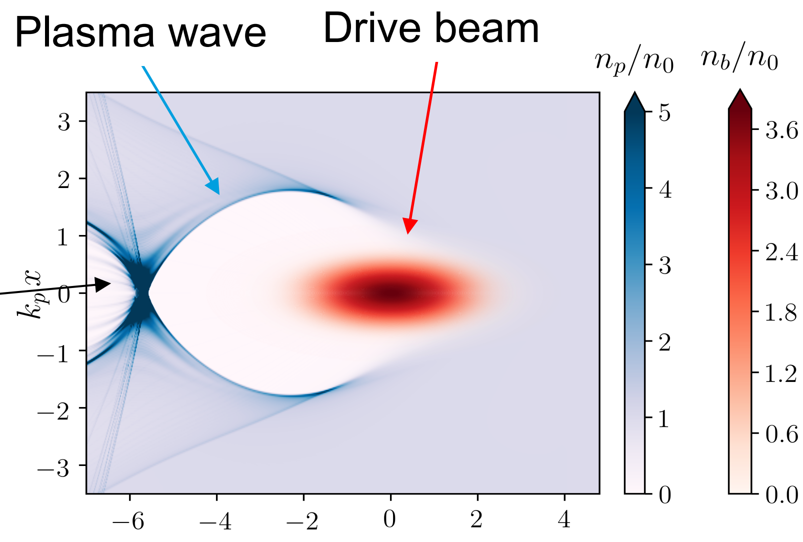
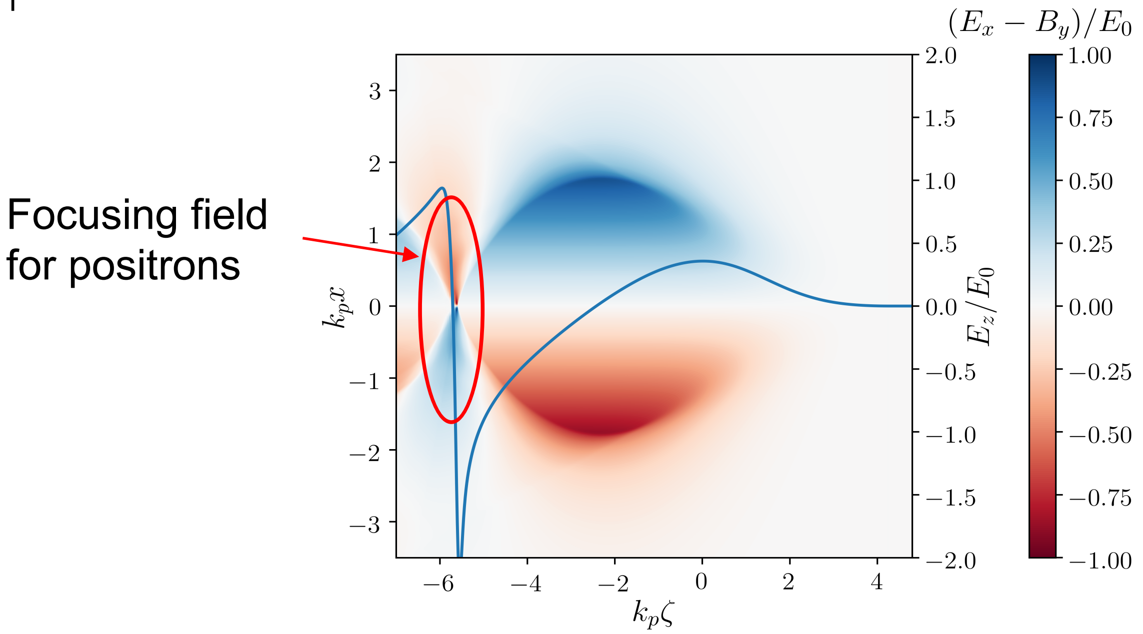
Positron acceleration is a challenge

In the blowout regime

- Plasma electrons return to axis on the same spot, forming a **narrow, high density electron cusp**
- Positron focusing fields only within the small region of high electron density

Other concepts, using hollow core drive beams,[1] hollow core plasma channels,[2] or positron drive beams[3] are either **inefficient** or **unstable**





[1]N. Jain *et al*., Phys. Rev. Lett. 115, 195001 (2015)
[2]S. Gessner *et al*., Nat. Commun. 7, 11785 (2016)
[3]S. Corde *et al*., Nature (London) 524, 442 (2015)

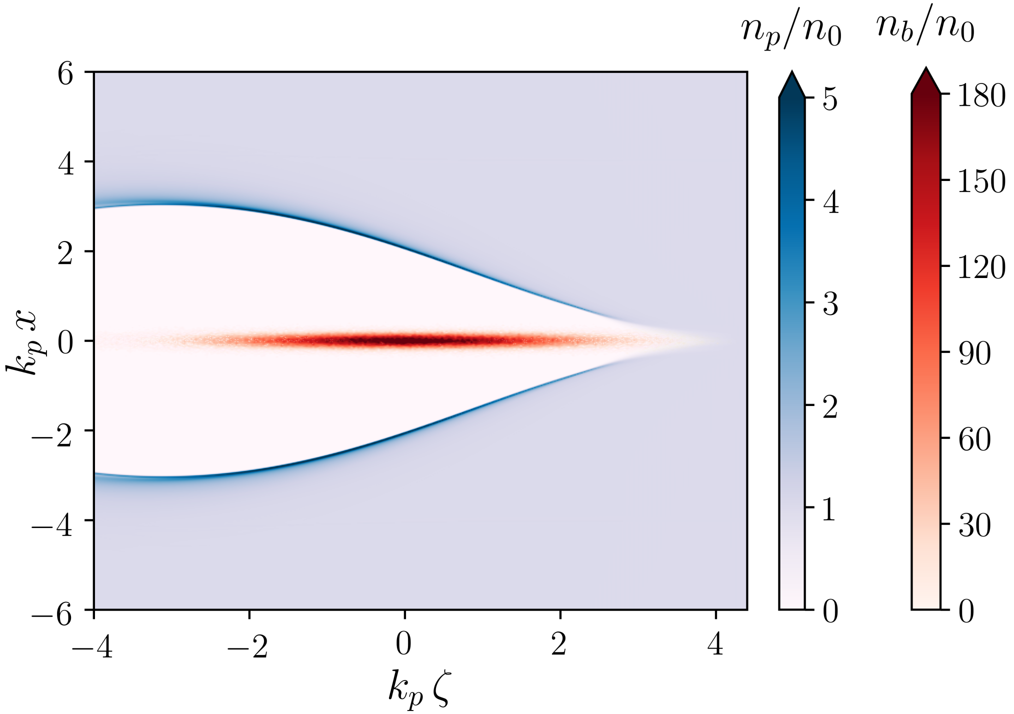
Wakefield generation in plasma columns

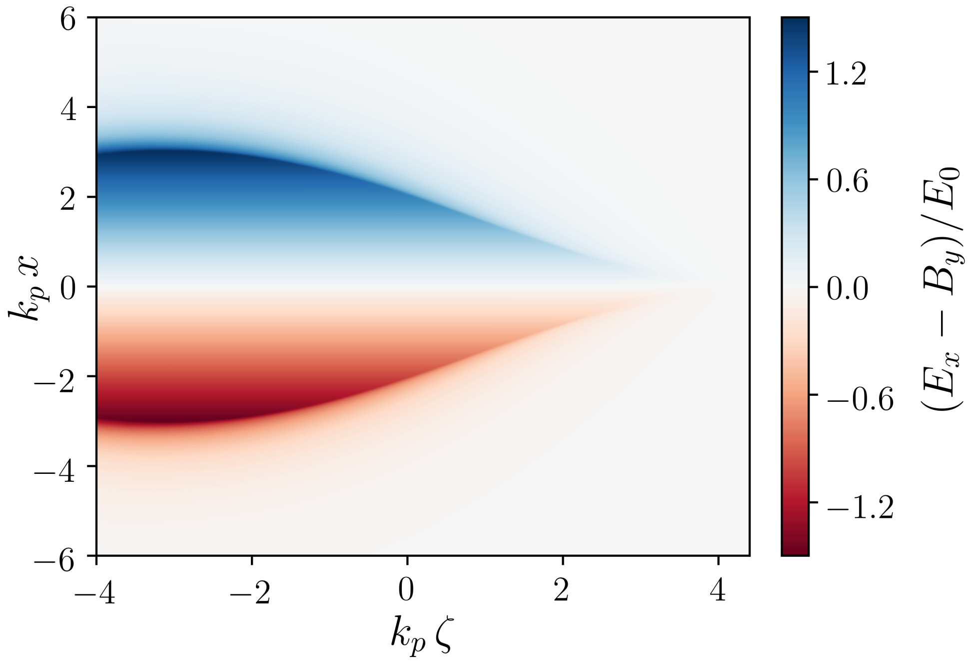
with regard to positron acceleration

Wakefield generation in plasma columns

in pre-ionized plasma columns

In the homogeneous, infinite plasma case:





Unless stated otherwise, the simulations were performed with HiPACE

T. J. Mehrling *et al.*, Plasma Phys. Controlled Fusion 56, 084012 (2014)
T. J. Mehrling *et al.*, 2018 IEEE AAC Proceedings

Wakefield generation in plasma columns

in pre-ionized plasma columns

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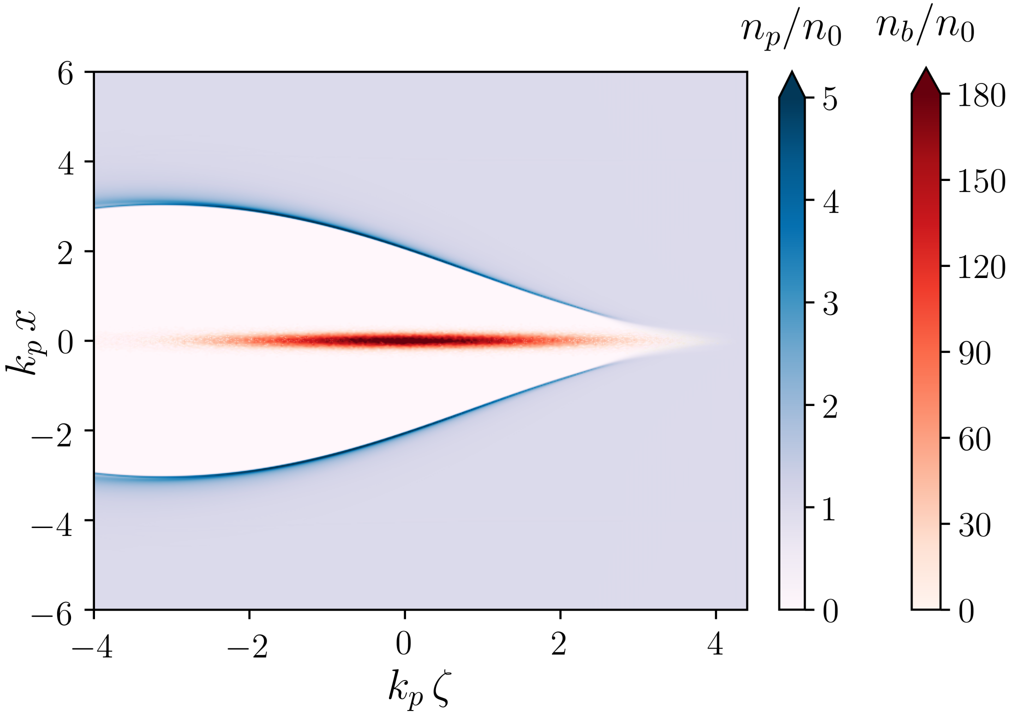
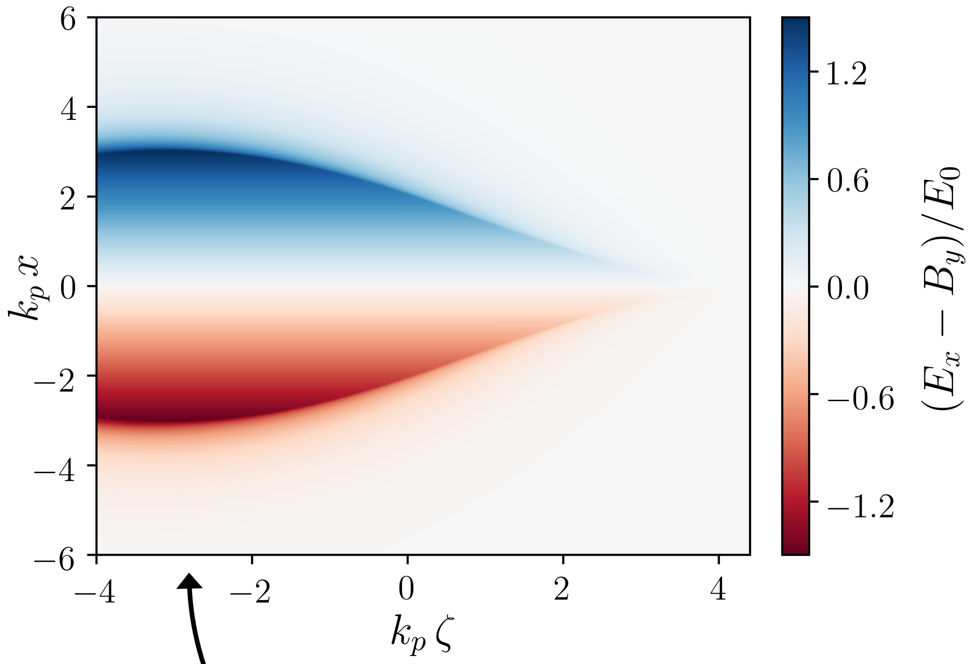
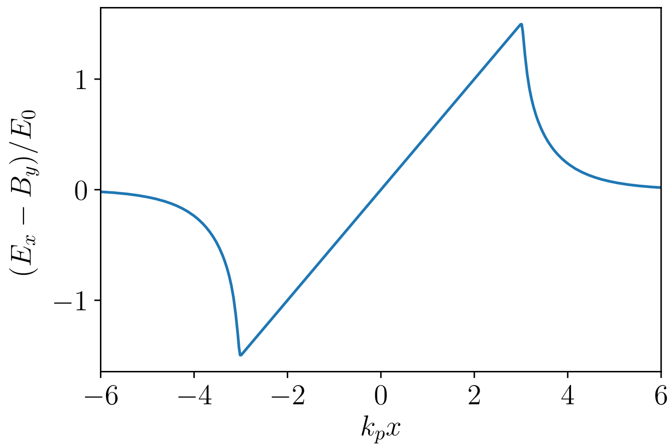




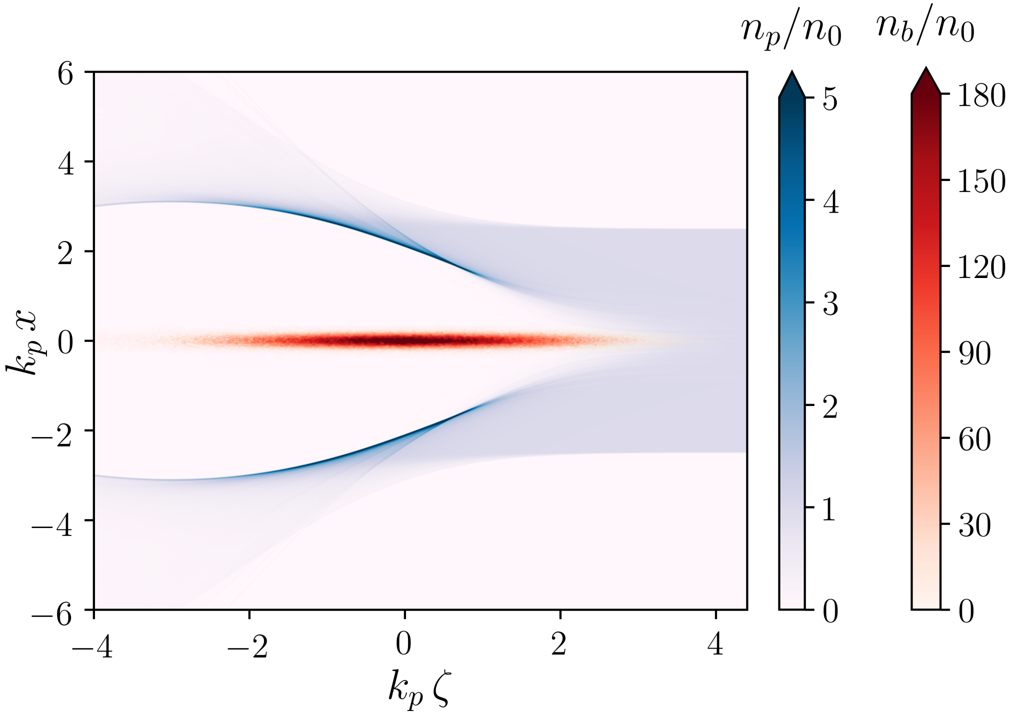
Line-out at ζ = -3.0

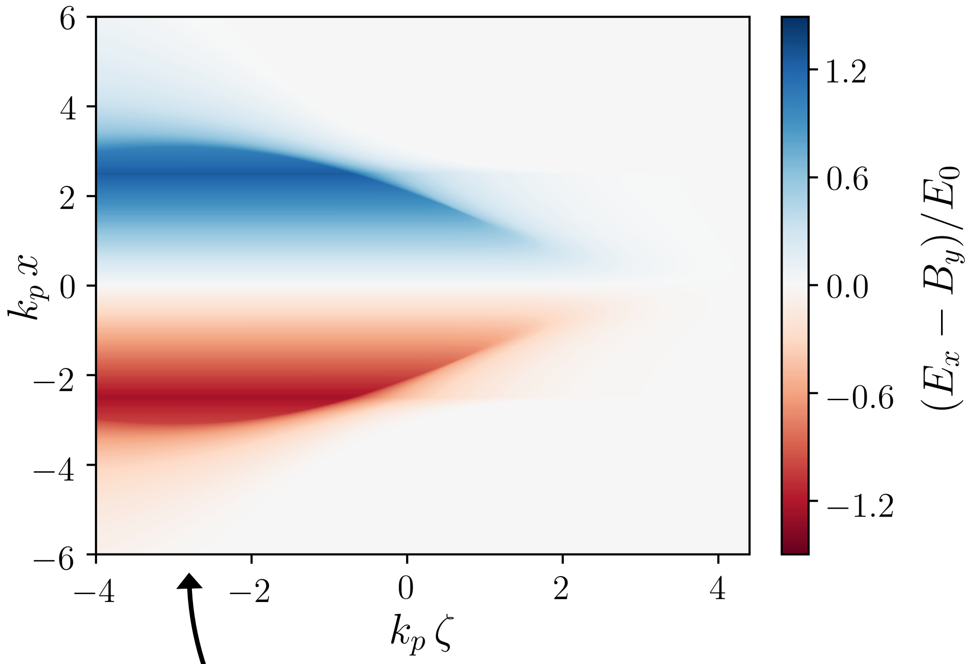


Wakefield generation in plasma columns

in pre-ionized plasma columns

Now, using a finite, pre-ionized plasma column:





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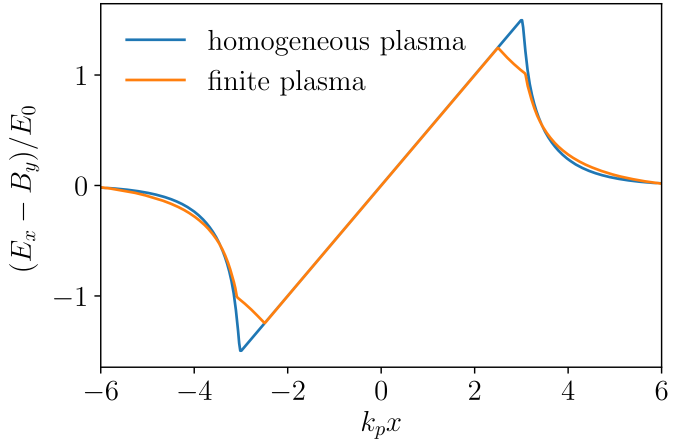

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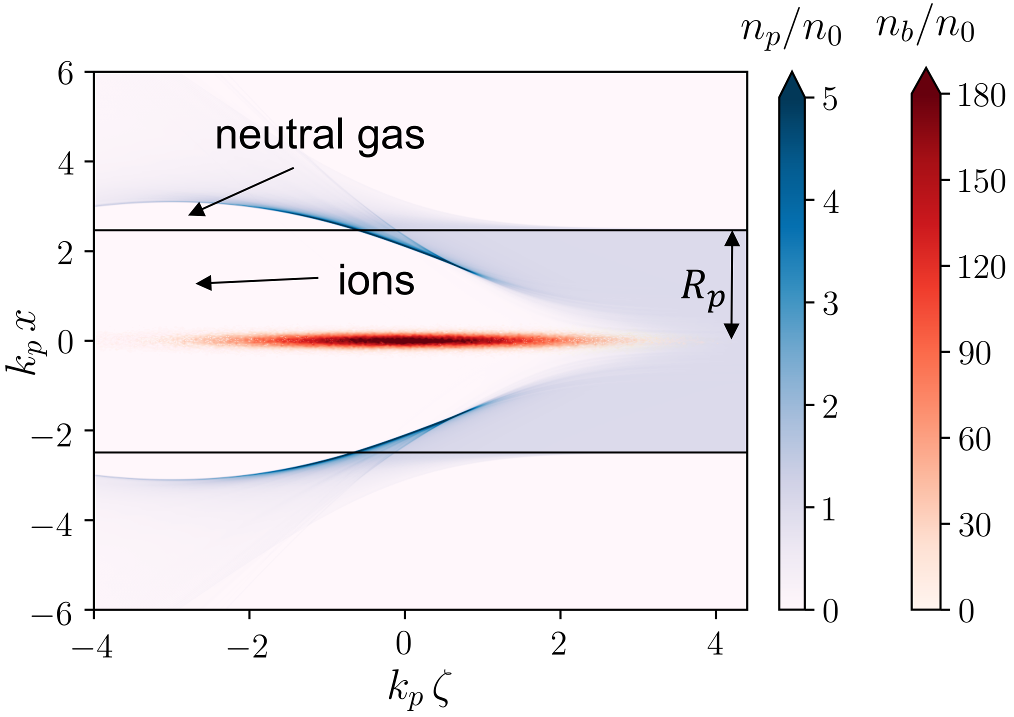

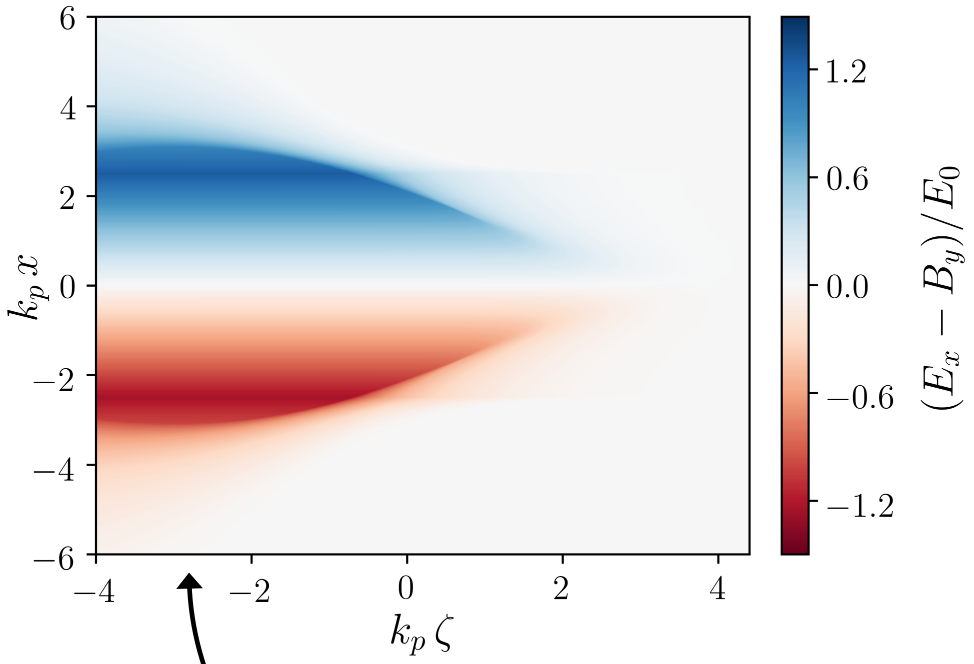

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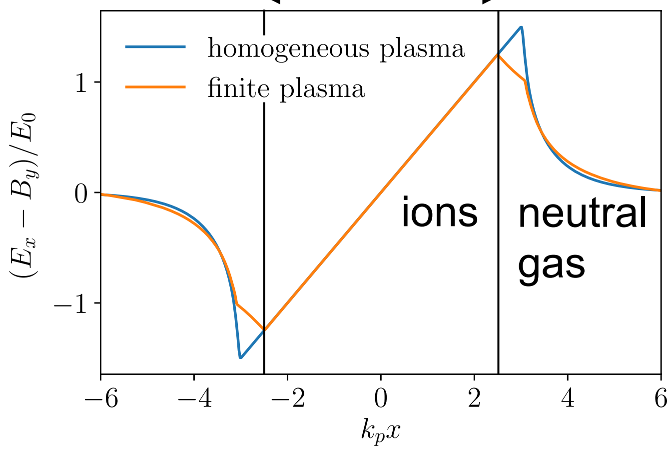
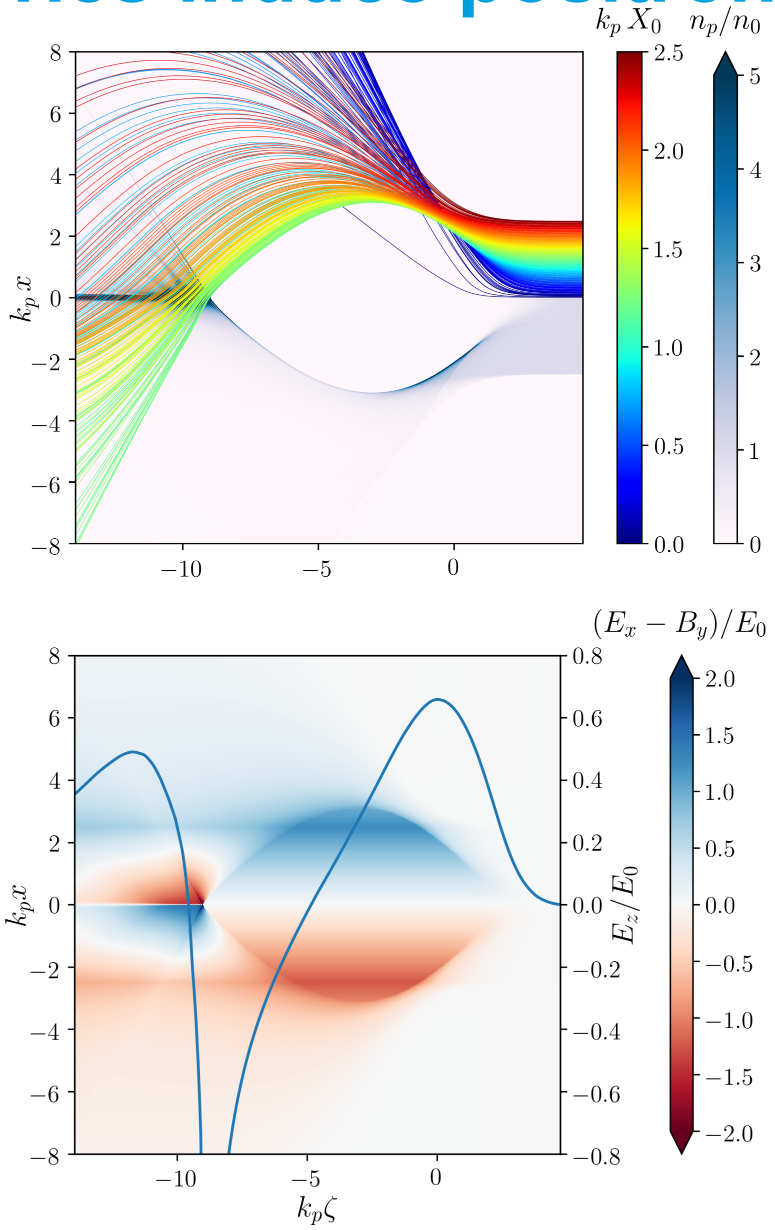


Lack of ions due to finite plasma column leads to a **modified transverse wakefield**

Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns

- Modified transverse wakefield leads to **elongated plasma electron trajectories**
- Elongated plasma electron trajectories create **long, high-density electron filament**
- This leads to a region with accelerating and focusing fields for positrons



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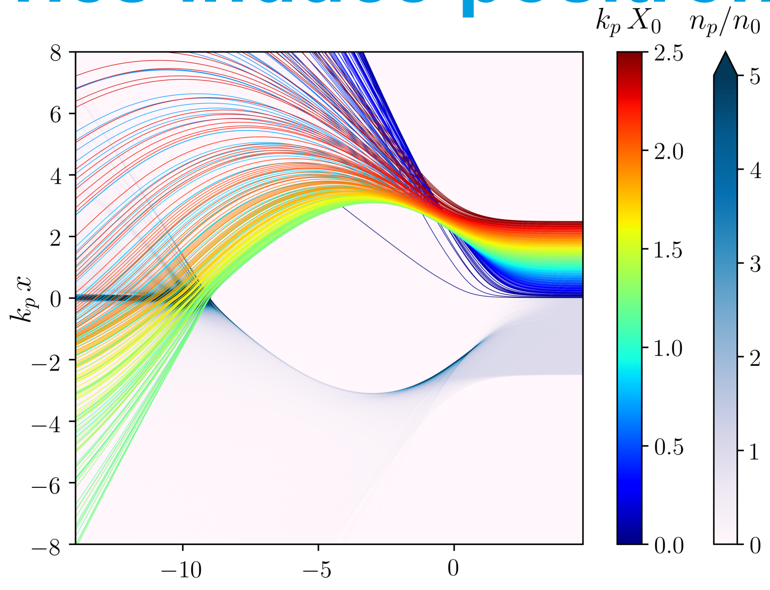
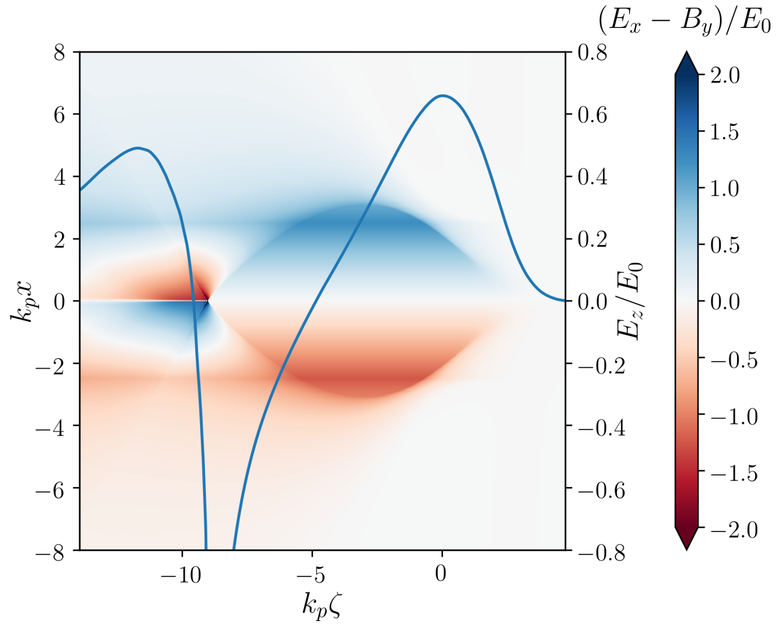




Which is the optimal plasma column radius w.r.t. high gradient, stable positron acceleration?

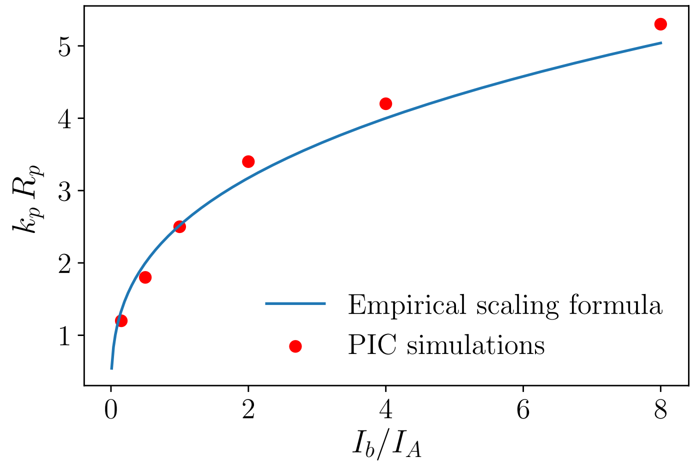
Plasma radius can be optimized w.r.t. efficient positron acc.

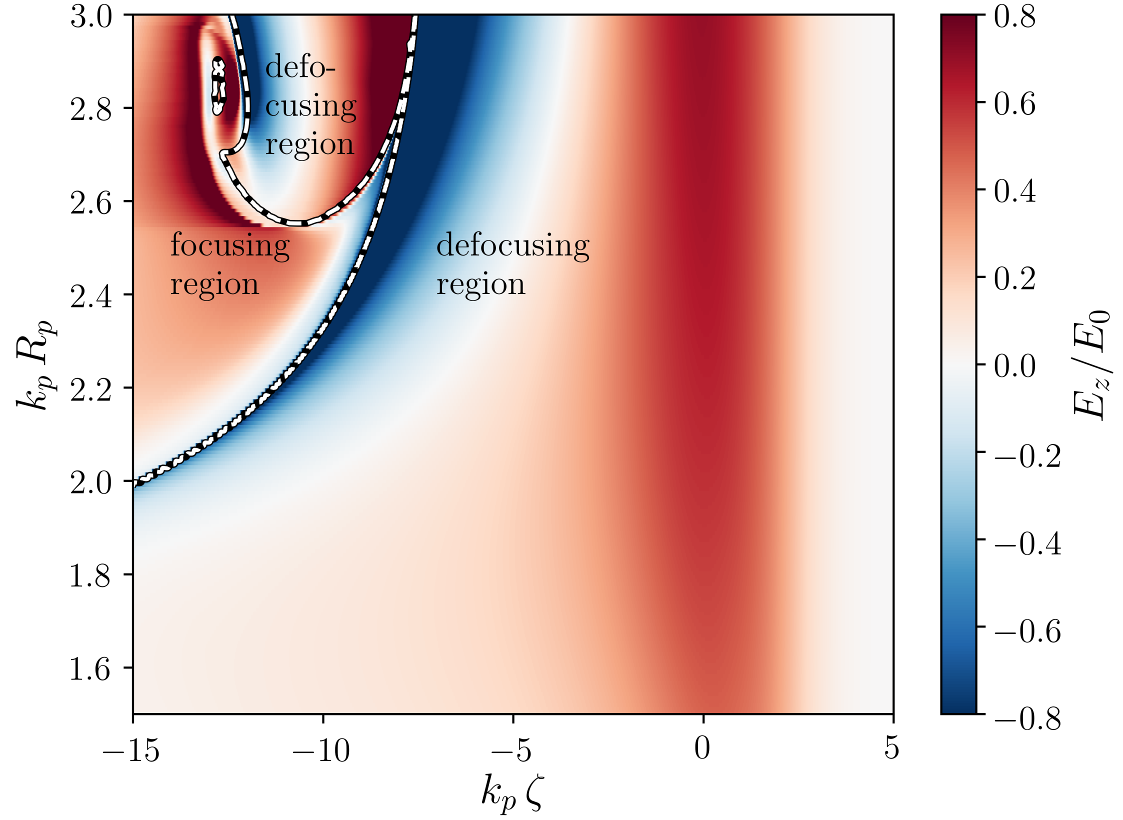
in pre-ionized plasma columns

Simulation performed with cylindrically-symmetric, quasi-static PIC code INF&RNO[1,2]

- The optimal plasma column radius for a bi-Gaussian beam can be calculated by

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





Here: $\sigma_x = 0.3\, k_p^{-1}, \sigma_z = \sqrt{2}\, k_p^{-1}, I_b/I_A = 1$

[1]C. Benedetti *et al.*, AIP Conf. Proc. 1299, 250 (2010).
[2]C. Benedetti *et al.*, AIP Conf. Proc. 1812, 050005 (2017).

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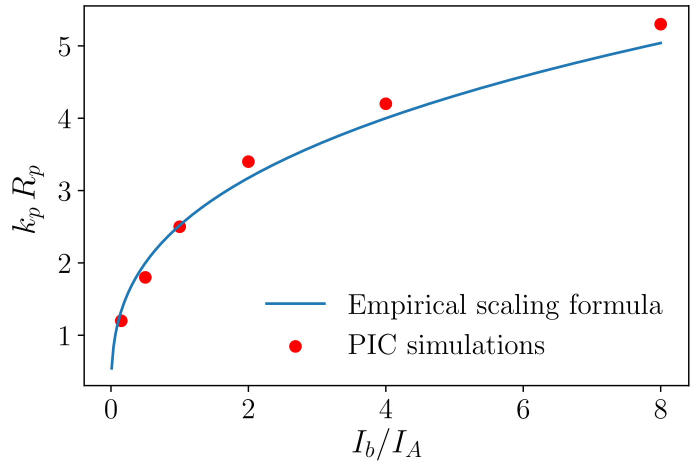
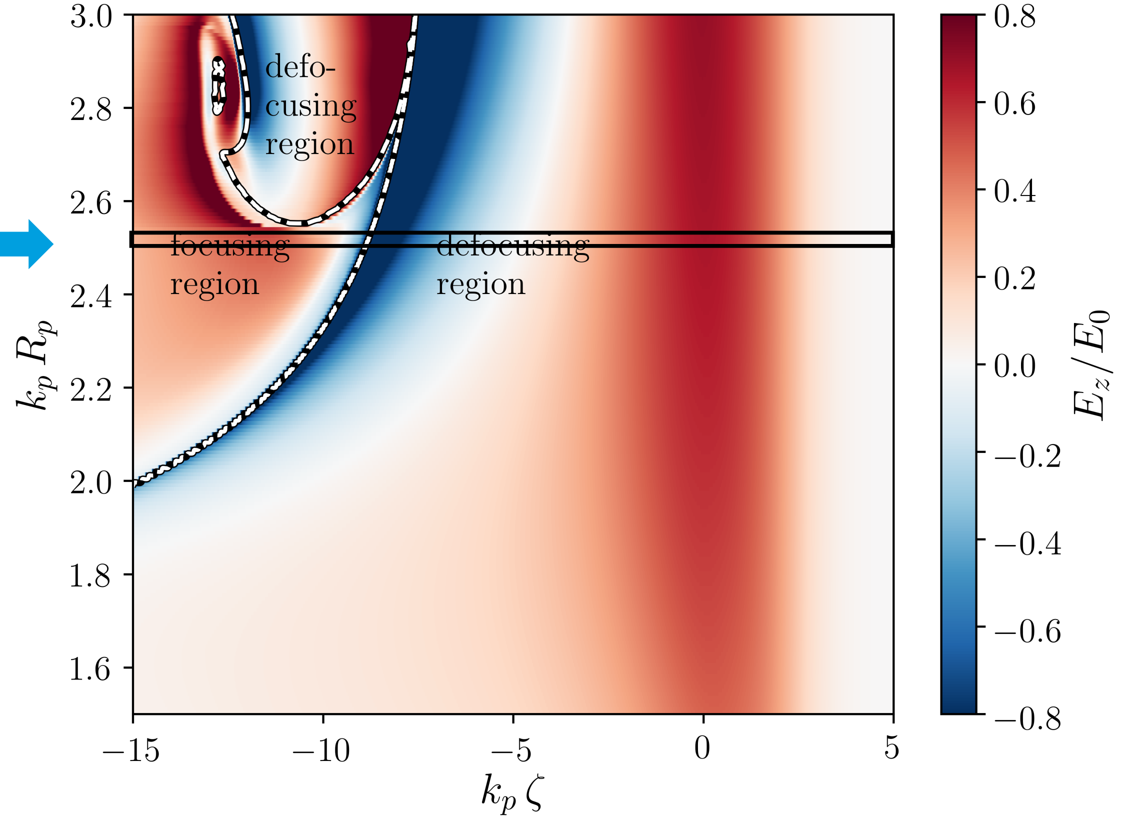


Optimal plasma radius $R_p \approx 2.5\, k_p^{-1}$



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Positron transport and acceleration in plasma columns

Important requirements for collider applications:

- High accelerating gradient
- High witness bunch charge
- Low emittance → emittance needs to be preserved during acceleration

Emittance (normalized to $m_e c$): $\epsilon_x = \sqrt{\langle x^2 \rangle \langle u_x^2 \rangle - \langle x u_x \rangle^2}$
for a Gaussian beam with no correlation: $\epsilon_x = \sigma_x \sigma_{u_x}$

- Emittance is usually preserved in linear focusing fields

Emittance preservation achievable with matched beams

- Here: focusing fields are almost like a **step-function:**

$$\frac{E_x - B_y}{E_0} = -\alpha \operatorname{sgn}(x)$$

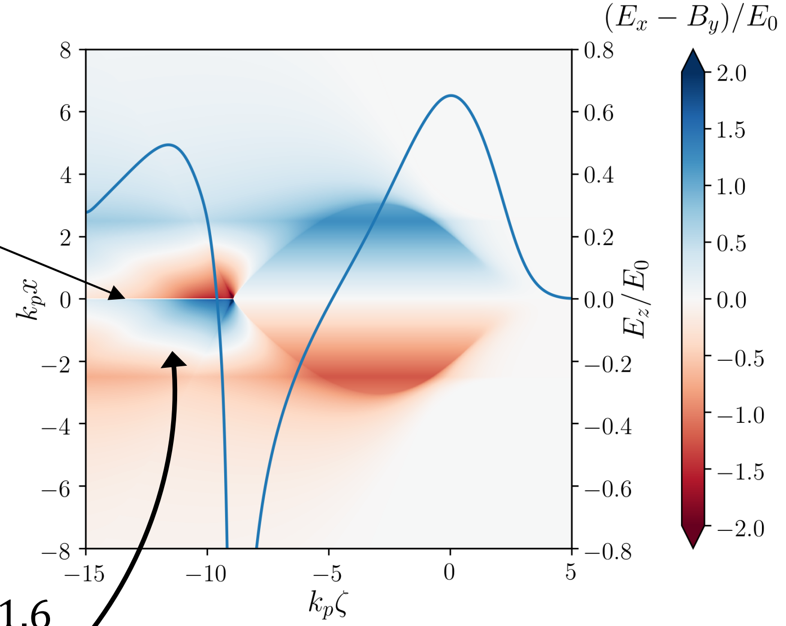
- For quasi-matched beams emittance growth at saturation can be calculated numerically and even for a simple Gaussian with

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

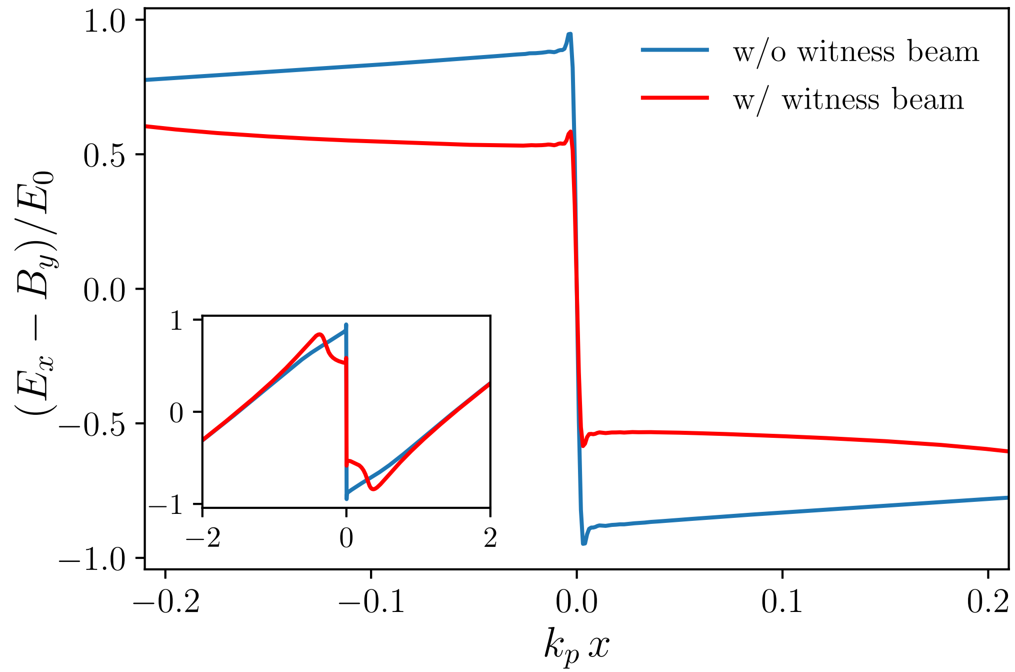
  it yields $\simeq 2\%$.

- Non-linear matching condition:
  for a chosen emittance ϵ_x, the optimal witness beam rms size σ_x can be calculated for a given field strength α and beam energy γ

Optimal positron witness bunch position



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



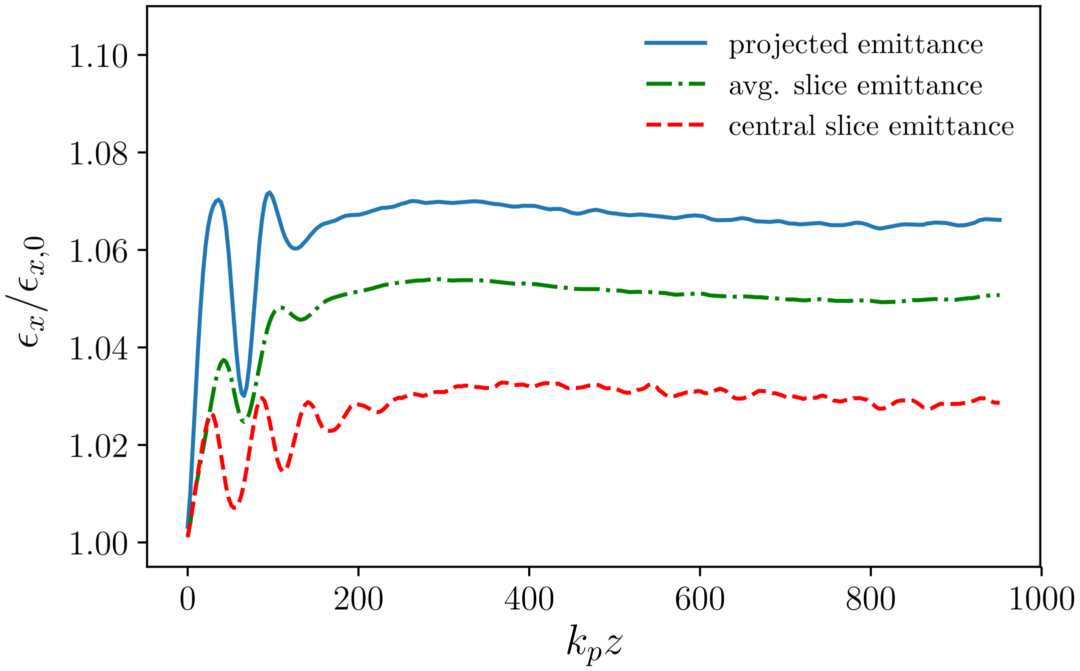
Simulations performed with INF&RNO

Demonstration of emittance-preserving positron acceleration

Comparison to PIC simulation

The drive beam is kept rigid in this simulation

- Witness beam parameters: $\epsilon_x = 0.1\ k_p^{-1}$, $\sigma_x = 0.025\ k_p^{-1}$, $\gamma = 2000$
  With background plasma density $n_0 = 5 \times 10^{17} cm^{-3}$:
  Charge $Q_w \approx 84\ pC,\ \ Q_D \approx 1.5\ nC$
- Average acceleration gradient: $30\ GeV/m$

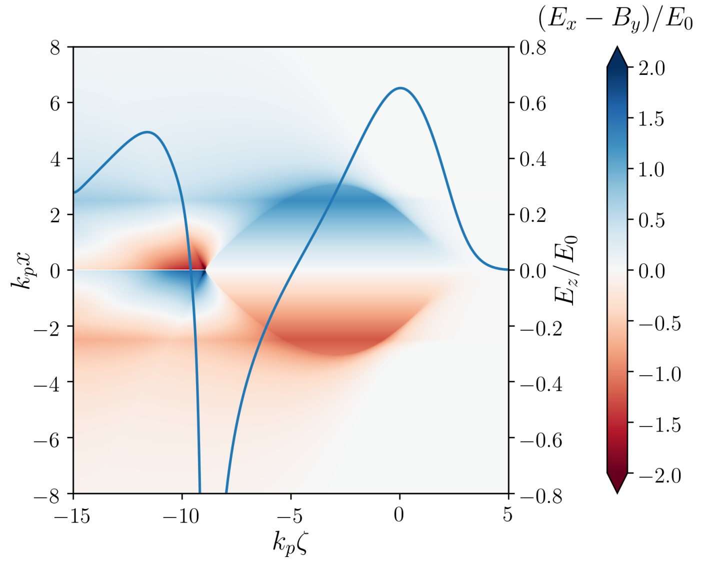


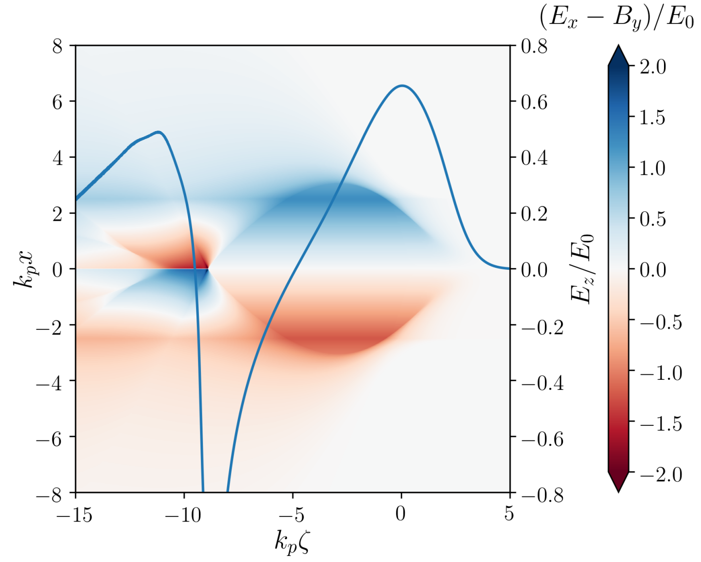
Emittance growth from simulation:
Quasi-matched central slice: $\simeq 3\%$
total (projected) bunch: $\simeq 7\%$

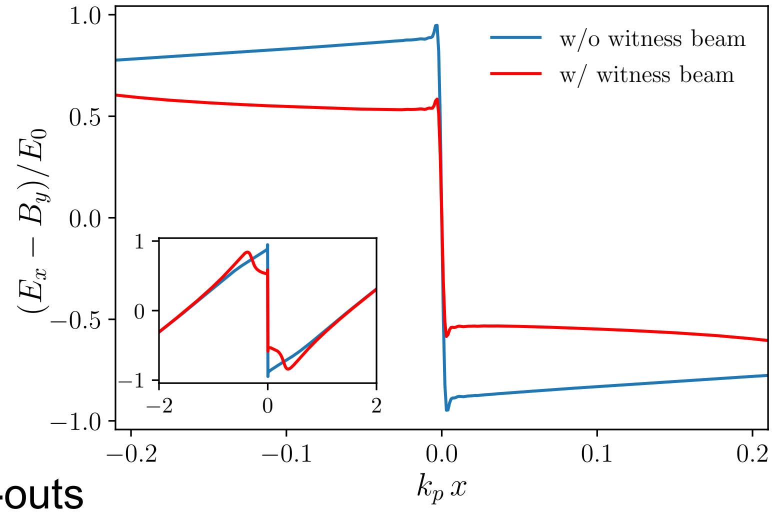
Energy spread can be controlled by beam loading

Results for a simple Gaussian:

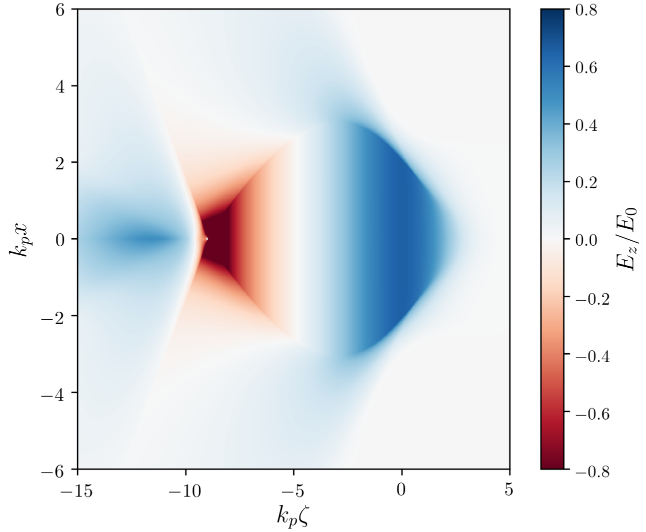
Simulations by INF&RNO

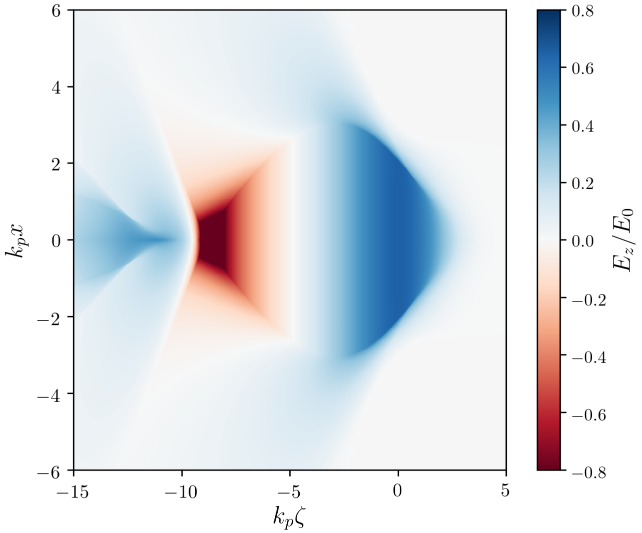


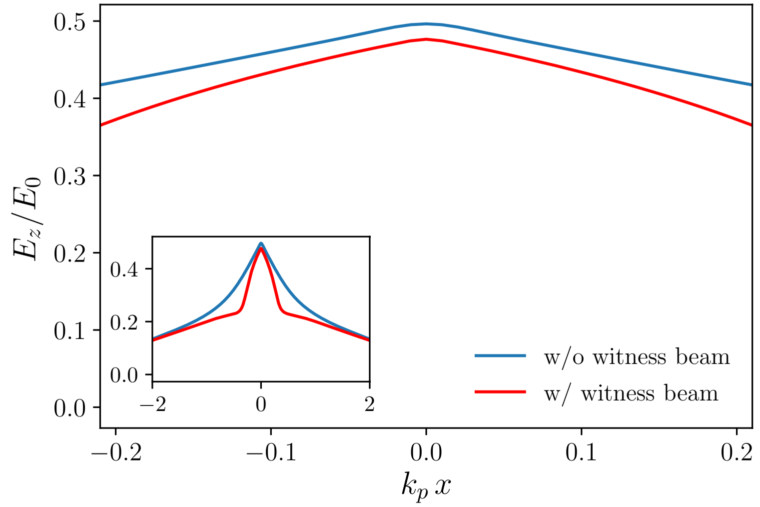




Line-outs
at $\zeta \approx -11.6$

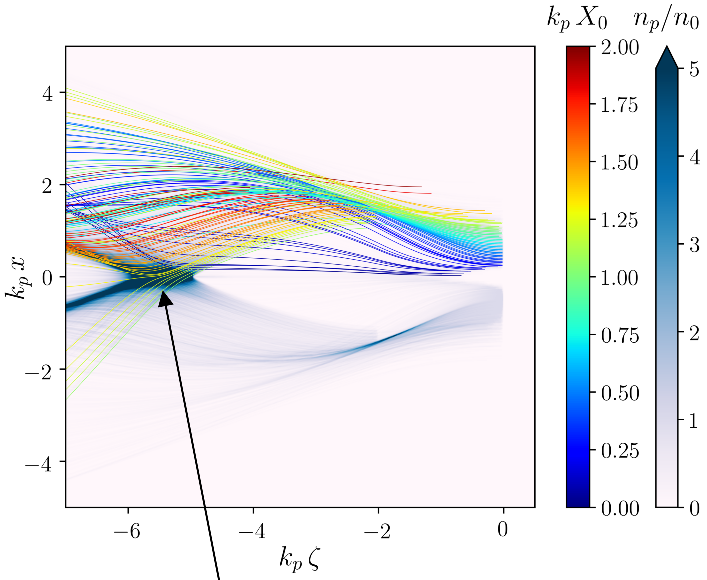






Plasma column can be generated by beam-field-ionization

Space-charge fields of beam ionize a plasma column, wakefield ionizes further behind drive beam



Advantage: self-inherent alignment between drive beam and plasma column

Expanded region of high electron density, possibly allowing for positron acceleration

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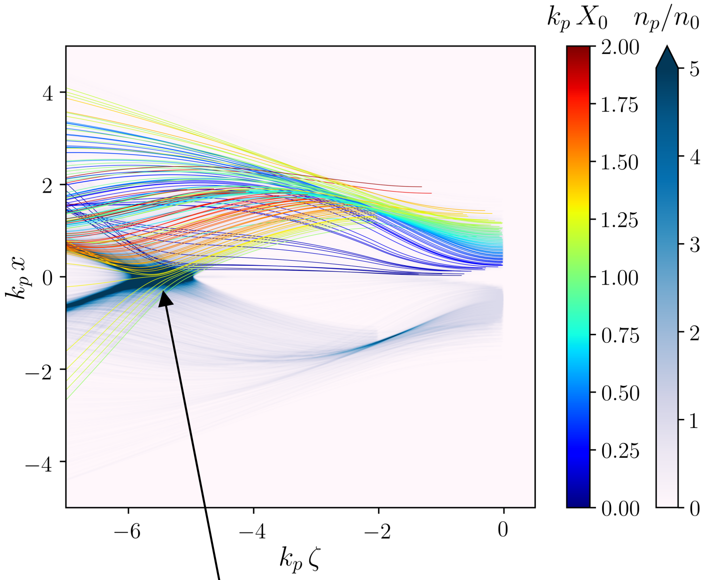

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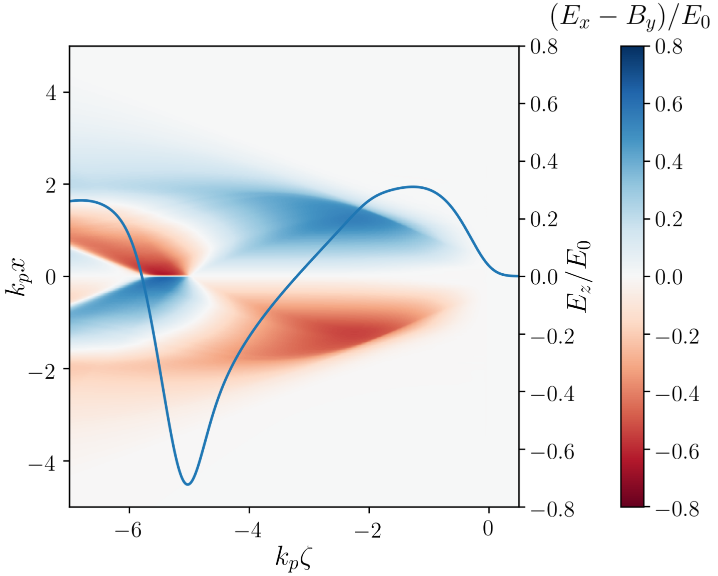
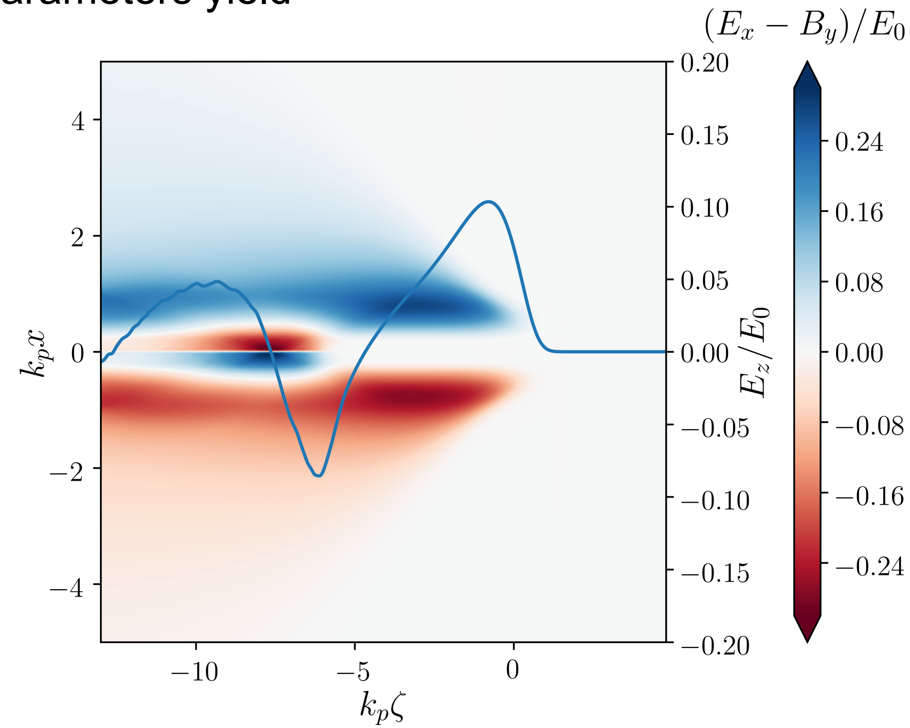


Not in this case, positron accelerating and focusing field don‘t match

Solvable by parameter optimization!

Coupled plasma column generation limits accelerating fields

Optimized (Gaussian) drive beam parameters yield



Problem:
Plasma column generation is **coupled** to drive beam parameters, strongly limiting the usable parameter space!

Additionally: scheme is vulnerable to drive beam variations (e.g. head erosion)

Therefore: Higher accelerating gradient and more stable scheme by using laser-pre-ionized plasma columns, as this **decouples** plasma generation and the drive beam.

Summary

- Plasma structure suitable for positron transport and acceleration has been proposed
- The wakefields in these structures were studied and optimized with respect to positron acceleration
- The superior concept of using laser-pre-ionized plasma columns was used to demonstrate quality-preserving positron acceleration

For more details, see our publication: **Diederichs *et al.*, Phys. Rev. Accel. Beams 22, 081301 (2019)** or my master‘s thesis

Thank you.