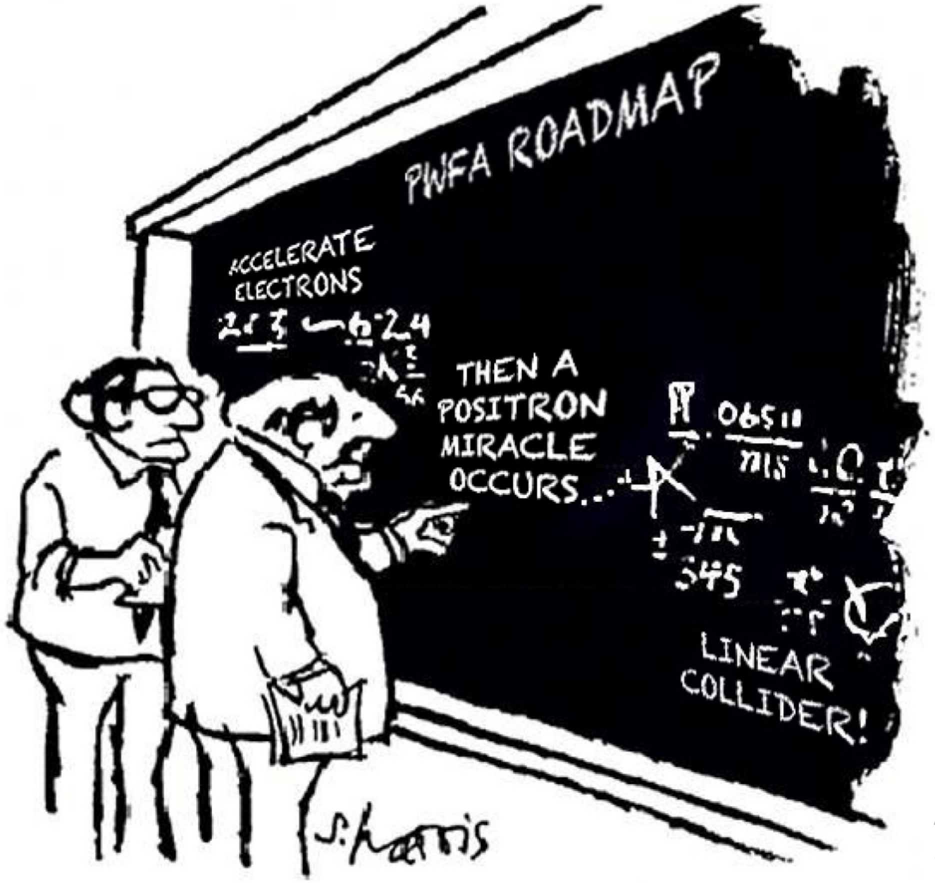

Adopted from S. Harris and C. Lindstrøm

"These

Temperature effects in plasma-based positron acceleration

are really miraculous!"

Severin Diederichs

Practical requirements for a linear collider

A plasma accelerator for a collider must fulfill:

1.	High gradient (reduce the construction costs)	$>$ GV/m
2.	Low emittance (ability to focus the beam)	$<$ 100s of nm
3.	Low energy spread (ability to focus the beam, narrow energy spectrum)	$<$ 1%
4.	No instrinsic instability	
5.	High wall-plug efficiency (reduce run time costs)	$>$ 5%

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Promising experiments:
Corde Nature 2015
Gessner et al. Nat. Comm. 2016
Doche Sci. Rep. 2017
Lindstrøm PRL 2018

→ Emittance preservation and stability challenging
New concepts needed!

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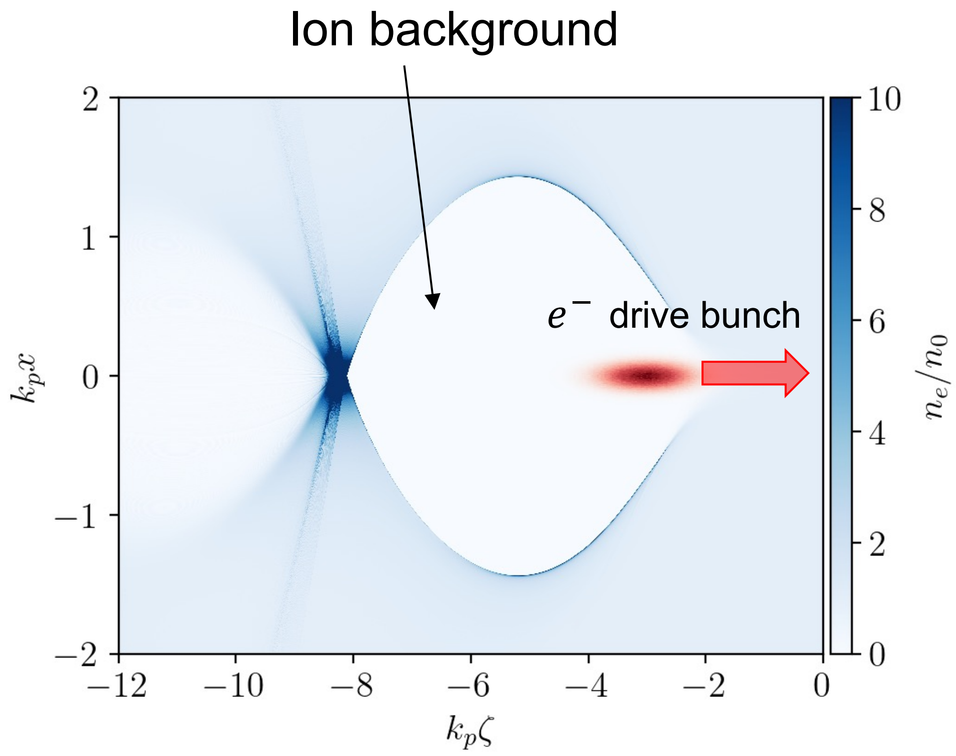
Promising experiments:
Corde Nature 2015
Gessner et al. Nat. Comm. 2016
Doche Sci. Rep. 2017
Lindstrøm PRL 2018

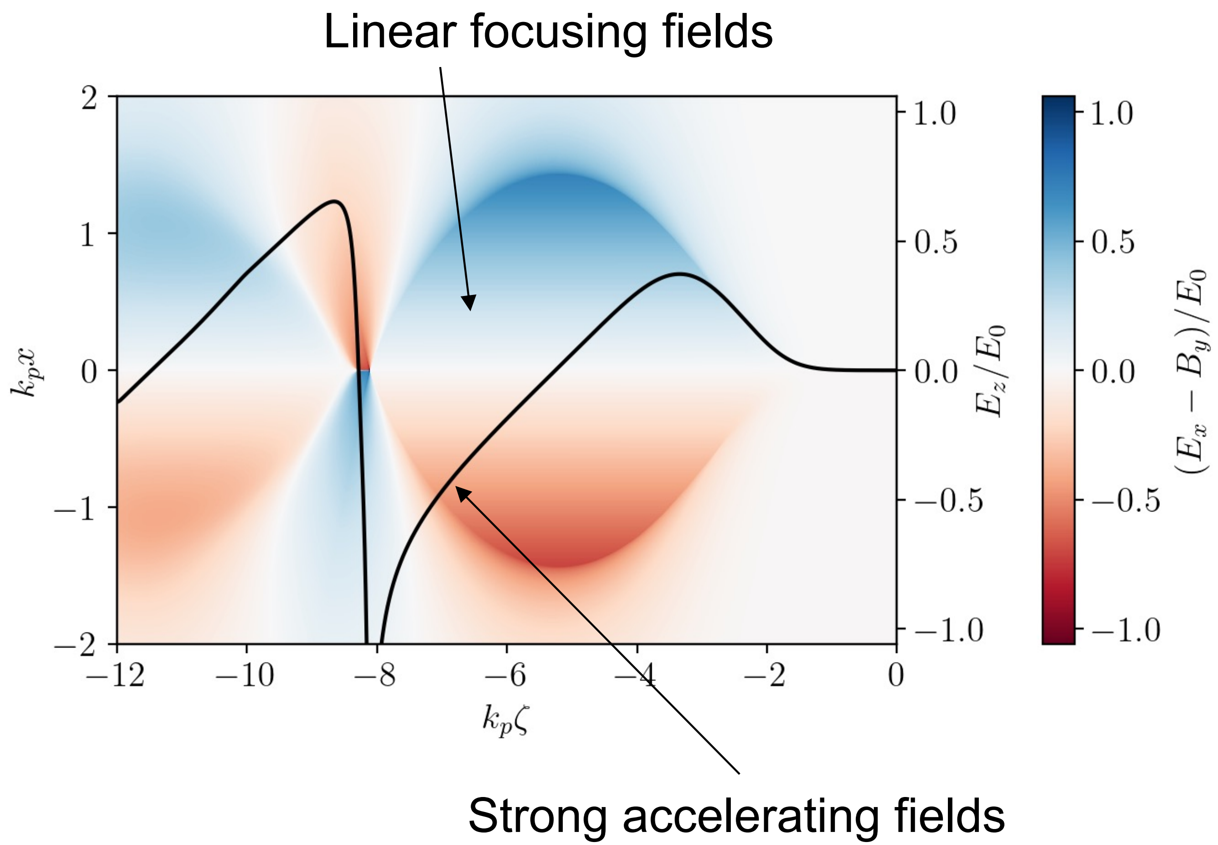
→ Emittance preservation and stability challenging
Many new concepts have been proposed!

- (Quasi-)Hollow core plasmas
  Zhou PRL 2021, Zhou PRAB 2022, Silva PRL 2021
- Plasma columns
  Diederichs PRAB 2019, 2020, 2022, PoP 2022, 2023, Reichwein PRE 2022
- Utilizing the back of the blowout
  Zhou arXiv 2022, Lotov PoP 2007, Wang arXiv 2021, Liu PRR 2023
- Fireball beams
  Silva PRAB 2023

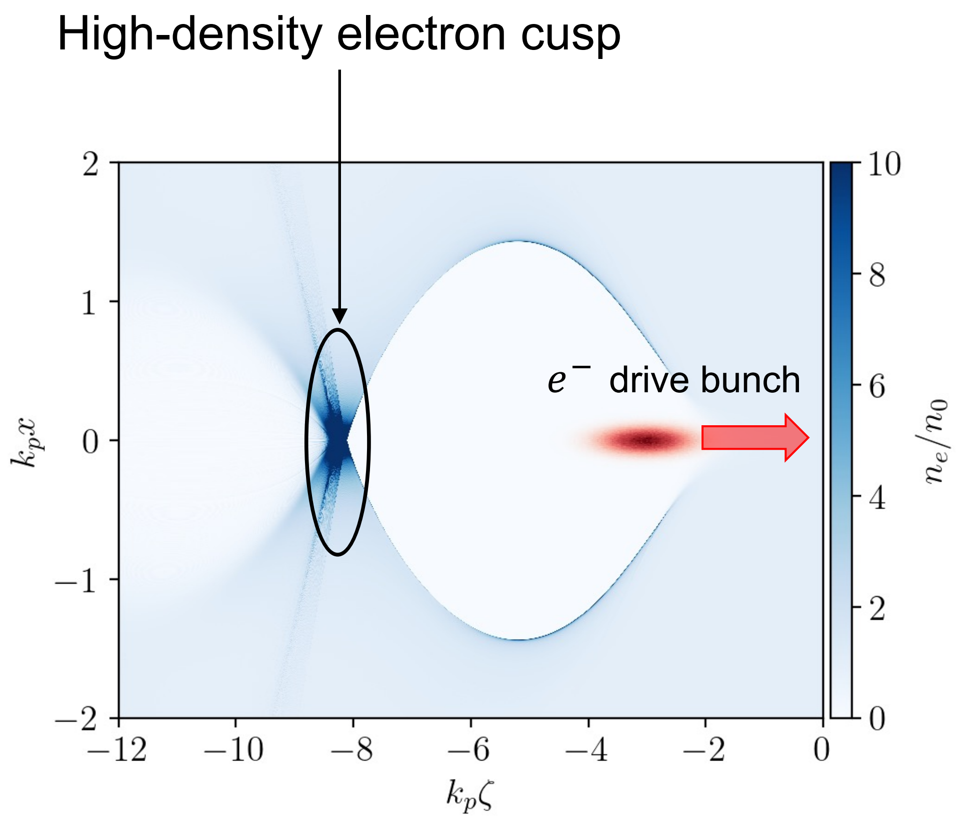
Need to decide on the best positron acceleration scheme for HEP!

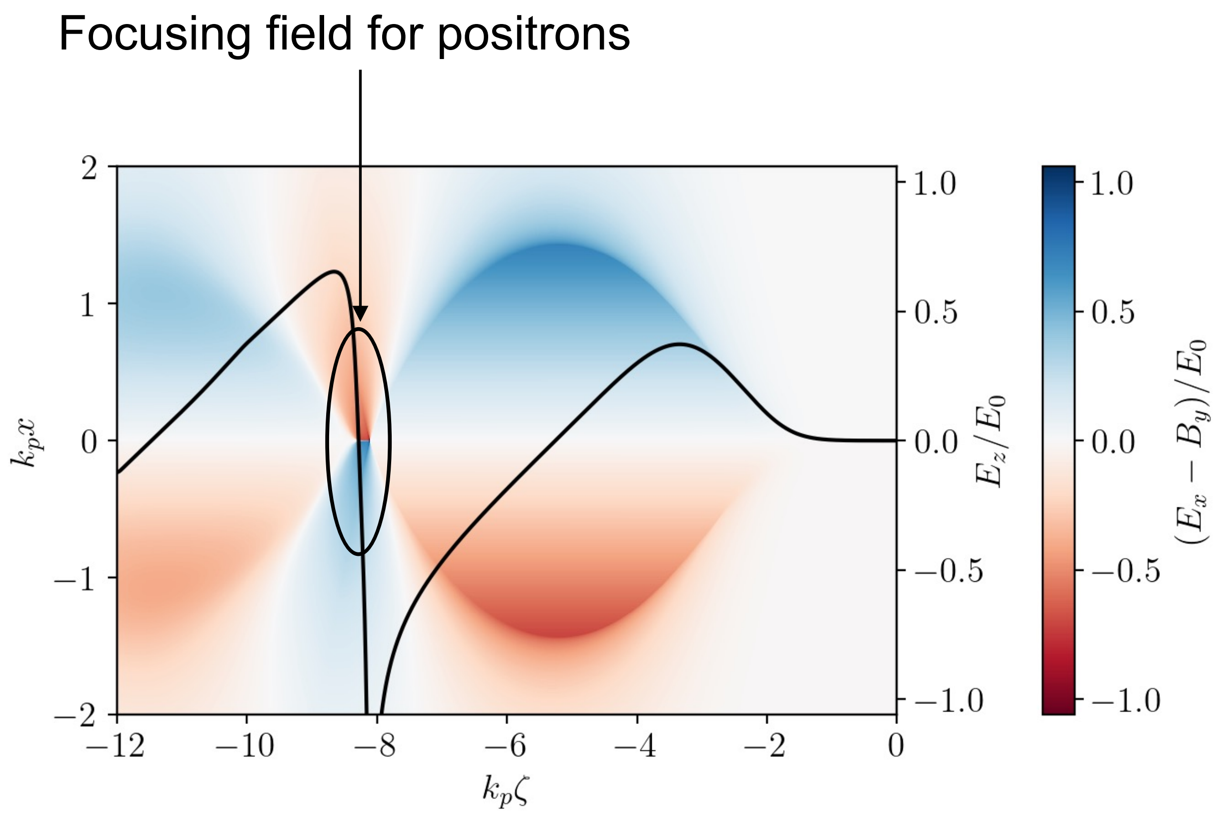
Plasma wakefield accelerators enable high-quality, high-gradient *electron* acceleration



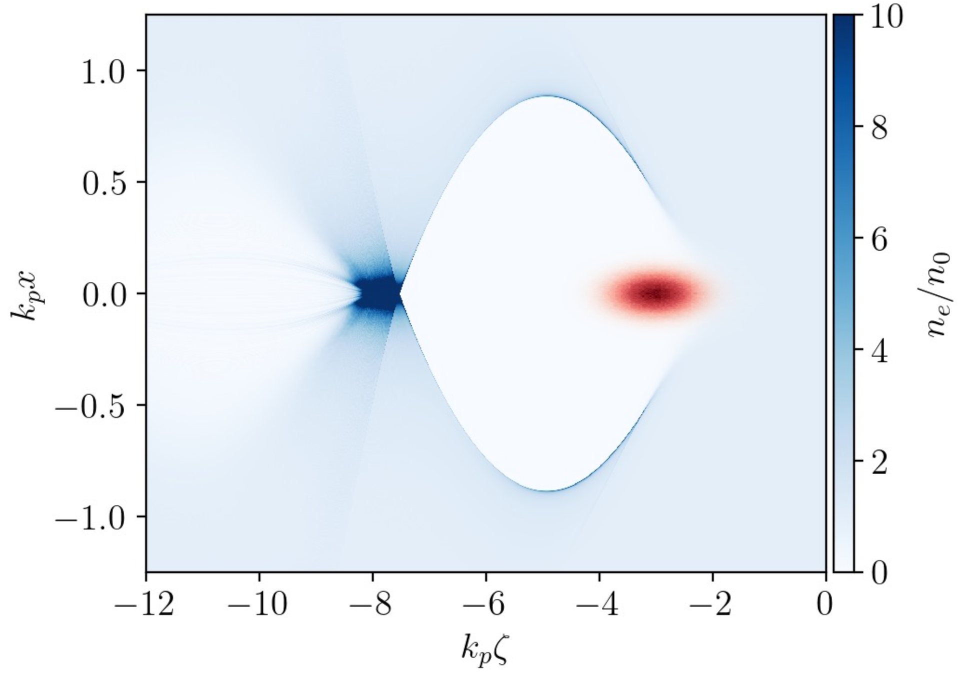


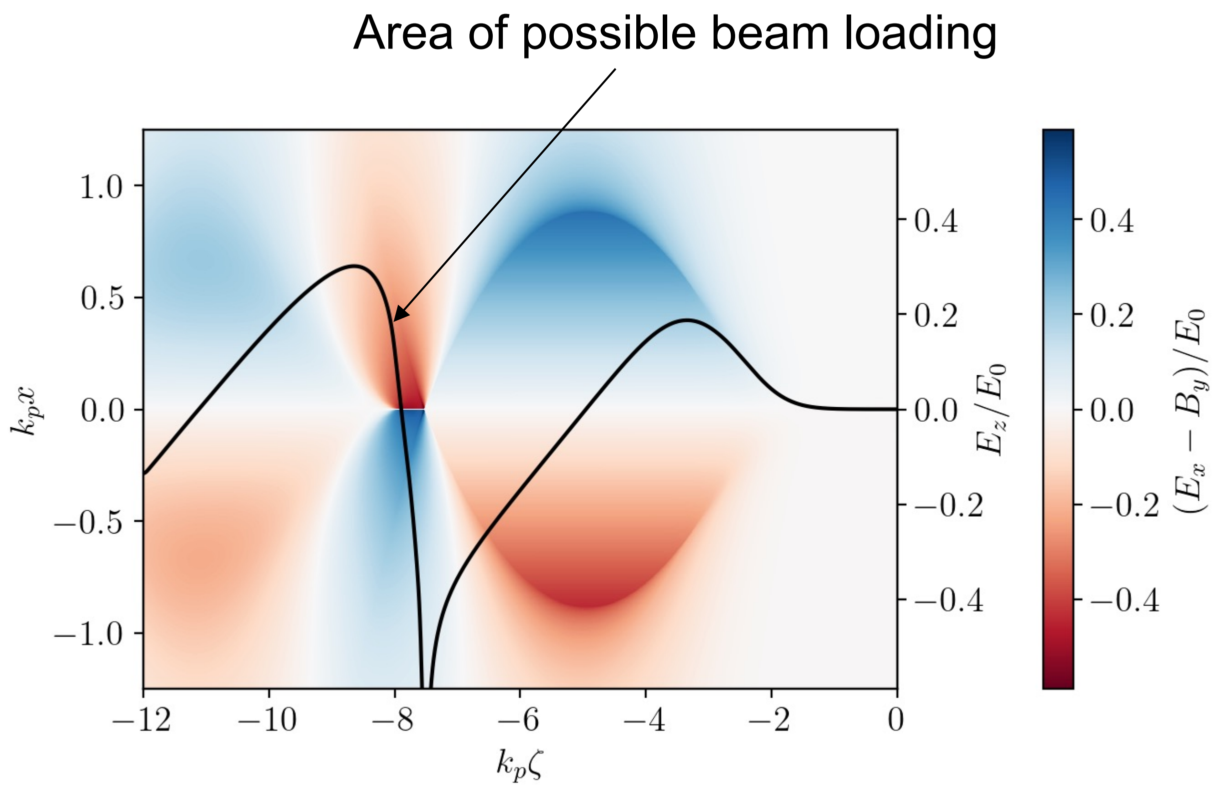
The electron spike at the back of the bubble enables positron acceleration





Weaker blowout is preferable

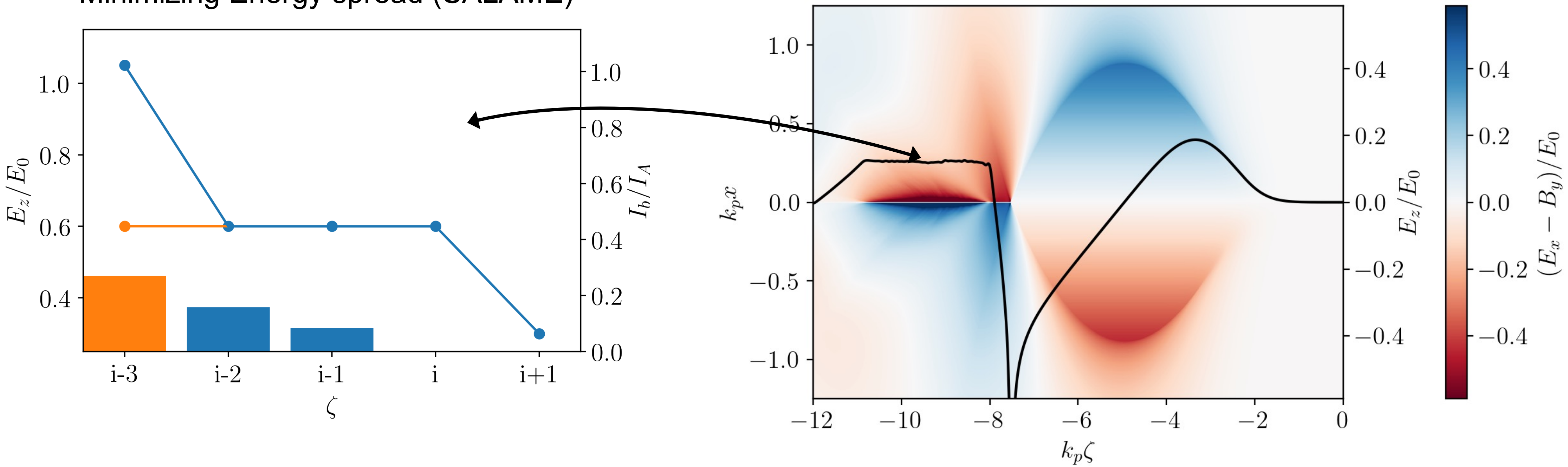




Lotov, PoP 14, 023101 (2007)

Weaker blowout is preferable

Slicing Advanced Loading Algorithm for
Minimizing Energy spread (SALAME)



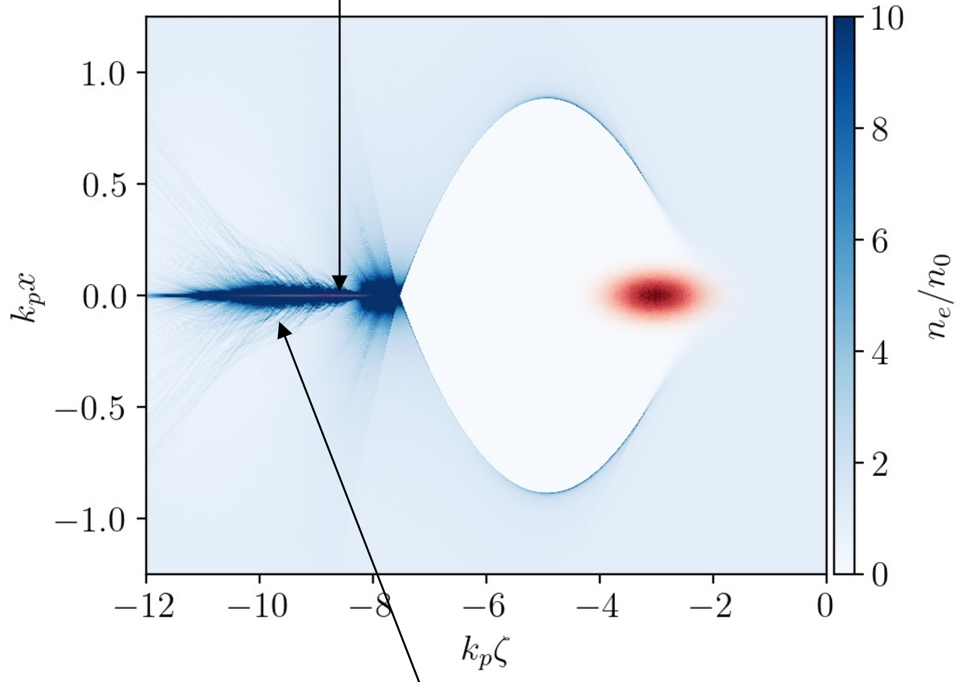
More information on the algorithm:
Diederichs et al., PRAB 23, 121301 (2020)
Lotov, PoP 12, 053105 (2005)
Lotov, PoP 14, 023101 (2007)

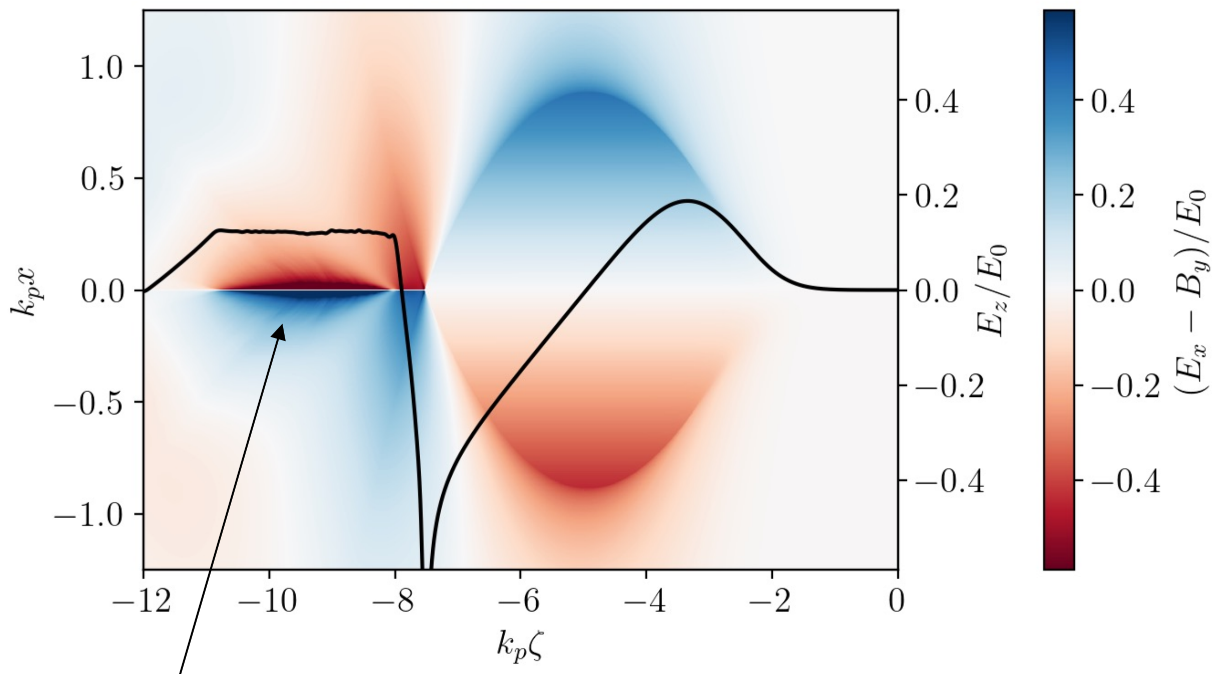
DESY. severin.diederichs@desy.de

Weaker blowout is preferable

Theory of beamloading in
Zhou et al. arXiv 2211.07962 (2022)

1. High-density positron bunch attracts plasma electrons





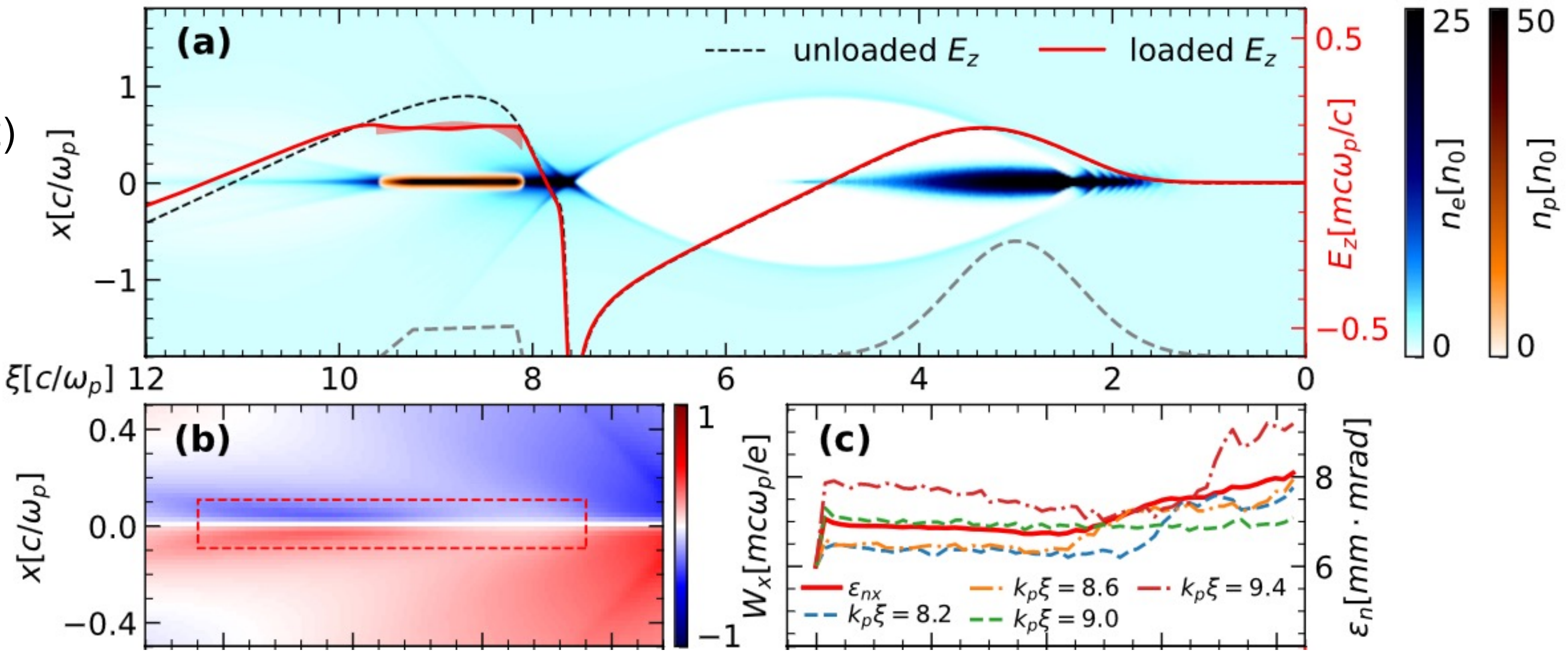
2. Electron filament provides strong focusing and accelerating fields
Focusing field only exists due to beamloading!

Lotov, PoP 14, 023101 (2007)

Optimal beam loading enables excellent parameters

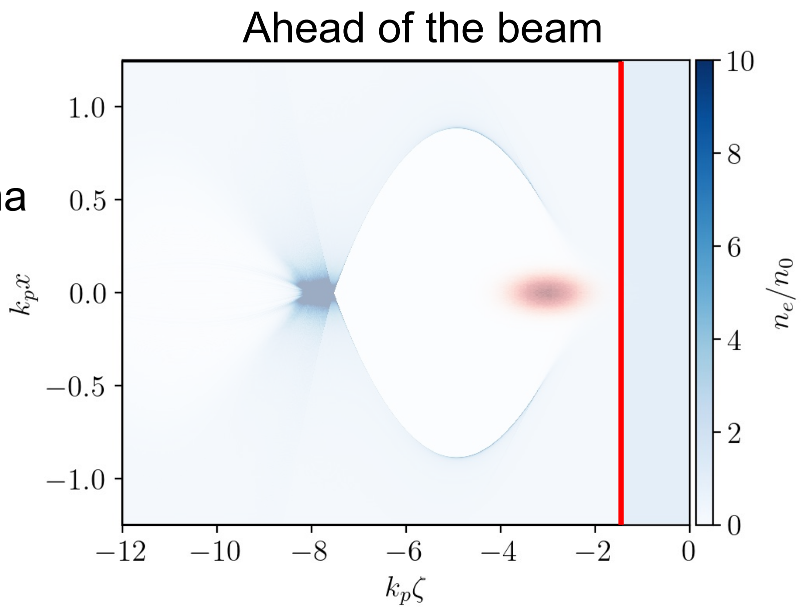
This has been optimized in
Zhou et al. arXiv 2211.07962 (2022)

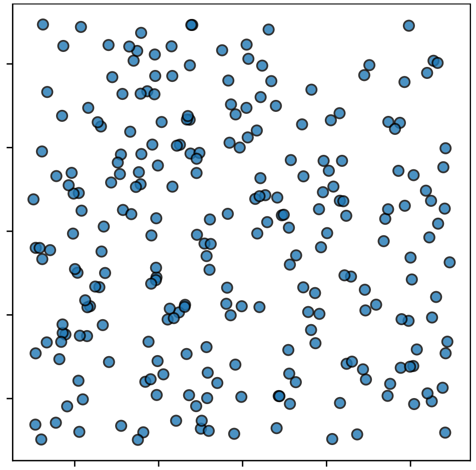
Excellent parameters:
130 pC
2% rms energy spread
< 10µm emittance
35% transfer efficiency



Temperature broadens electron spike at the back of the bubble

cold plasma





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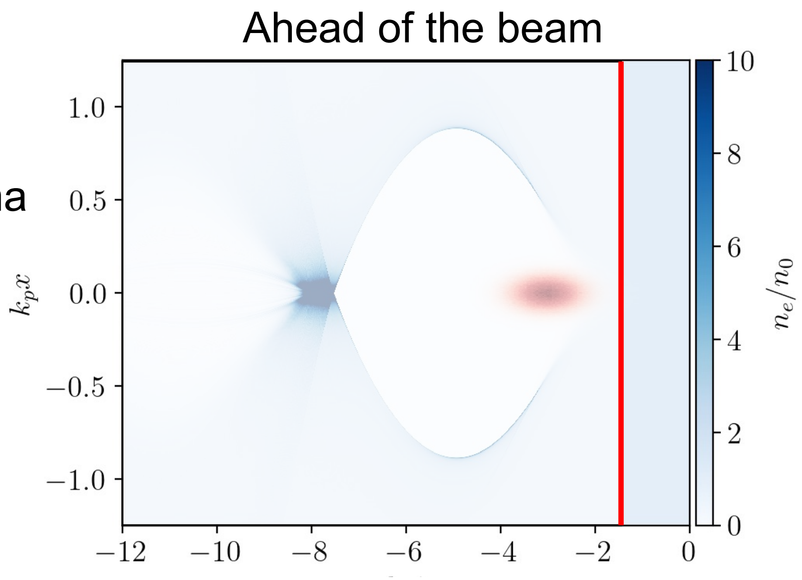
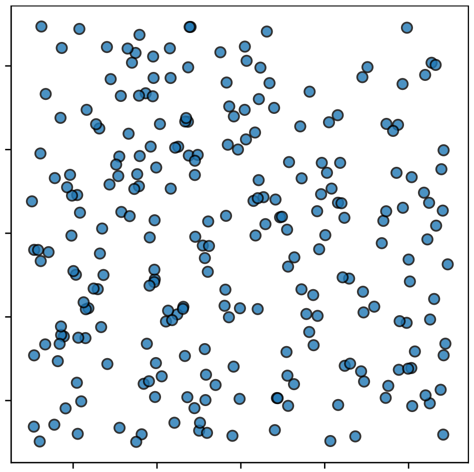
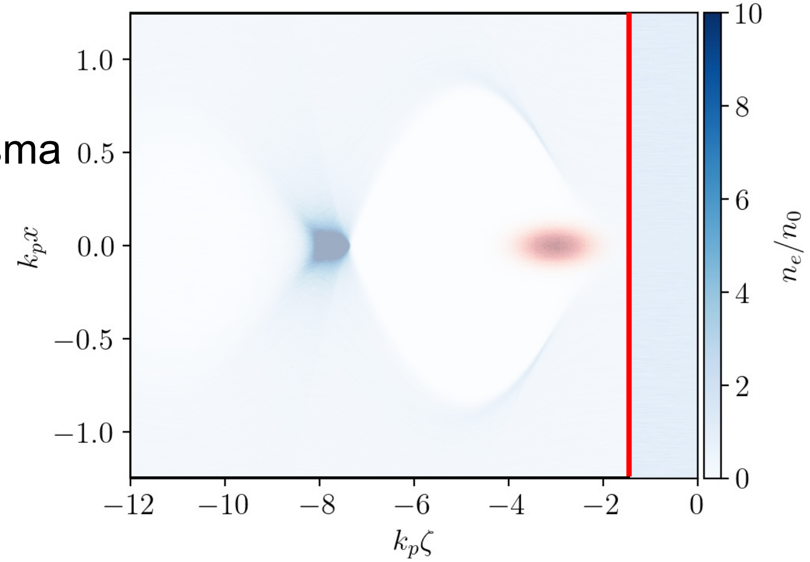
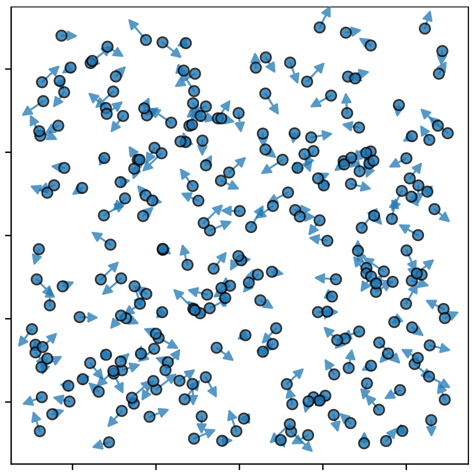




warm plasma

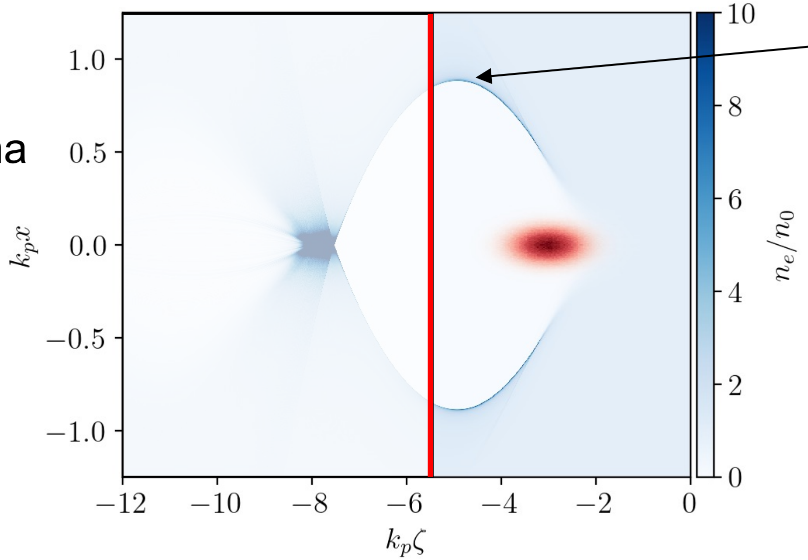




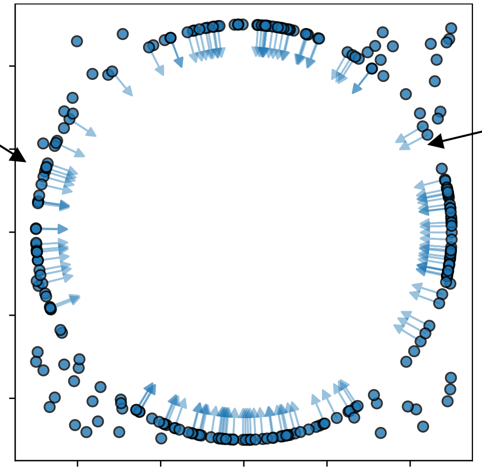
Temperature broadens electron spike at the back of the bubble

cold plasma

Within the blowout



sharp sheah

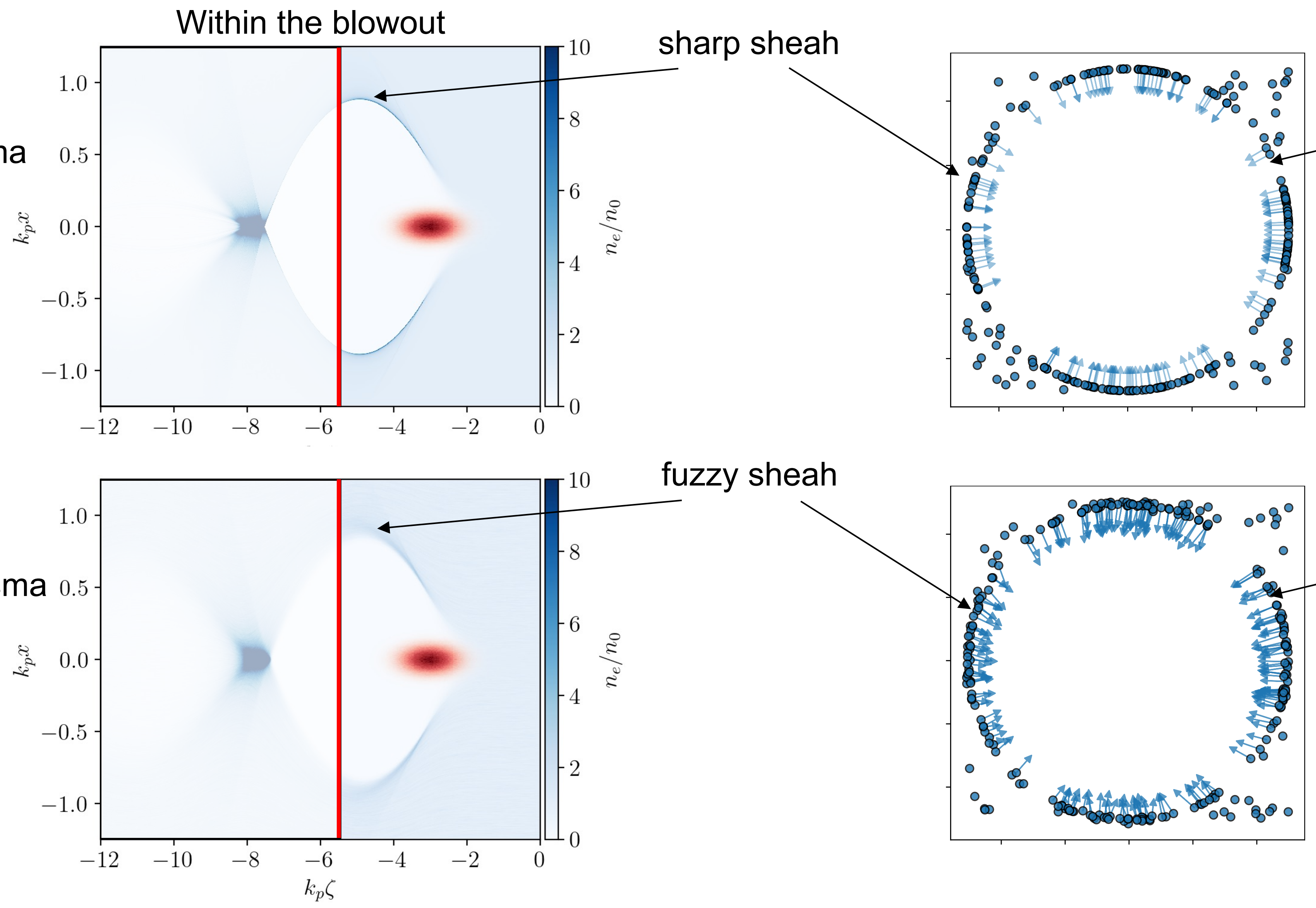


Momentum points exactly to the center

Temperature broadens electron spike at the back of the bubble

cold plasma

warm plasma



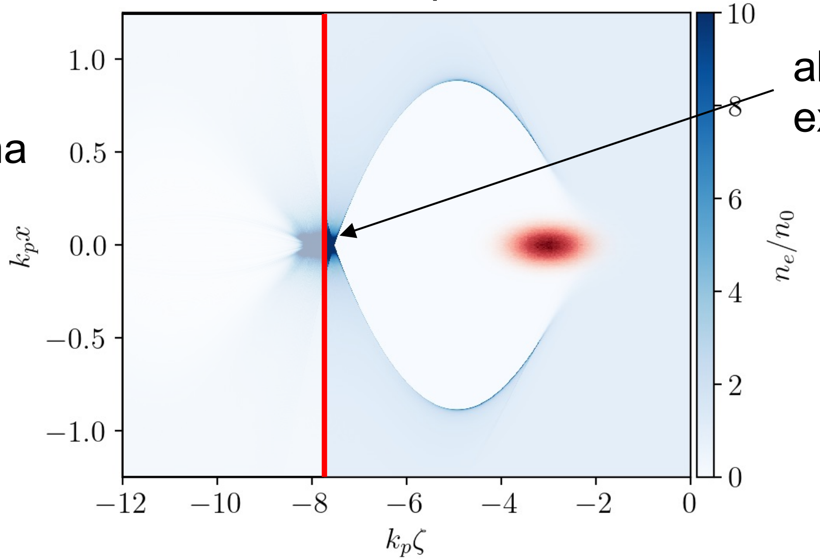
Momentum points exactly to the center

Momentum points roughly to the center

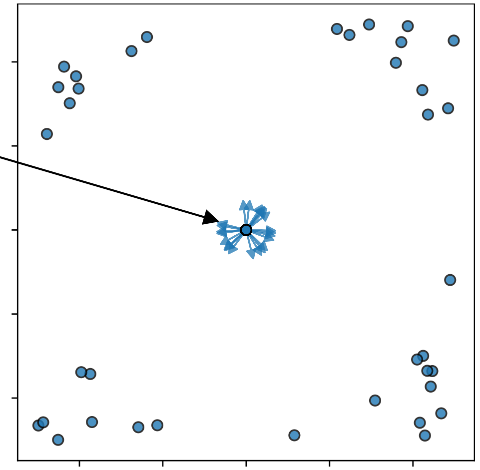
Temperature broadens electron spike at the back of the bubble

Within the cusp at the back of the blowout

cold plasma



all electrons return exactly to the center

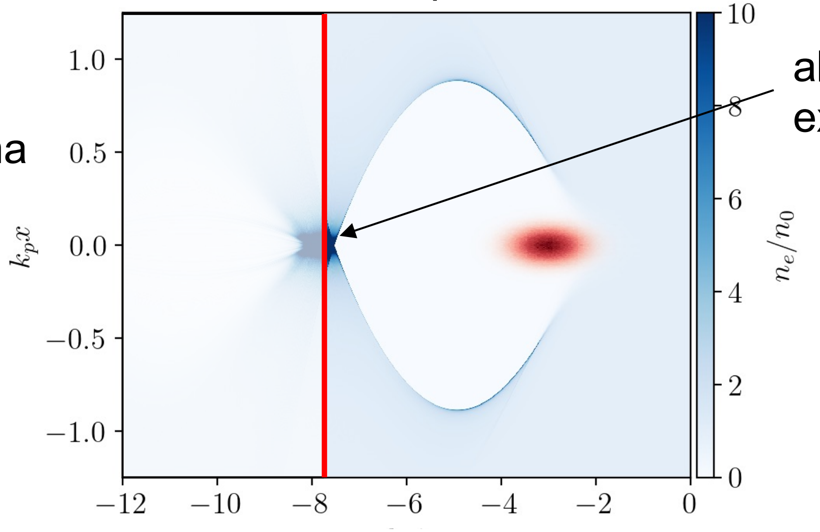


density catastrophe, fields converge extremely slowly!

Temperature broadens electron spike at the back of the bubble

Within the cusp at the back of the blowout

cold plasma



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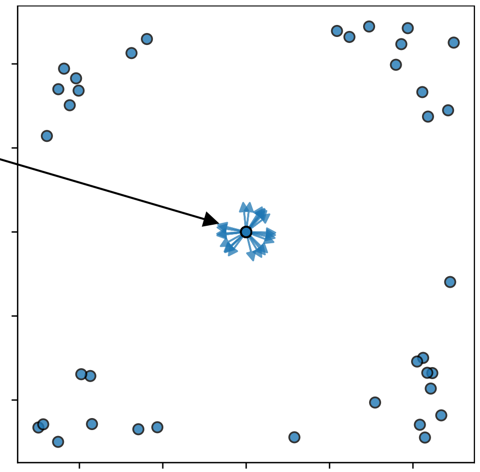

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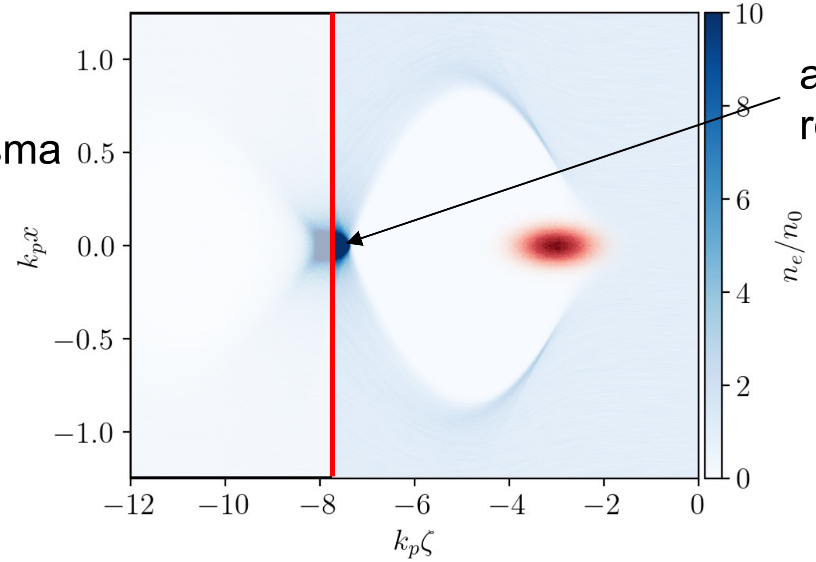

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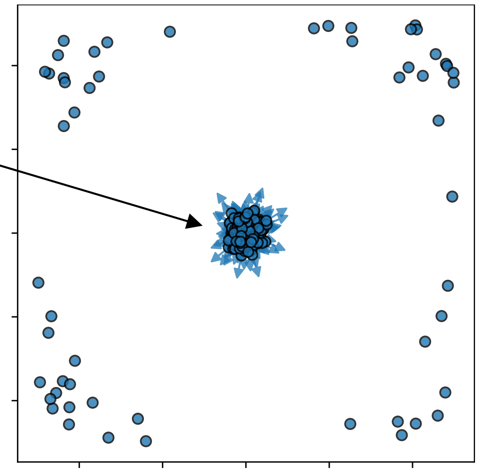
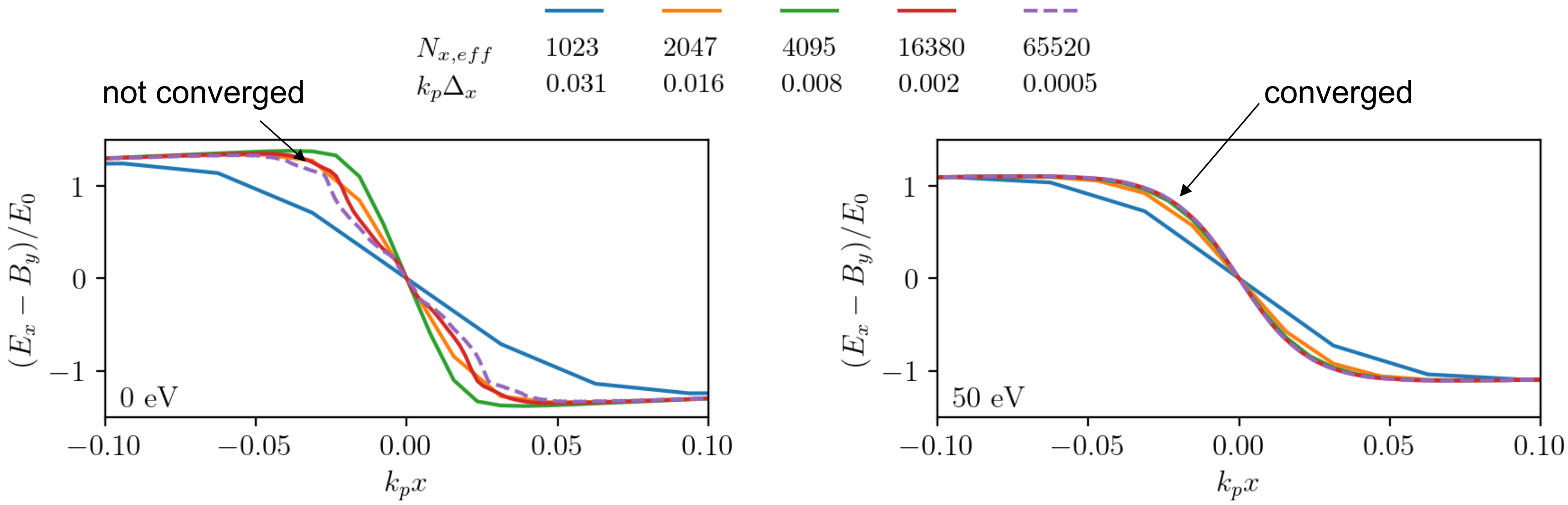


Peak density limited by temperature

Temperature rapidly accelerates convergence



Diederichs et al. PoP 30, 073104 (2023)
Wang et al., arXiv:2110.10290 (2021)
Jain et al. PoP 22, 023103 (2015)

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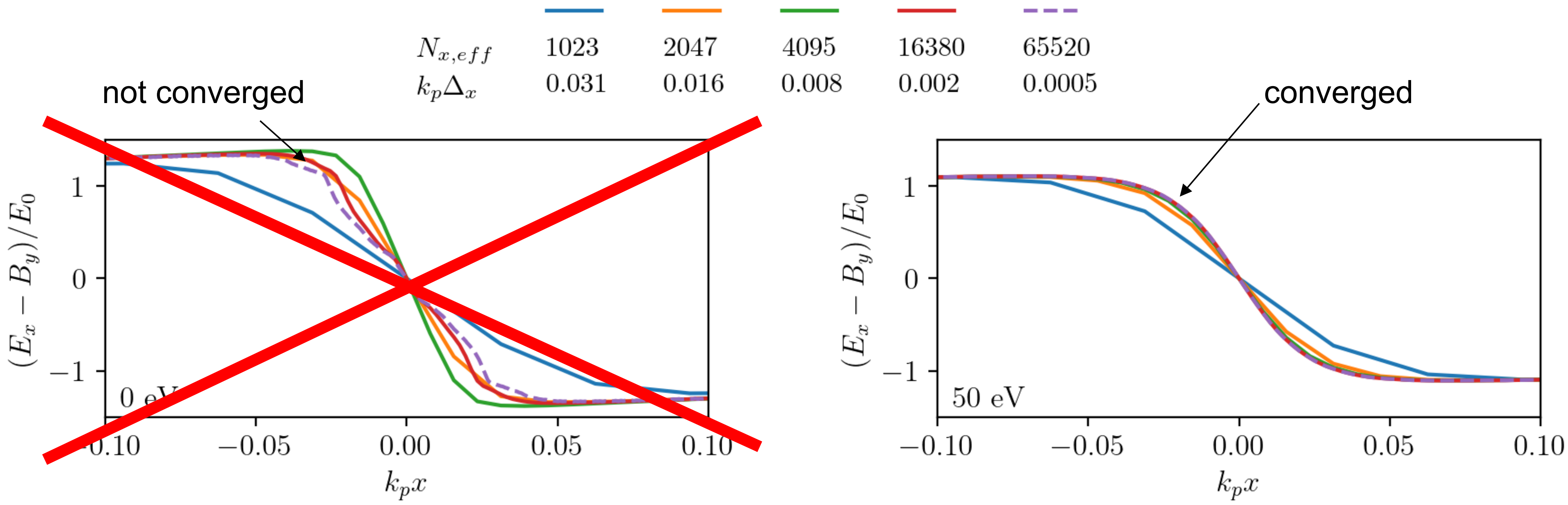
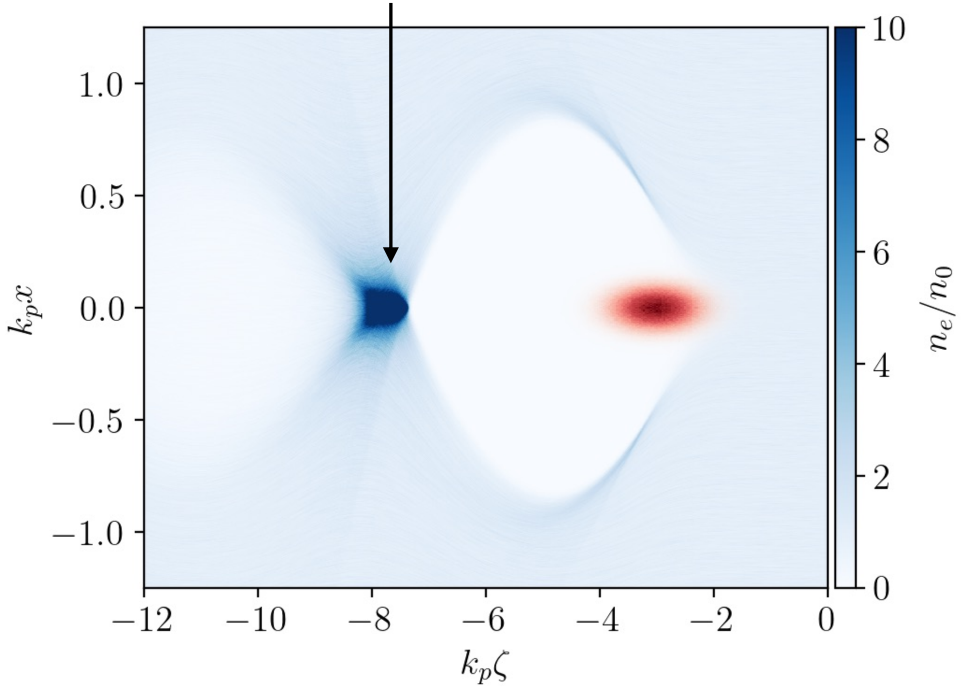


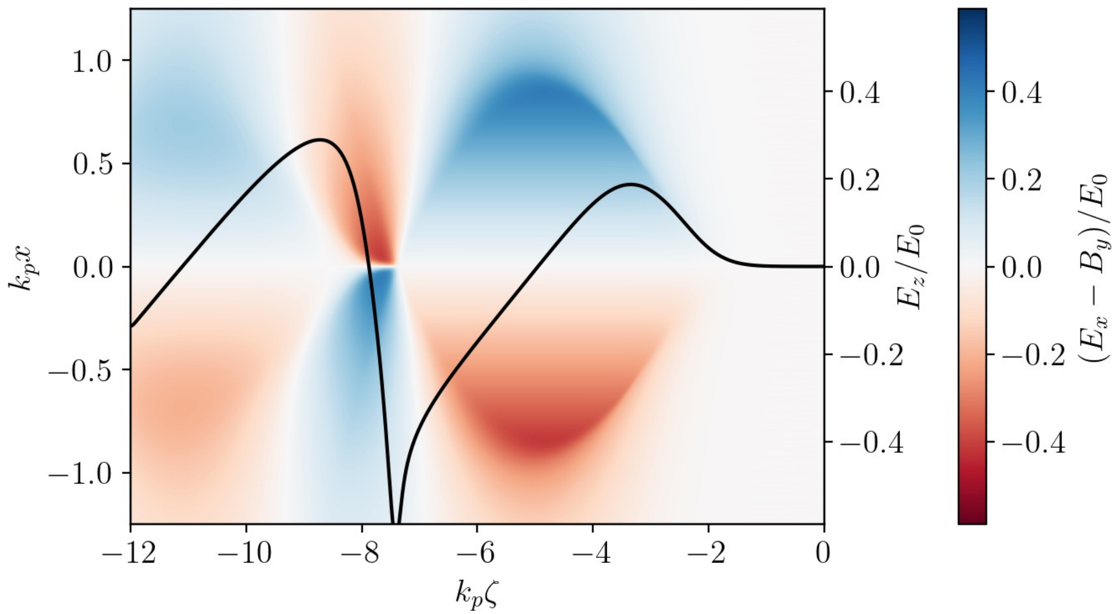
Fields in electron filaments of cold plasmas show numerical artifacts at high resolution.
Be very careful with cold plasmas for positron acceleration!

Diederichs et al. PoP 30, 073104 (2023)
Wang et al., arXiv:2110.10290 (2021)
Jain et al. PoP 22, 023103 (2015)

Temperature strongly modifies and linearizes focusing field

broadened electron cusp due to
temperature of 50 eV





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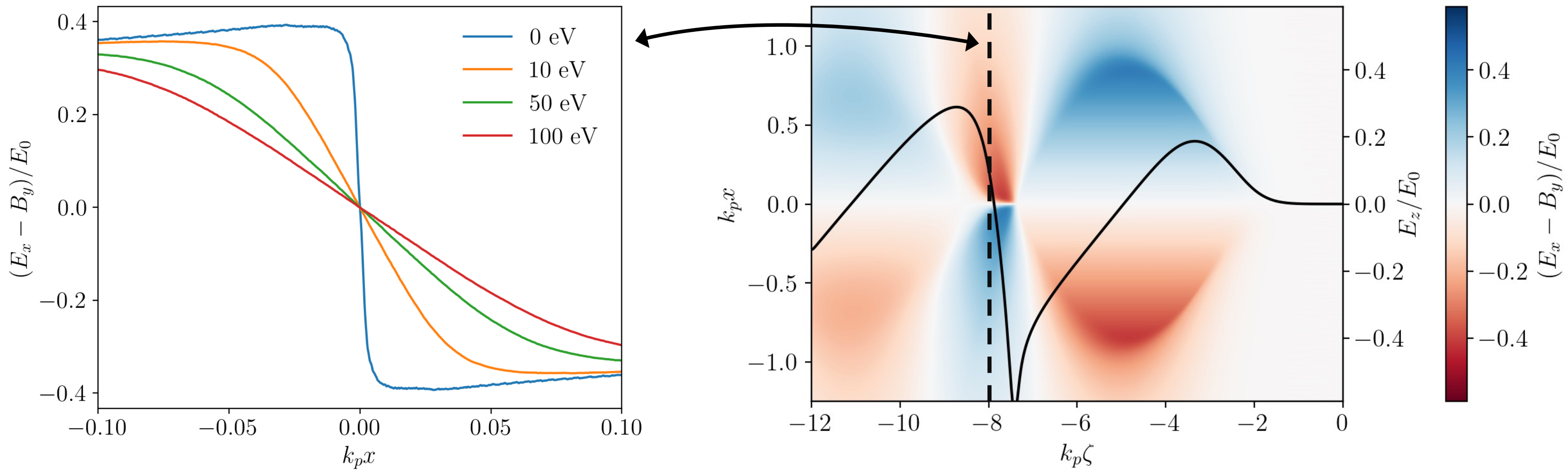
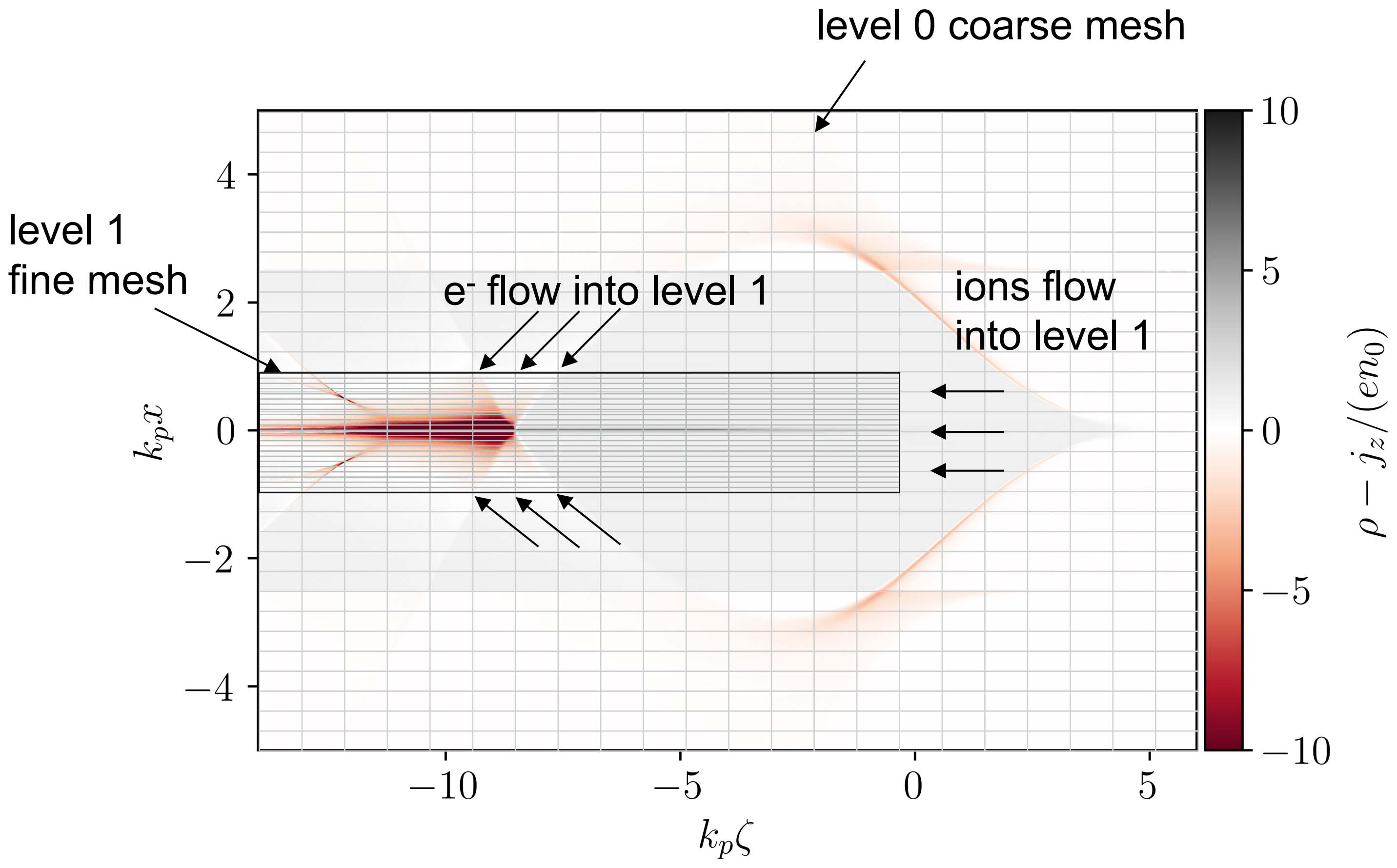


If we had a beam that fits into the linear region, we could preserve it's emittance!

Beam emittances of ~ 100nm required. **Only achievable with mesh refinement!**

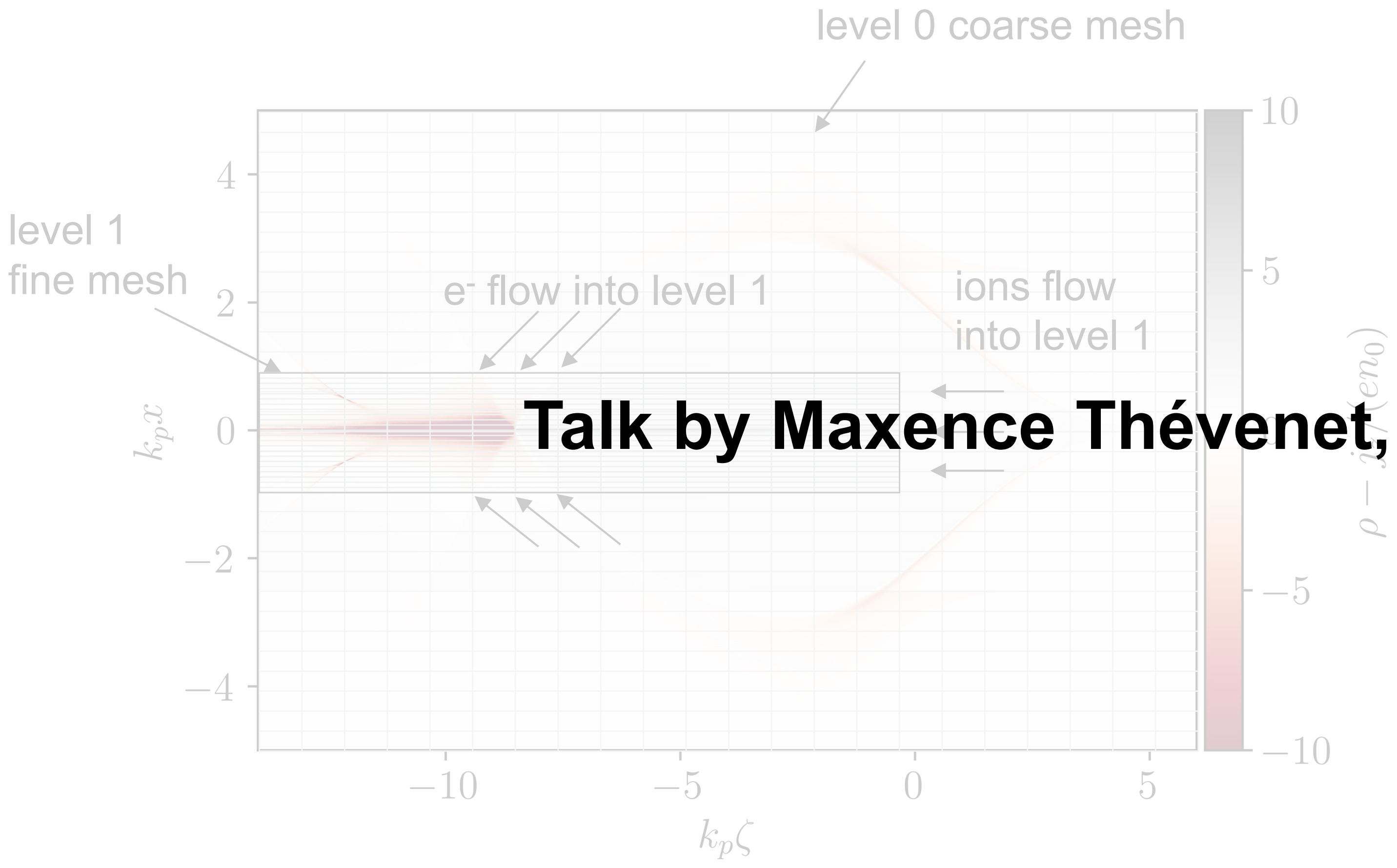
Mesh refinement in HiPACE++ allows for simulating collider-relevant plasma accelerators



Full mesh refinement:

- Fields are solved with nonzero Dirichlet BC
- Particles live on all meshes and deposit currents up to the highest level available
- Values of outer cells of level higher level are interpolated to ensure smooth currents

Mesh refinement in HiPACE++ allows for simulating collider-relevant plasma accelerators



Talk by Maxence Thévenet, today, WG 3, 16:20

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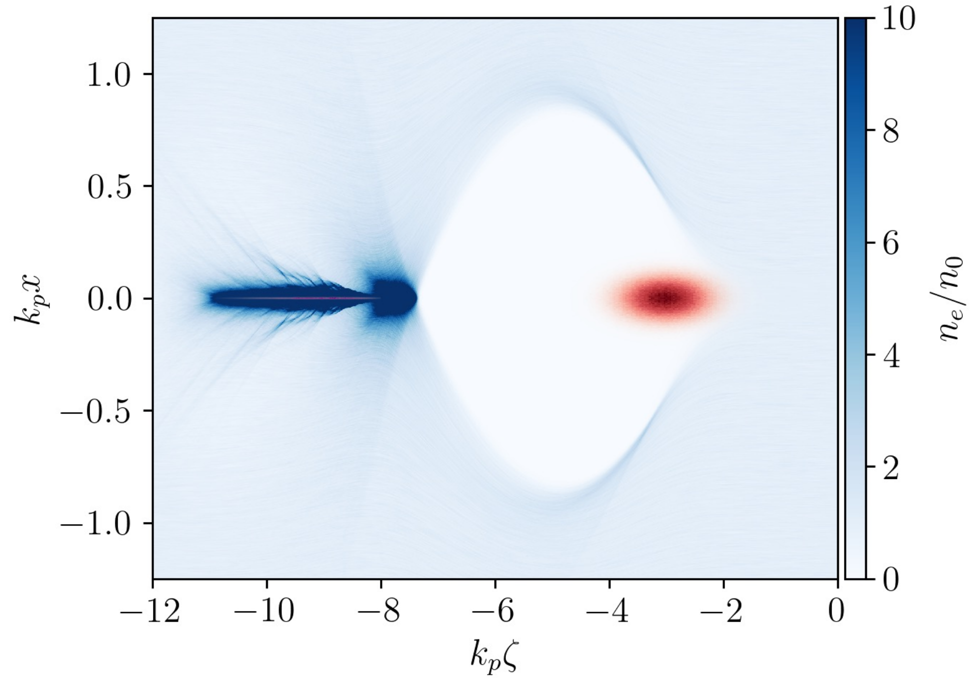
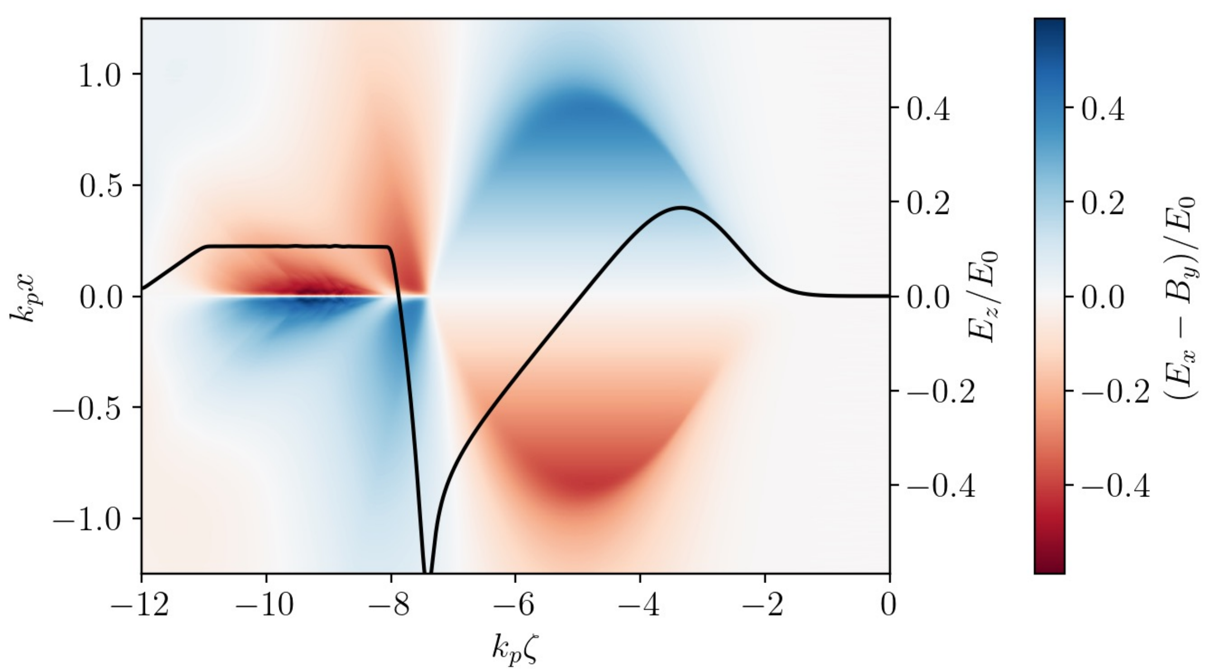
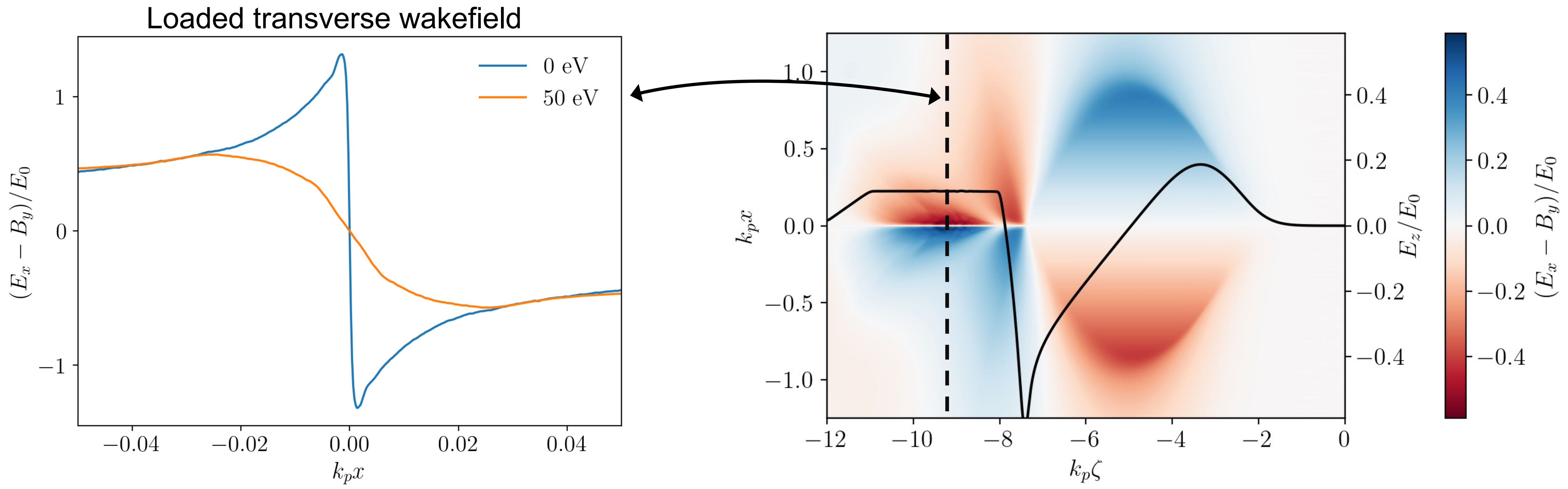




Same setup as Zhou et al. arXiv 2211.07962 (2022) except:

- **200 nm emittance**
- **50 eV electron temperature**
- **80x higher transverse resolution**

Mesh refinement in HiPACE++ allows for simulating collider-relevant plasma accelerators



Same setup as Zhou et al. arXiv 2211.07962 (2022) except:

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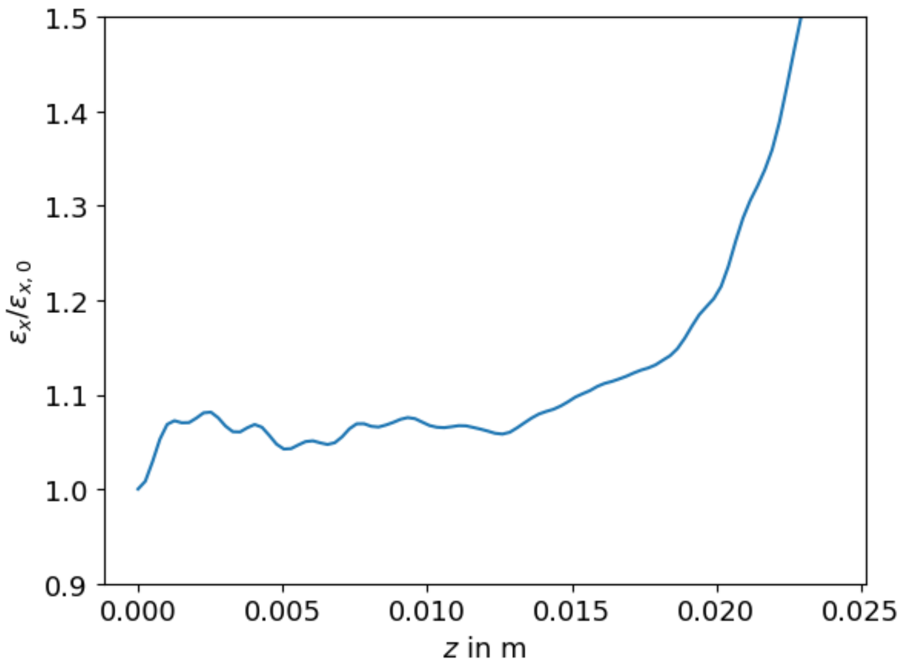
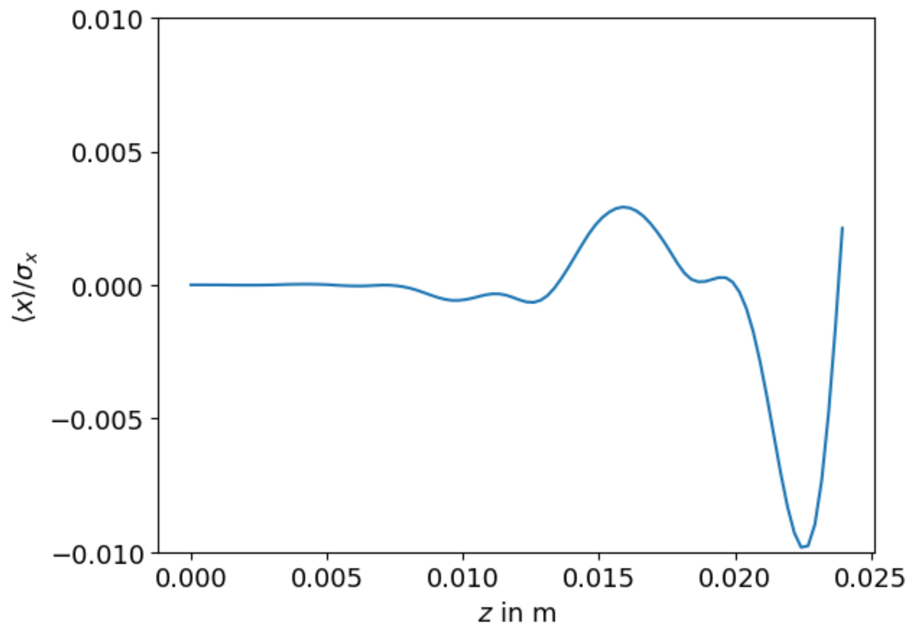
Stability seems to be an issue…



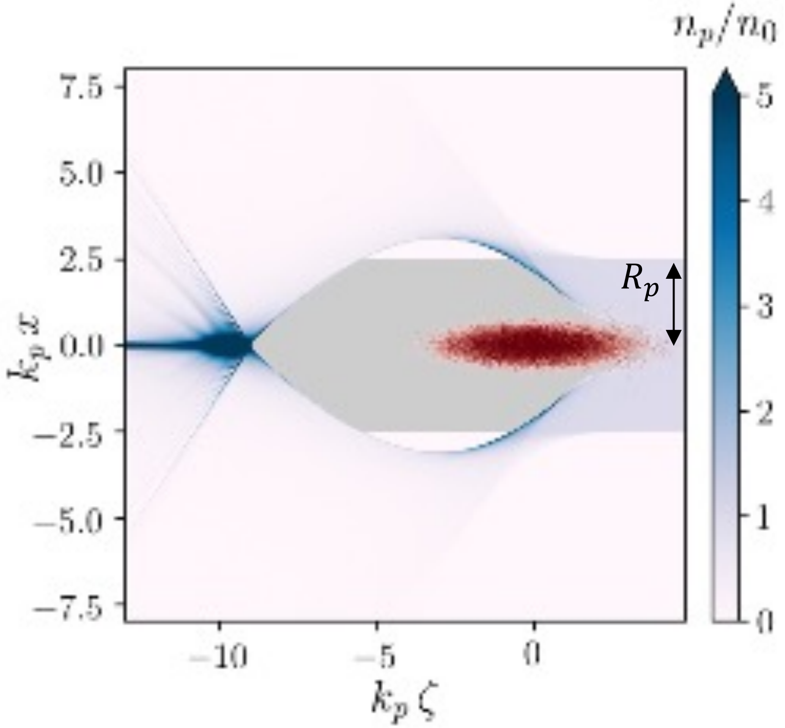


- Hosing rises from numerical noise
- Strong coupling between fields and witness beam due to absence of focusing field without beam

Scheme has very promising numbers, longitudinal and tranverse stability need to be investigated.

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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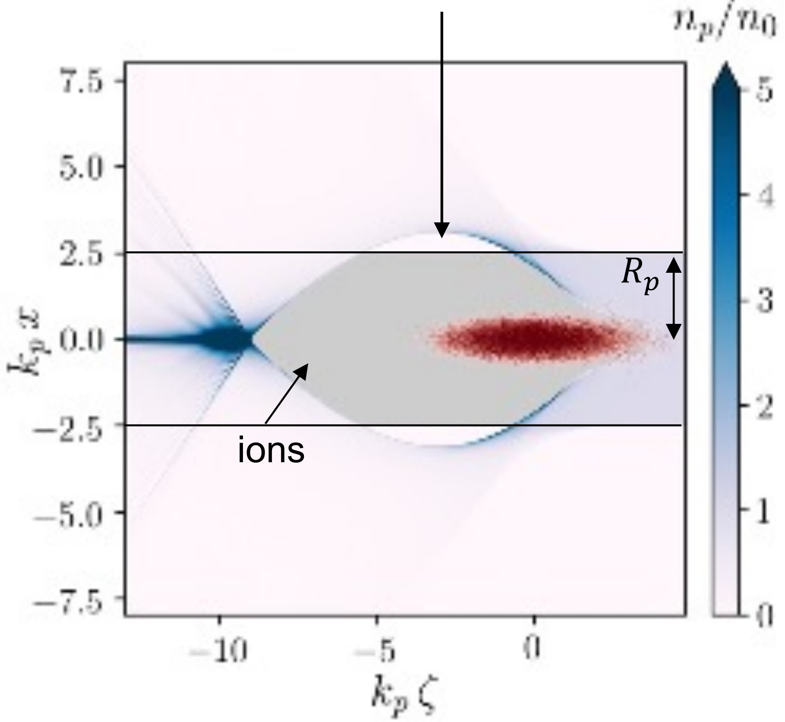
1. No ions outside the column



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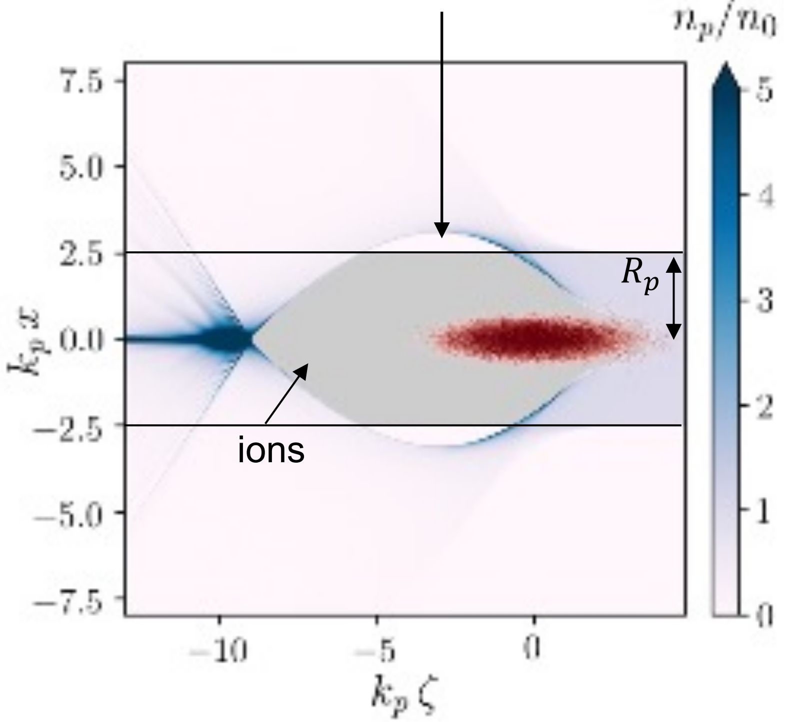
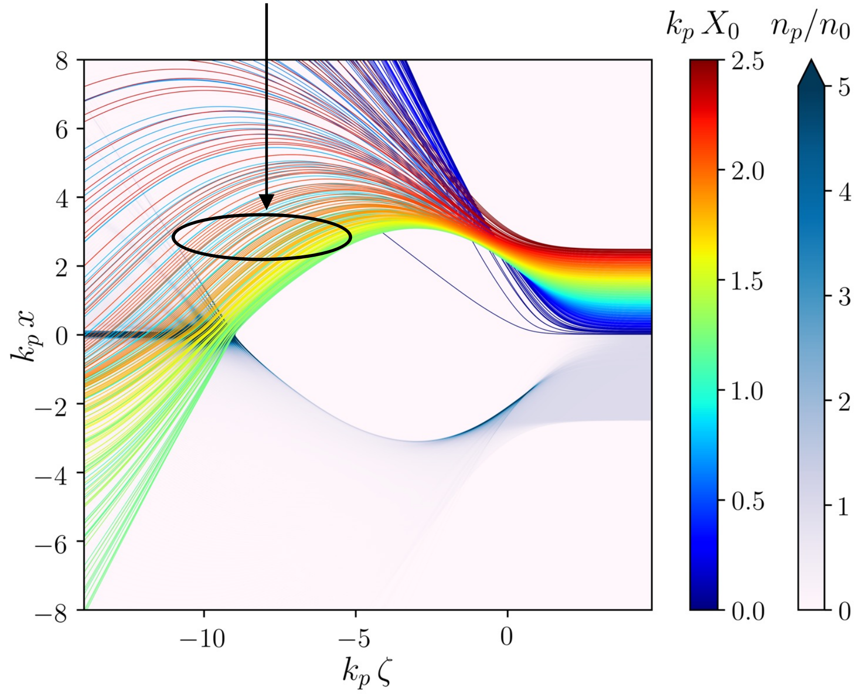


2. Elongated electron trajectories



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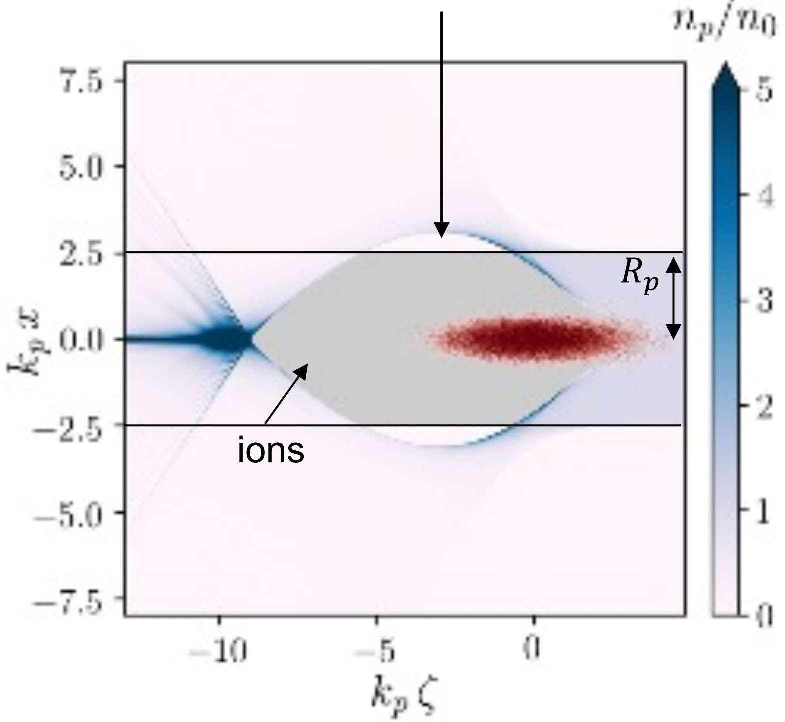

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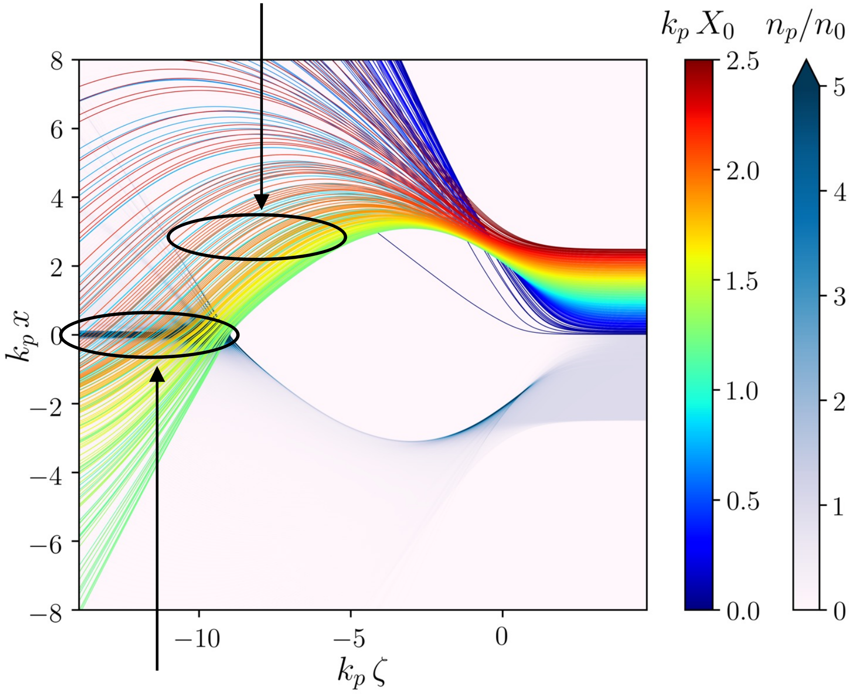
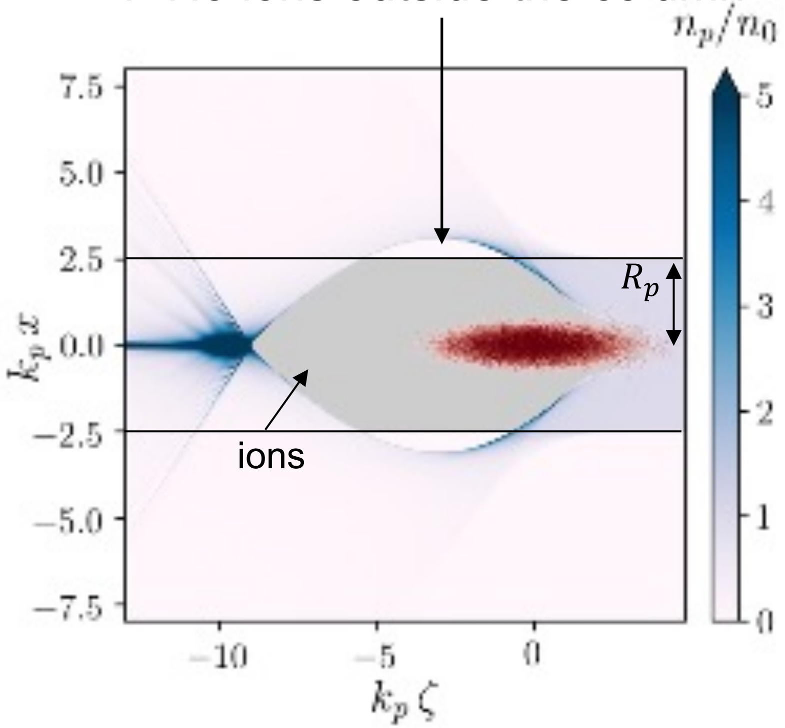


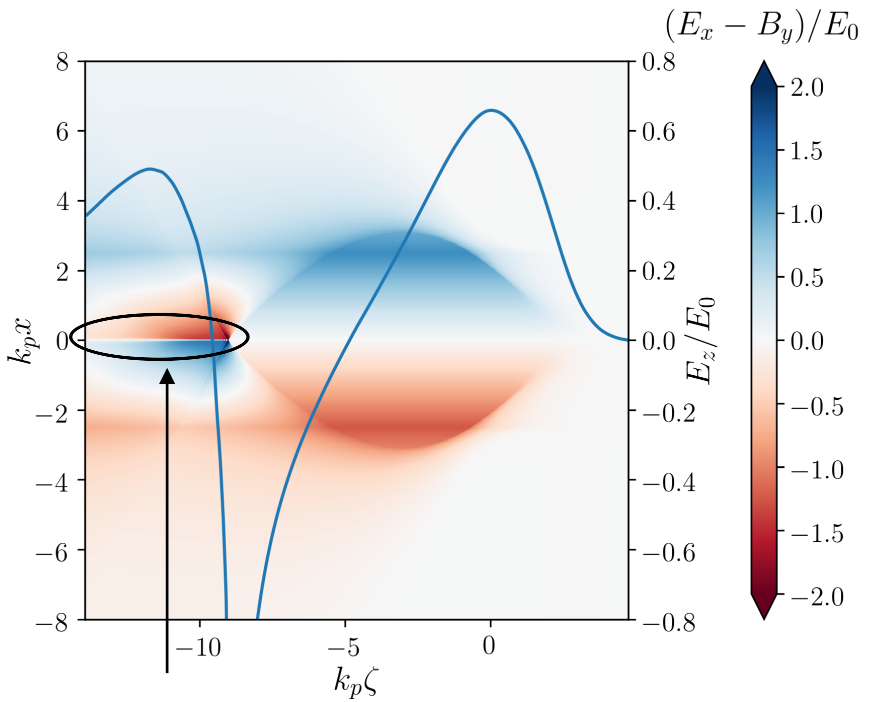
3. Long, high-density electron filament

Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns

1. No ions outside the column

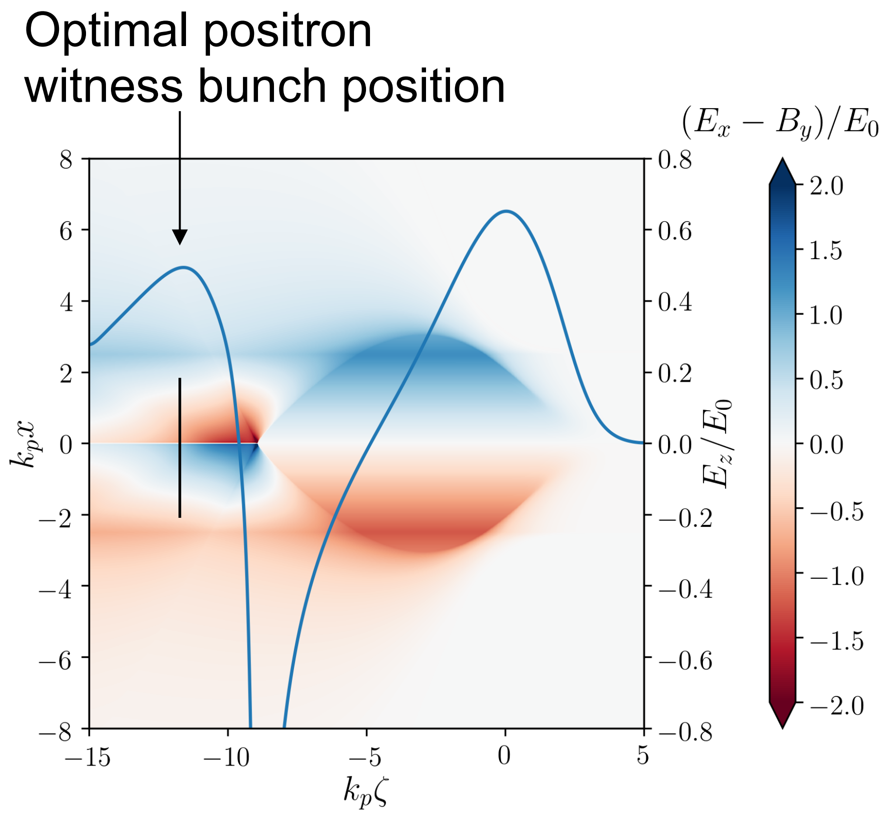




4. Accelerating and focusing fields for e^+

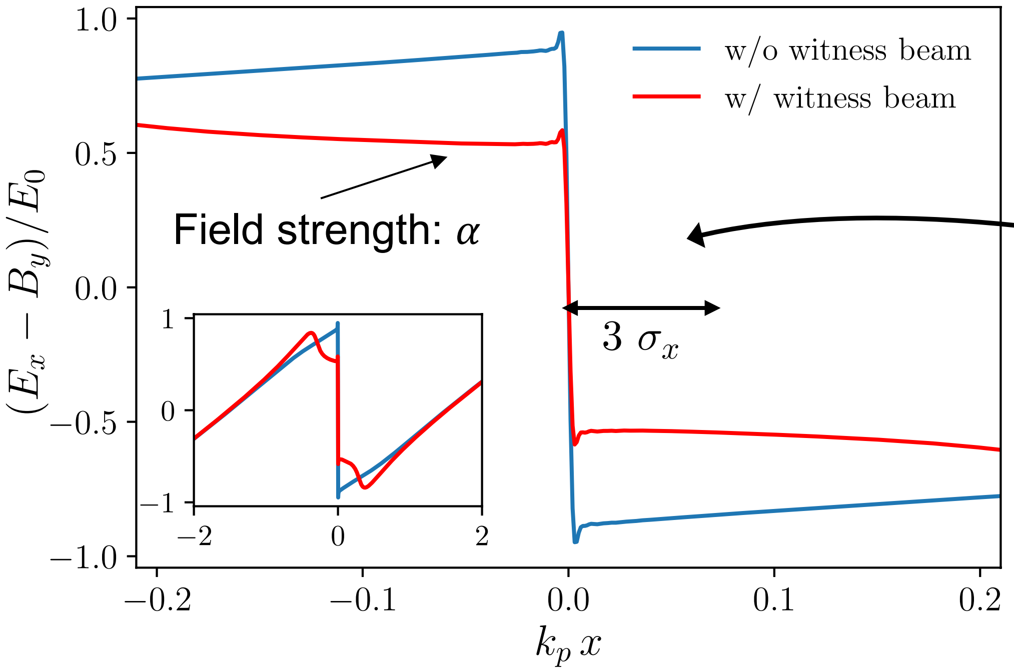
$0.5E_0 \approx$ 15 GV/m at $n_0 = 10^{17}\ cm^{-3}$

Emittance preservation requires matched beams



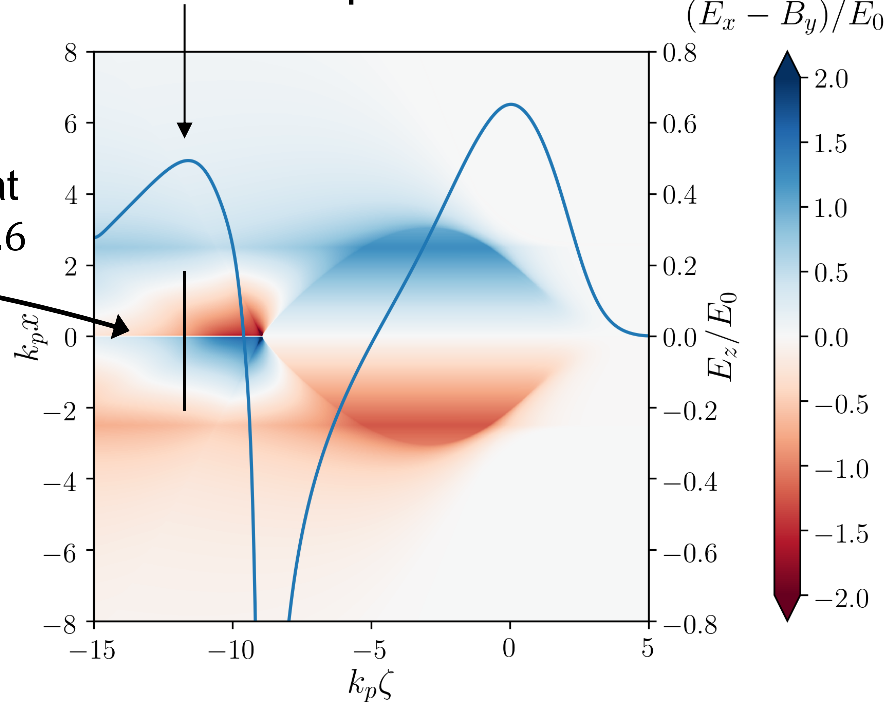
Emittance preservation requires matched beams

Ultra-high resolution simulation with INF&RNO (RZ)



Optimal positron witness bunch position

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

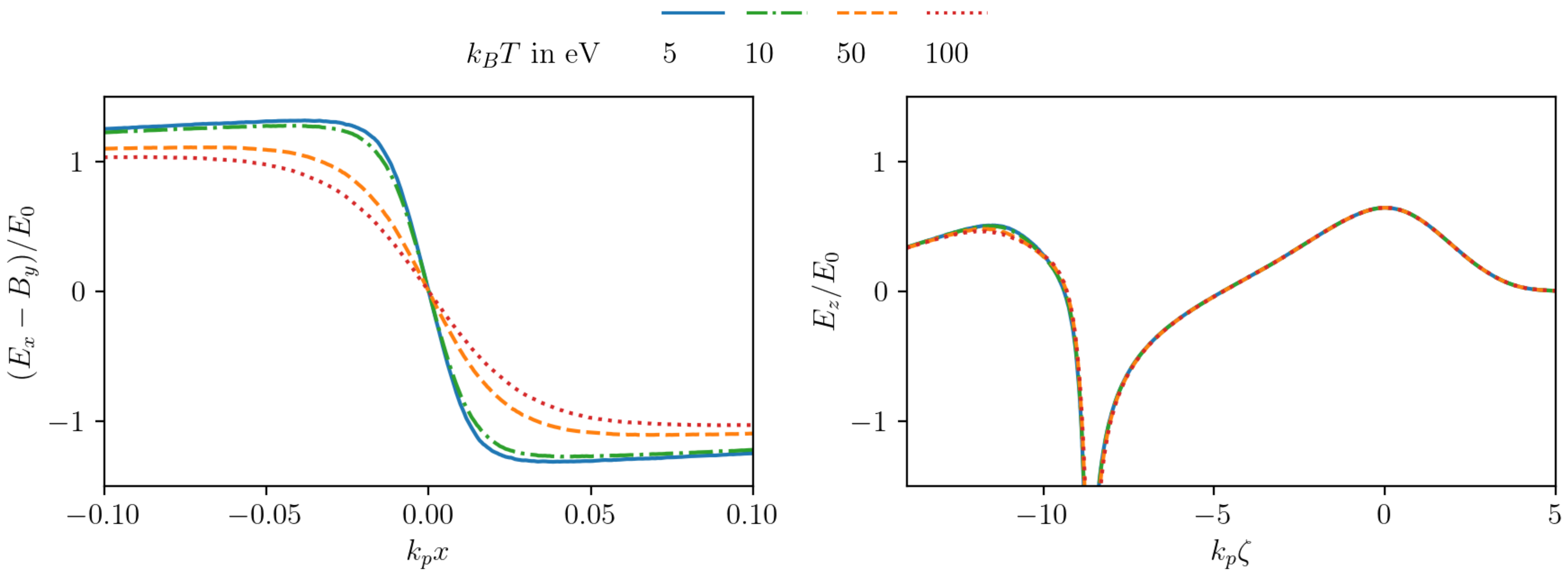


Witness beam parameters:

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

Temperature linearizes focusing field

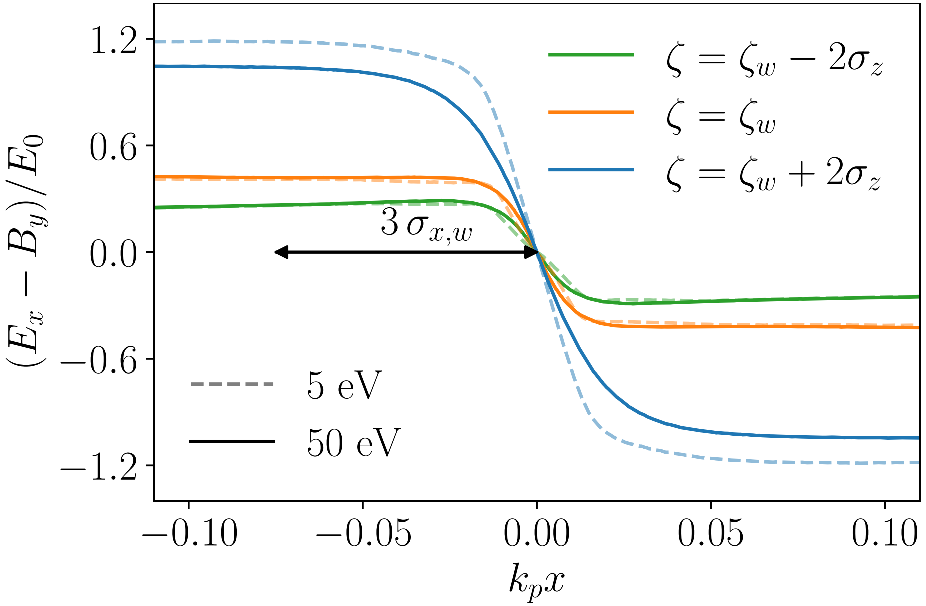
Unloaded wakefield in a plasma column

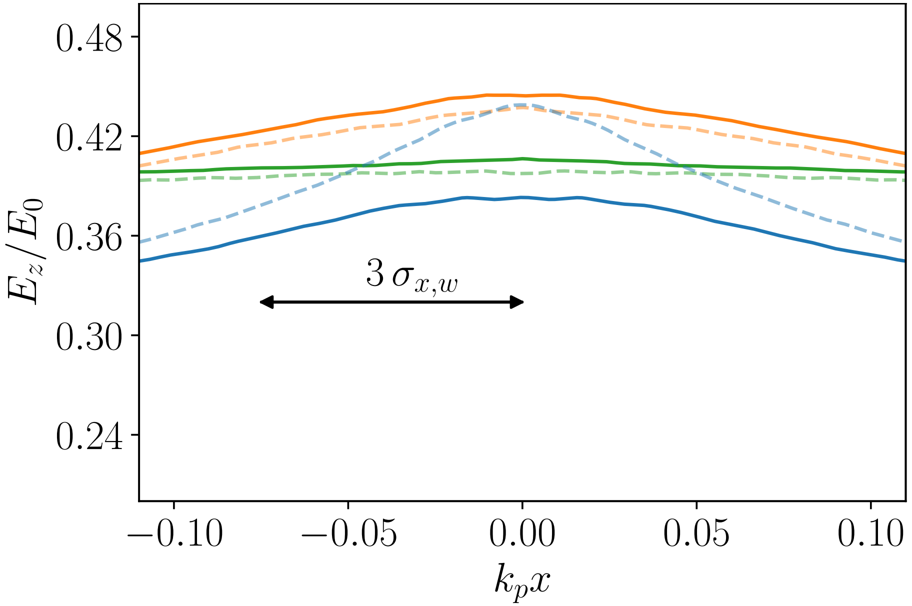


Diederichs et al. PoP 30, 073104 (2023)

Temperature linearizes focusing field and flattens accelerating field

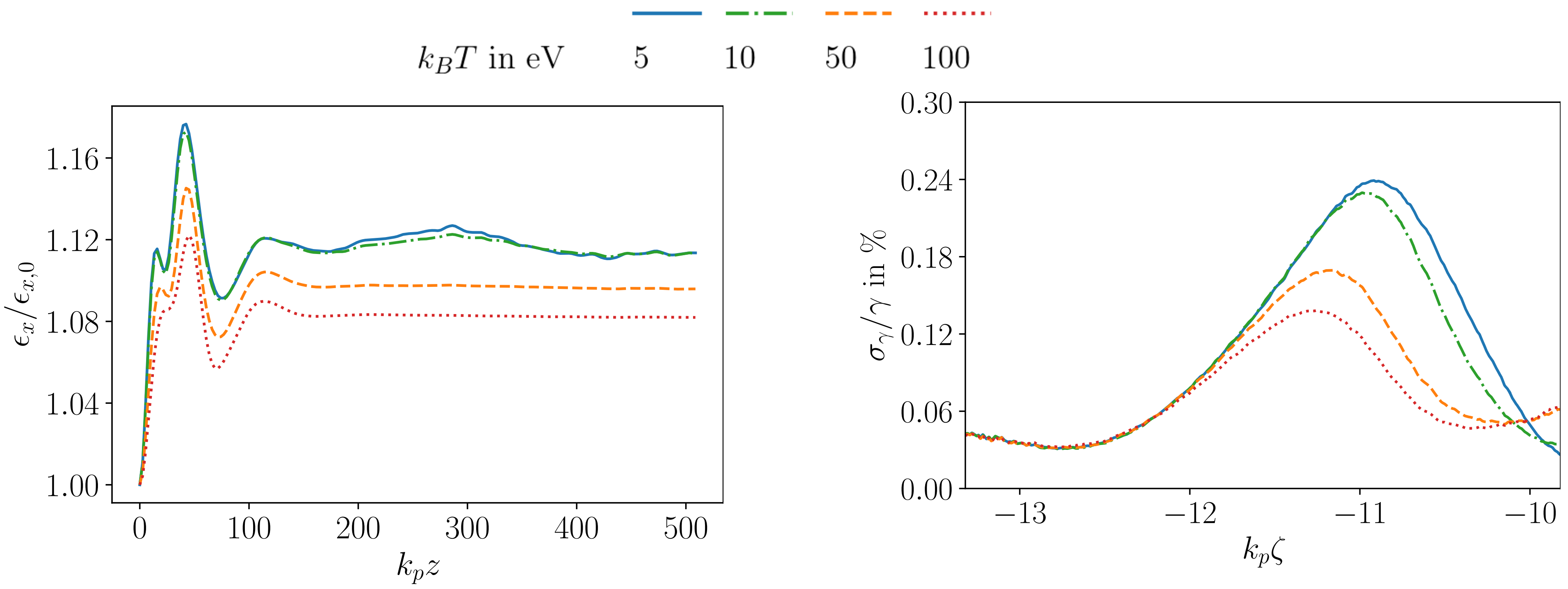
Wakefields loaded with same Gaussian bunch as before





Diederichs et al. PoP 30, 073104 (2023)

Temperature reduces emittance growth and slice energy spread



Emittance grows still by ≈10% at 50 eV because beam samples too much of the nonlinear field…
Let's look at collider-relevant emittances!

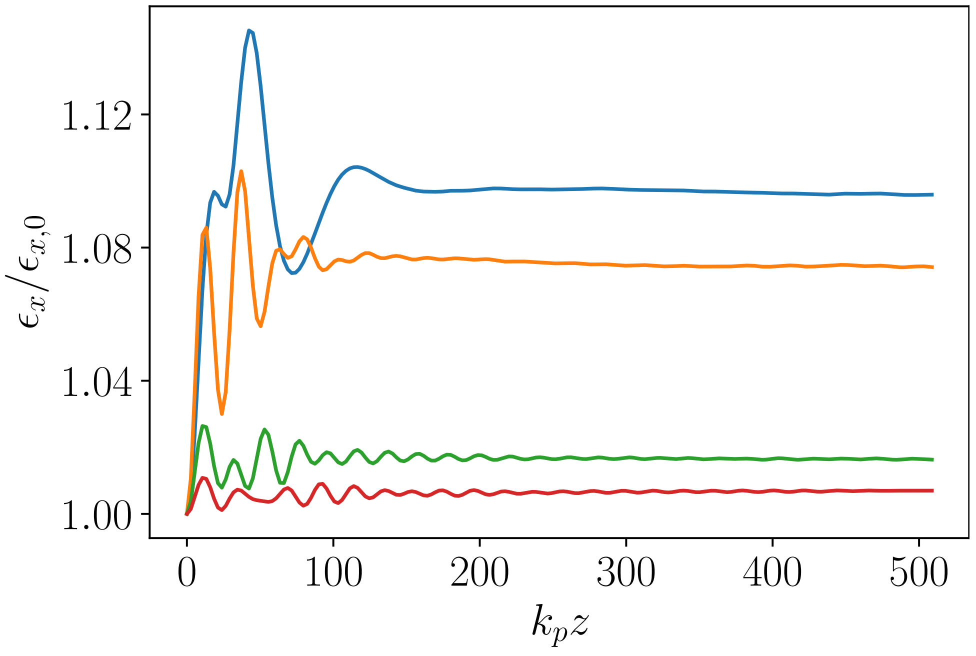
Diederichs et al. PoP 30, 073104 (2023)

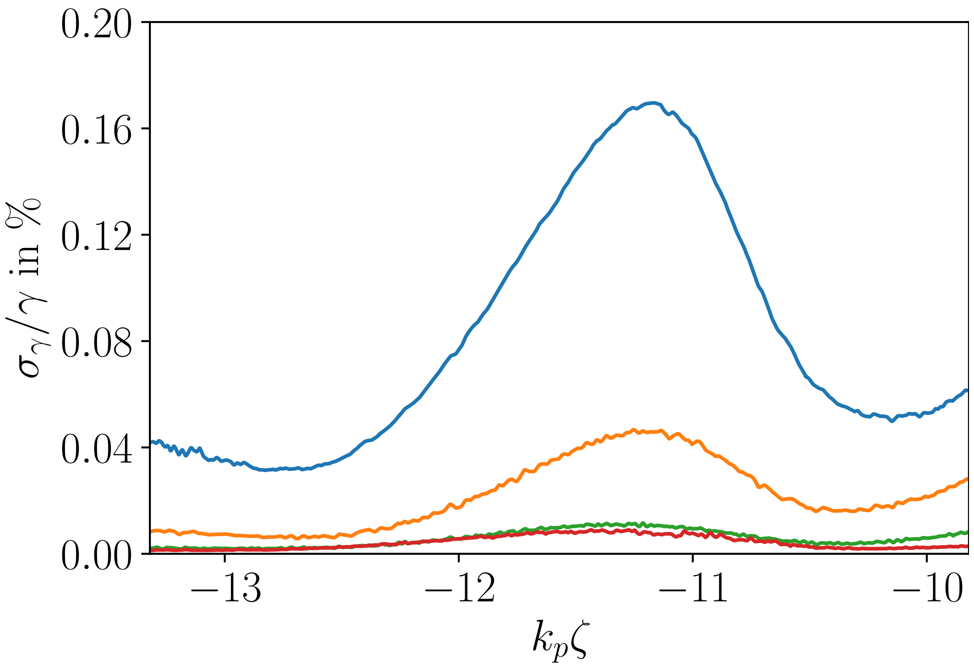
10s of nanometer emittance preserved to 1 %

Mesh refinement reveals the **“positron miracle”**:

With a temperature, a lower emittance can be better preserved,
while simultaneously achieving a lower slice energy spread and maintaining the same charge

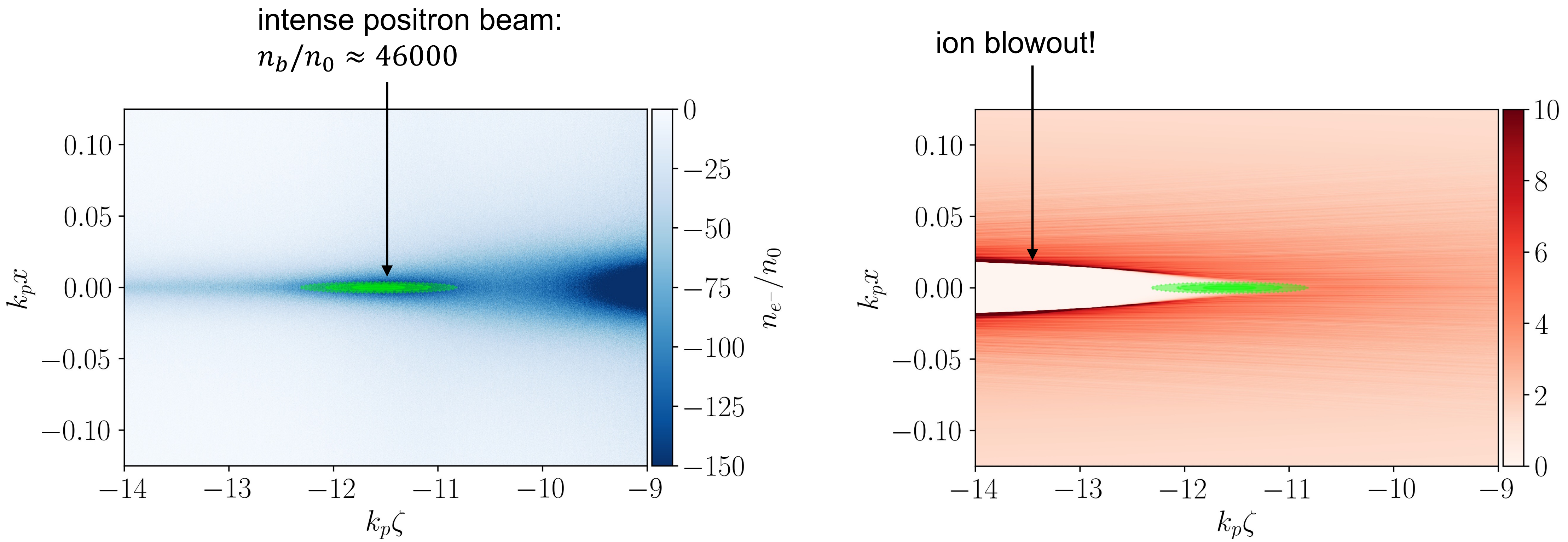
$k_p\epsilon_x$	0.1	0.025	0.00625	0.002	$\approx$ 33 nm at $n_0 = 10^{17}\ cm^{-3}$!





10s of nanometer emittance beams induce ion blowout

Wake persists despite $n_b/n_0 \gg n_e/n_0$



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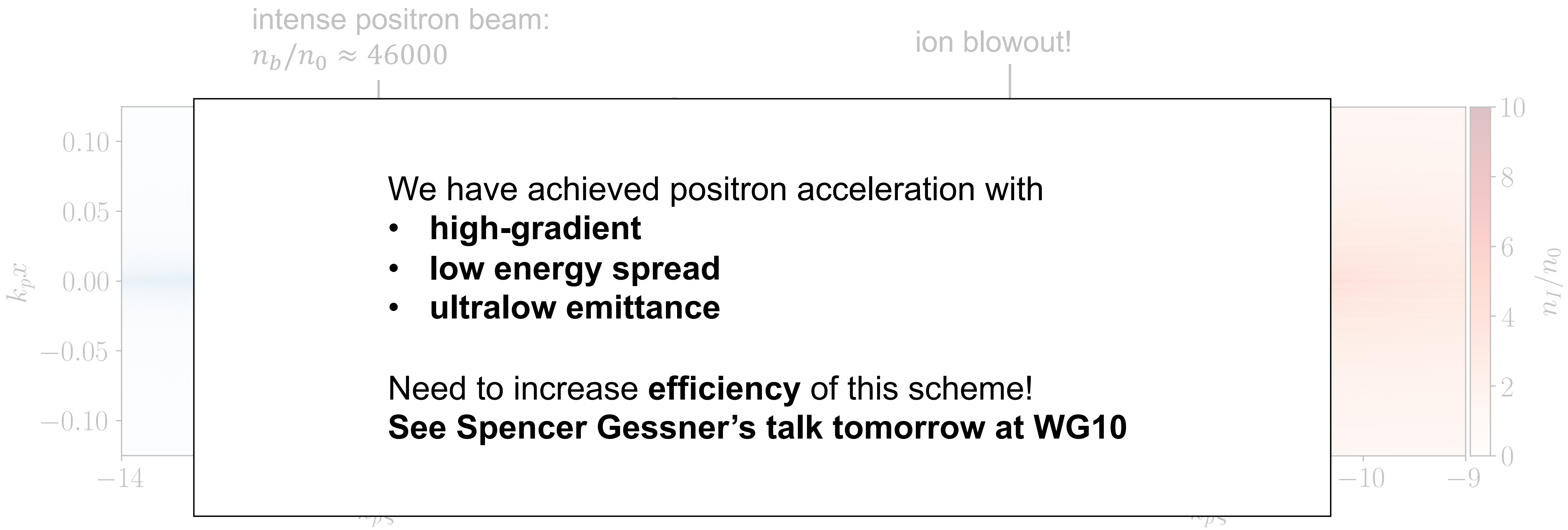

We have achieved positron acceleration with

- **high-gradient**
- **low energy spread**
- **ultralow emittance**

Need to increase **efficiency** of this scheme!
See Spencer Gessner's talk tomorrow at WG10

Summary

Temperature effects are **extremely important** in all positron schemes using electron filaments, so almost all of them

The temperature
1. broadens the filament, linearizes the focusing field, flattens the accelerating field transversely
2. enables emittance preservation due to linearized fields
3. help tremendously with numerical convergence

The **positron miracle**: with a temperature, a lower emittance can be better preserved, while simultaneously reducing the slice energy spread, and maintaining the same charge

Many further studies needed! All schemes must be reconsidered with temperature effects

Acknowledgements

DESY.

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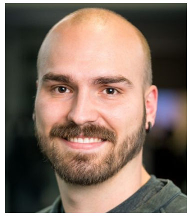

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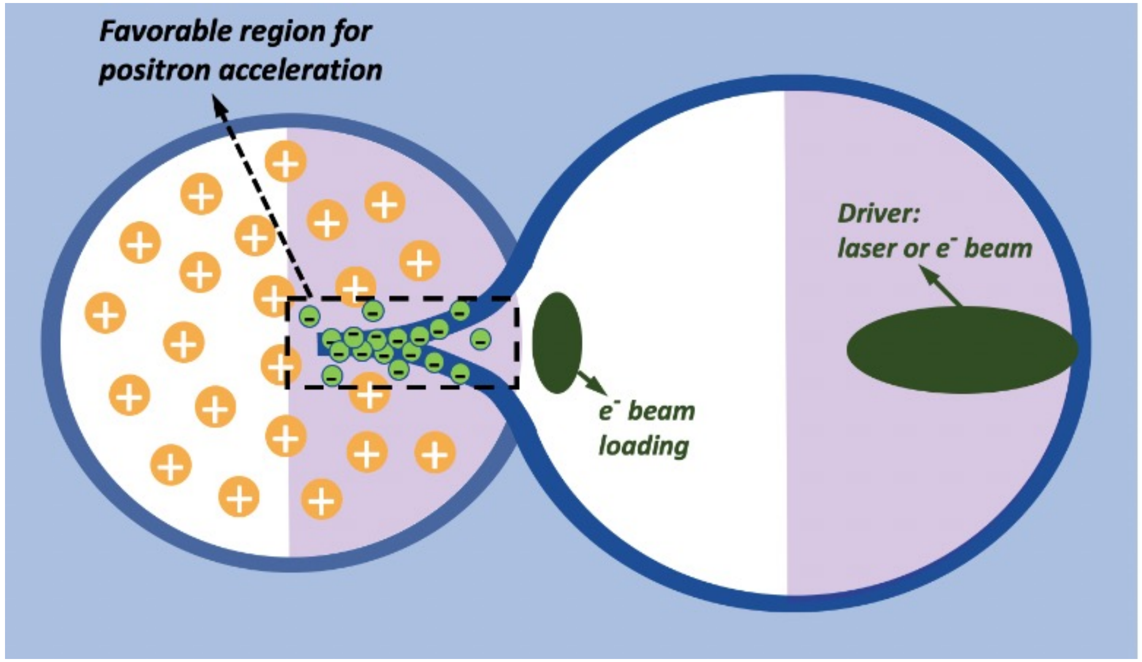
Weiqun Zhang

Rémi Lehe

Jean-Luc Vay

Backup

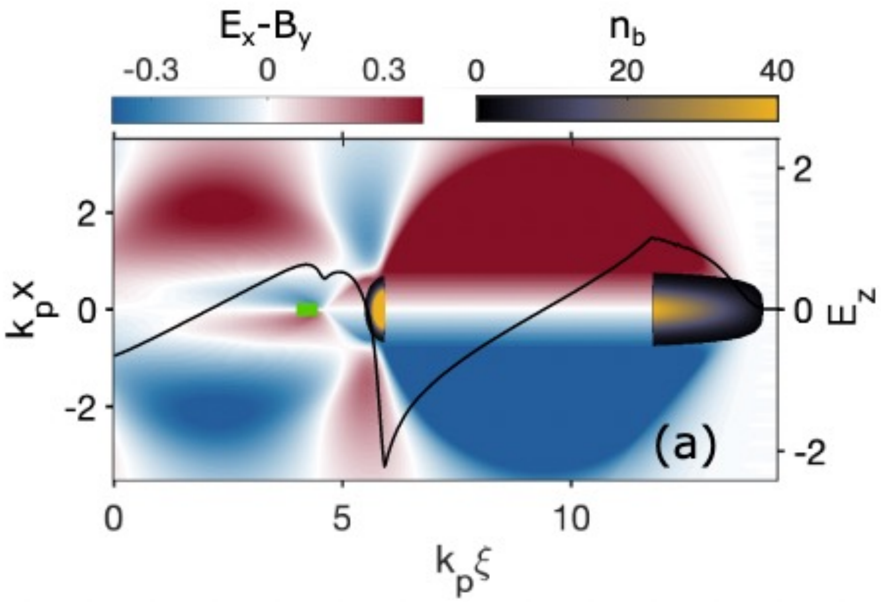
Electron witness bunch elongates plasma electron spike

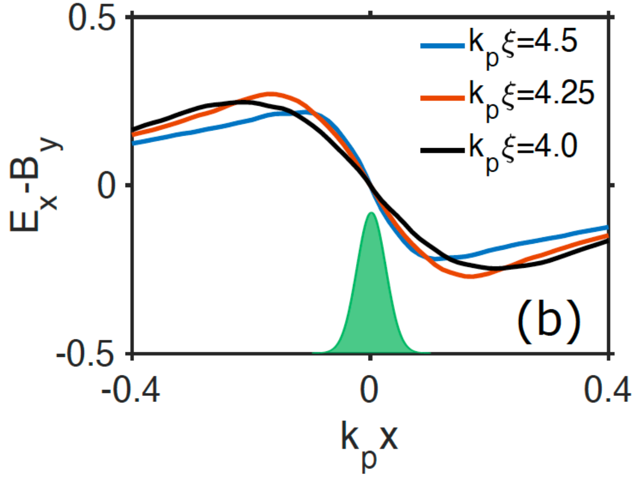


Warm plasma (72 eV) spreads the electron filament

Wang et al. arXiv 2110.10290 (2021)

Similar properties as in the plasma column can be achieved





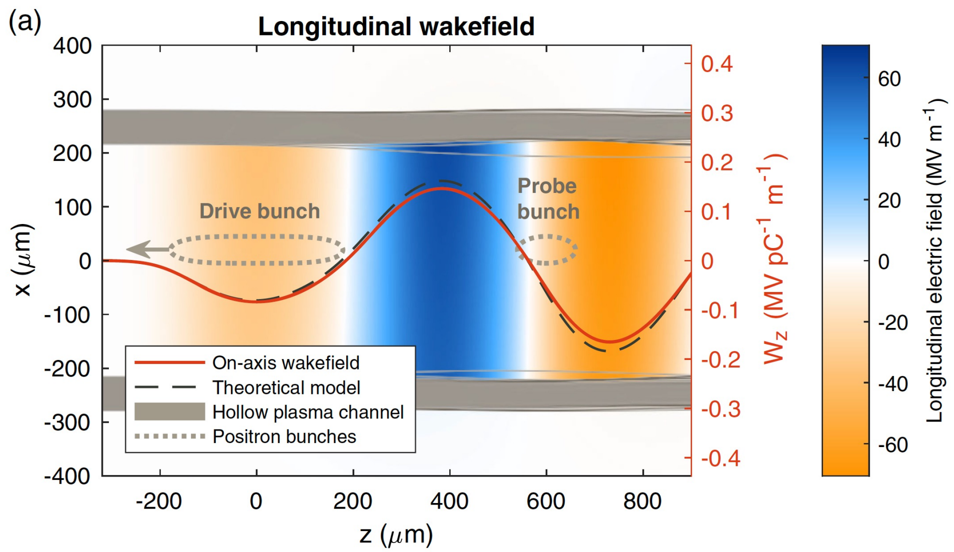
Linear focusing fields!
=> emittance preserved < 0.9 µm

1.4% rms energy spread
without beamloading

A lot of potential for optimization!

Wang et al. arXiv 2110.10290 (2021)

If ions defocus, let's ignore them altogether: Hollow core plasma accelerator



Hollow core plasma provides **accelerating, but no focusing fields**

Schroeder et al., PRL 82, 1177 (1999)
Lee et al., PRE 64, 045501 (2001)
Gessner et al., Nat. Comm. 7 11785 (2016)
Lindstrøm et al., PRL 120, 124802 (2018)

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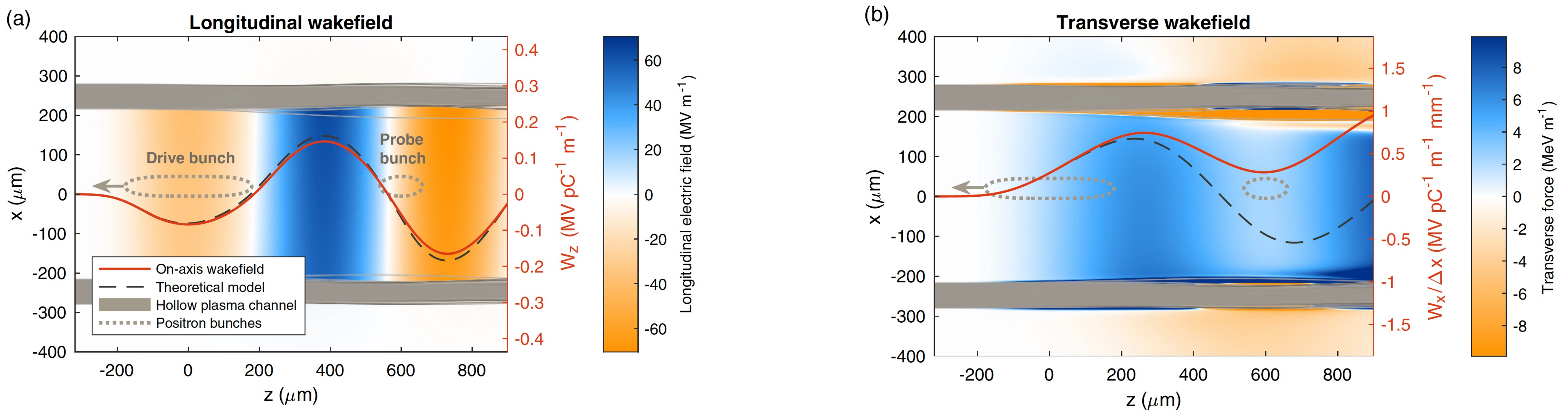
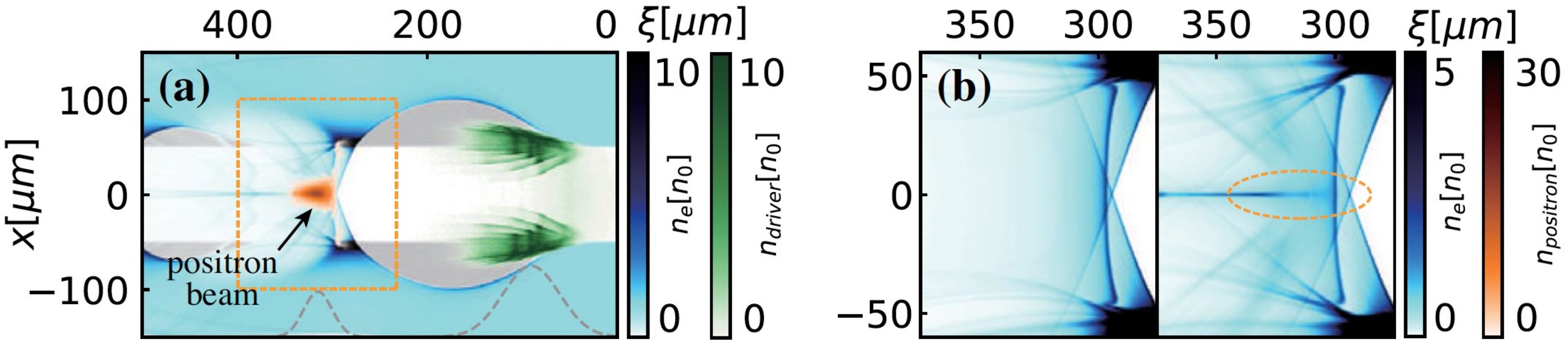


Hollow core plasma provides **accelerating, but no focusing fields**

Misaligned beams are deflected

Schroeder et al., PRL 82, 1177 (1999)
Lee et al., PRE 64, 045501 (2001)
Gessner et al., Nat. Comm. 7 11785 (2016)
Lindstrøm et al., PRL 120, 124802 (2018)

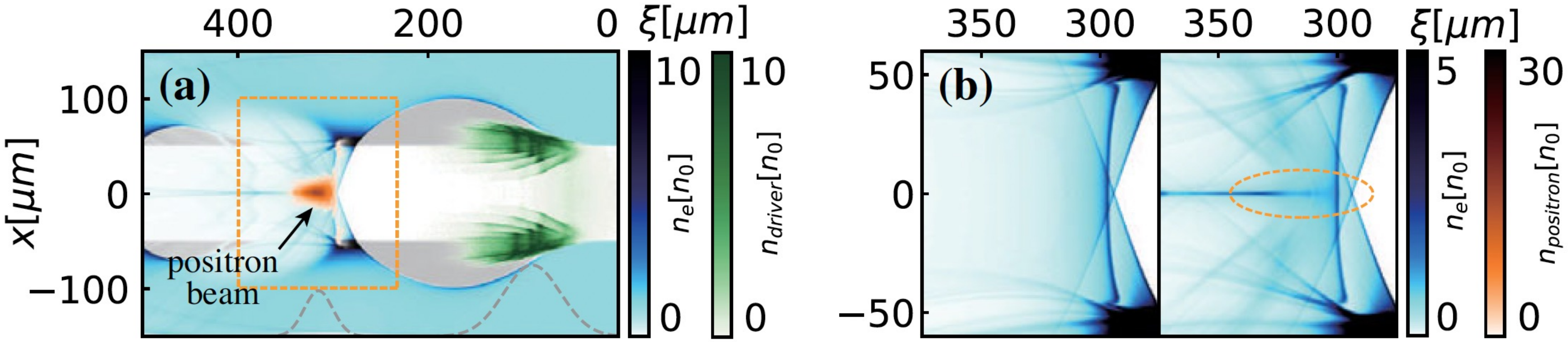
Strong drive beams + positron beam loading produce electron filament in hollow core plasma accelerator



Stable drive beam due to asymmetric mode

Zhou et al., PRL 127, 174801 (2021)

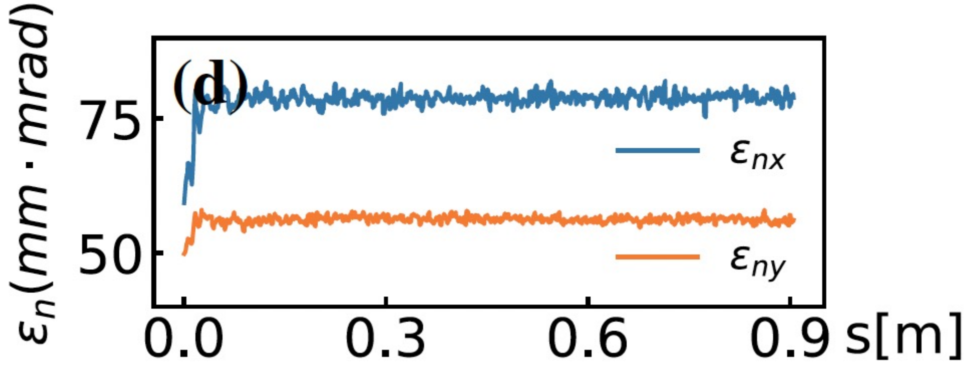
High-charge, low energy spread positron acceleration shown



0.49 nC charge
4.9 GV/m gradient
1.6% rms energy spread
33% energy transfer efficiency

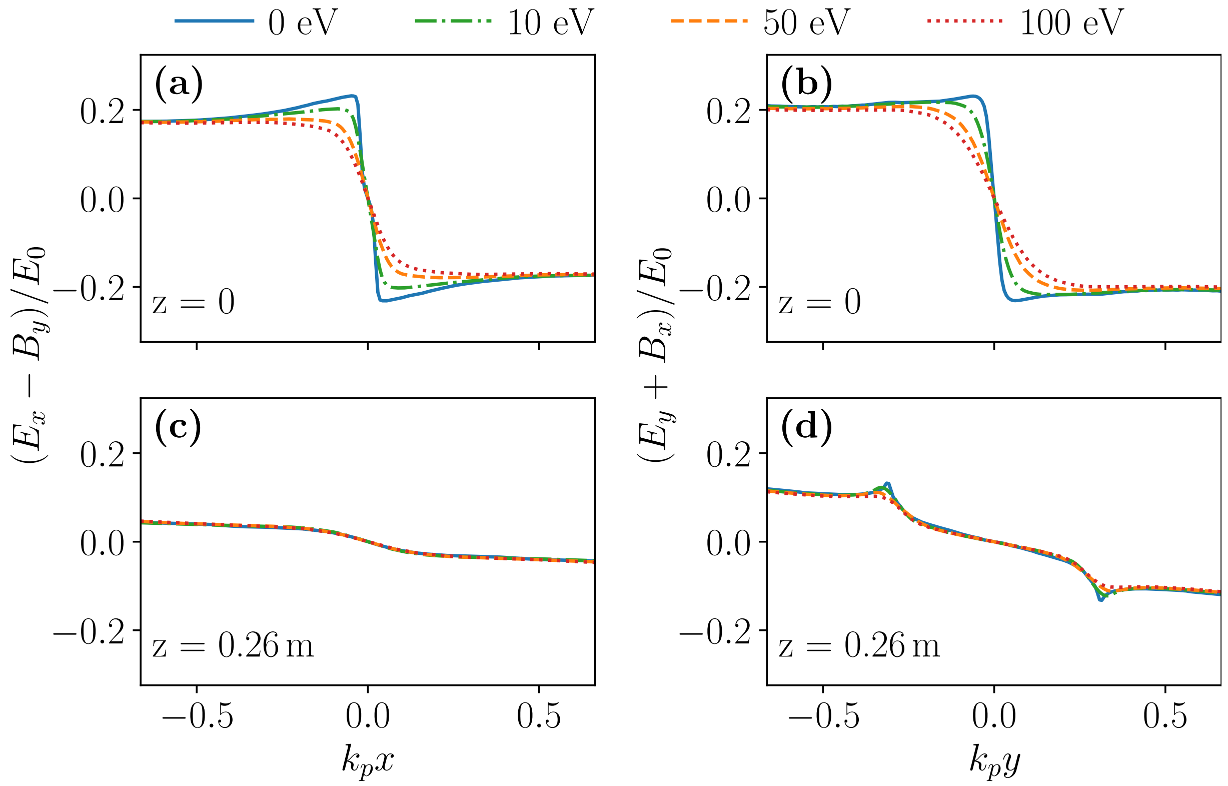
> 50 μm central slice emittance

A lot of potential for optimization

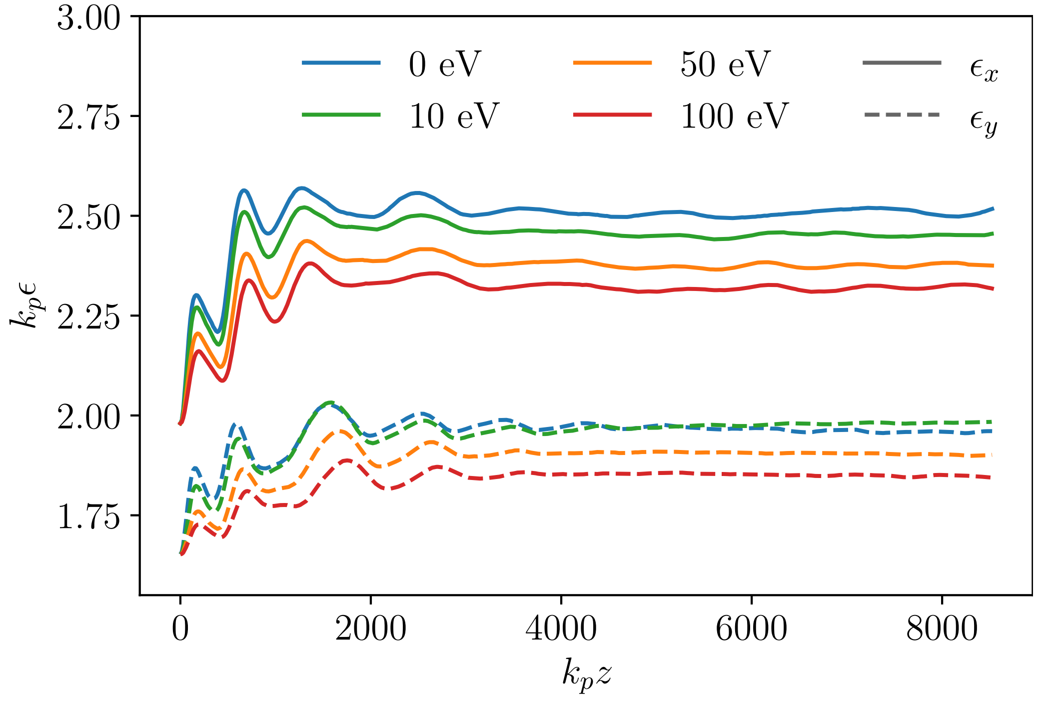


Zhou et al., PRL 127, 174801 (2021)

Temperature smoothes the fields again, reduces emittance growth



Temperature mitigates emittance growth



Diederichs et al. PoP 30, 073104 (2023)