Positron acceleration in plasmas

Severin Diederichs

EP-SFT

01.10.2024

Proton-beam-driven Positron acceleration in plasmas

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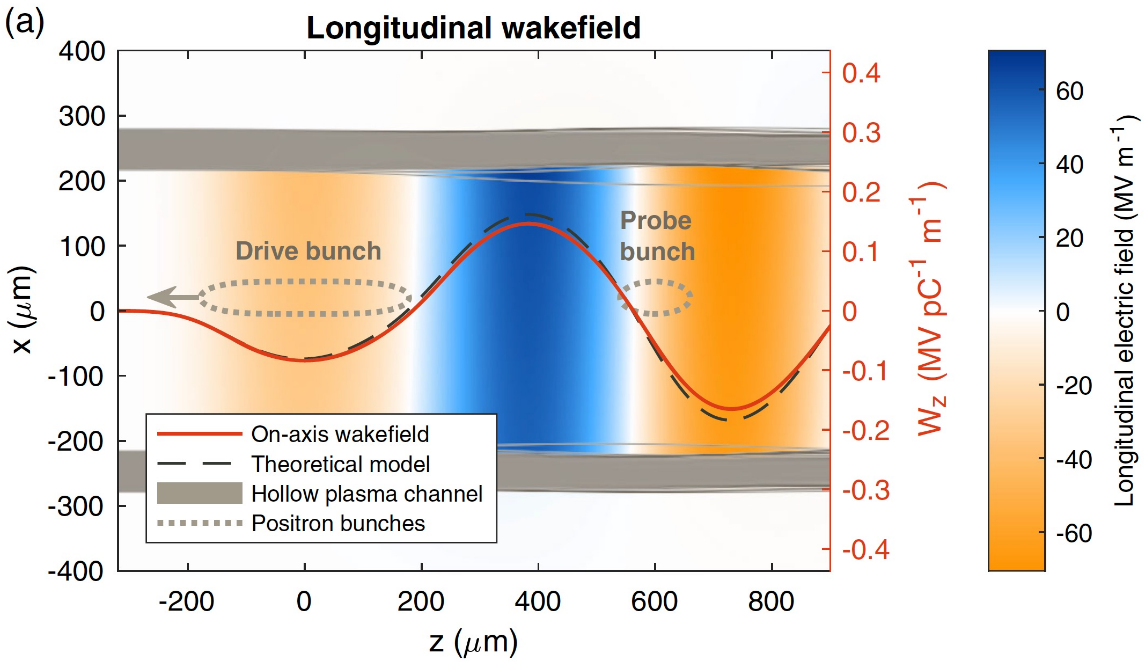
Hollow core plasma channel works for both e^- and e^+

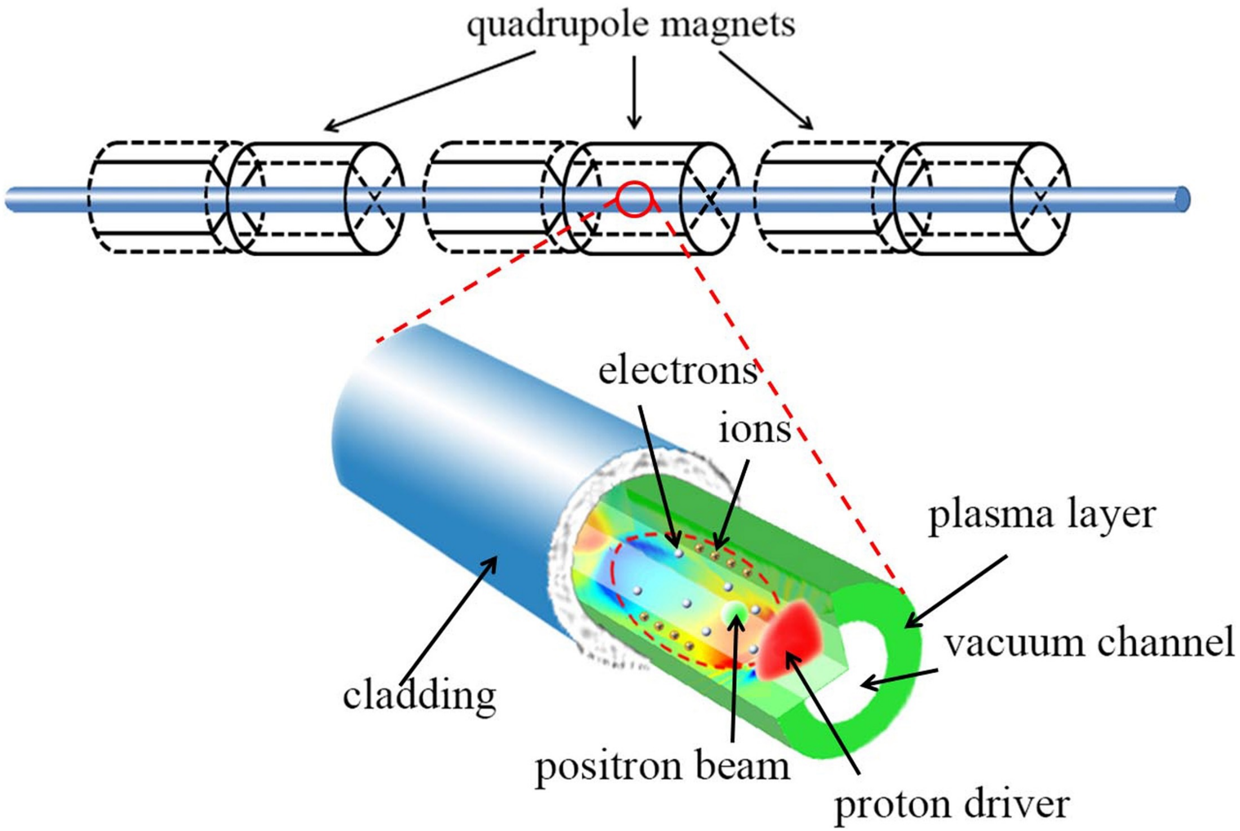


Hollow core plasma provides **accelerating, but no focusing fields**

→ requires **external focusing for stability**

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)

Proton-beam-driven positron acceleration up to TeV in the hollow core plasma channel



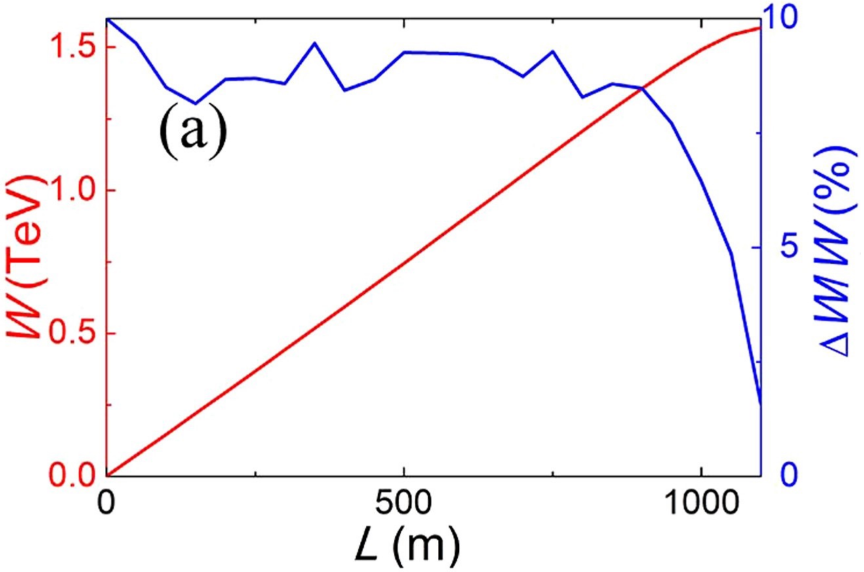
Driver:
10^{11} protons
2 TeV, $\Delta P_z/P_z = 0.1$
$\sigma_z = 100\mu m \;\; \sigma_r = 430\ \mu m$

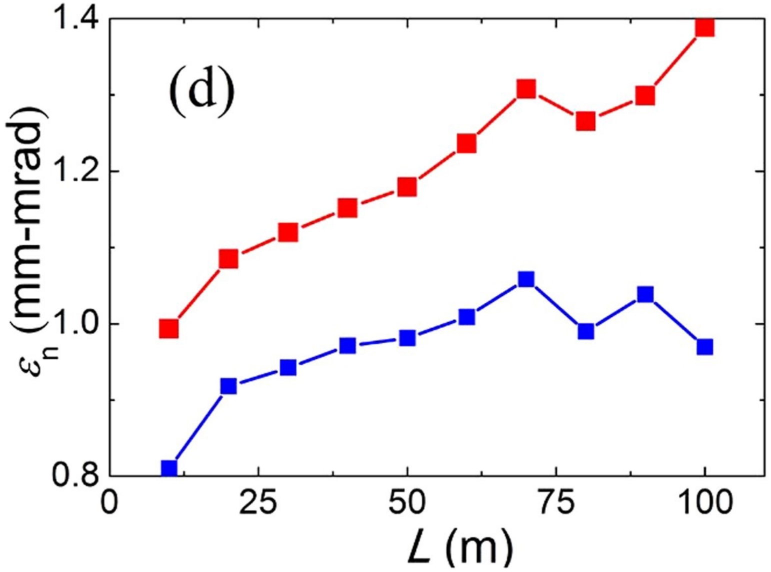
Witness:
5^9 positrons
$\sigma_z = 25\ \mu m \;\; \sigma_r = 50\ \mu m$
$\epsilon_n = 1$ mm-mrad

Plasma:
$n_0 = \ 5^{15} cm^{-3}$
$r_0 = 75\mu m$

Yi et al., Sci Rep 4, 4171 (2014)

Proton-beam-driven positron acceleration up to TeV in the hollow core plasma channel

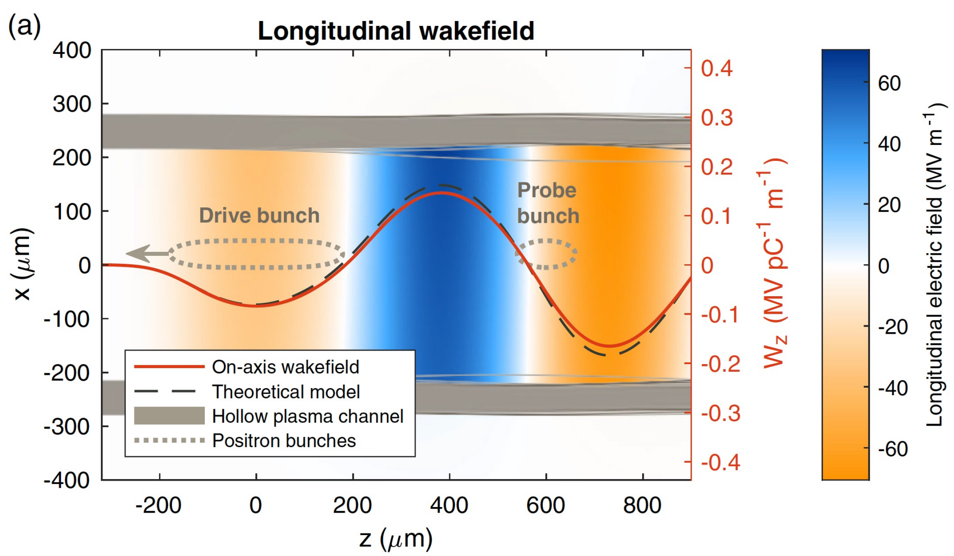


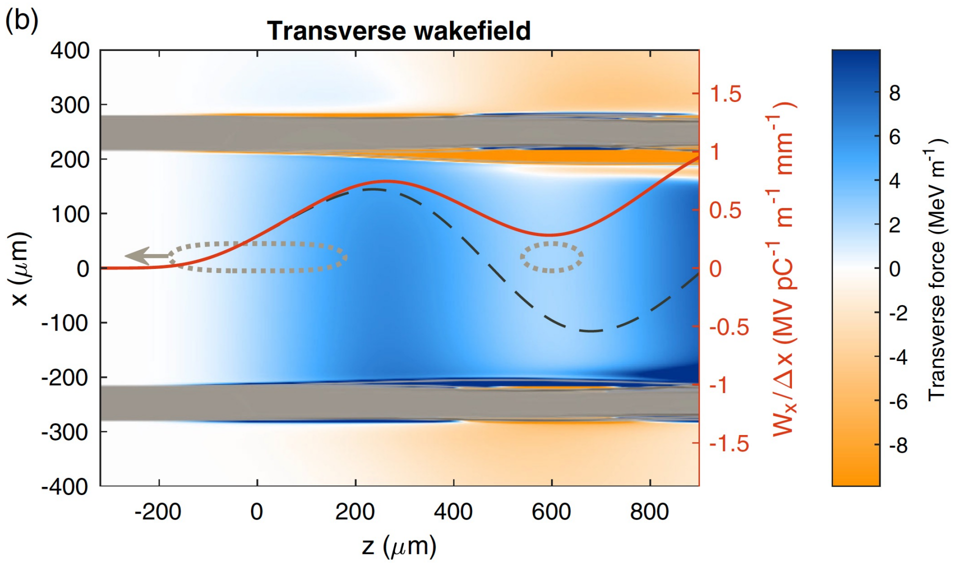


Red: full bunch
Blue: “core” bunch

Yi et al., Sci Rep 4, 4171 (2014)

Hollow core plasma channels intrinsically unstable





Misaligned beams are deflected

Experiments extremely challenging,
25 cm hollow core plasma channel
enabled 70 MeV/m acceleration

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)
Gessner et al. arXiv 2304.01700 (2023)

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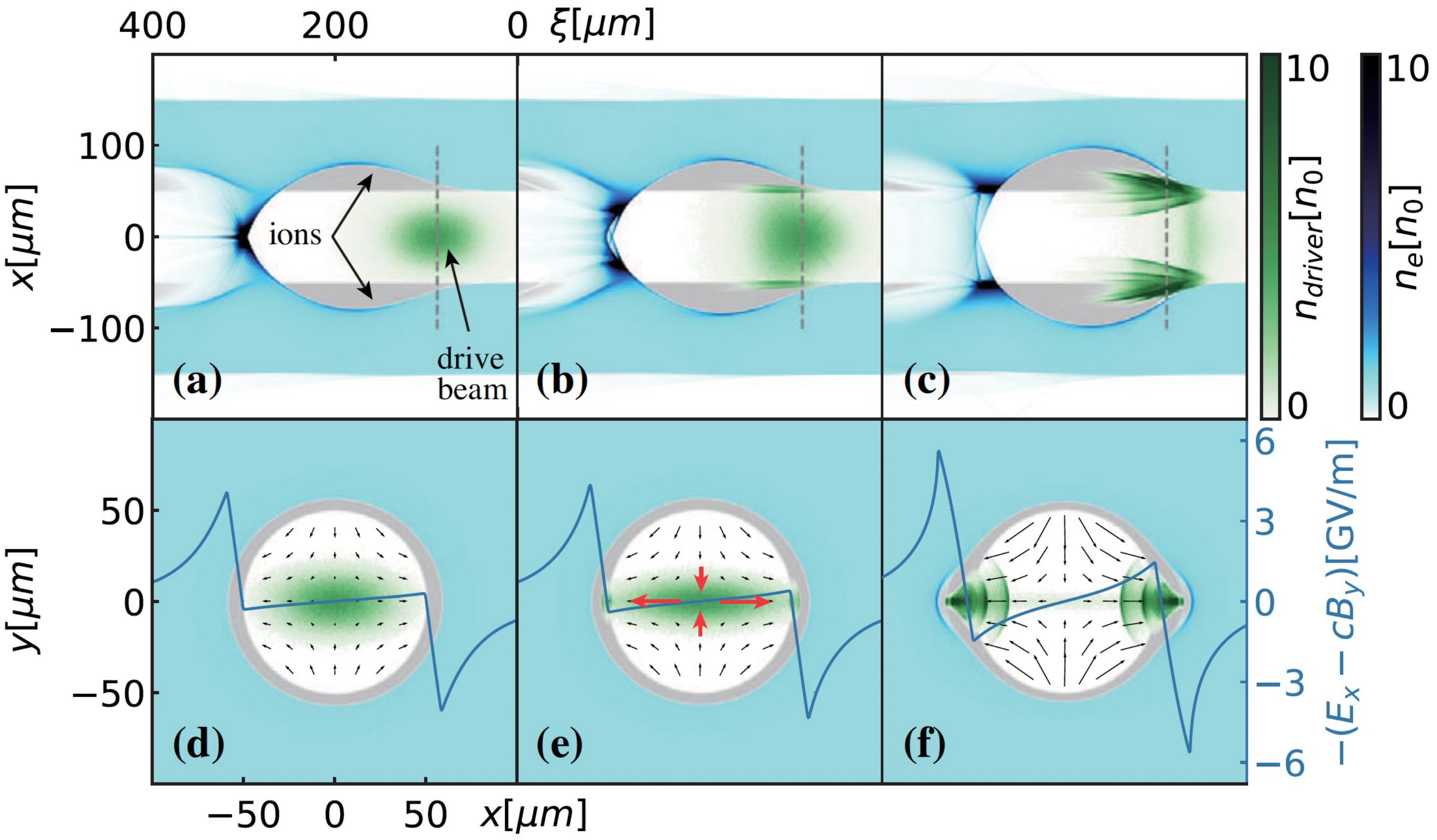
Asymmetric drive beams stabilize hollow core plasma accelerator

Quadrupole moment:
Drive beam hits channel wall
in a **controlled** manner



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

Asymmetric drive beams stabilize hollow core plasma accelerator

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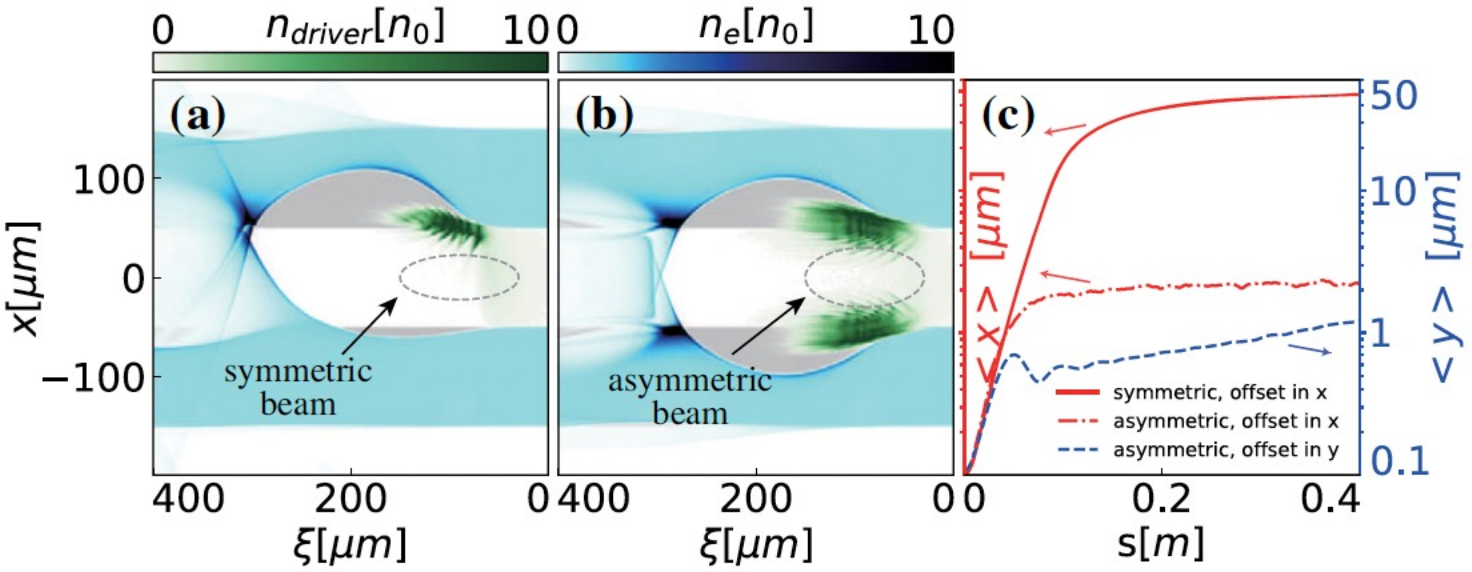
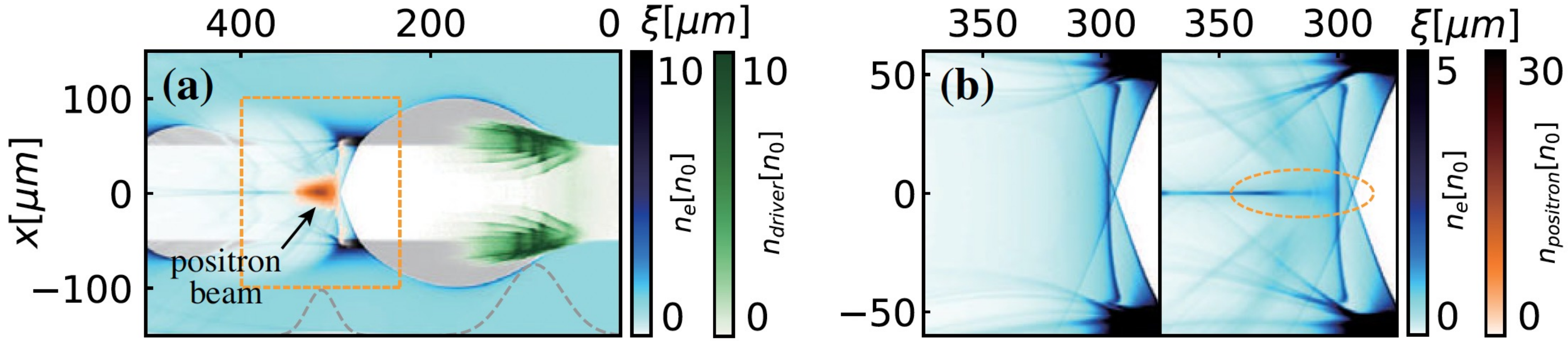


Stabilizes drive beam in hollow core channel!

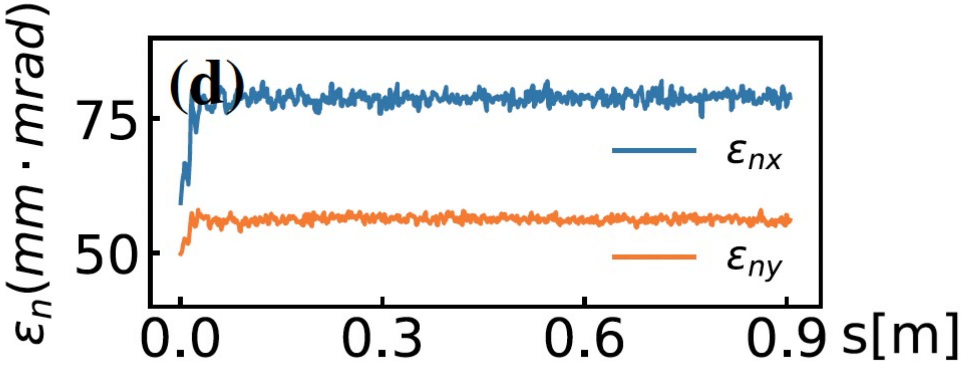
Zhou et al., PRL 127, 174801 (2021)

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



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

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PEEP beam parameters are challenging

Beam parameters:
$Q = 2\times10^{10}\ e^{+} \approx 3.6$ nC
$\epsilon_n = 100$ nm
$E_{max} = 125$ GeV

→

Strongly nonlinear wakefields,
quasilinear and linear regime will collapse

PEEP beam parameters are challenging

Beam parameters:
$Q = 2\times10^{10}\ e^{+} \approx 3.6$ nC
$\epsilon_n = 100$ nm
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→ Strongly nonlinear wakefields,
quasilinear and linear regime will collapse

Embrace the nonlinearity

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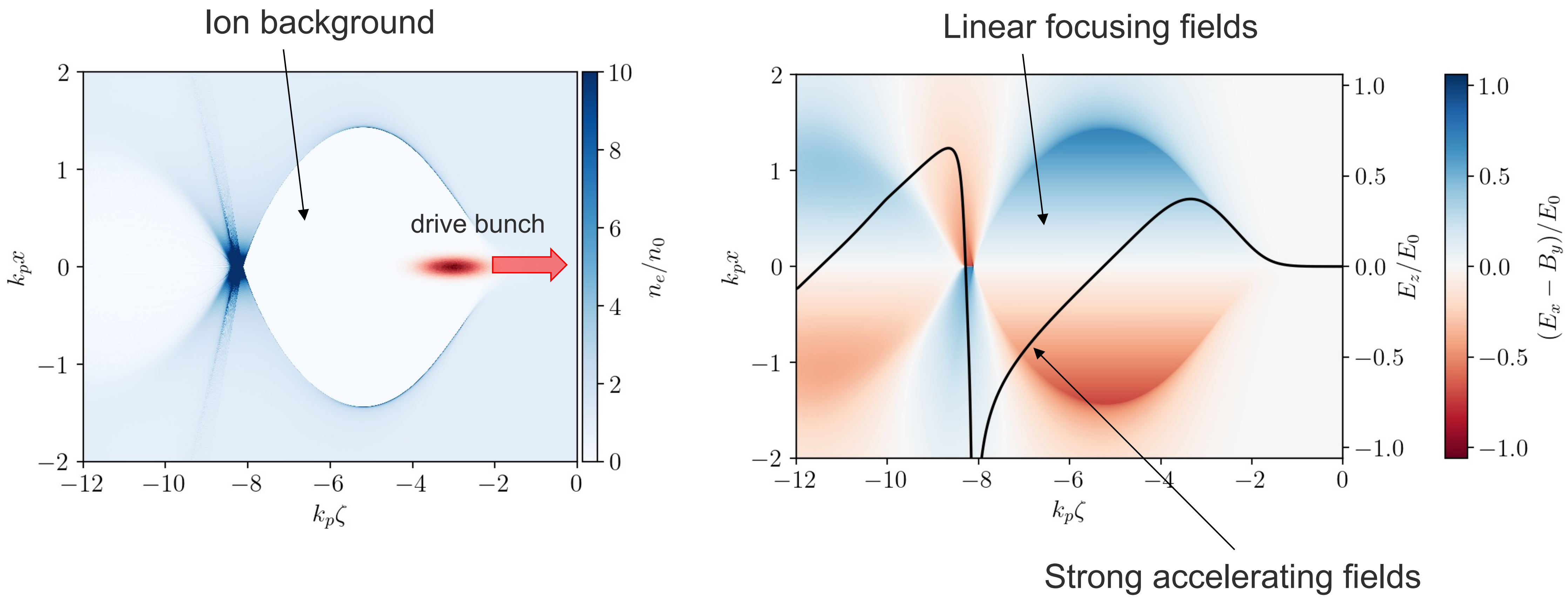
Plasma wakefield accelerators enable high-quality, high-gradient *electron* acceleration



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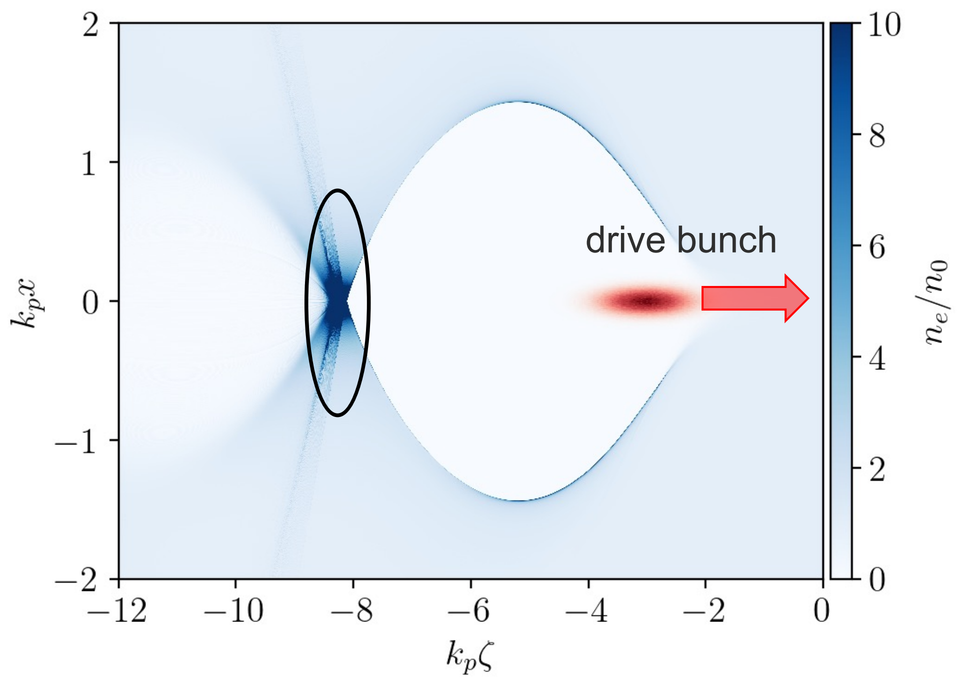
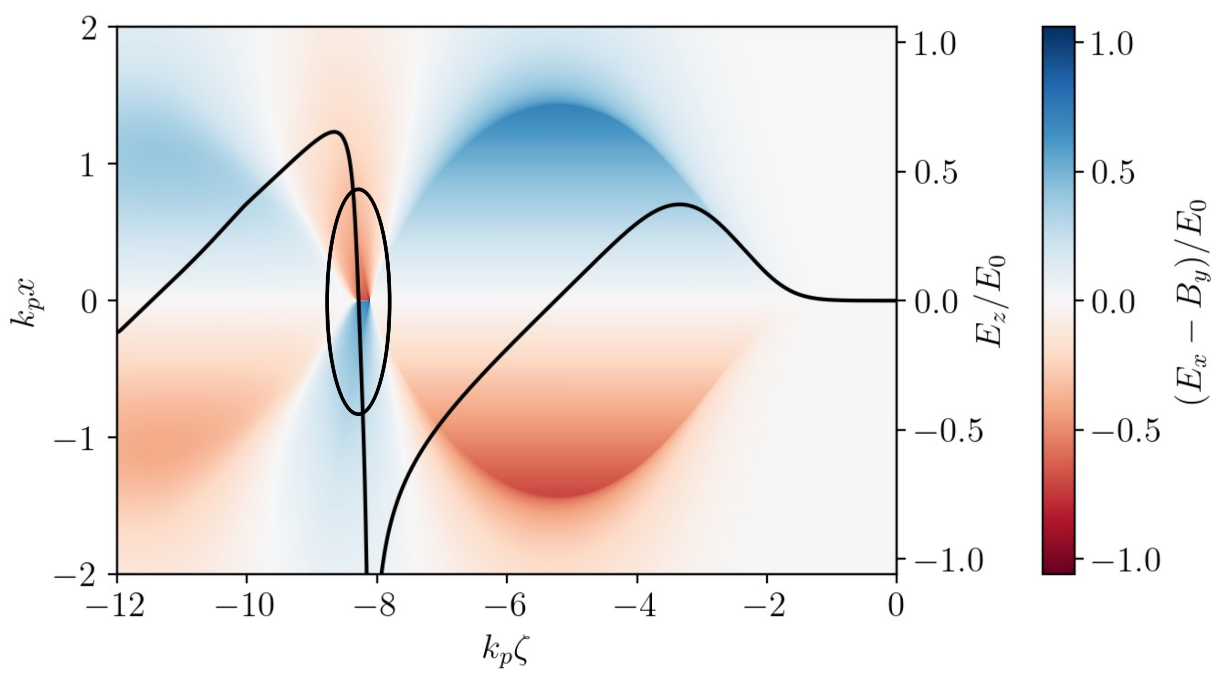
The electron spike at the back of the bubble enables positron acceleration

High-density electron cusp



Focusing field for positrons



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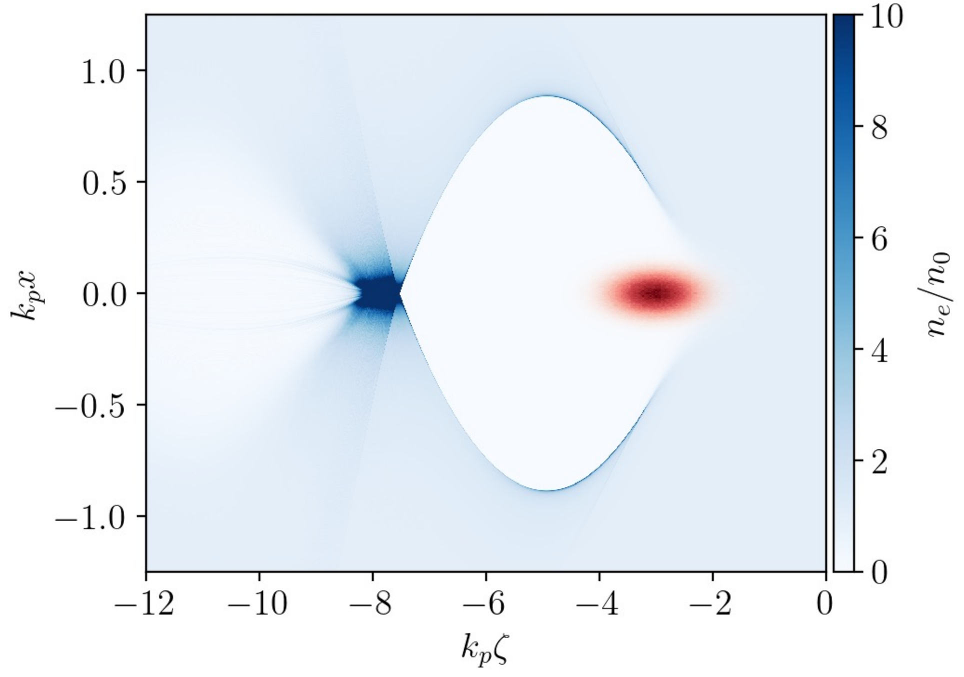
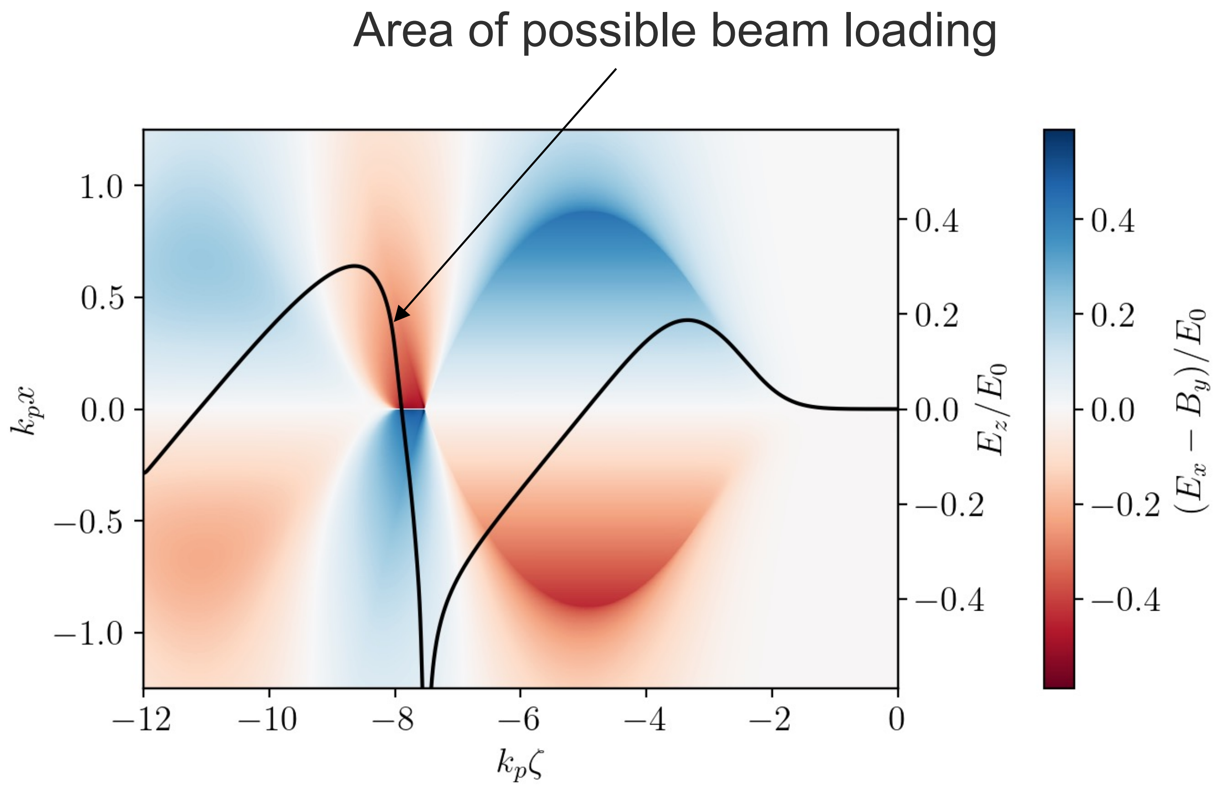
Weaker blowout is preferable





Lotov, PoP 14, 023101 (2007)

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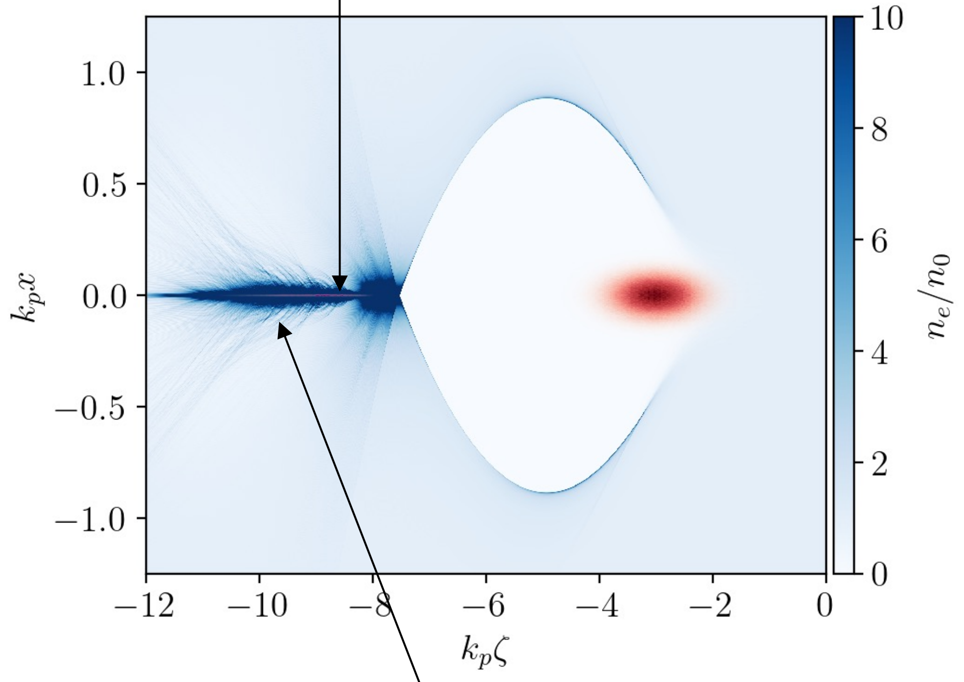
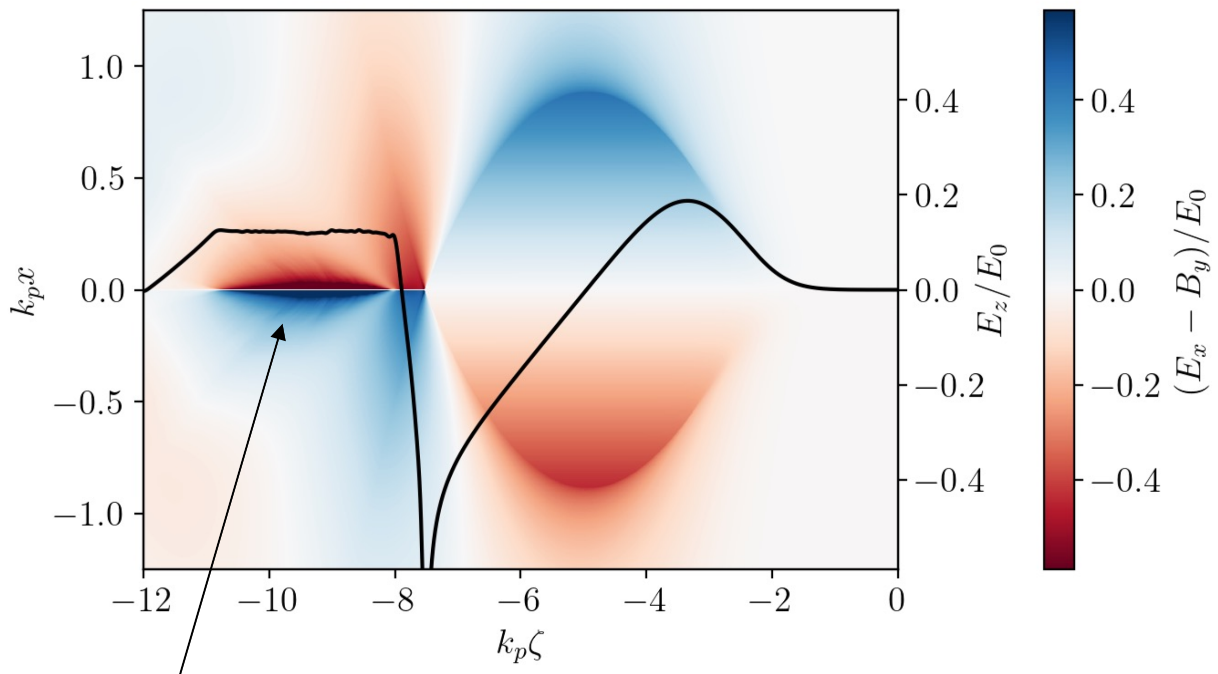
Weaker blowout is preferable

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)

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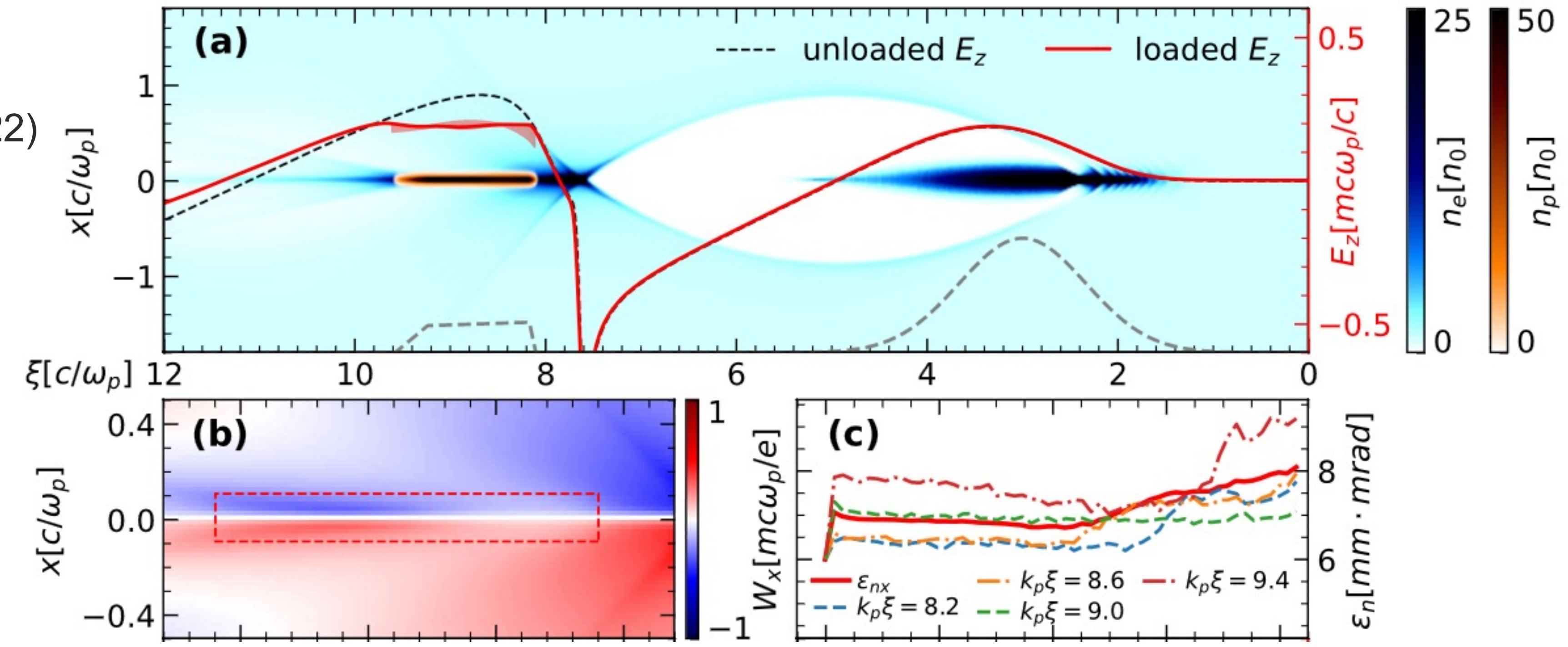
Optimal beam loading enables excellent parameters

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

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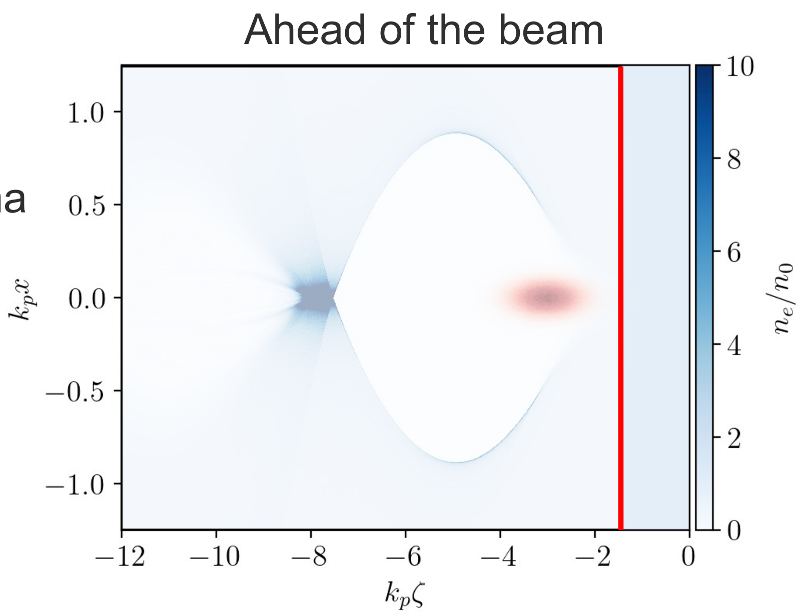
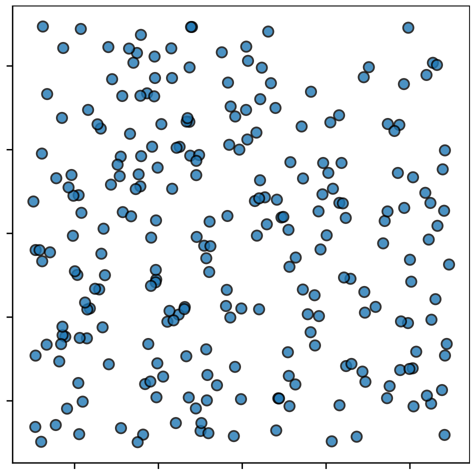
Temperature broadens electron spike at the back of the bubble

cold plasma





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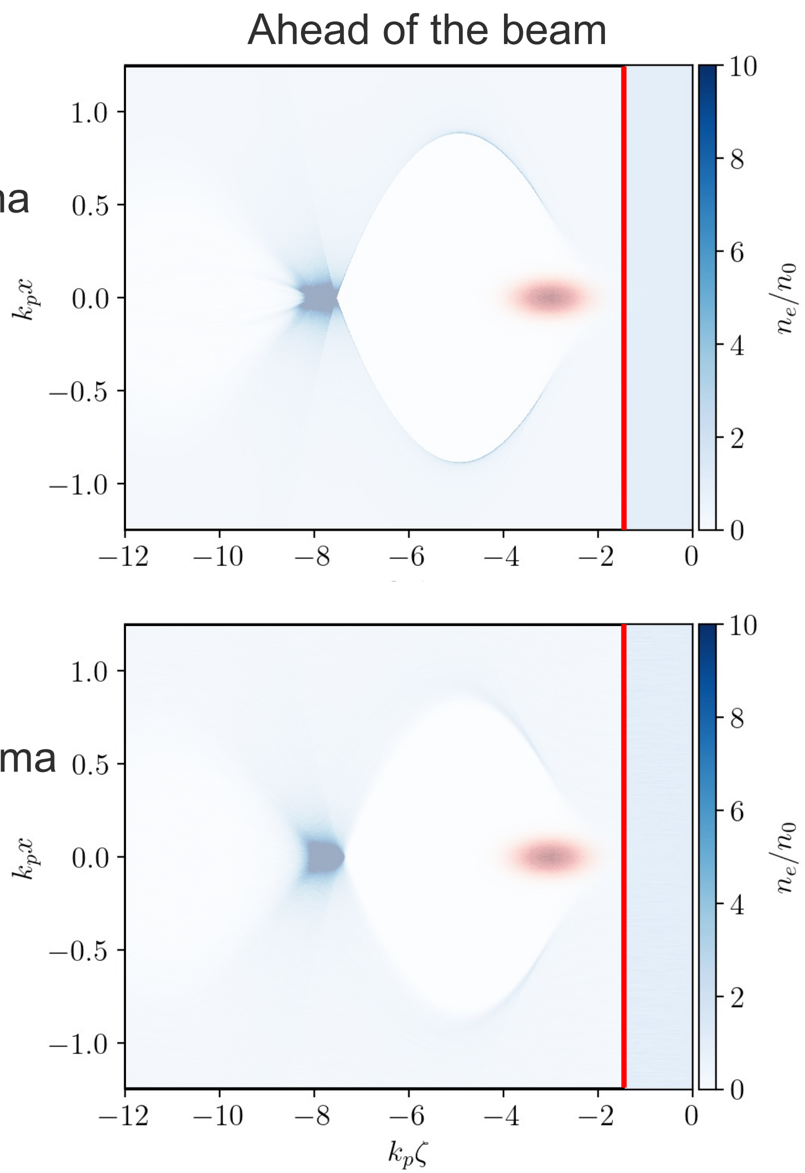
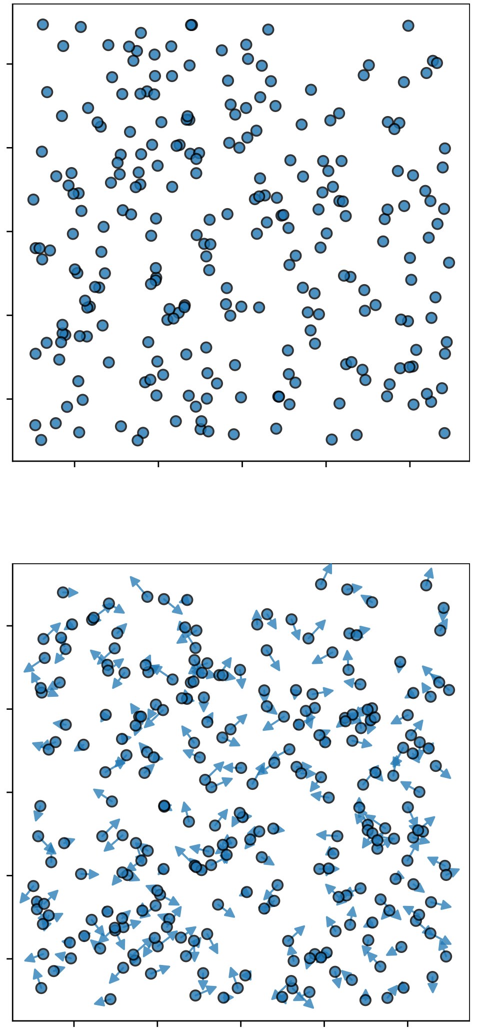
Temperature broadens electron spike at the back of the bubble

cold plasma

warm plasma





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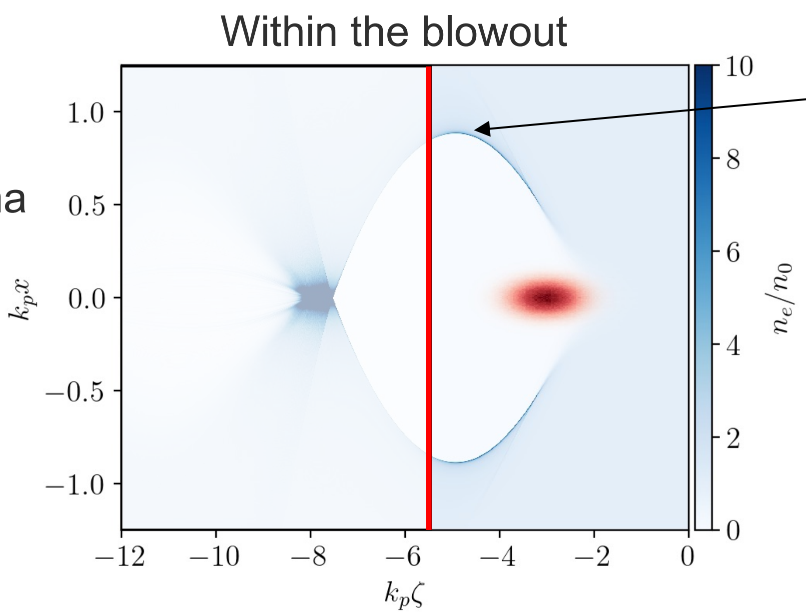
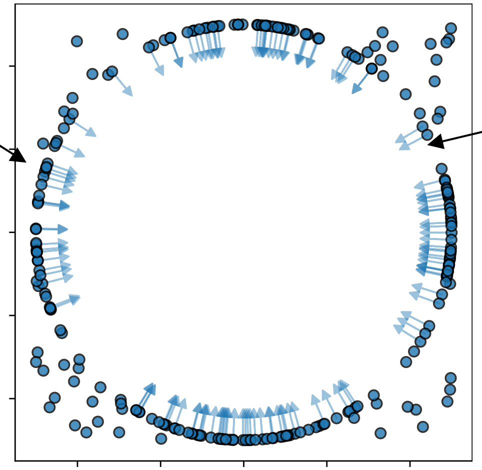
Temperature broadens electron spike at the back of the bubble

cold plasma





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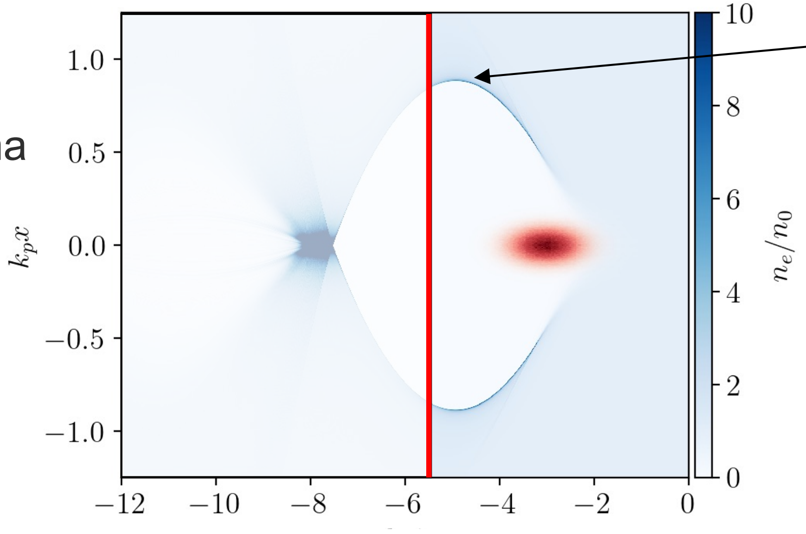
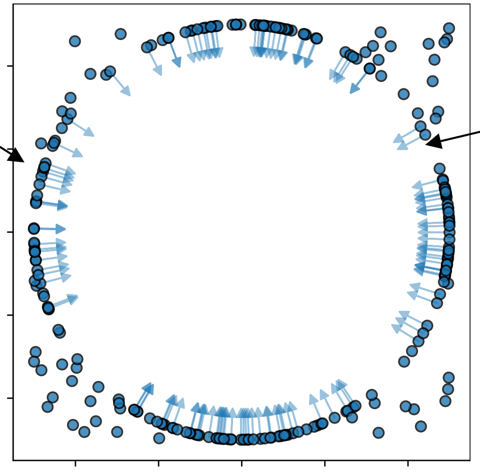
Temperature broadens electron spike at the back of the bubble

Within the blowout

cold plasma

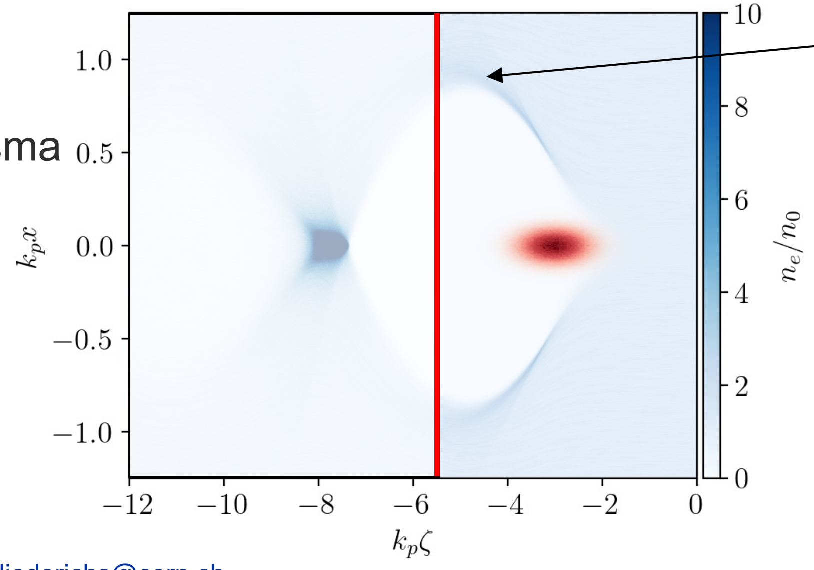


sharp sheath

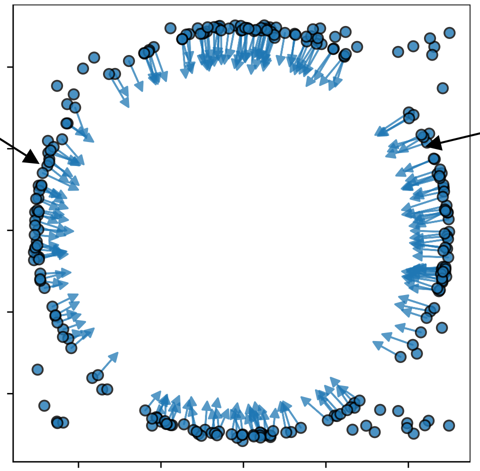


Momentum points exactly to the center

warm plasma



fuzzy sheath



Momentum points roughly to the center

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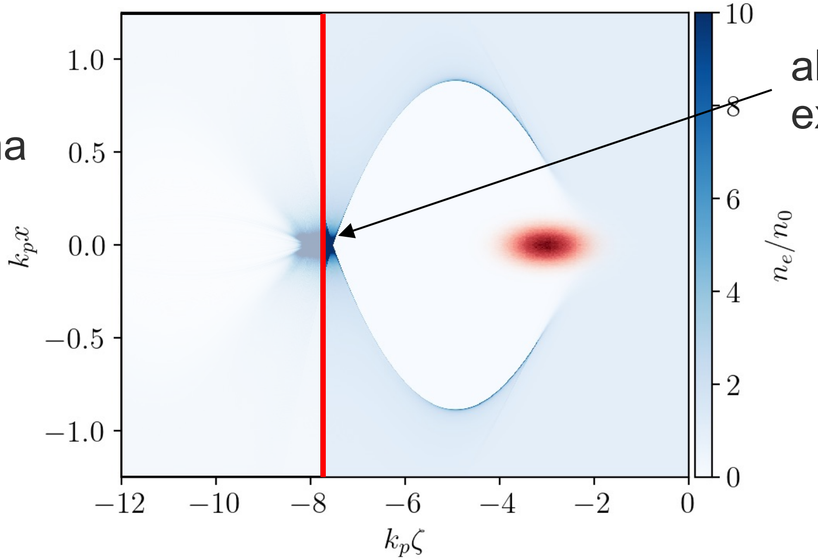
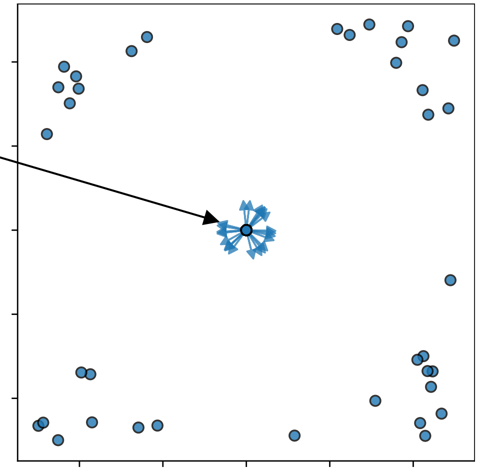
Temperature broadens electron spike at the back of the bubble

cold plasma

Within the cusp at the back of the blowout



all electrons return exactly to the center



Density catastrophe, fields converge extremely slowly!

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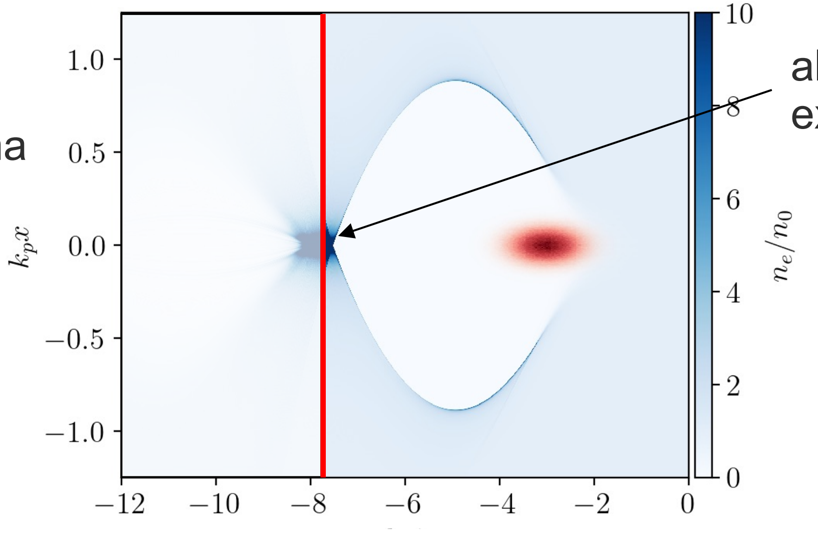
Temperature broadens electron spike at the back of the bubble

Within the cusp at the back of the blowout

cold plasma



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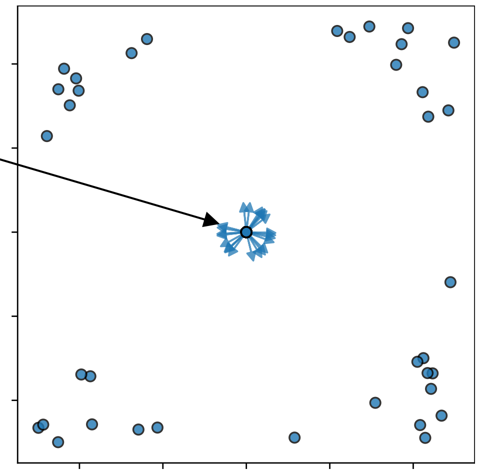

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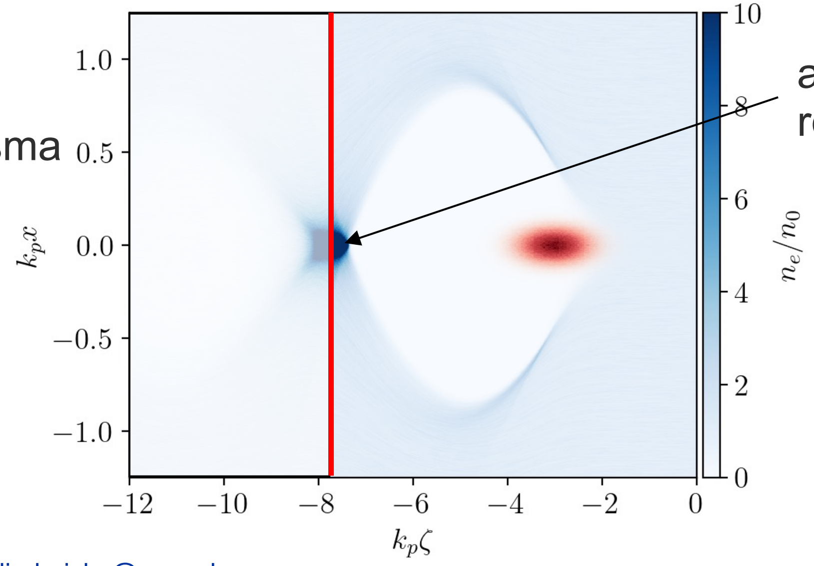

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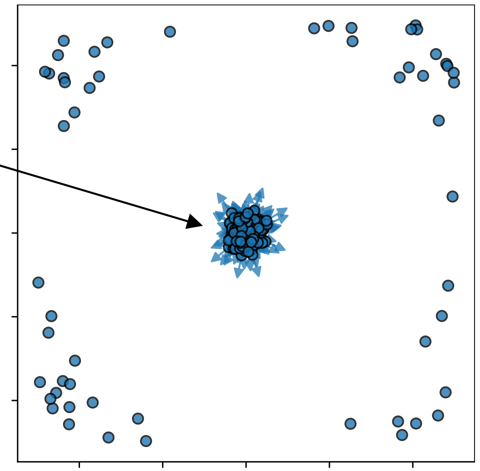

Peak density limited by temperature

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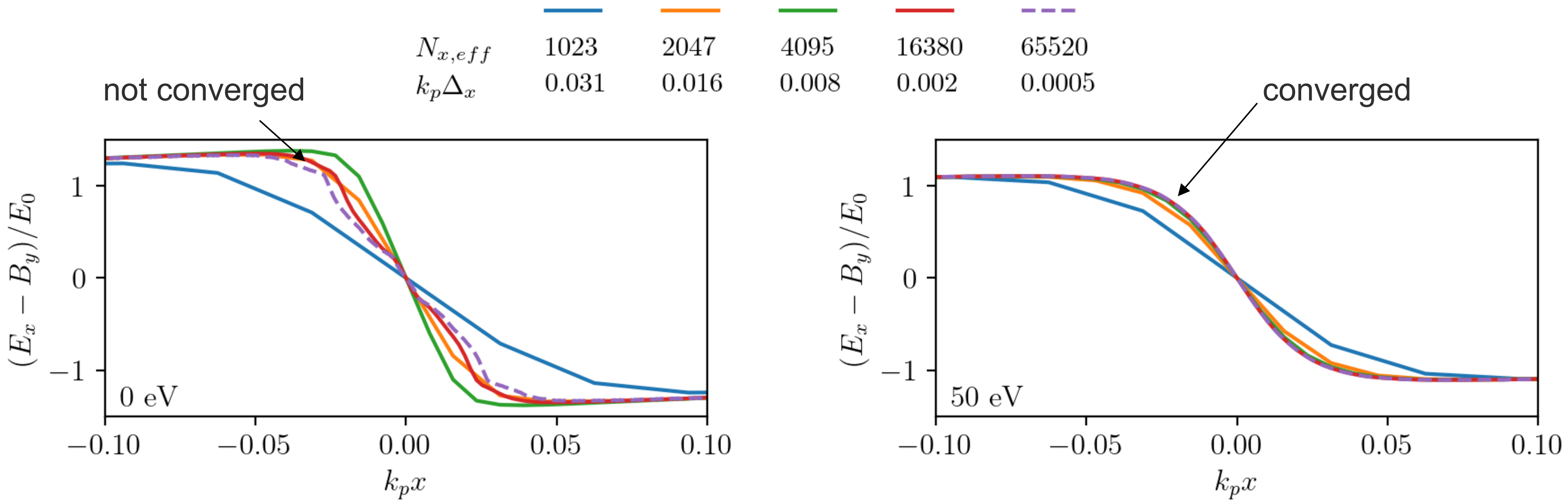
Temperature rapidly accelerates convergence



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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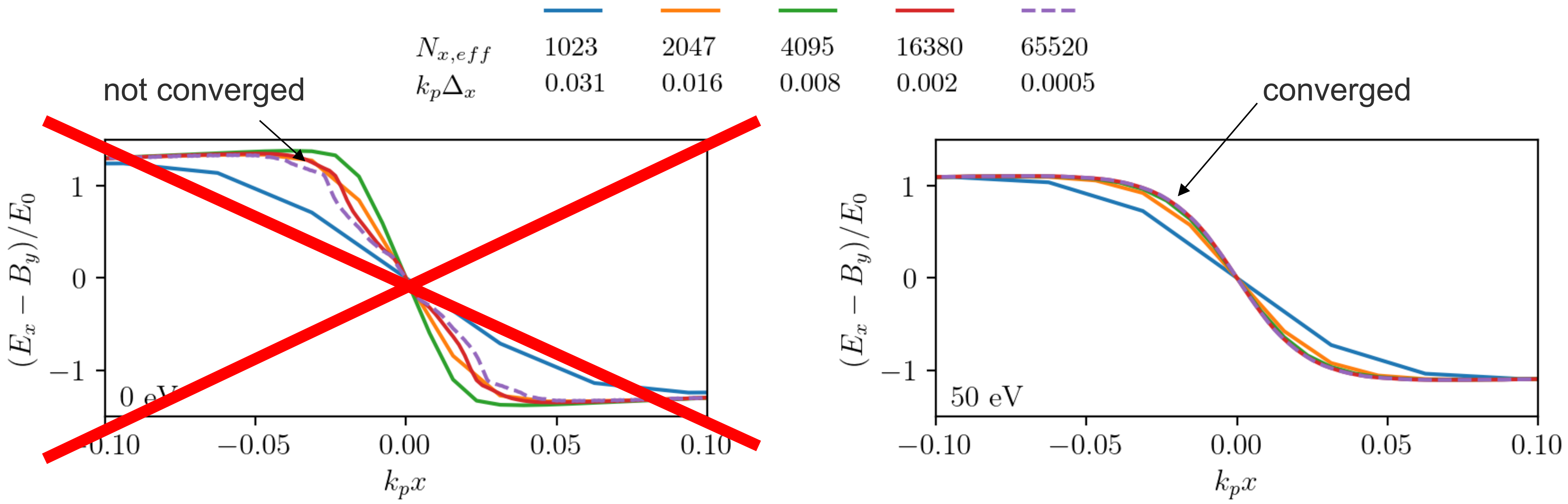
Temperature ~~rapidly accelerates~~ convergence is required for

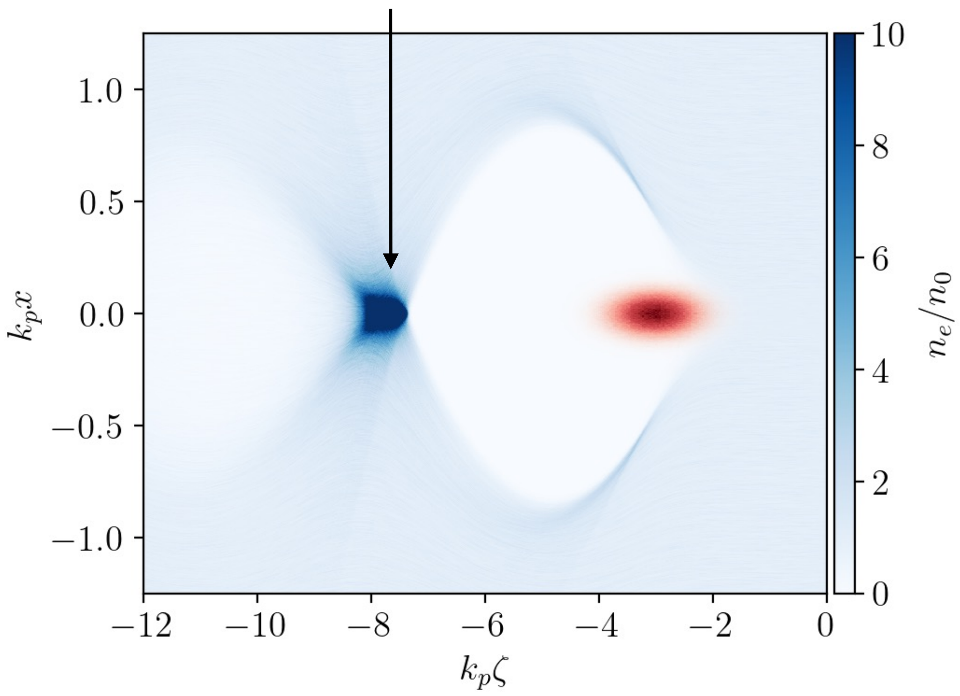


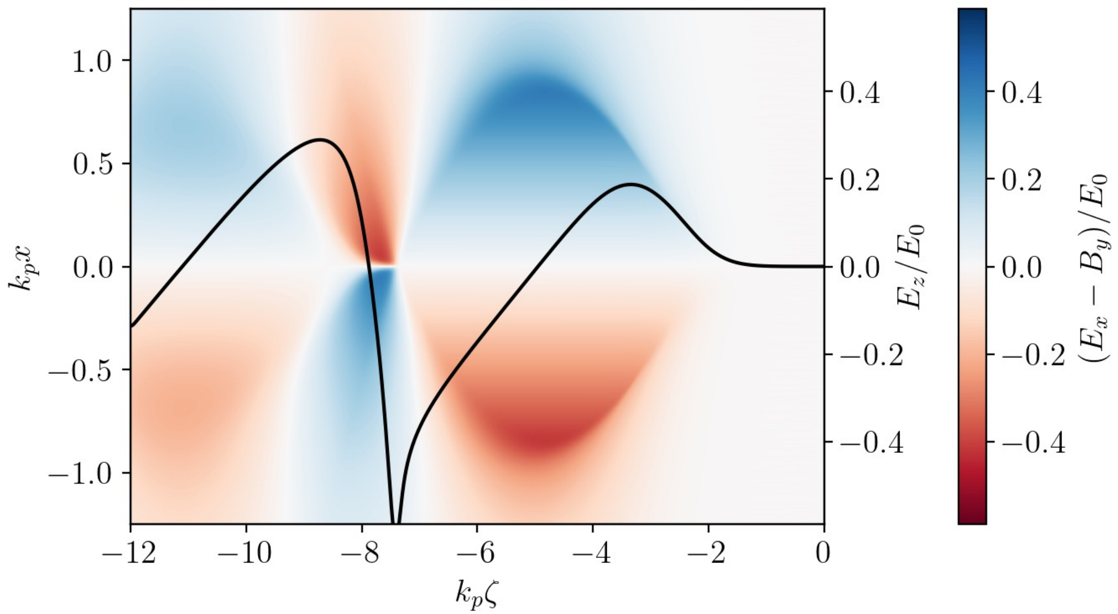
Fields in electron filaments of cold plasmas show numerical artifacts at high resolution.
Be very careful with cold plasmas for positron acceleration!

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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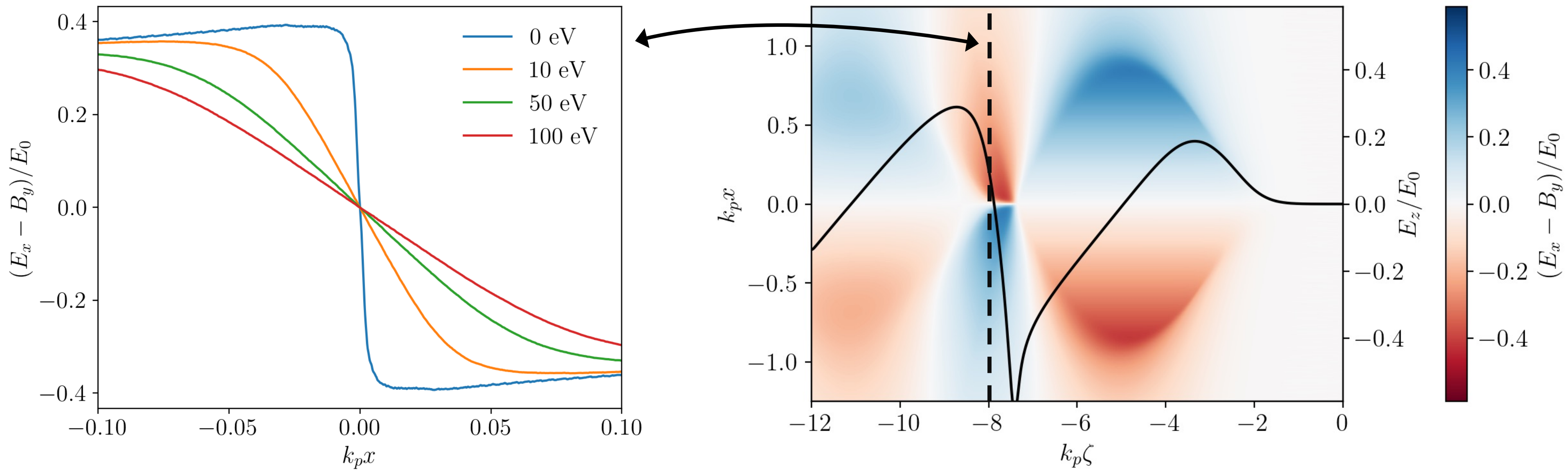

If we had a beam that fits into the linear region, we could preserve it’s emittance!

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

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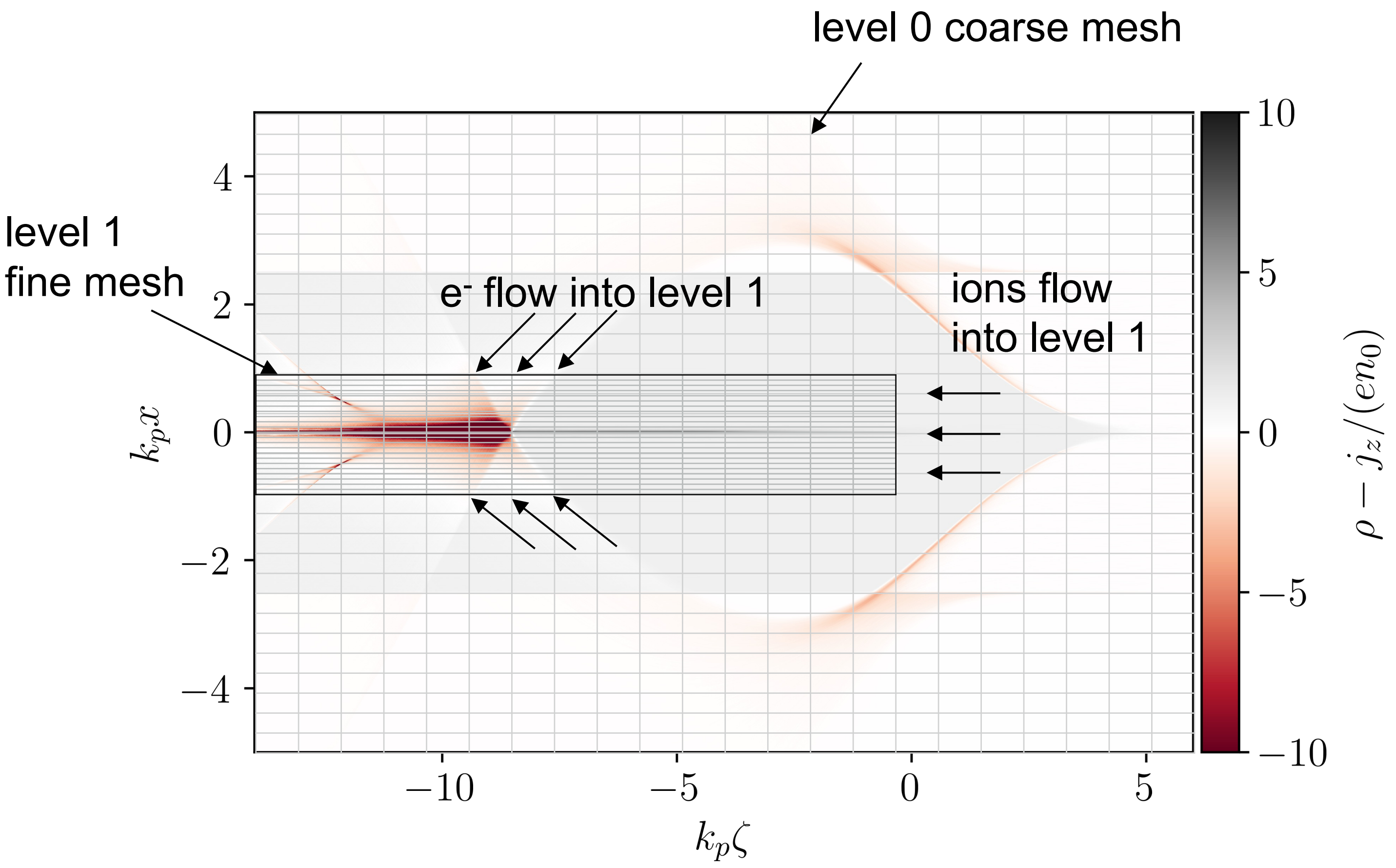
Mesh refinement in HiPACE++ allows for simulating collider-relevant plasma accelerators



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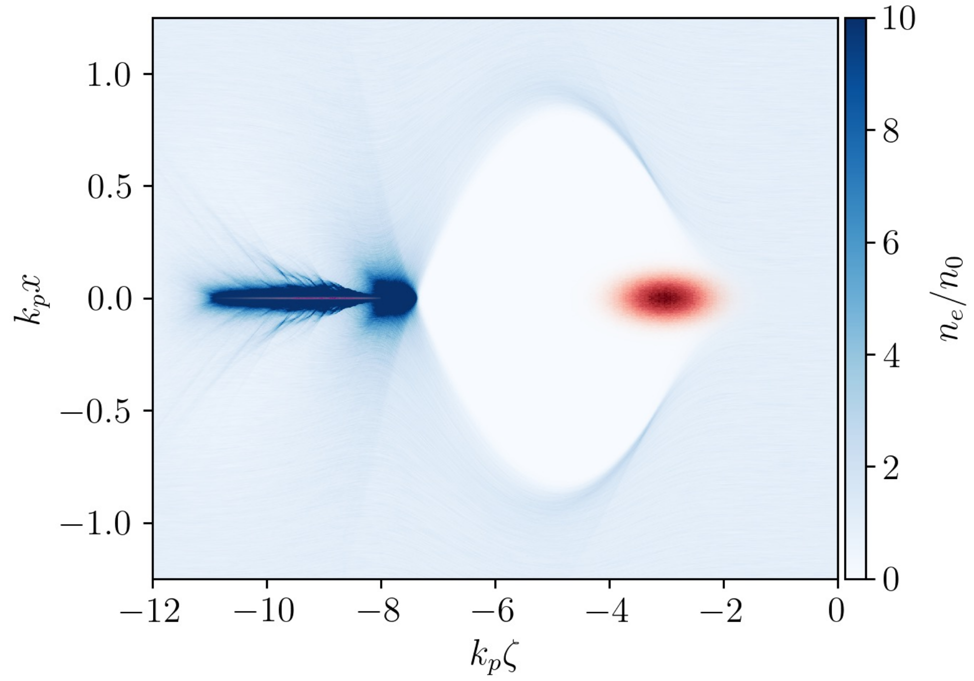

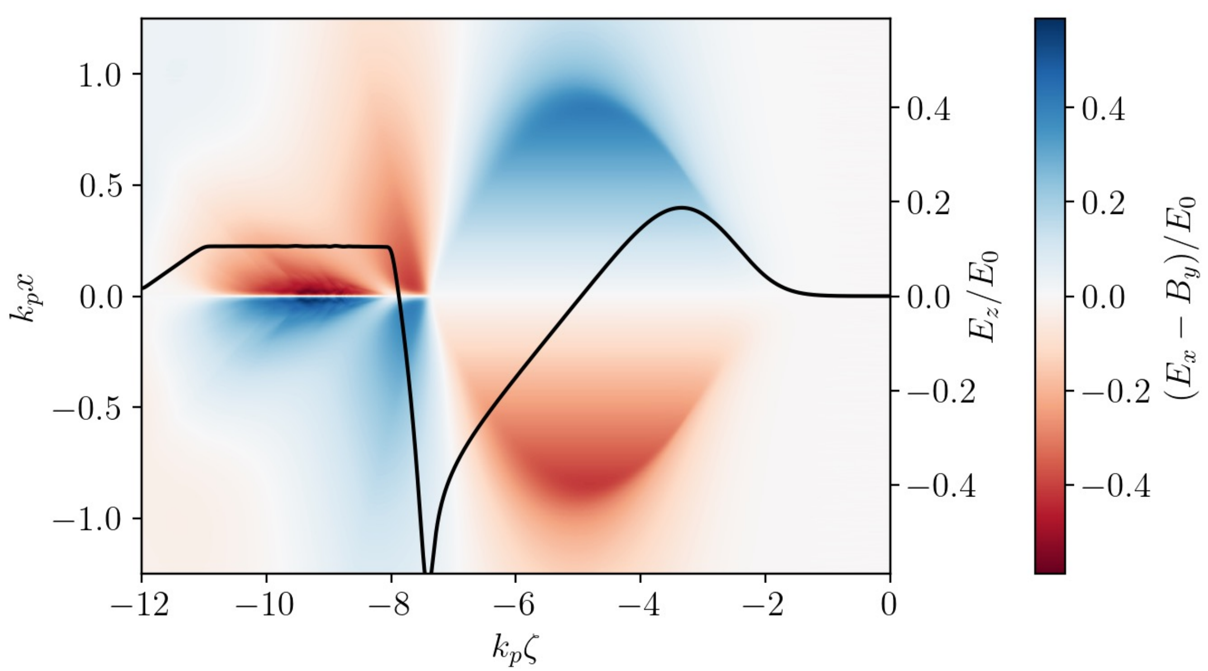

Same setup as Zhou et al. arXiv 2211.07962 (2022) except:

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

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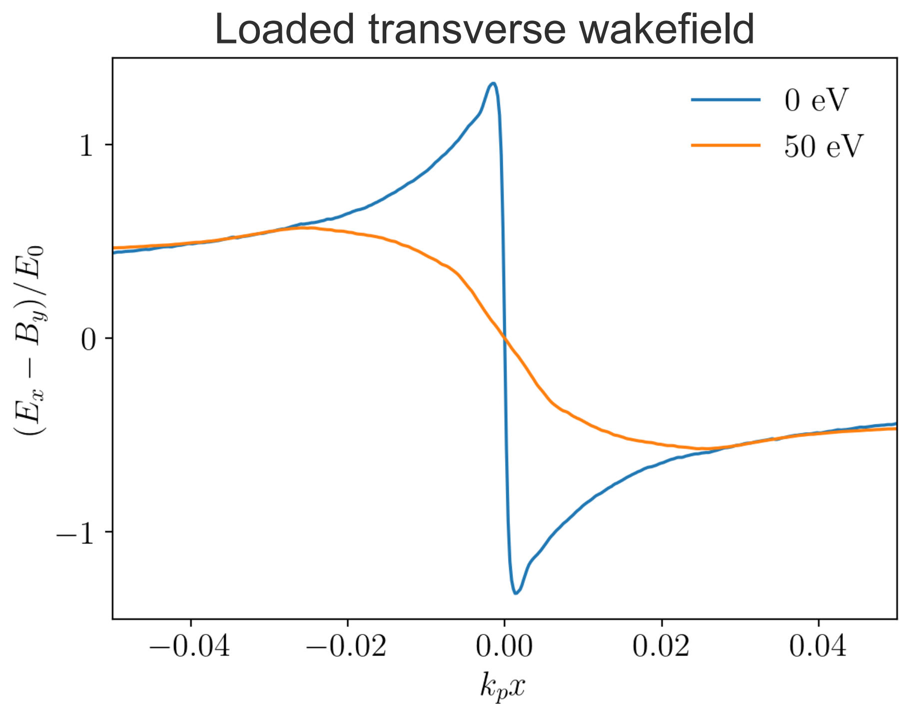
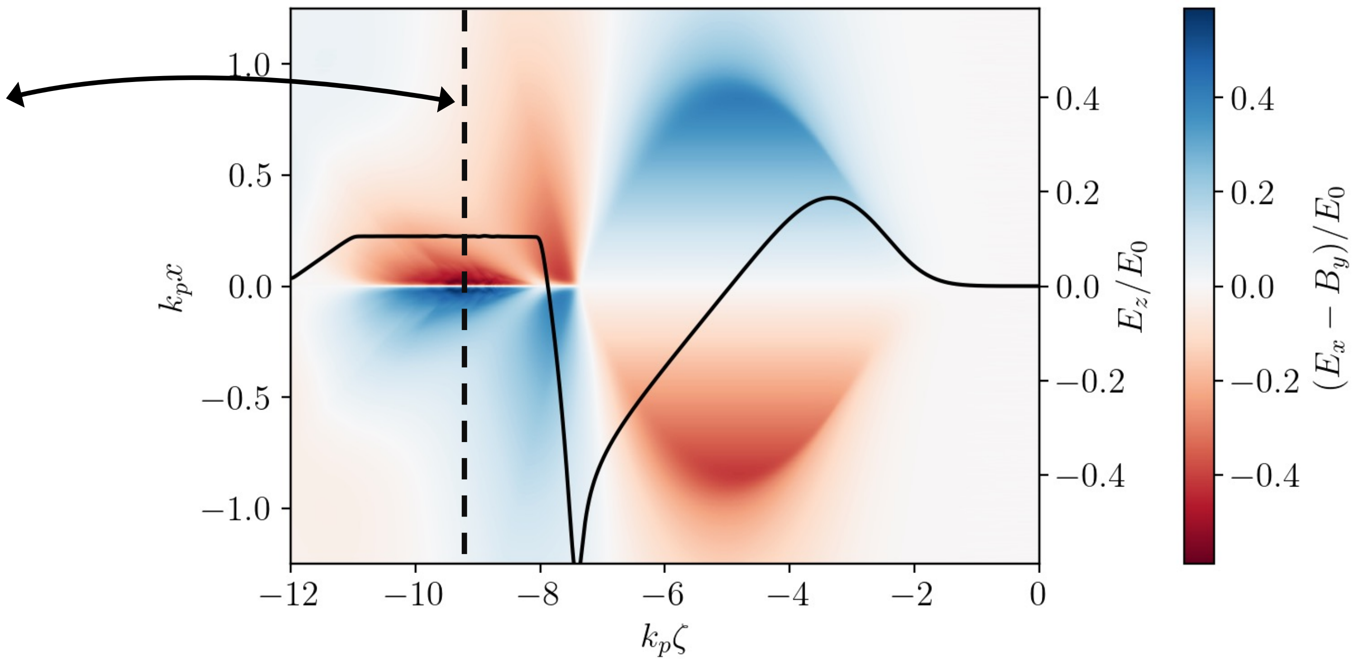
Mesh refinement in HiPACE++ allows for simulating collider-relevant plasma accelerators





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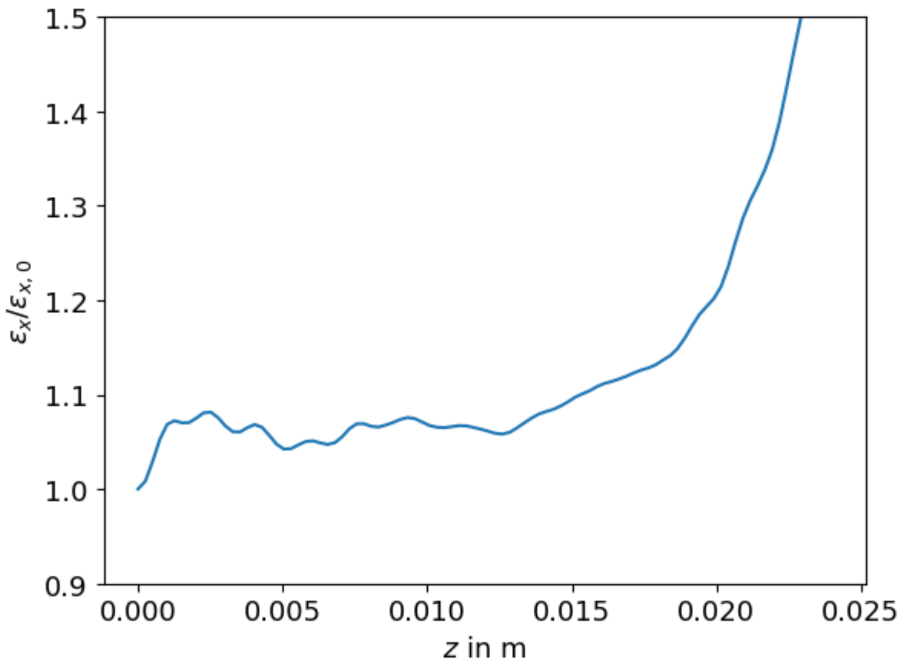
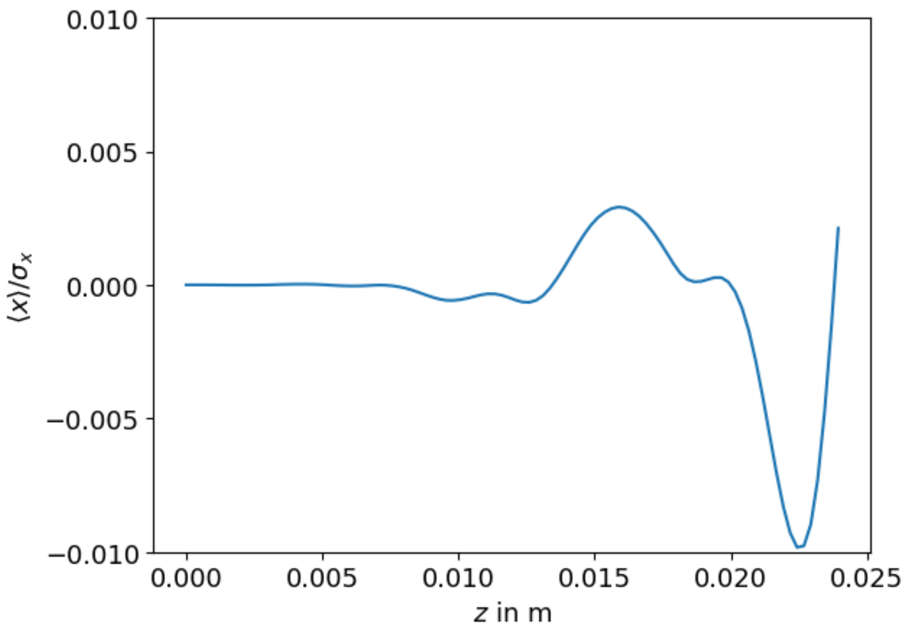
Stability seems to be an issue…

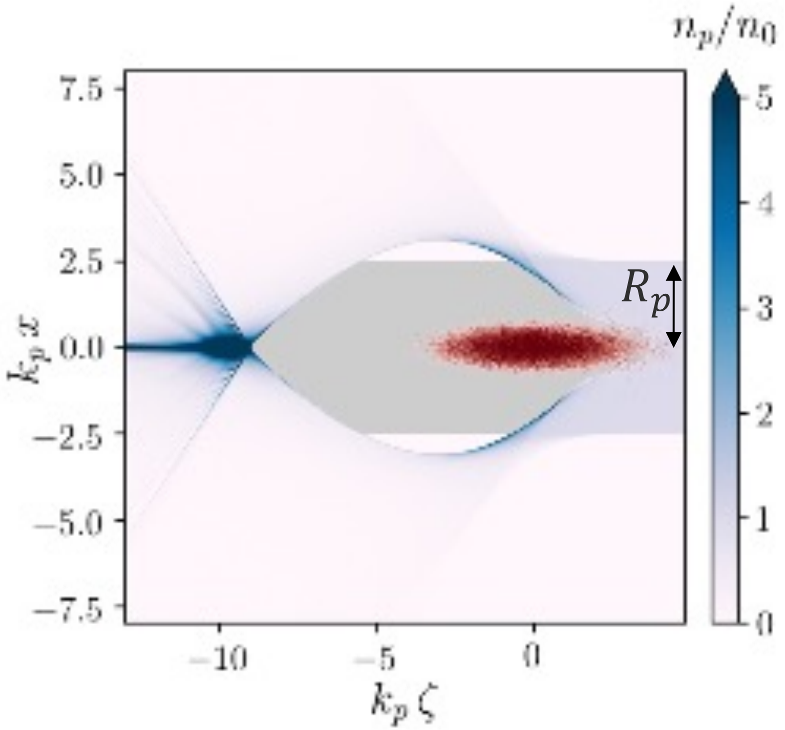




- Hosing rises from numerical noise
- Strong coupling between fields and witness beam due to absence of focusing field *without* beam

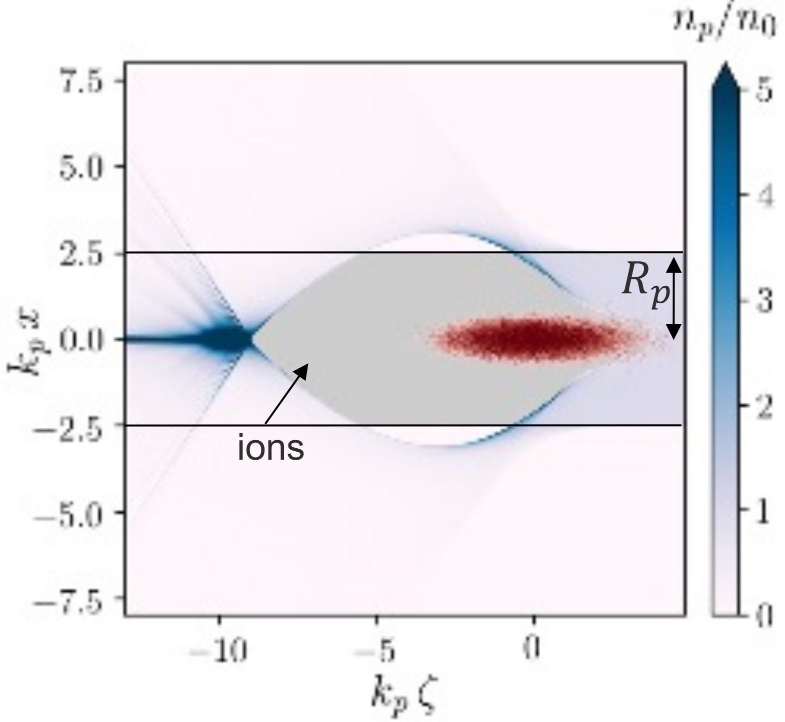
Scheme has very promising numbers, longitudinal and transverse stability need to be investigated.

Plasma columns enable positron focusing fields without beamloading



Plasma columns enable positron focusing fields without beamloading

1. No ions outside the column



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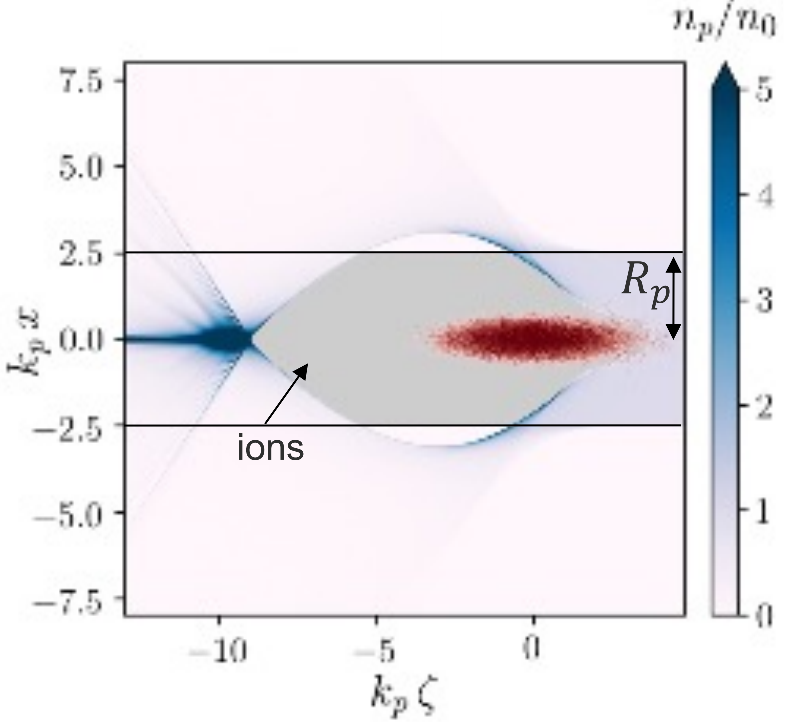
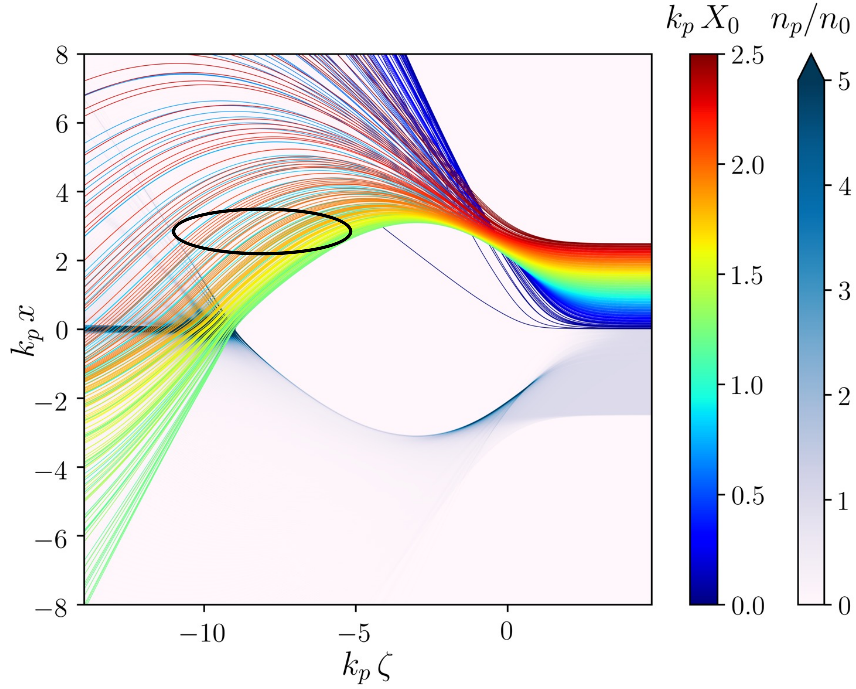


2. Elongated electron trajectories



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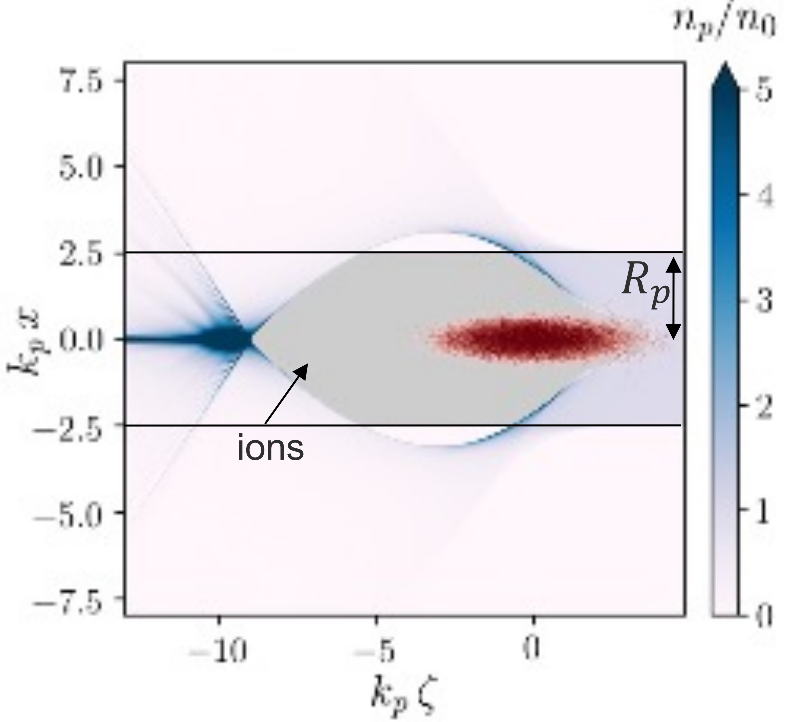

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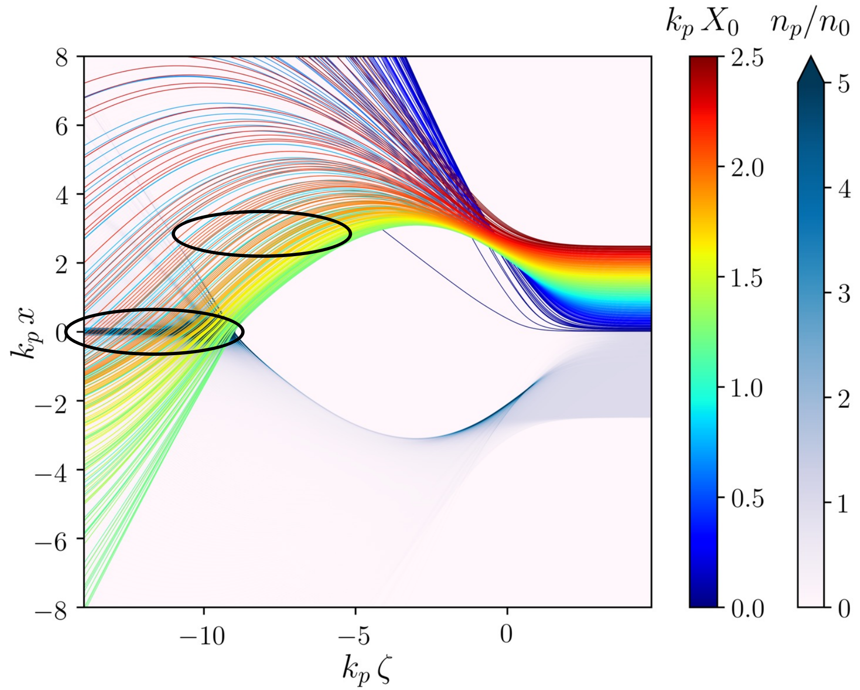

3. Long, high-density electron filament

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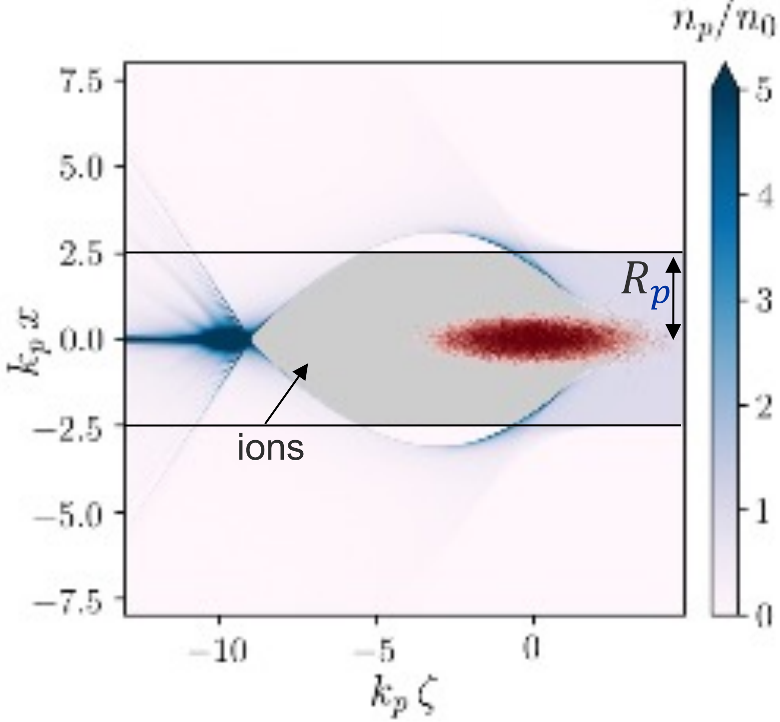
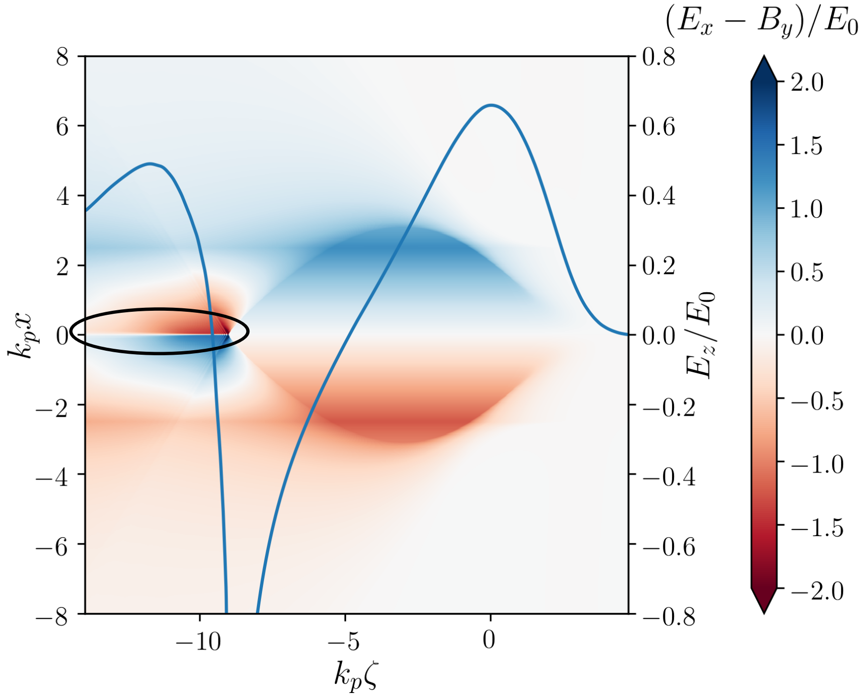
Plasma columns enable positron focusing fields without beamloading

1. No ions outside the column





4. Accelerating and focusing fields for

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

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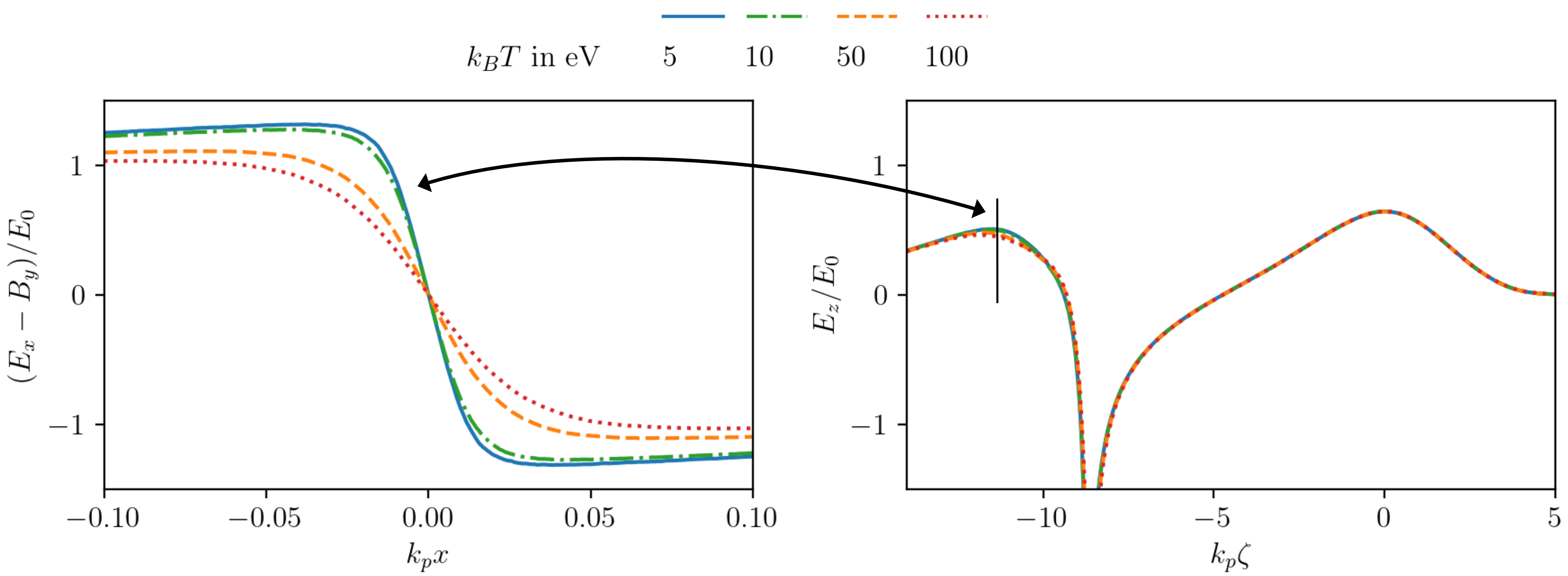
Temperature linearizes focusing field

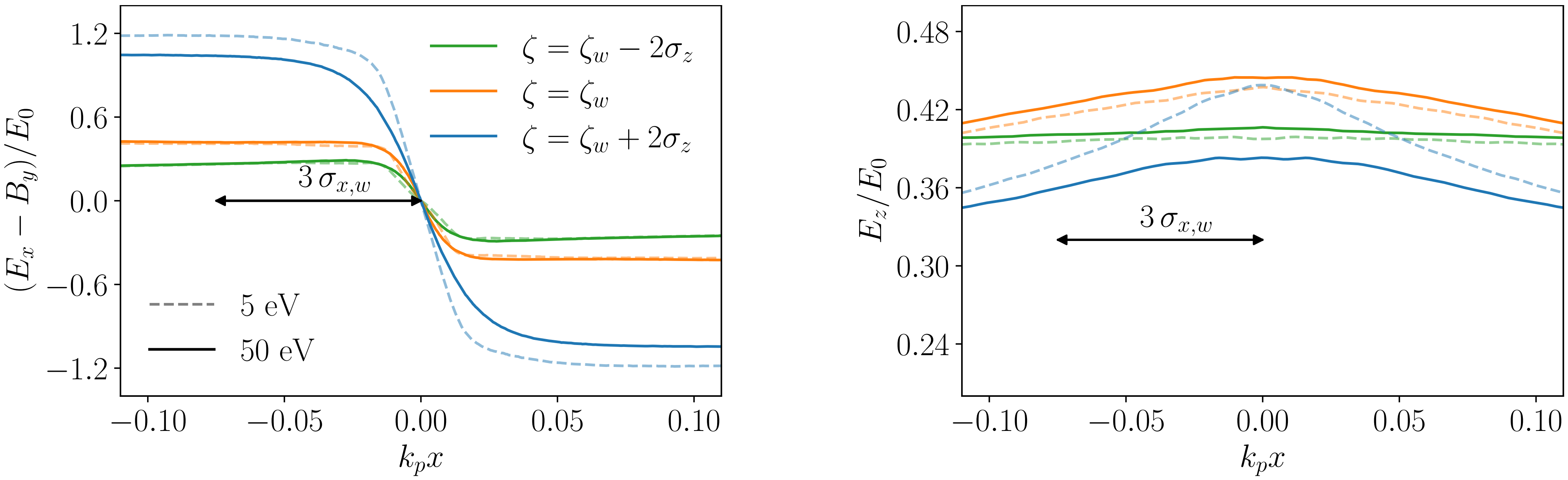
Unloaded wakefield in a plasma column



Diederichs et al. PoP 30, 073104 (2023)

Temperature linearizes focusing field and flattens accelerating field

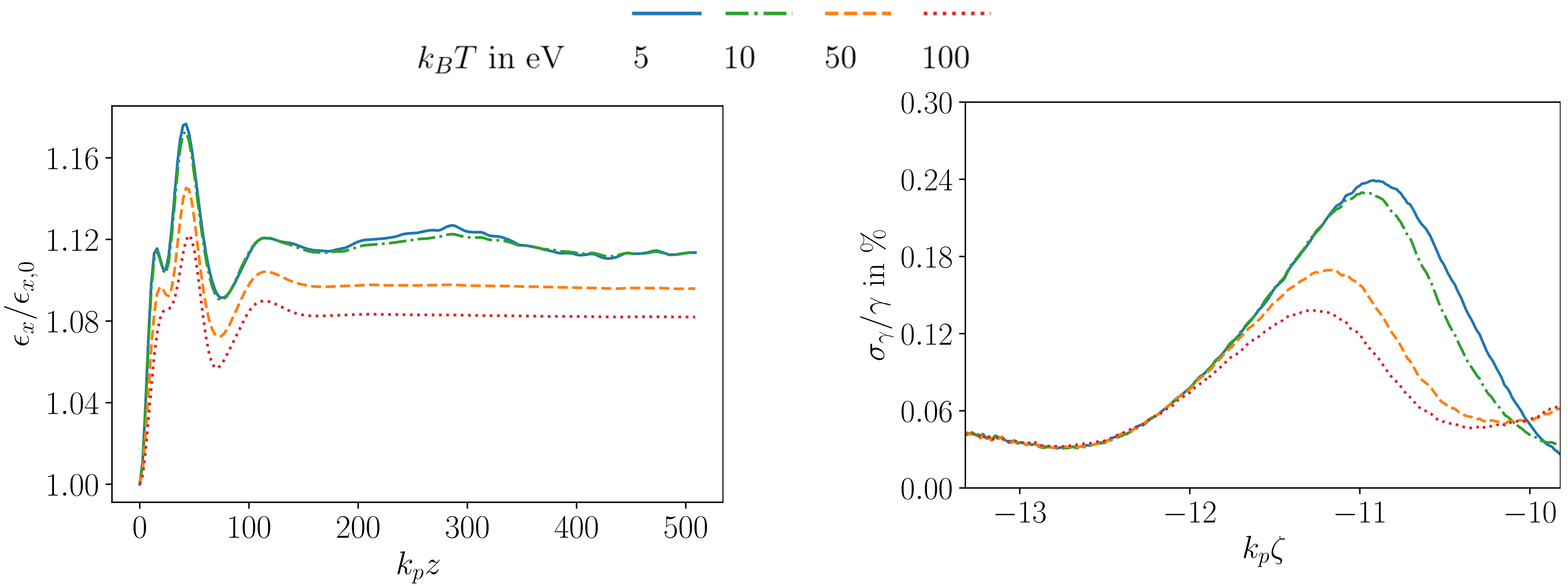
Wakefields loaded with same Gaussian bunch as before



Diederichs et al. PoP 30, 073104 (2023)

severin.diederichs@cern.ch

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)

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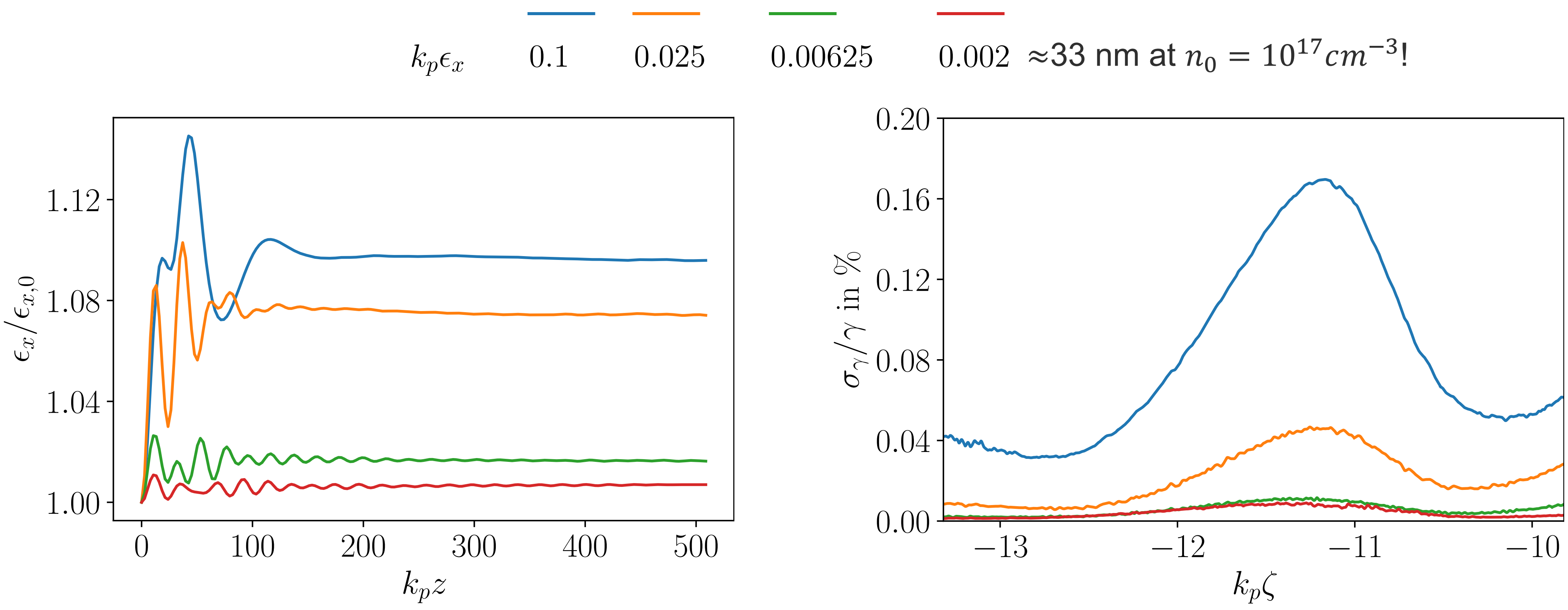
10s of nanometer emittance preserved to 1 %

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



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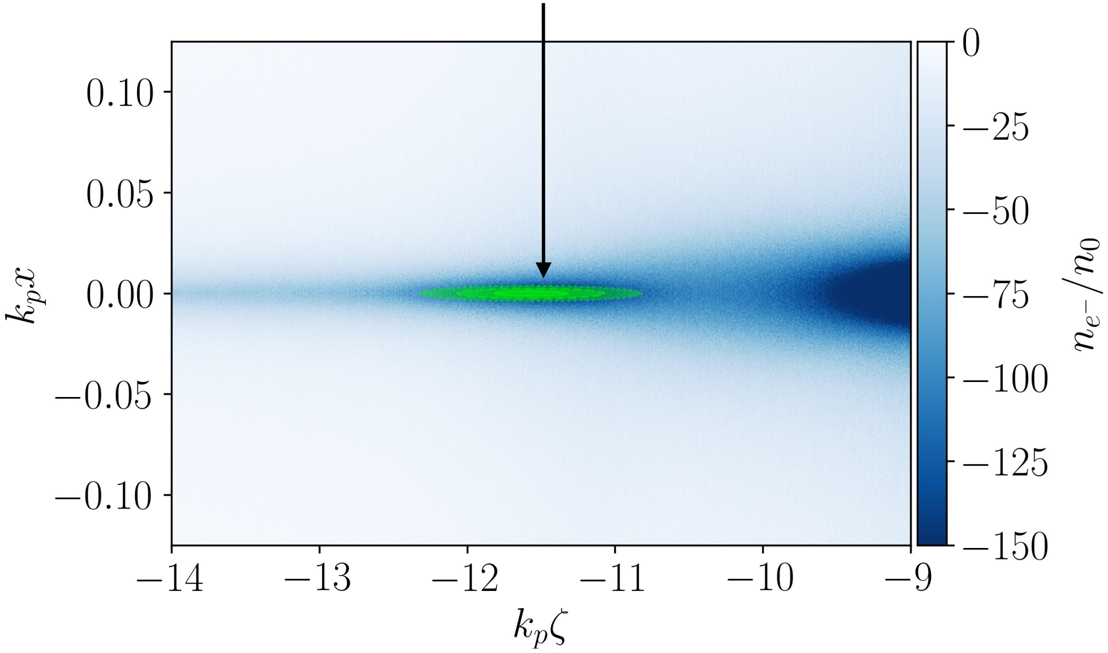
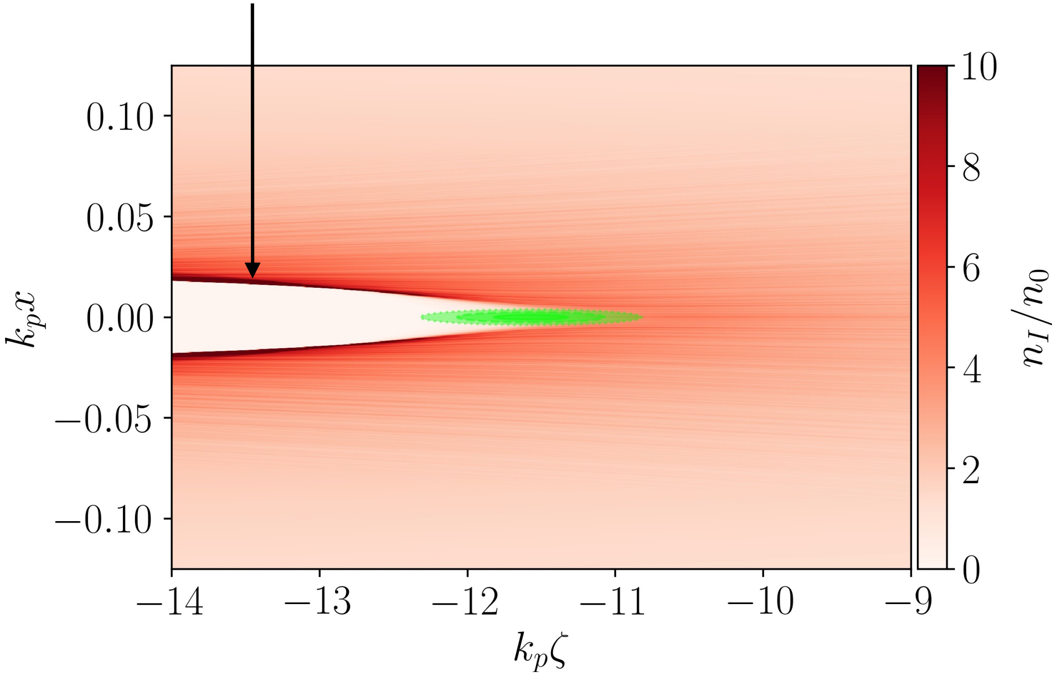
10s of nanometer emittance beams induce ion blowout

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

intense positron beam:



ion blowout!



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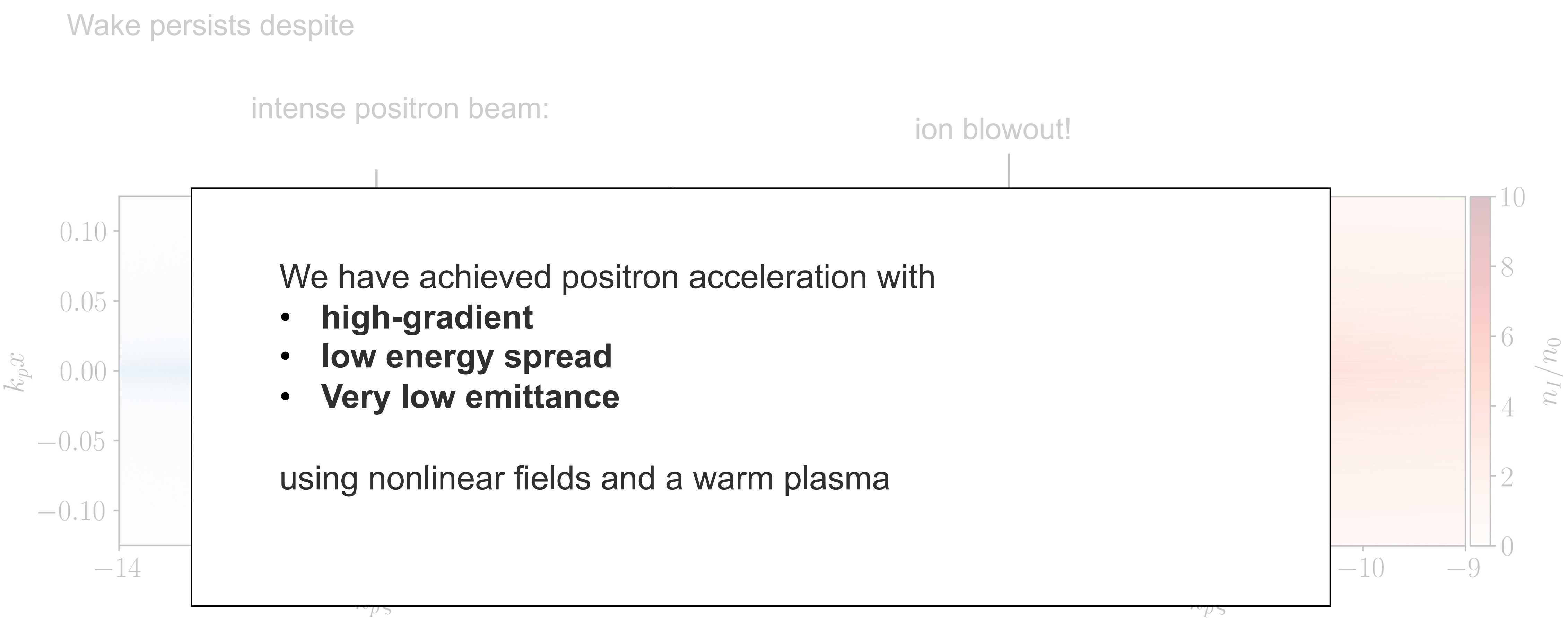
10s of nanometer emittance beams induce ion blowout



We have achieved positron acceleration with

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

using nonlinear fields and a warm plasma

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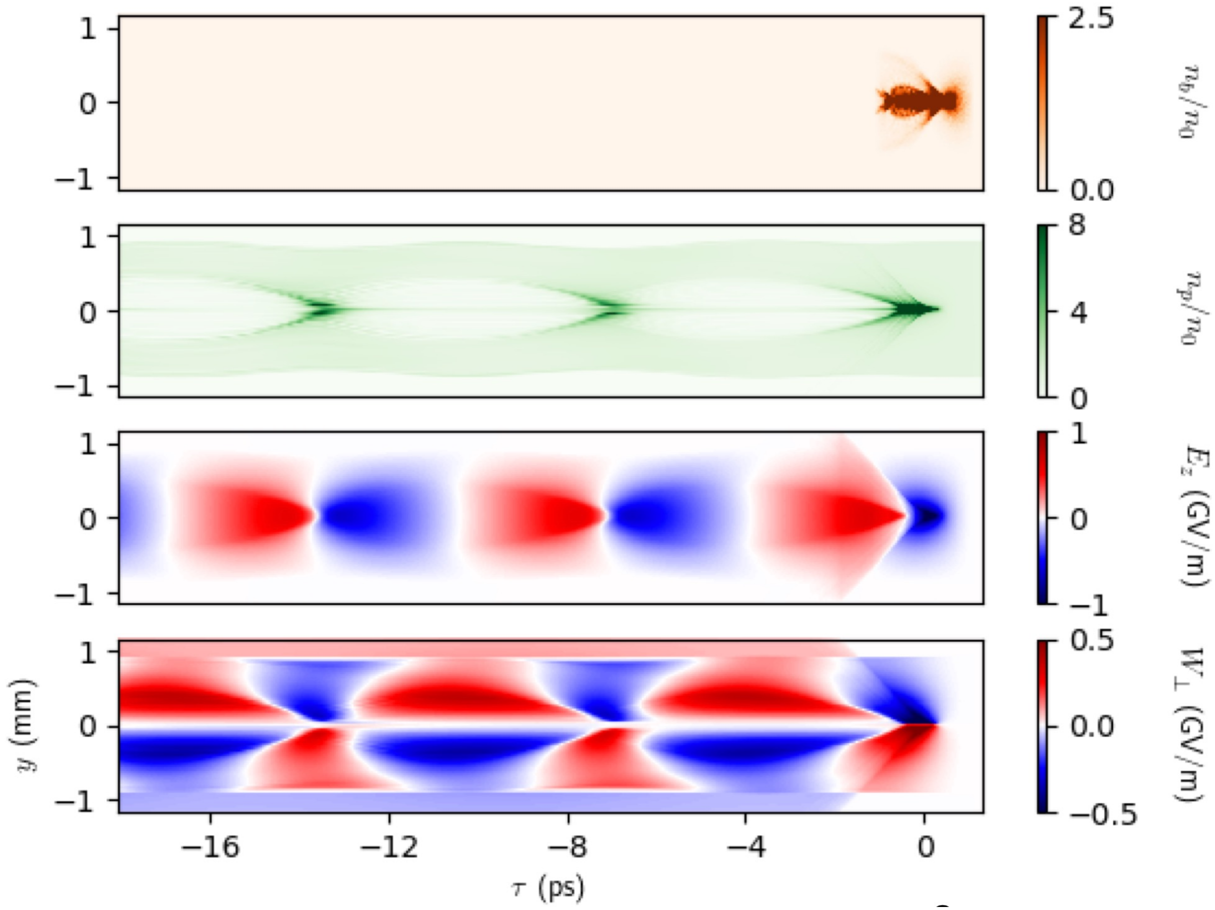
Roadmap to PEEP positron acceleration?

- Proton-driven inverse blowout has a wider electron trajectory spread;
  Let the drive beam pinch!

- Hope for a 2nd positron miracle:
  Try an even lower emittance witness beam to blow away the ions, use a warm plasma

- Be careful with instabilities, focusing fields are required before beamloading



Warning:
dephasing much worse for positrons…

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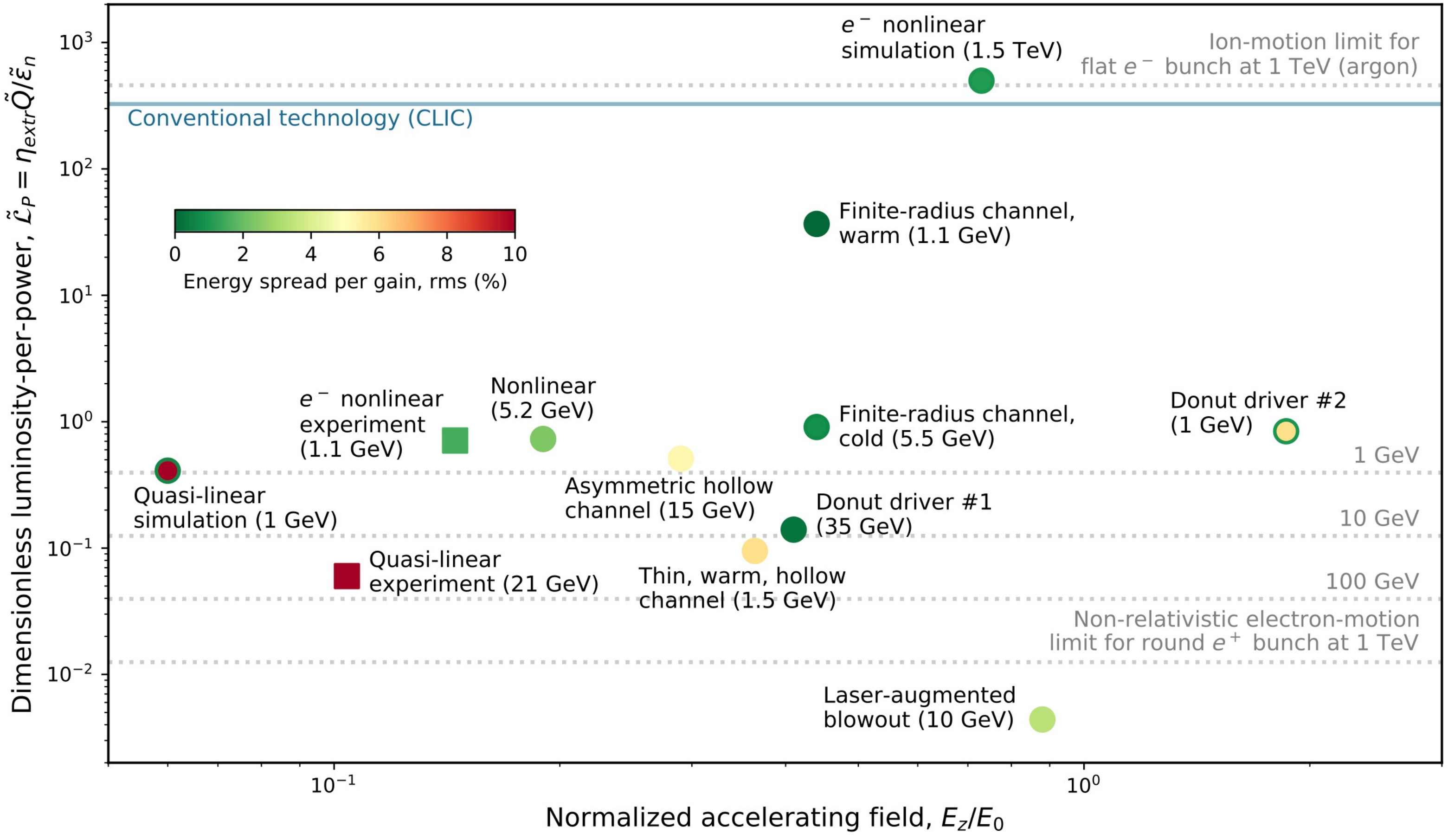
Supplemental material

Luminosity-per-power comparison of schemes



Cao et al, PRAB 27, 034801 (2024)

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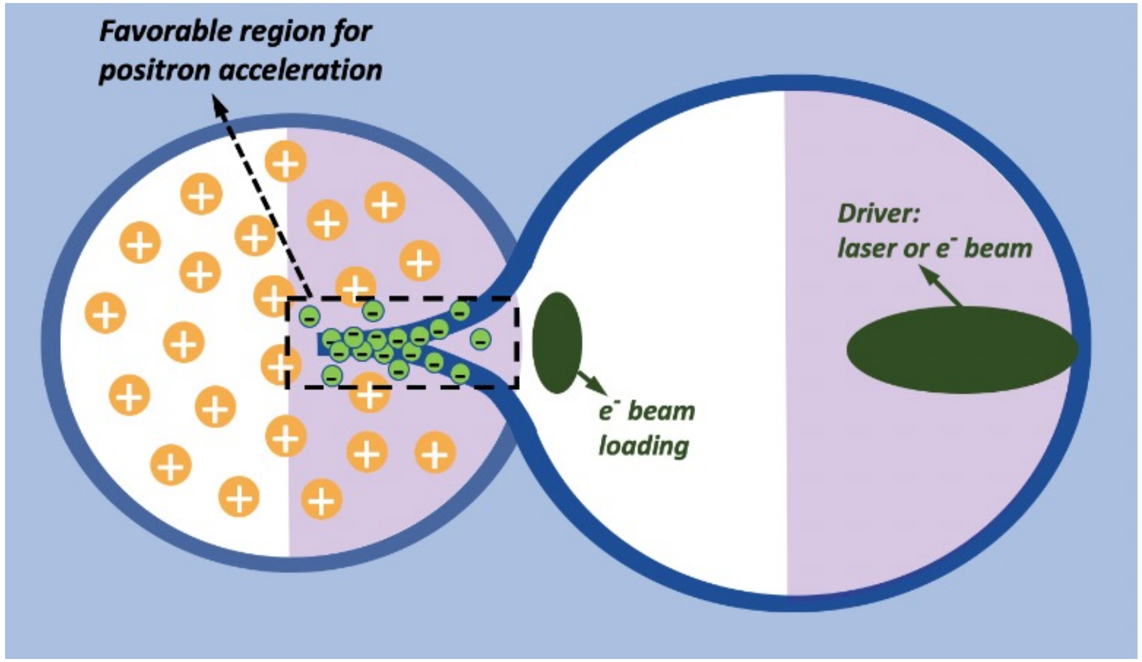
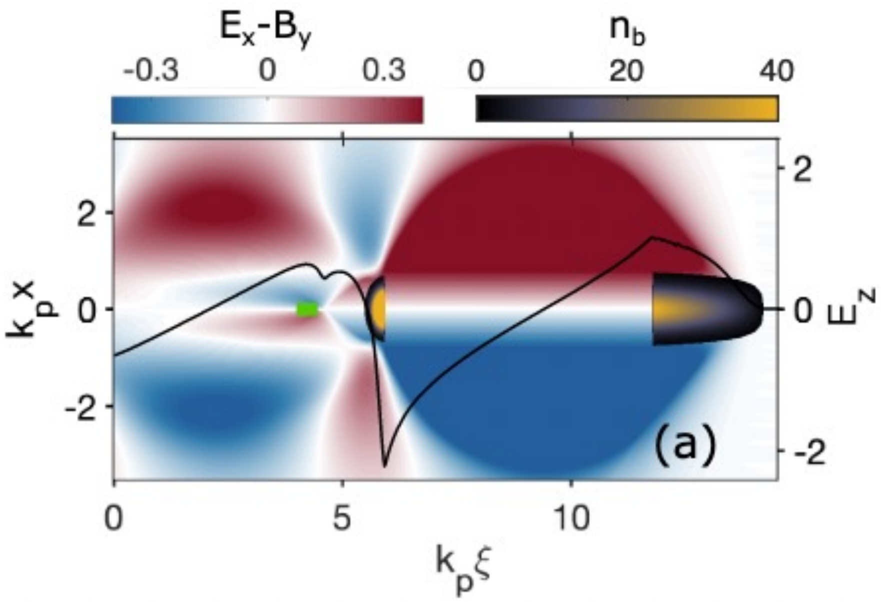
Electron witness bunch elongates plasma electron spike

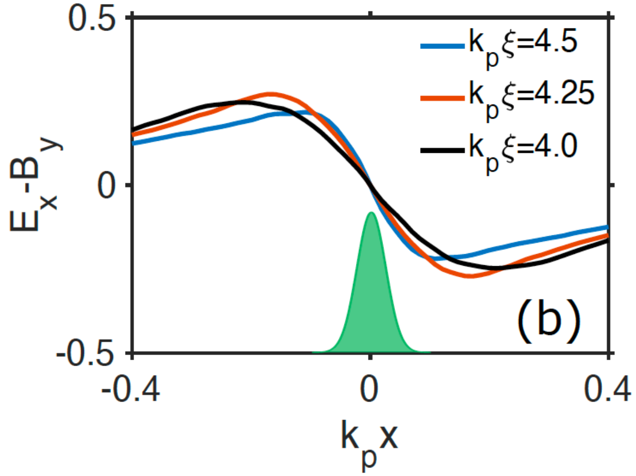


Warm plasma (72 eV) spreads the electron filament

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)

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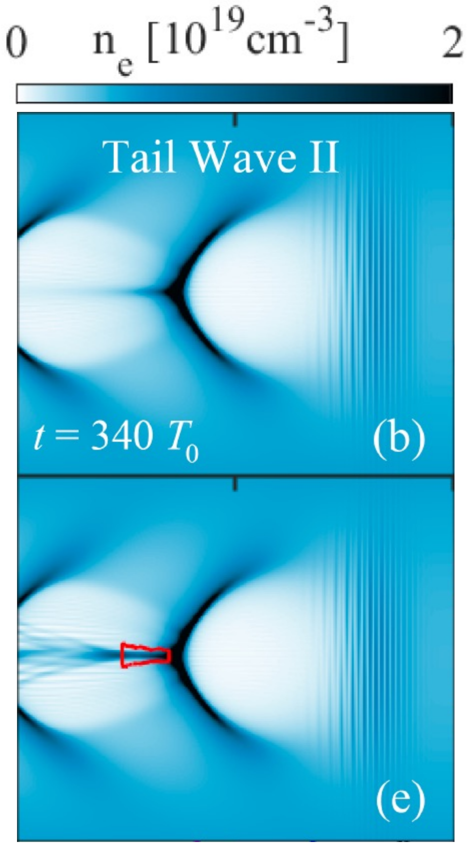
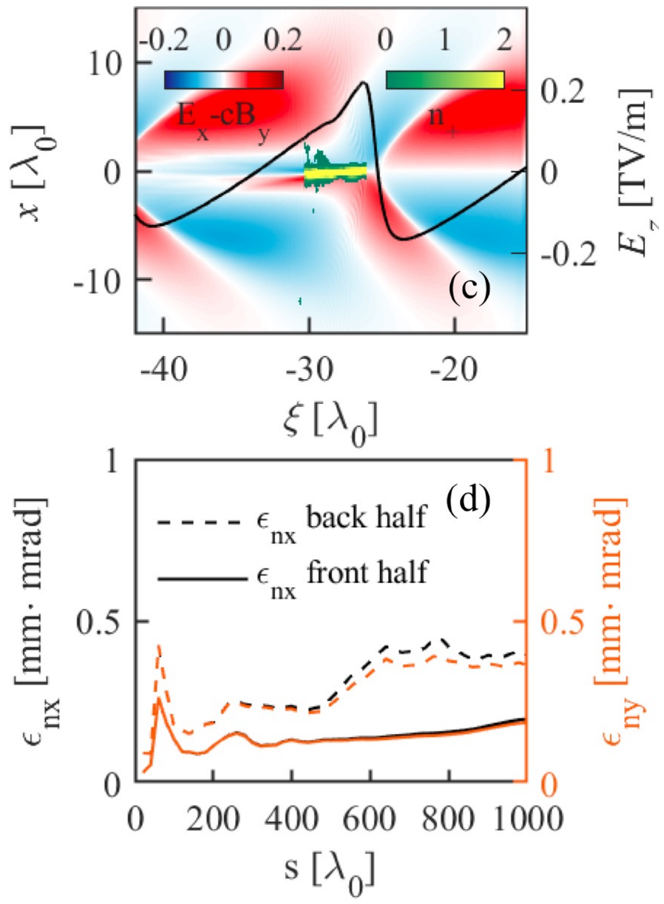
Similar setting with laser driver demonstrated





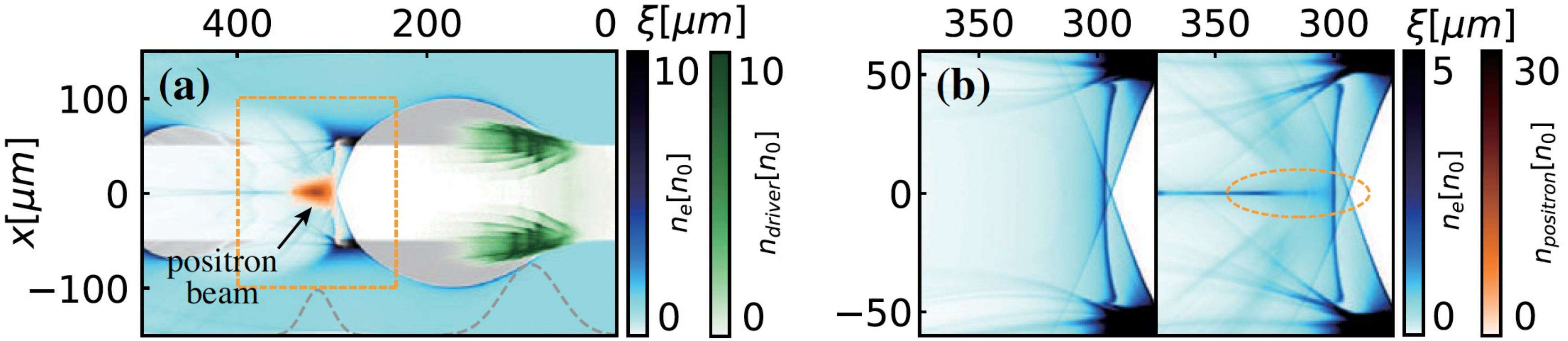
- Very simple setup
- High gradients: 100 GV/m fields
- A lot of potential for optimization

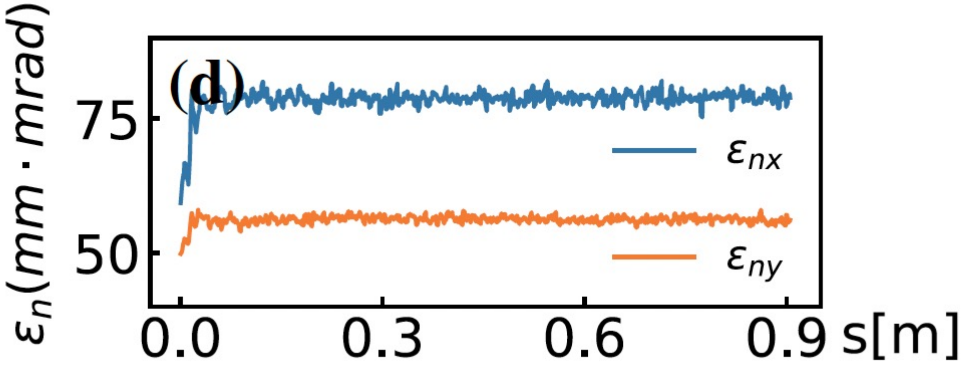
Liu et al. (arXiv 2207.14749 2022)

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





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

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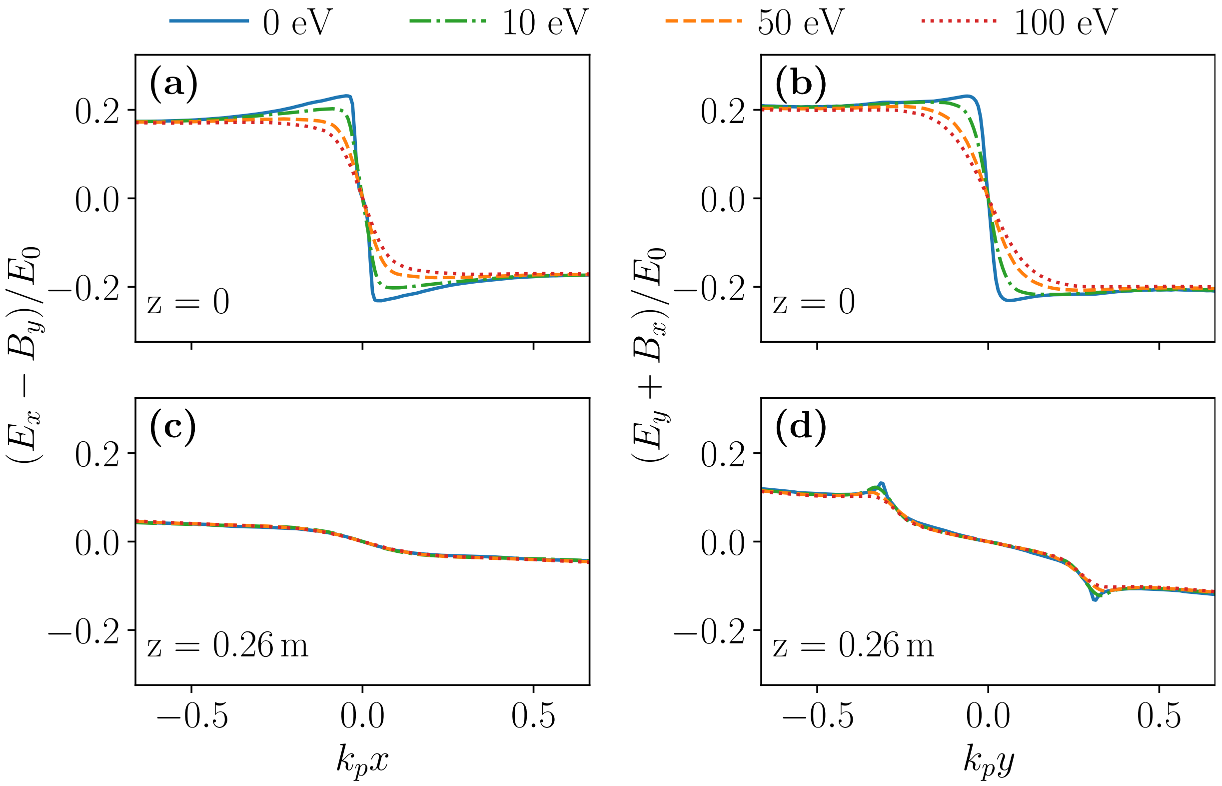
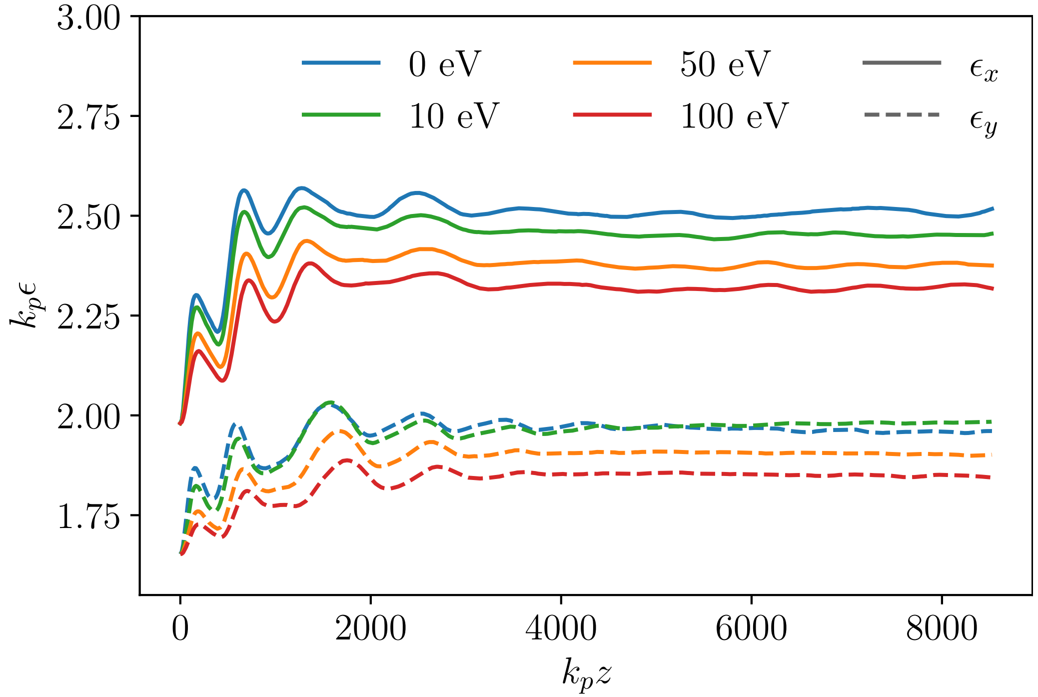
Temperature smoothes the fields again, reduces emittance growth



Temperature mitigates emittance growth



Diederichs et al. PoP 30, 073104 (2023)

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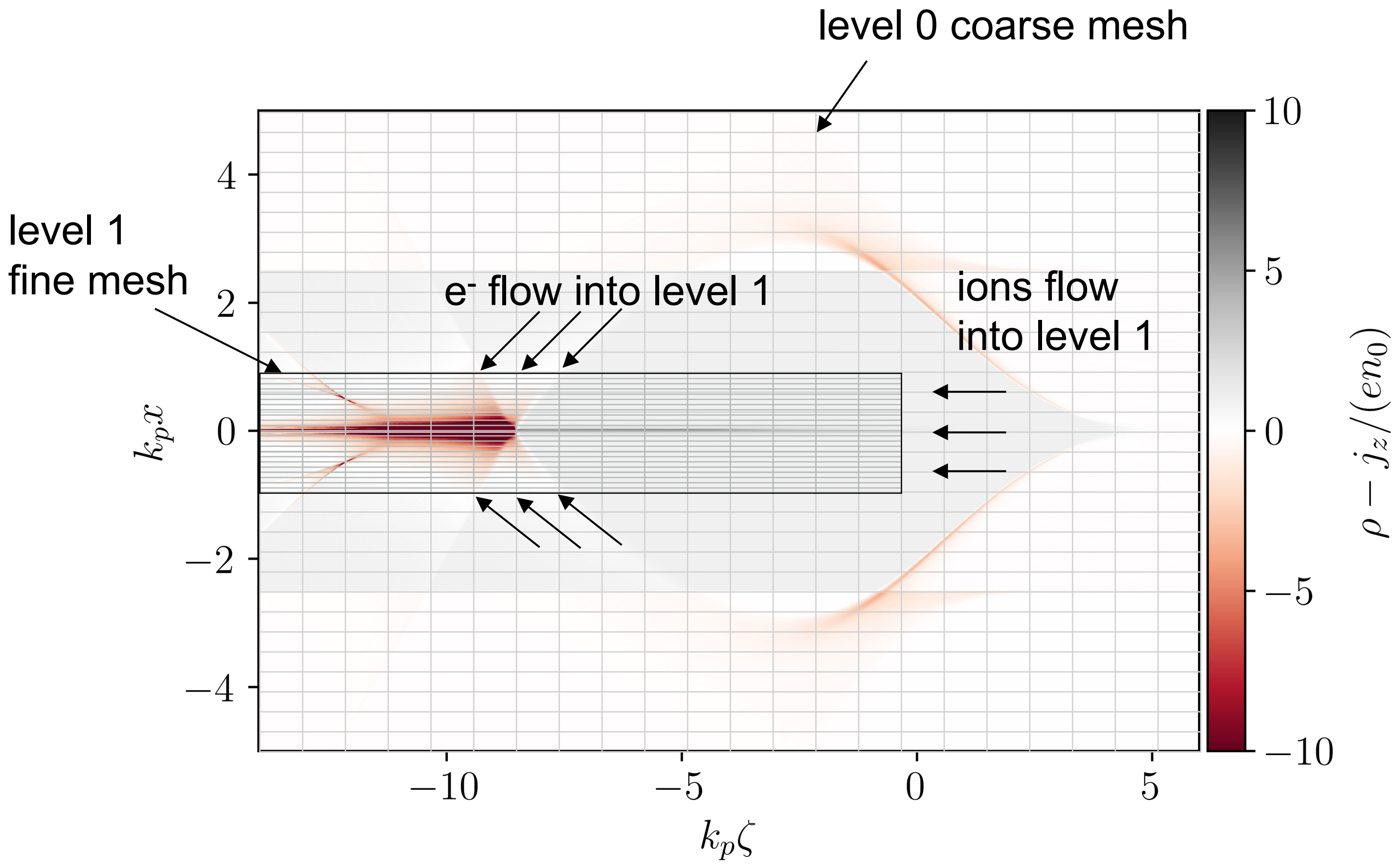
Mesh refinement in HiPACE++ allows for simulating collider-relevant plasma accelerators



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

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