Positron acceleration: a systematic overview

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“Key challenges to reach the high energy frontier include ***a scheme*** *for positron bunch acceleration in plasma, that still needs to be demonstrated on paper.”*

CERN-2022-001

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

European Strategy Update

LDG Laboratory Directors Group

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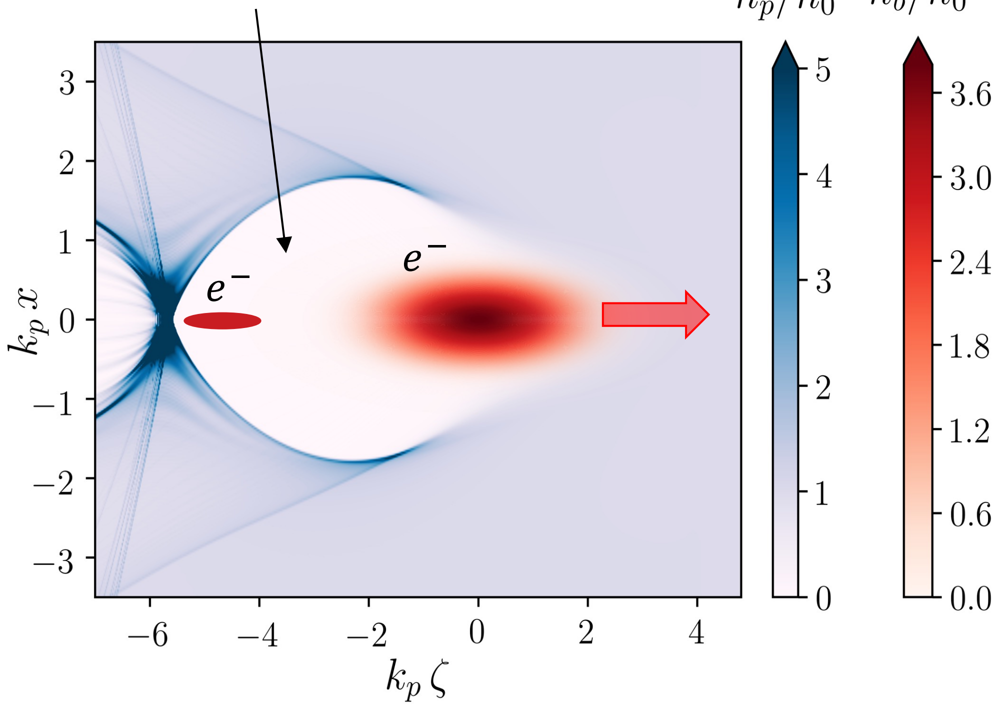
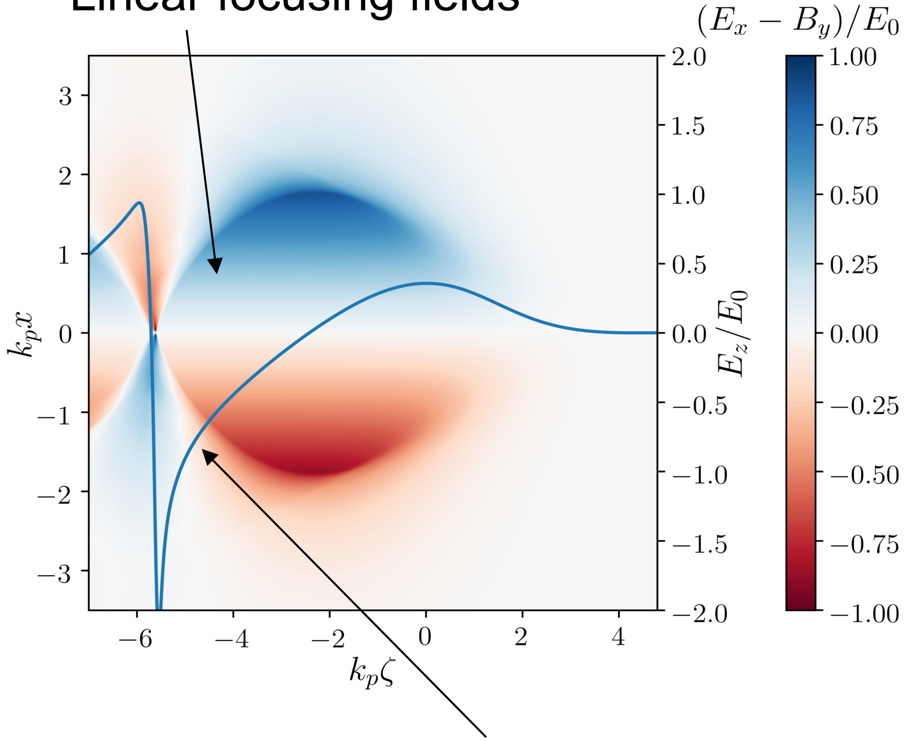
Plasma wakefield accelerators enable high-quality, high-gradient *electron* acceleration


Ion background

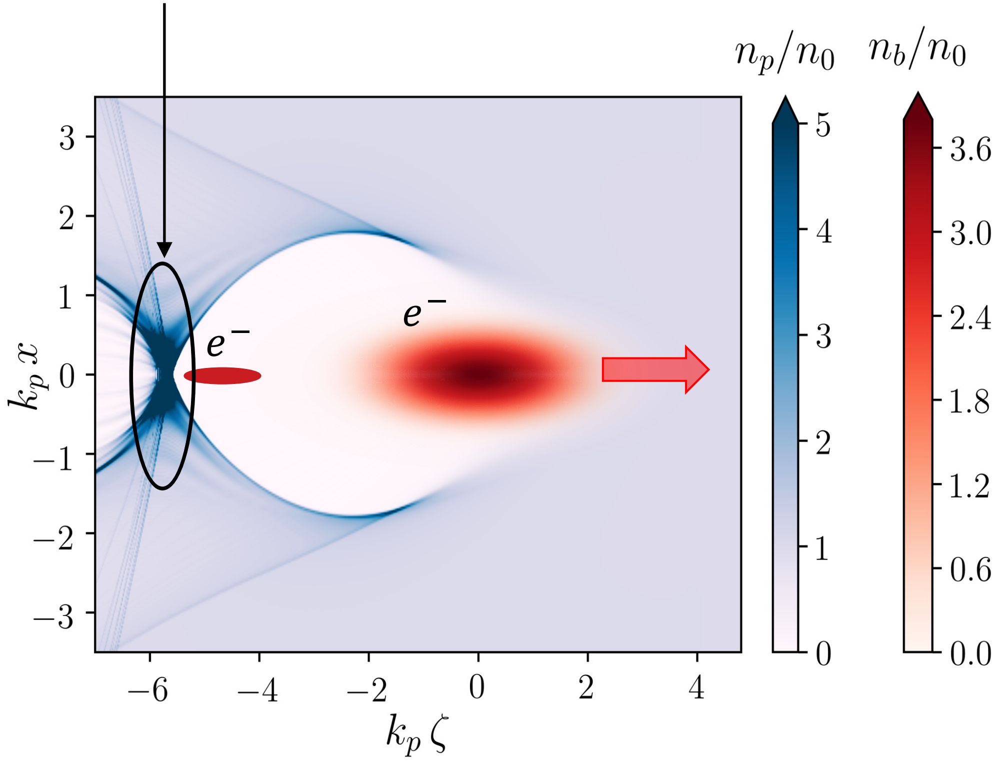

Linear focusing fields

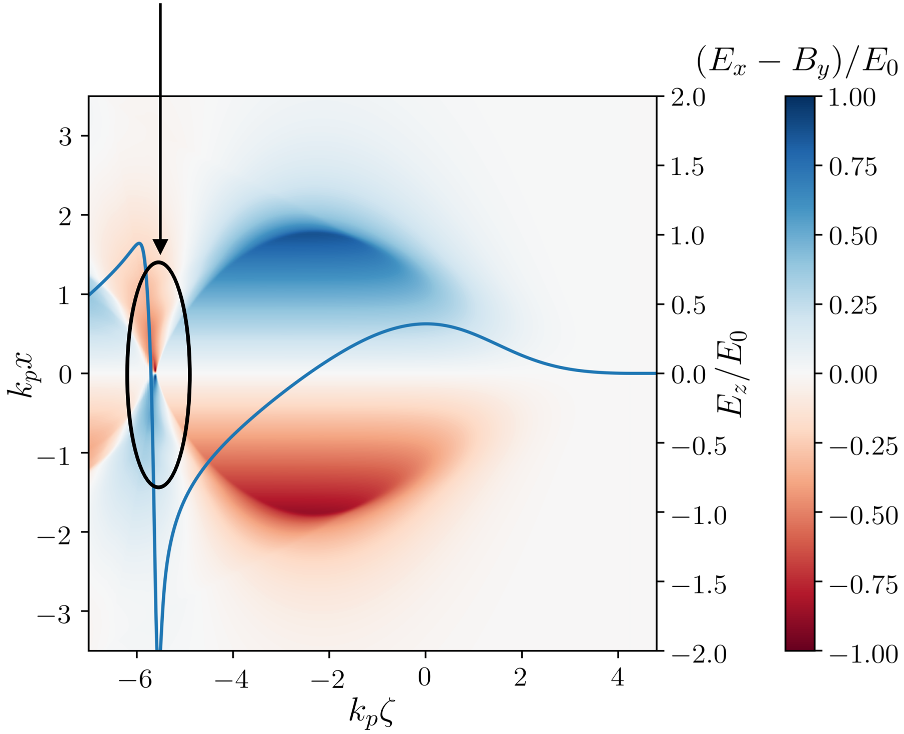
Strong accelerating fields

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

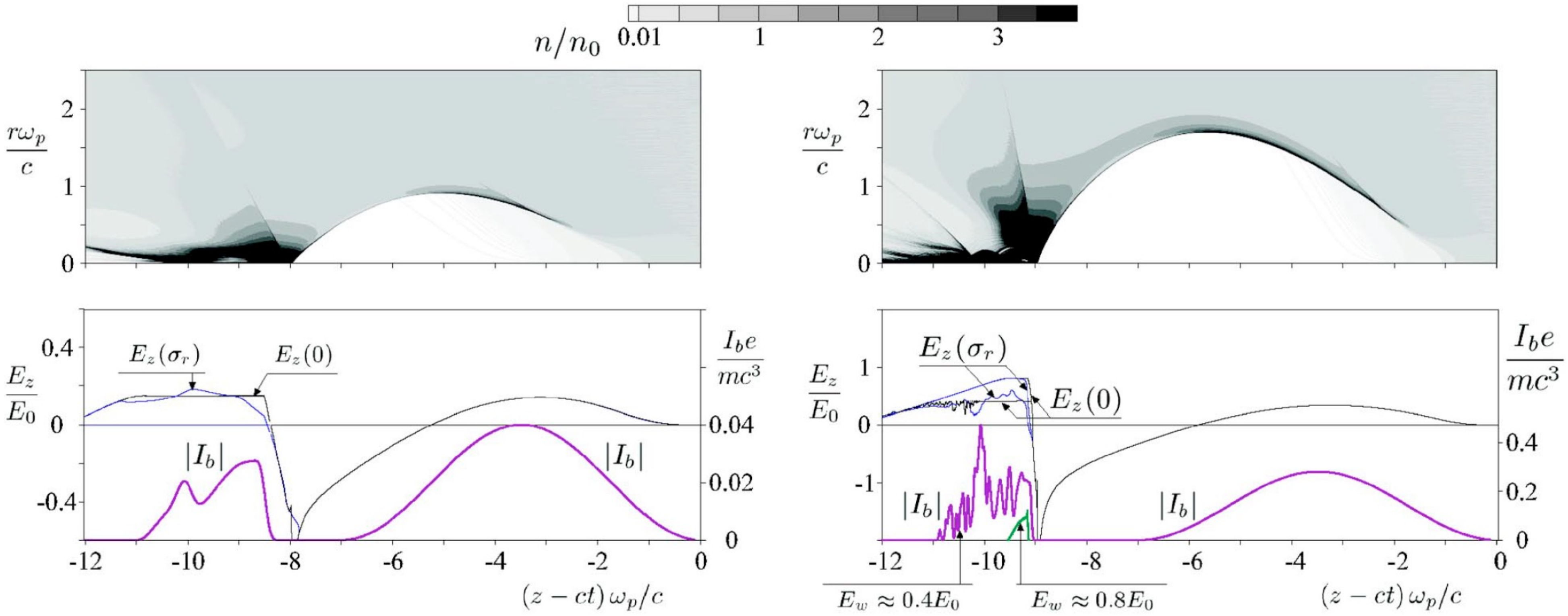
High density electron cusp

Focusing field for positrons



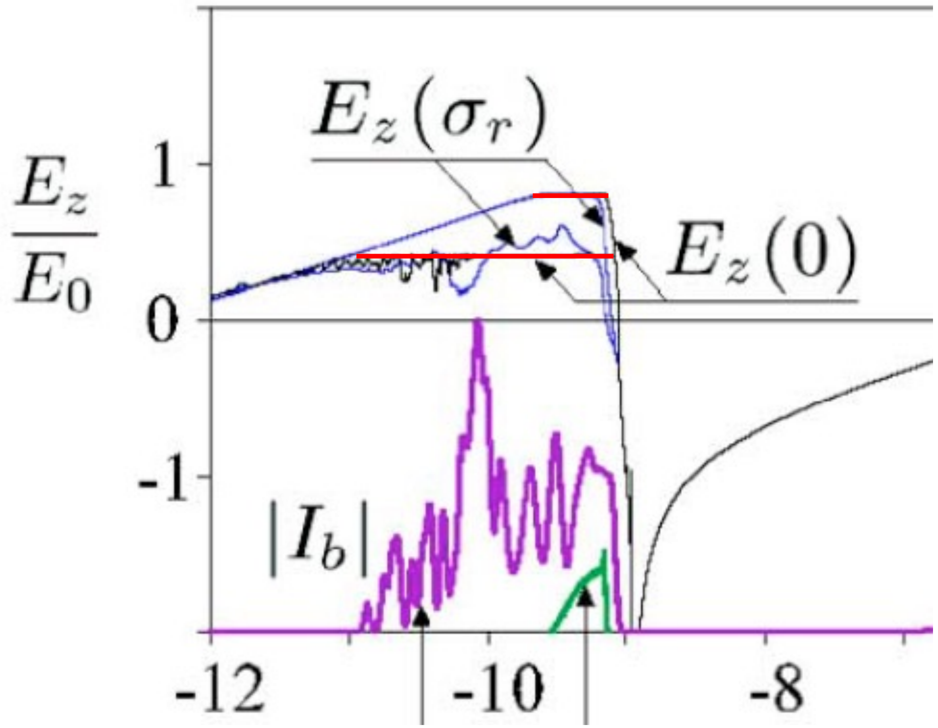


Proper beamloading enables positron acceleration at the back of the bubble



Lotov, PoP 14, 023101 (2007)

Any wakefield can be flattened by proper bunch shaping



Lotov, PoP 14, 023101 (2007)

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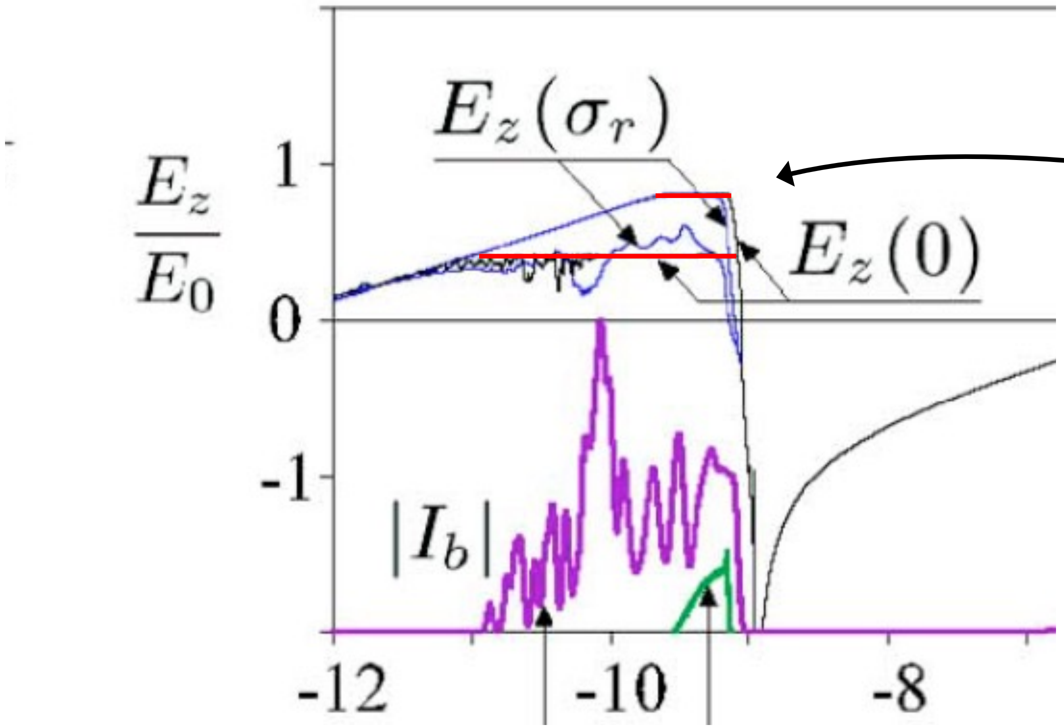
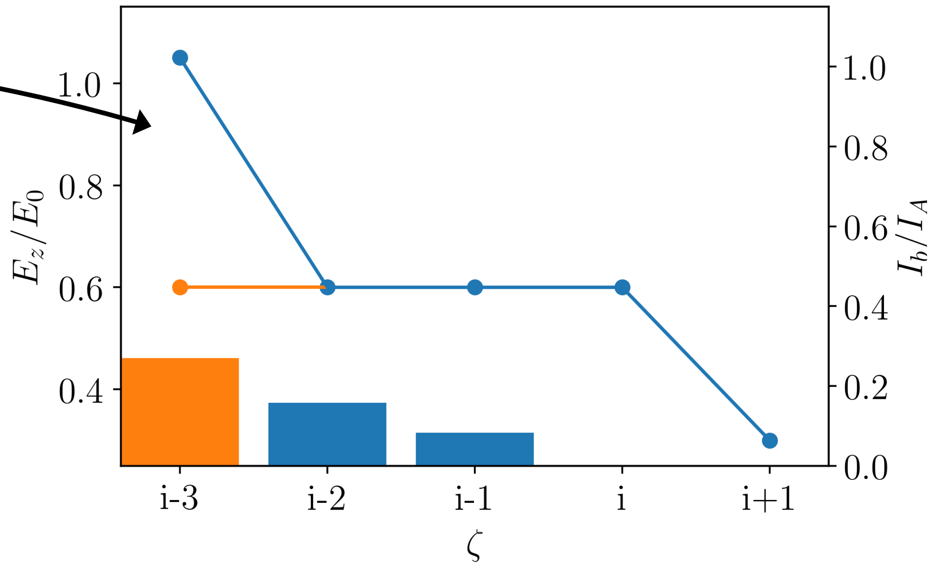


Slicing Advanced Loading Algorithm for Minimizing Energy spread (SALAME)



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

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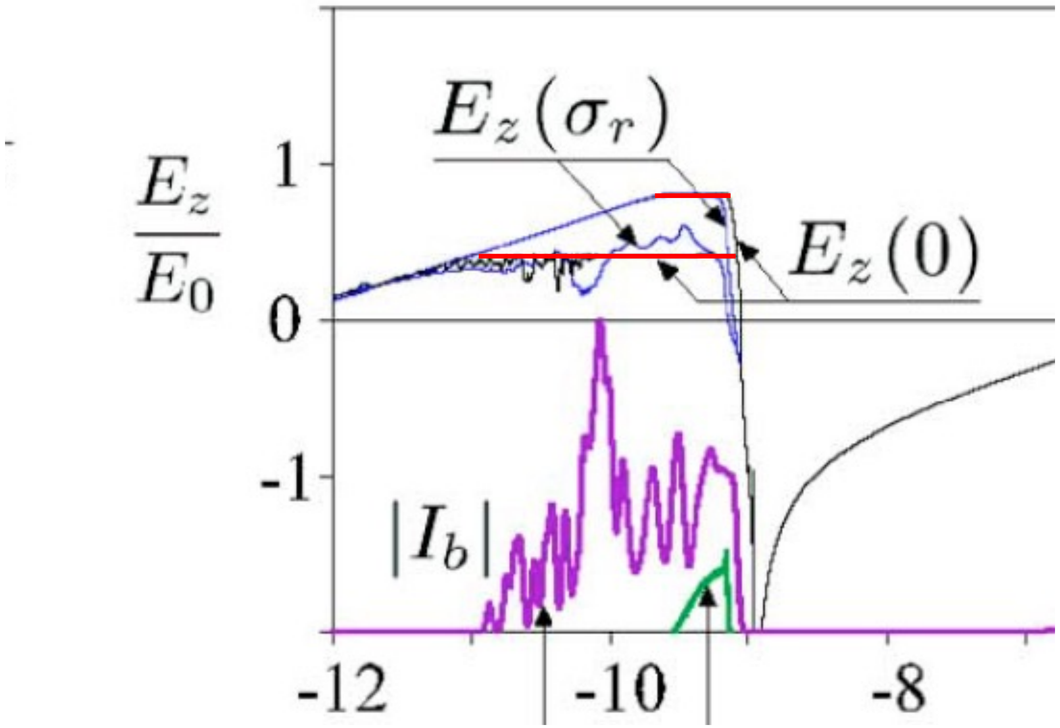
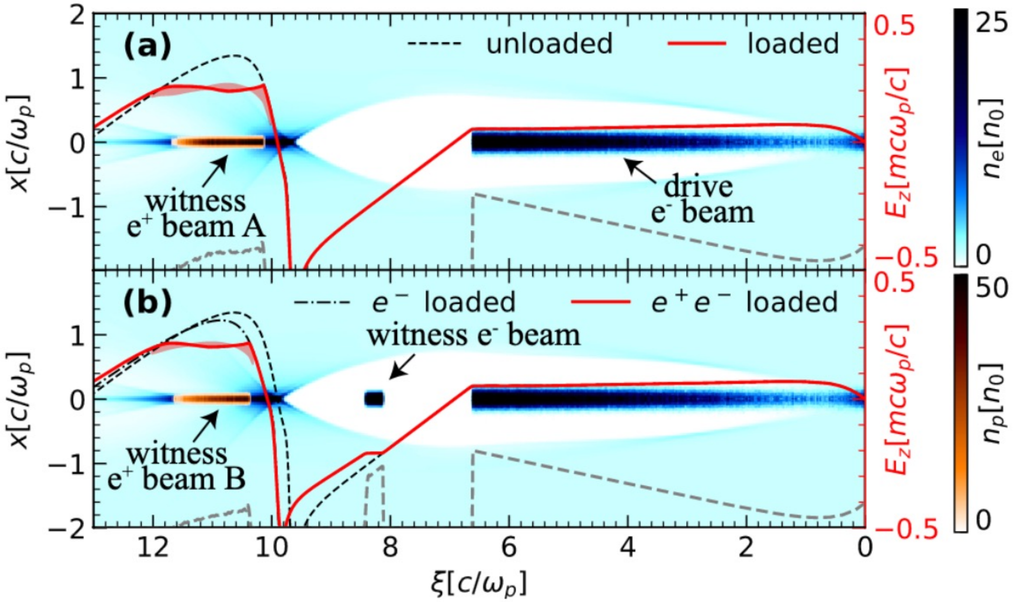
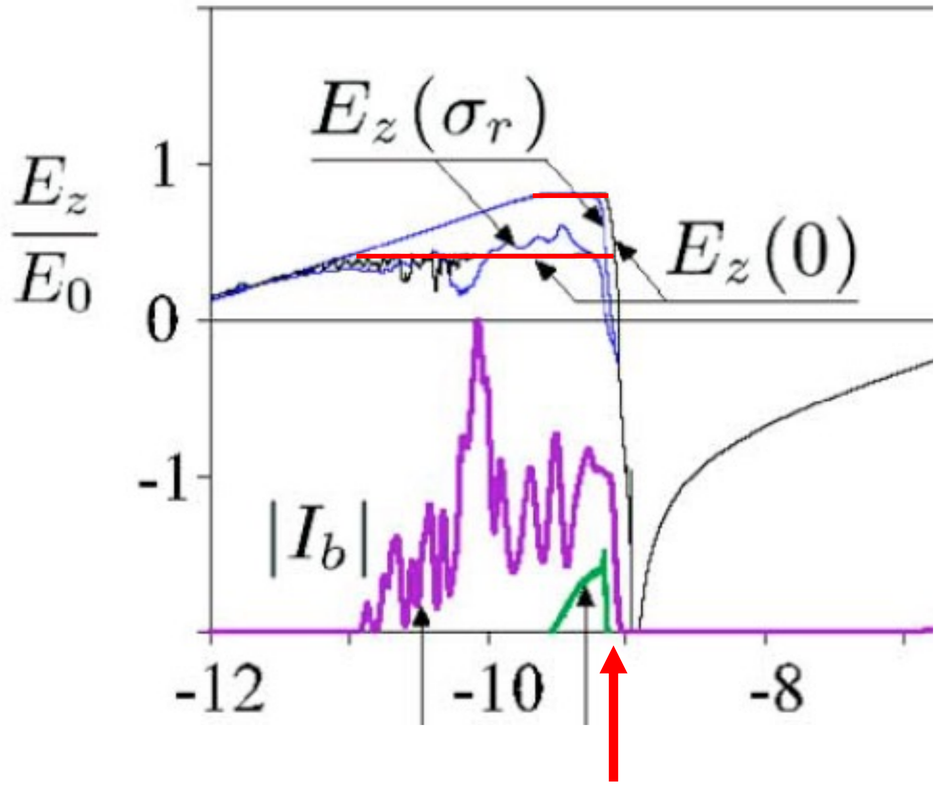




Optimized to:
130 pC
2% rms energy spread
< 10µm emittance
35% transfer efficiency

Lotov, PoP 14, 023101 (2007)
Zhou et al. arXiv:2211.07962v1

Required bunch shape in the electron spike sensitive to starting position

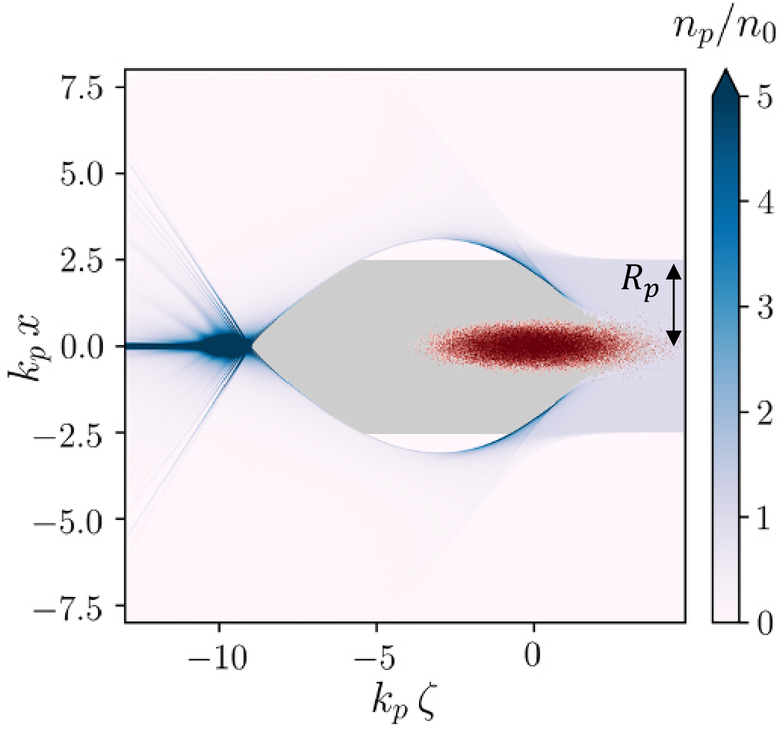


Can we relax the constraints?

Lotov, PoP 14, 023101 (2007)
Zhou et al. arXiv:2211.07962v1

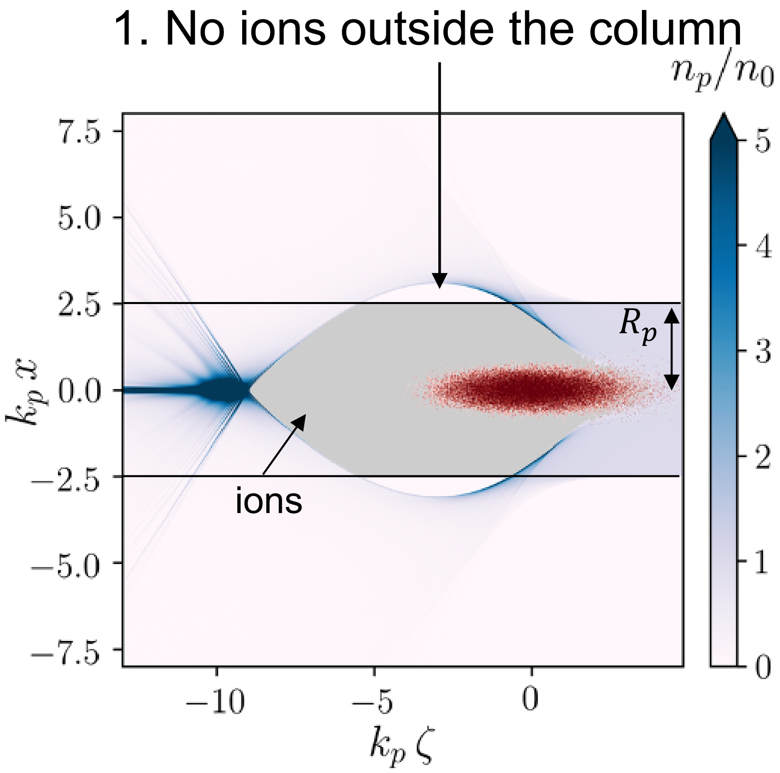
Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns



Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns



1. No ions outside the column

ions

Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns

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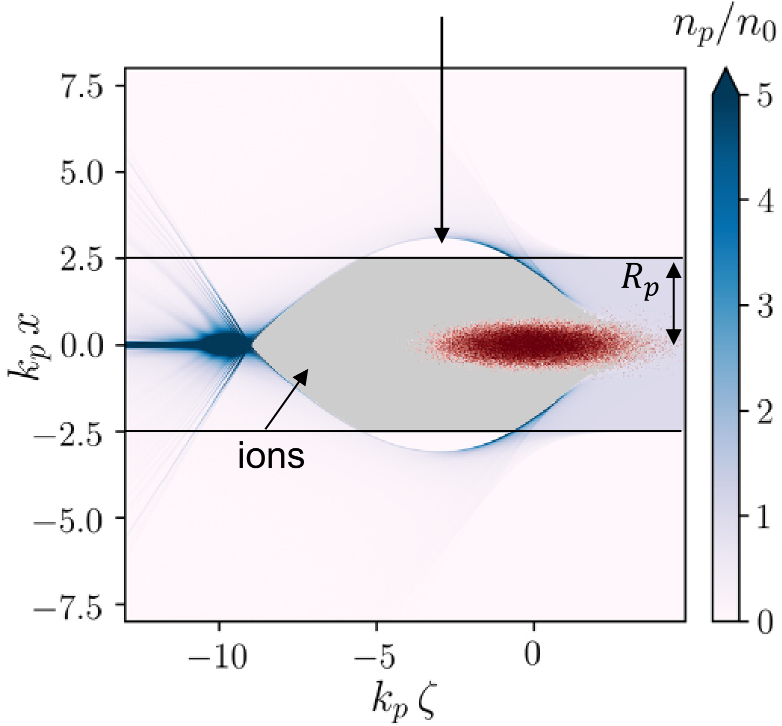
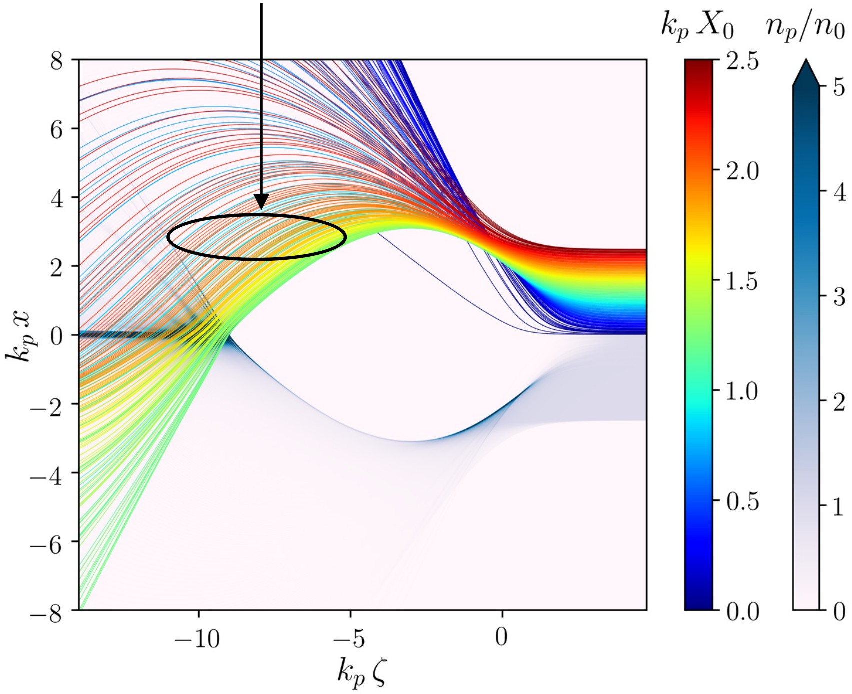


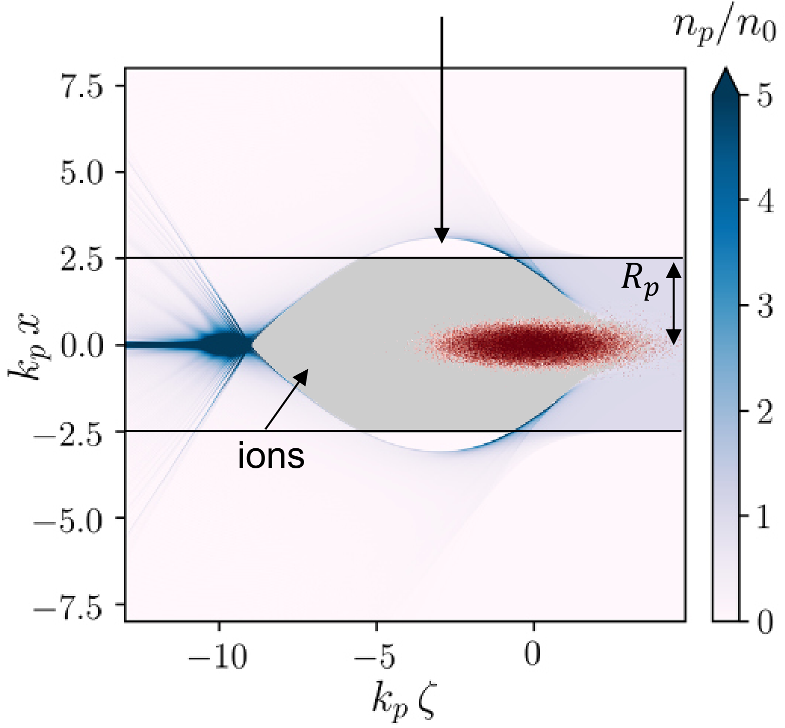
2. Elongated electron trajectories



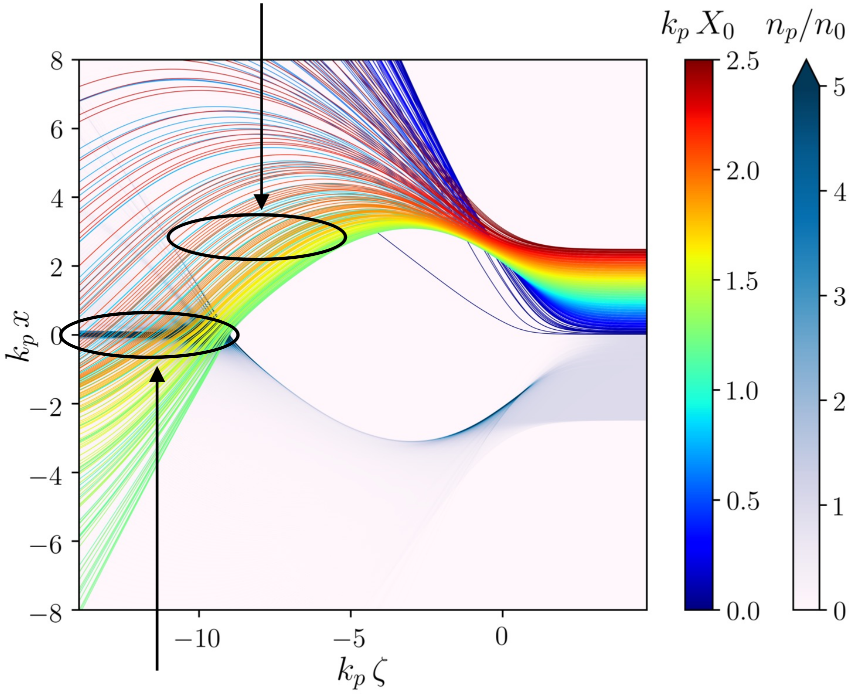
Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns

1. No ions outside the column



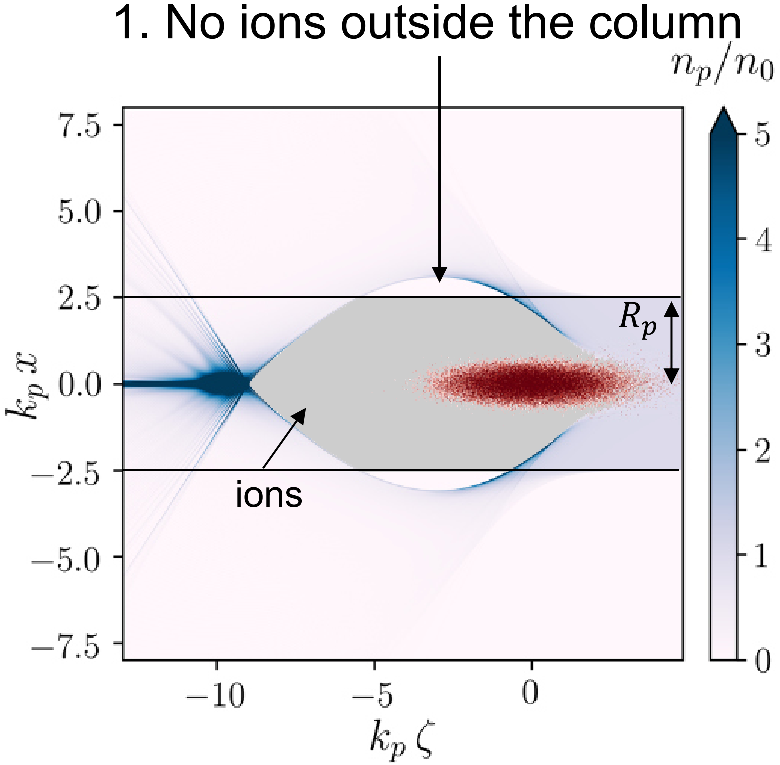
2. Elongated electron trajectories



3. Long, high-density electron filament

Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns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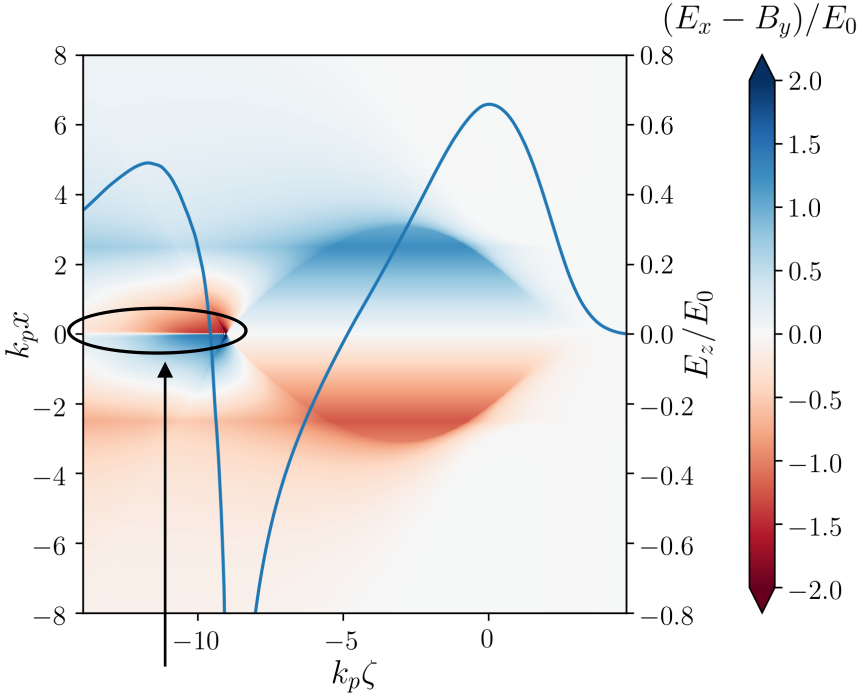

4. Accelerating and focusing fields for e^+

$0.5E_0 \approx$ 15 GV/m at $n_0 = 1\times10^{17}\ cm^{-3}$

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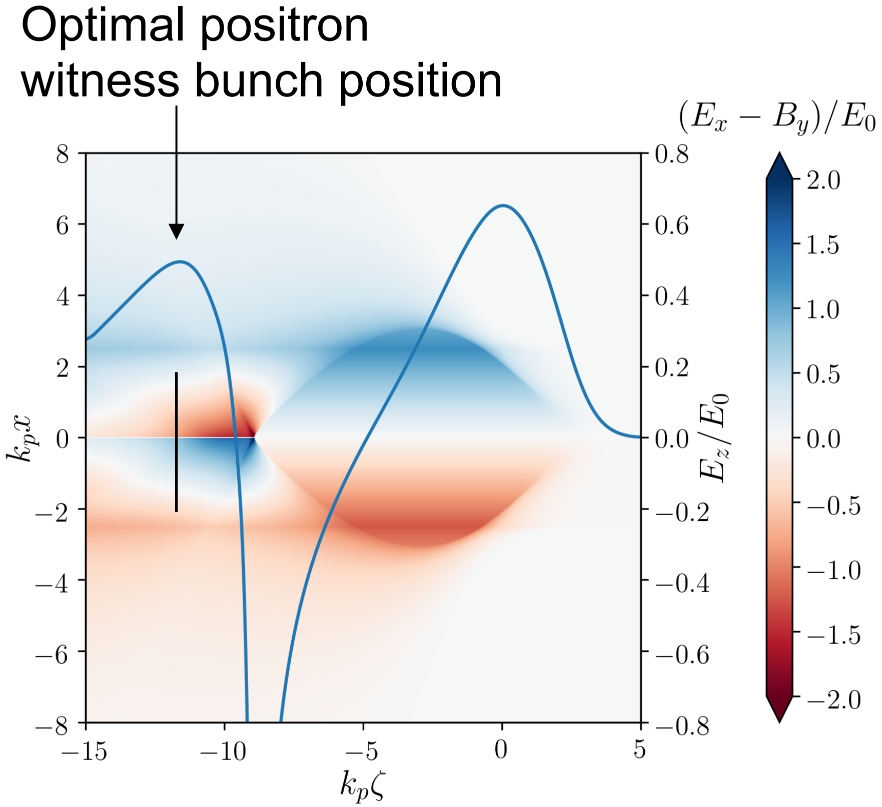
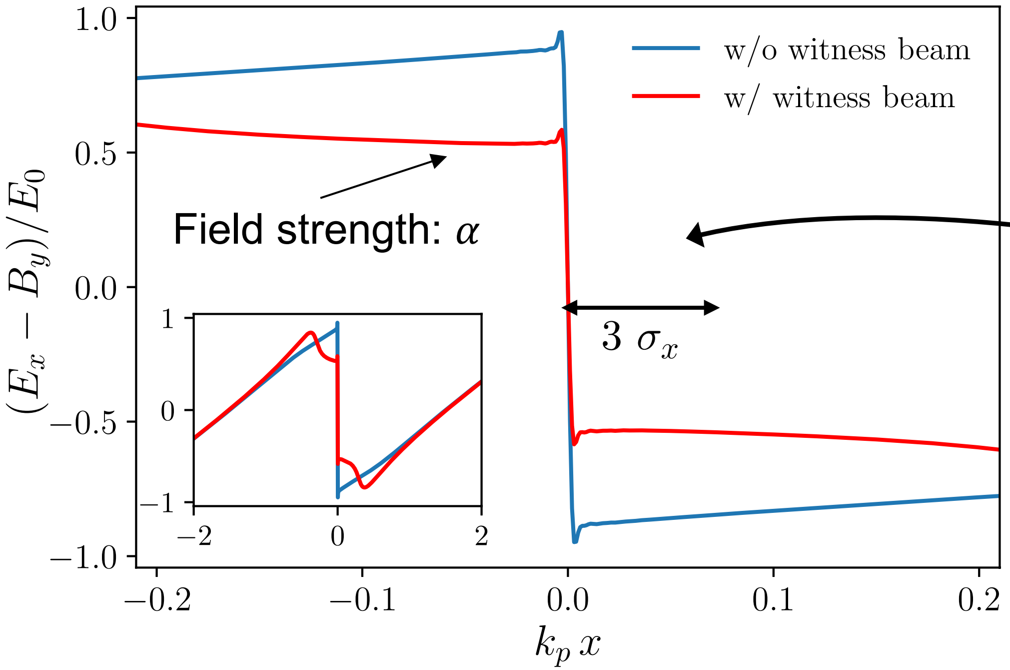
Emittance preservation requires matched beams


Optimal positron witness bunch position

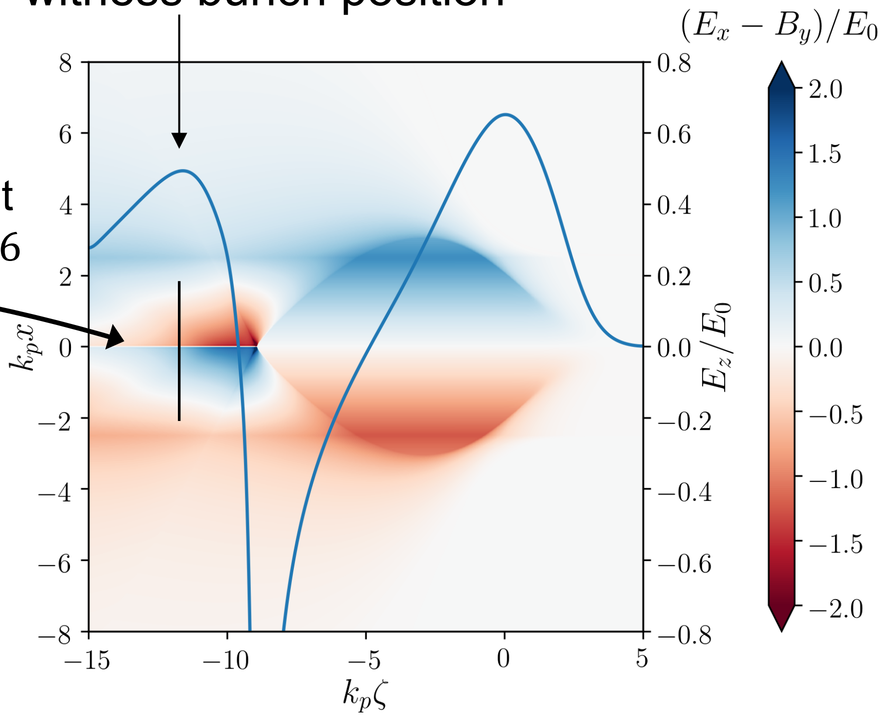
Emittance preservation requires matched beams

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



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

Optimal positron witness bunch position



Witness beam parameters:

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

Non-linear field induces emittance growth

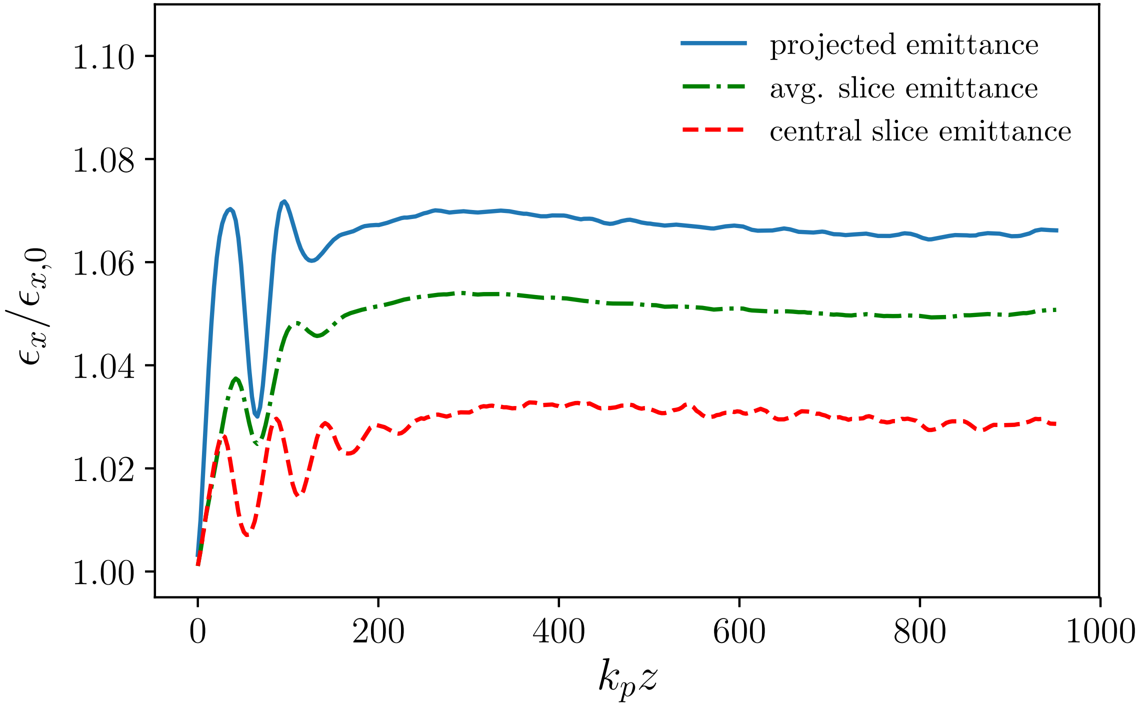
Quasi-matching?

Emittance growth quickly saturates

At $\mathrm{n}_0 = 5\times10^{17}\ \mathrm{cm}^{-3}$: $\epsilon_{x,0} = 0.7\mu m$

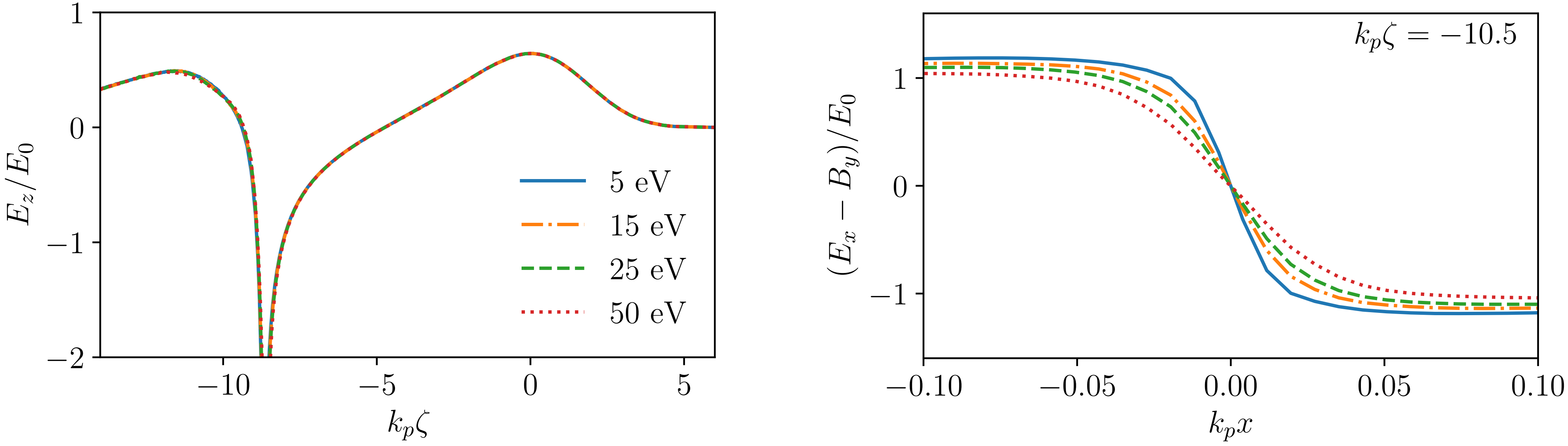
Emittance is resolution limited,
cannot resolve smaller beams

Positron beam emittance evolution with a fixed driver



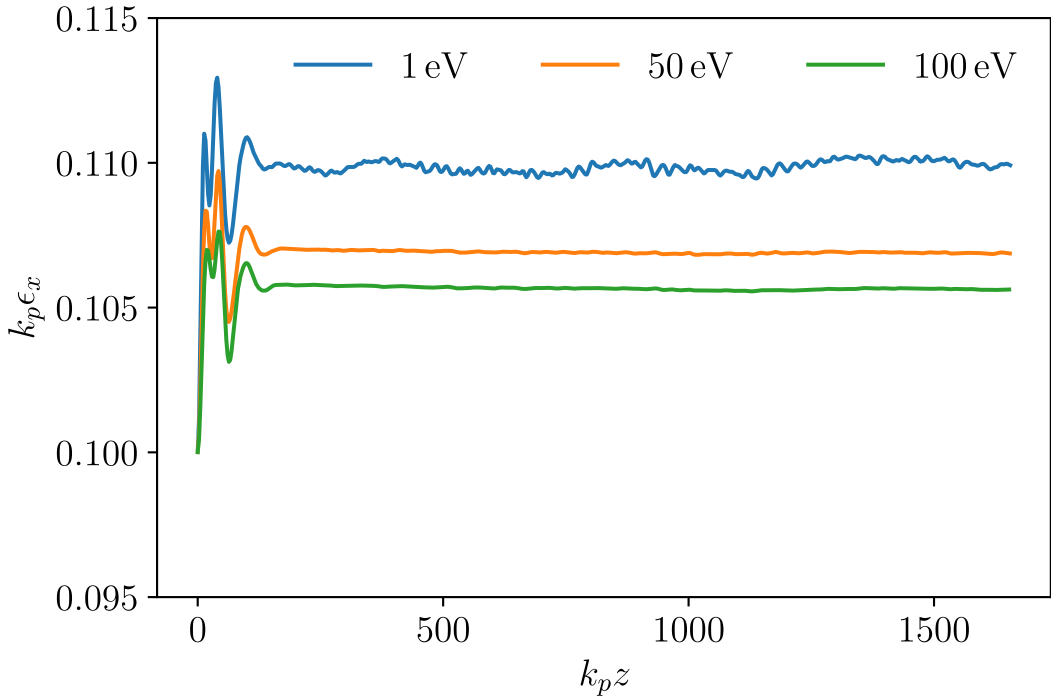
C. Benedetti et al., PRAB 2017
S. Diederichs et al., PRAB 2019

Temperature linearizes focusing field



Diederichs et al. (in preparation)
Wang et al., arXiv:2110.10290 (2021)

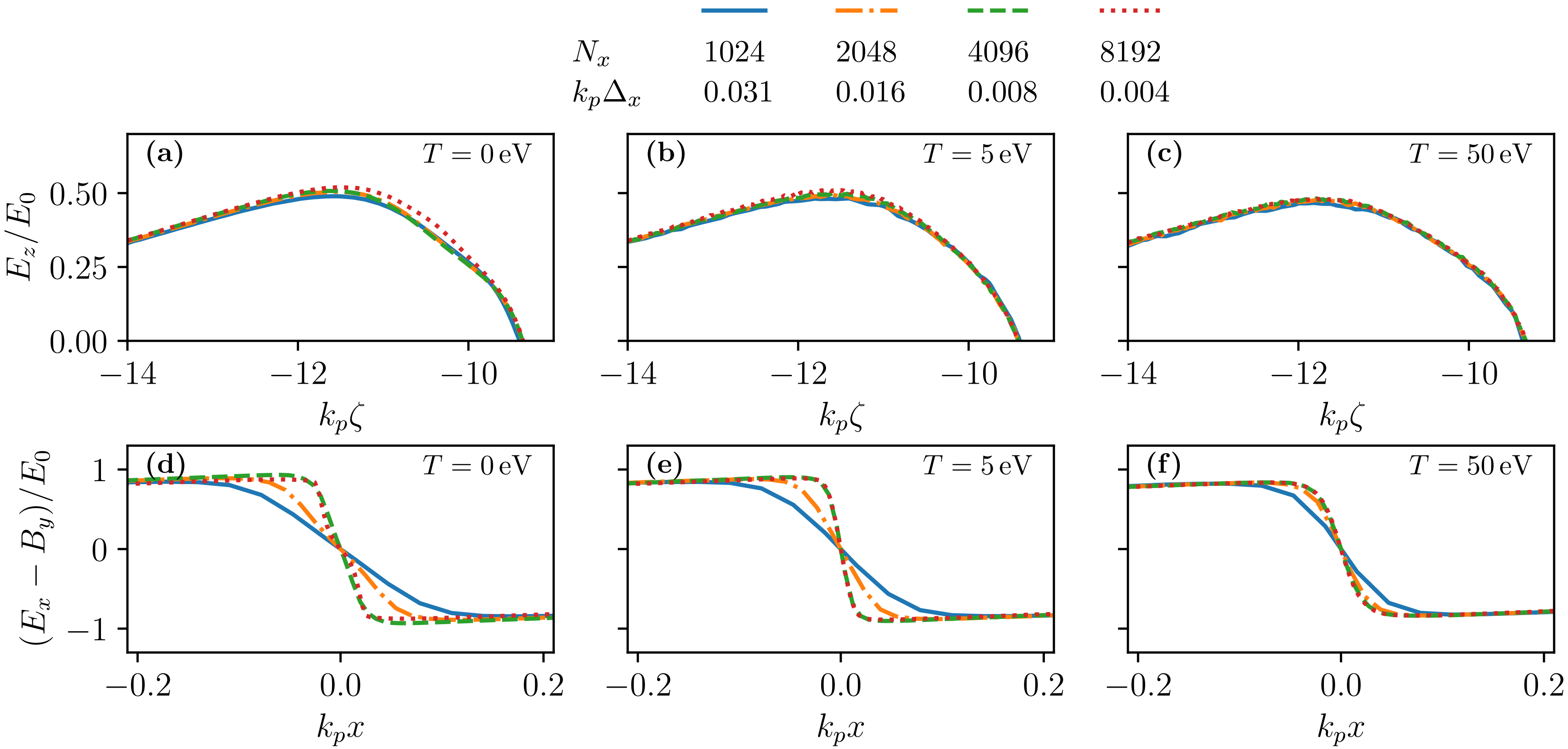
Temperature linearizes focusing field



Even better for emittance preservation!

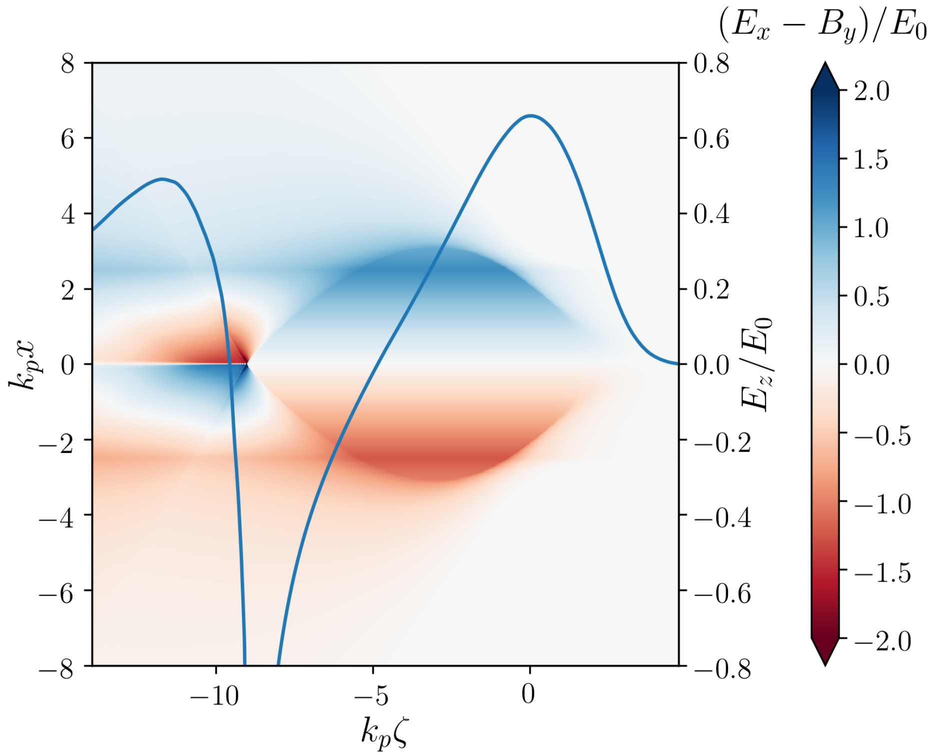
Diederichs et al. (in preparation)

Temperature mandatory for convergence



Diederichs et al. (in preparation)
Wang et al., arXiv:2110.10290 (2021)
Jain et al. PoP (2015)

Positron accelerating field is non-uniform



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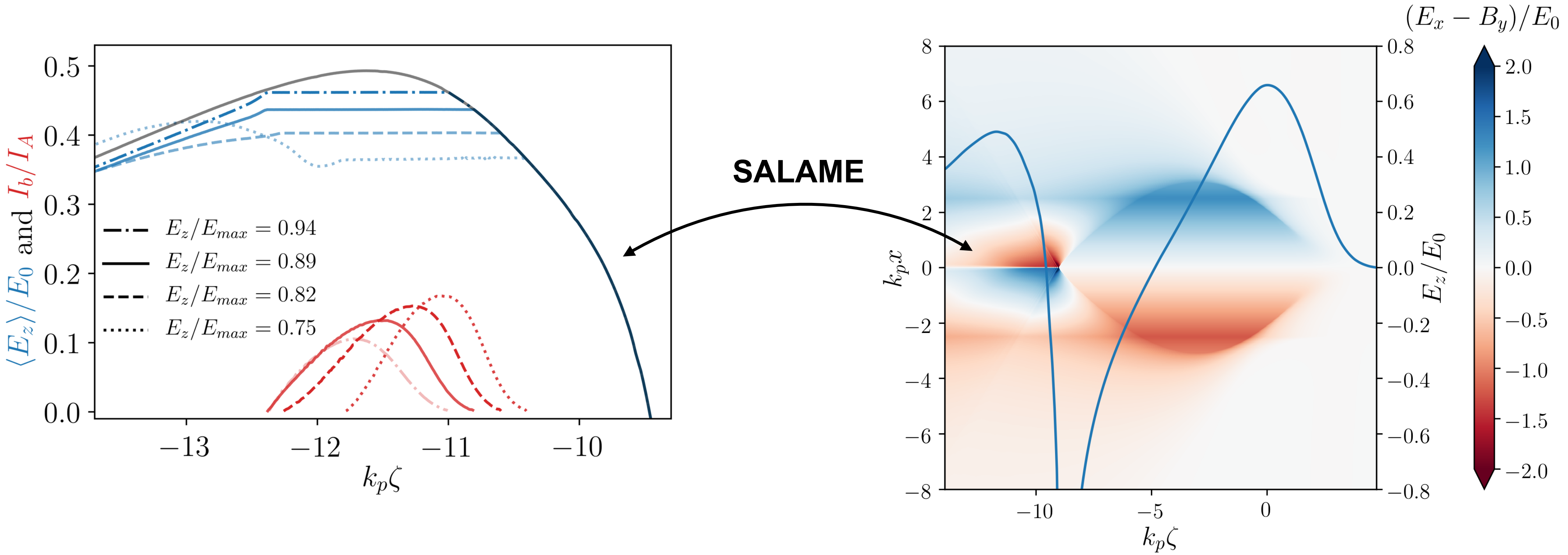
Optimal beam loading enables low-energy-spread and low-emittance positron acceleration



witness beam: 50 pC
< 0.5 µm normalized emittance
< 1% relative energy spread
≈ 3% transfer efficiency (to be optimized)

Diederichs et al., PRAB 2020

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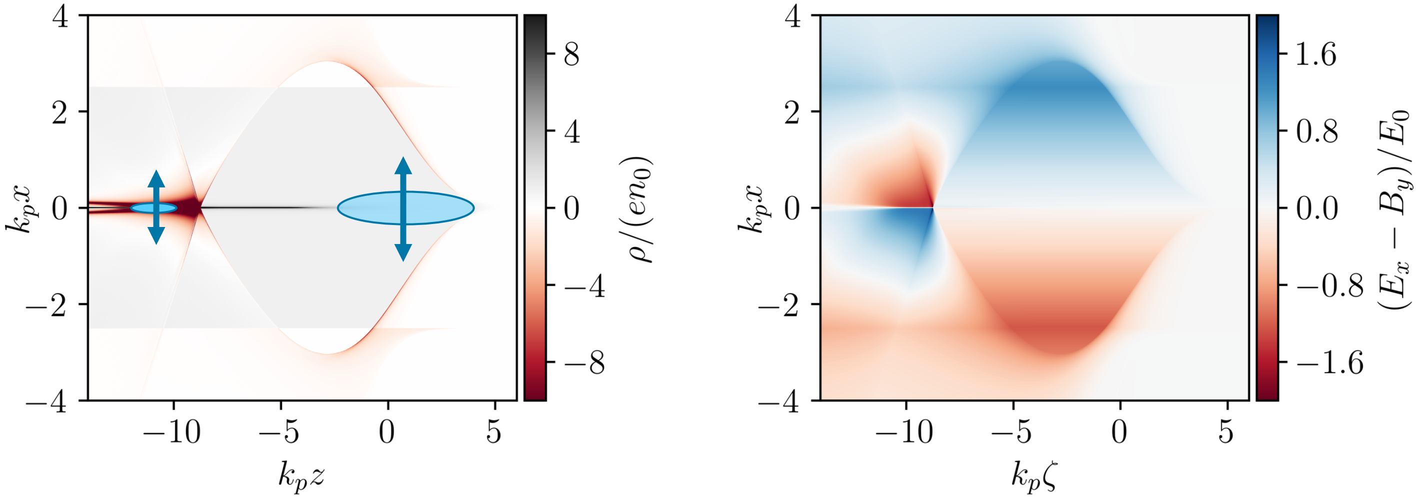
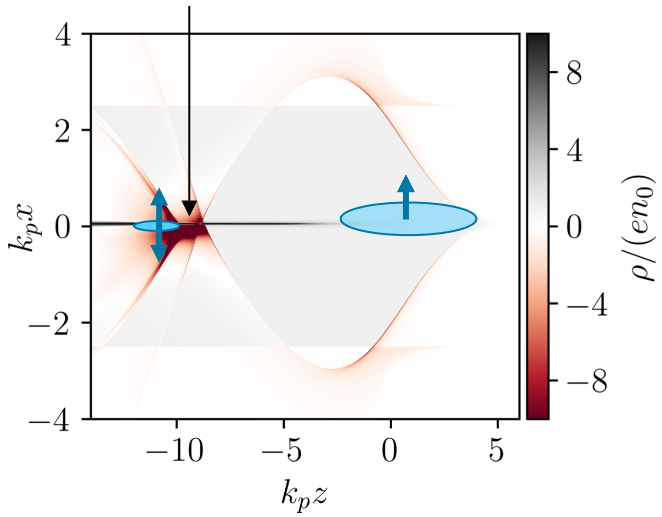
Stability is crucial for a cylindrical symmetric setup



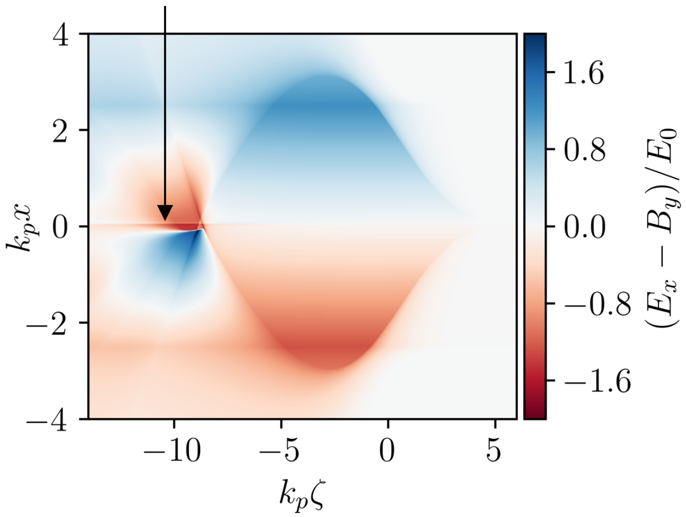
Instabilities can be induced by
- Misalignment between driver and column
- Beam asymmetries, e.g., tilts

Stability is crucial for a cylindrical symmetric setup

Perturbed electron filament



Perturbed wakefield centroid $\langle W \rangle$



Instabilities can be induced by

- Misalignment between driver and column
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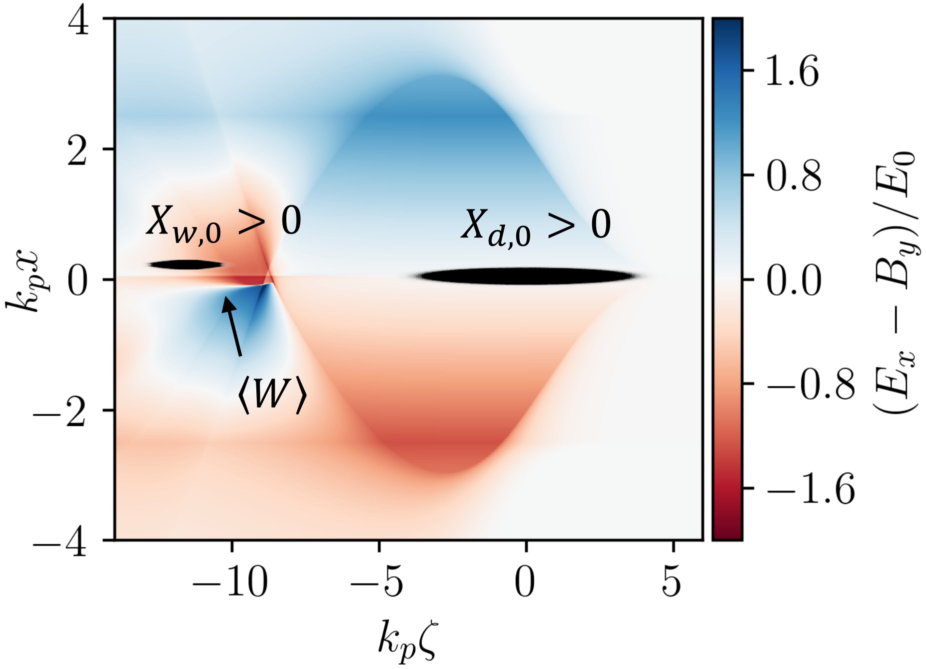
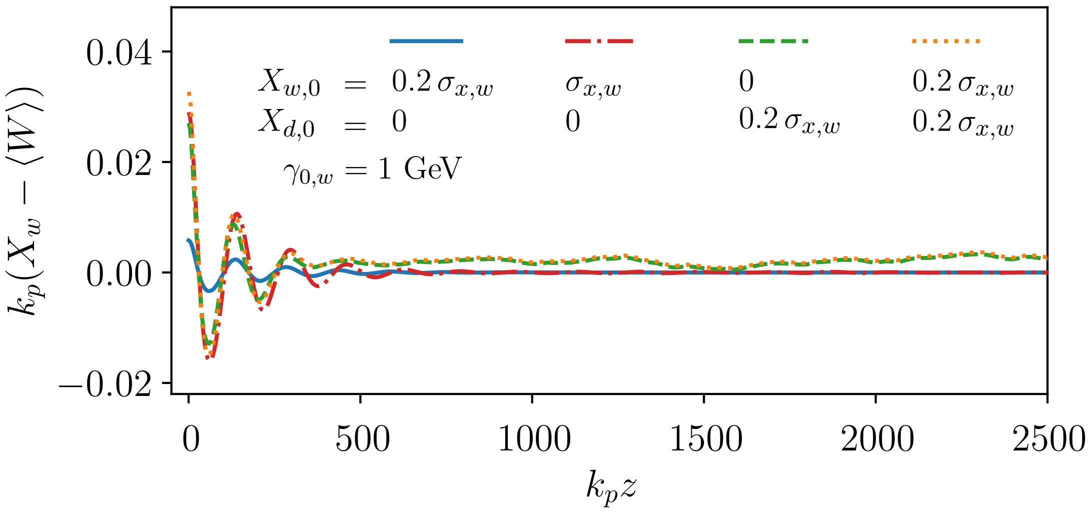
What is the impact on the witness beam quality?

Witness beam is not susceptible to hosing





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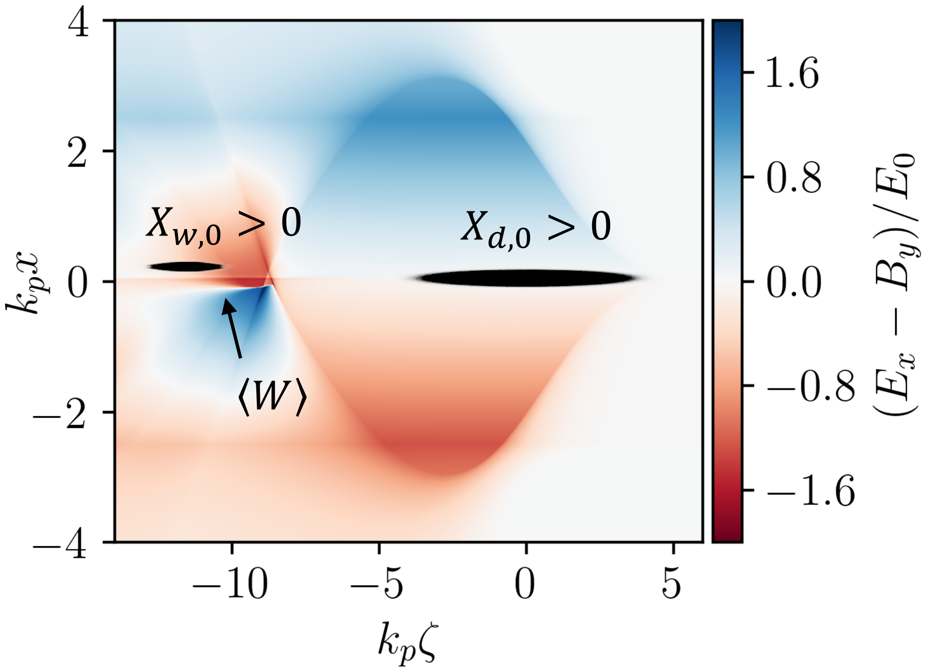
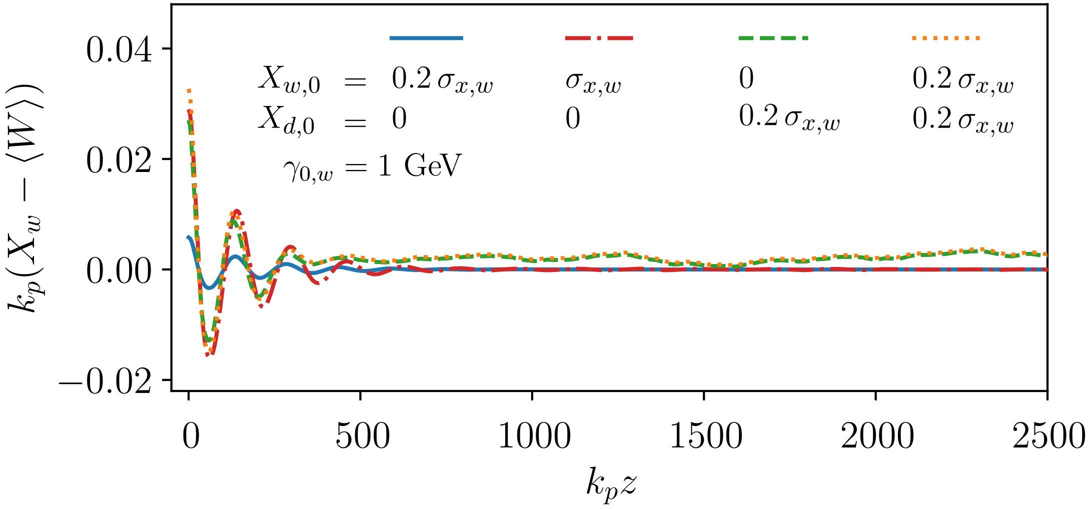
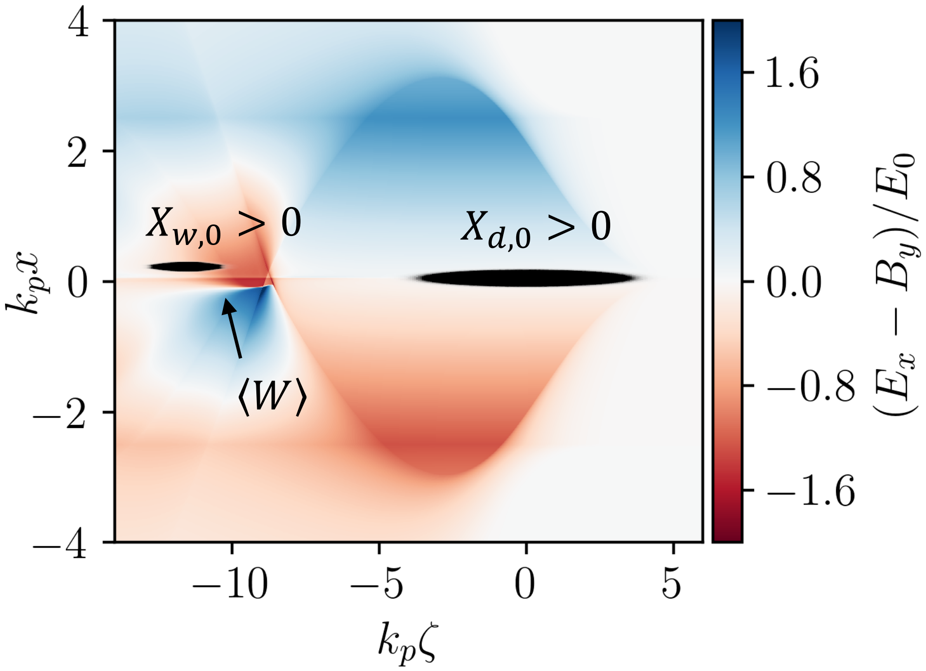




Hosing is prevented for 2 reasons:

1. **Longitudinally varying focusing field (BNS damping)**
2. Phase-mixing within each slice

Witness beam is not susceptible to hosing



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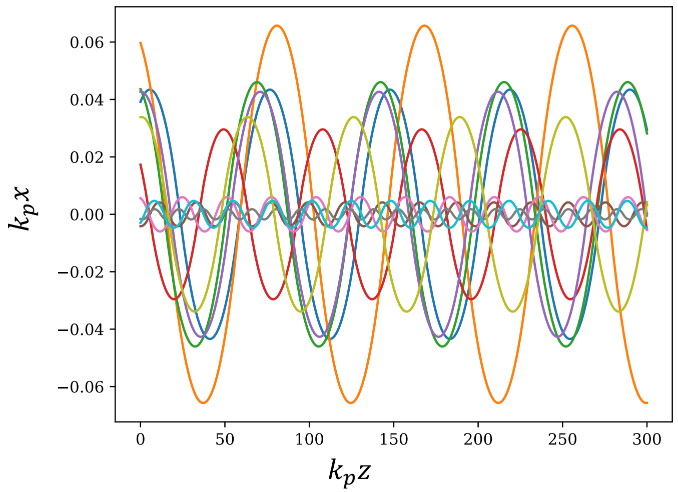
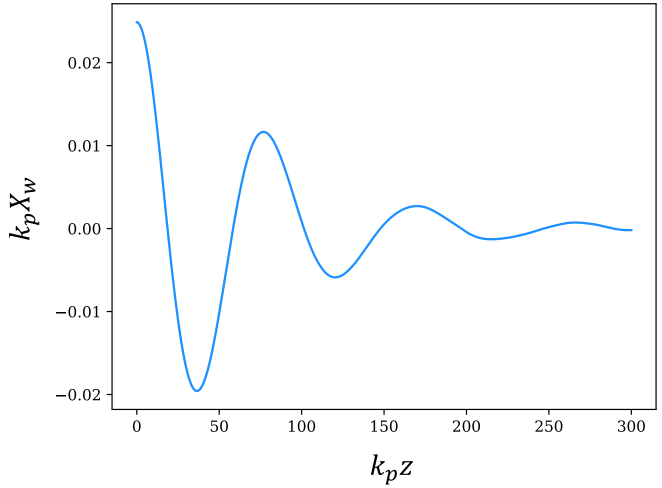
Single-particle trajectories



Bunch centroid trajectory

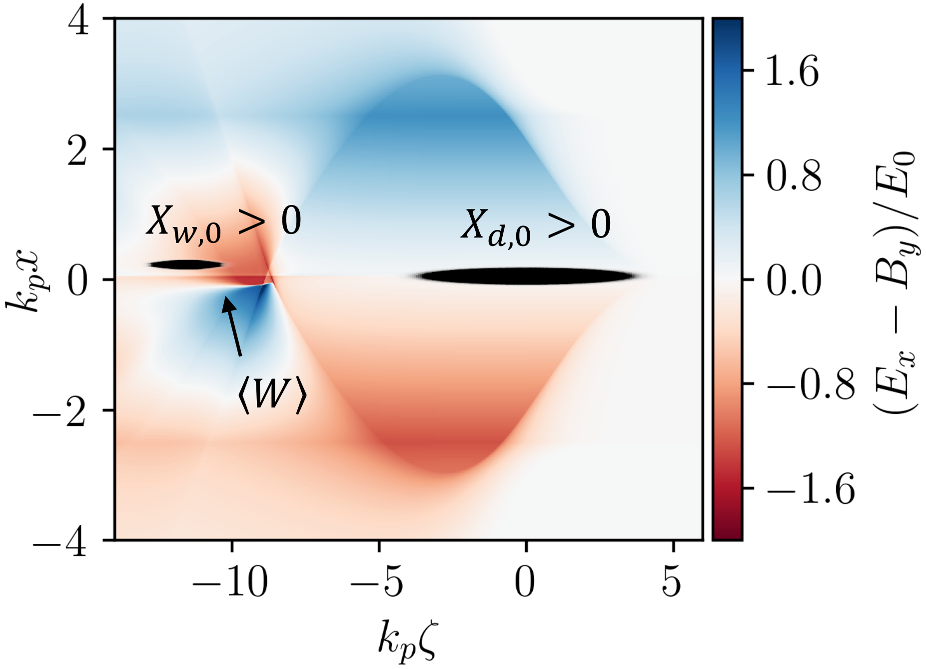


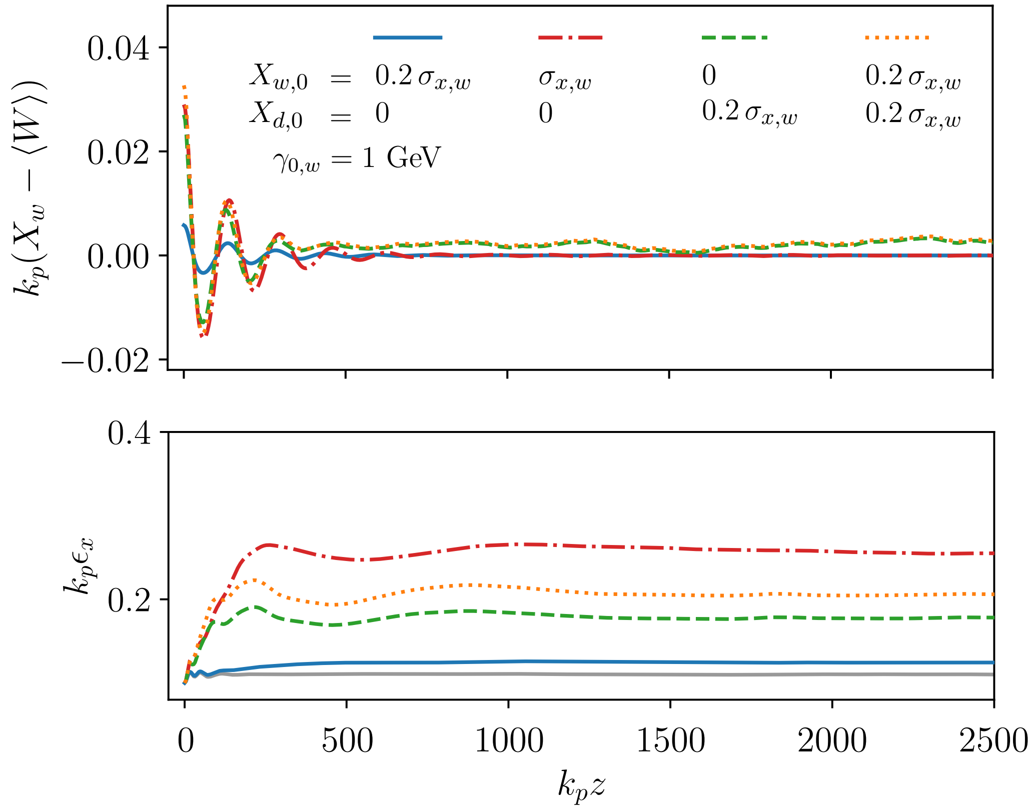
1D beam in step-like field with field strength α

Damping length:

$$k_p S_{\mathrm{damp}} \propto \sqrt{\frac{k_p \sigma_{x,w} \gamma}{\alpha}}$$

Witness beam is not susceptible to hosing





Initial offsets increase the emittance but growth saturates quickly! Similar to e^-

Diederichs et al., PRAB 2022

Hosing is prevented for 2 reasons:

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2. **Phase-mixing within each slice**

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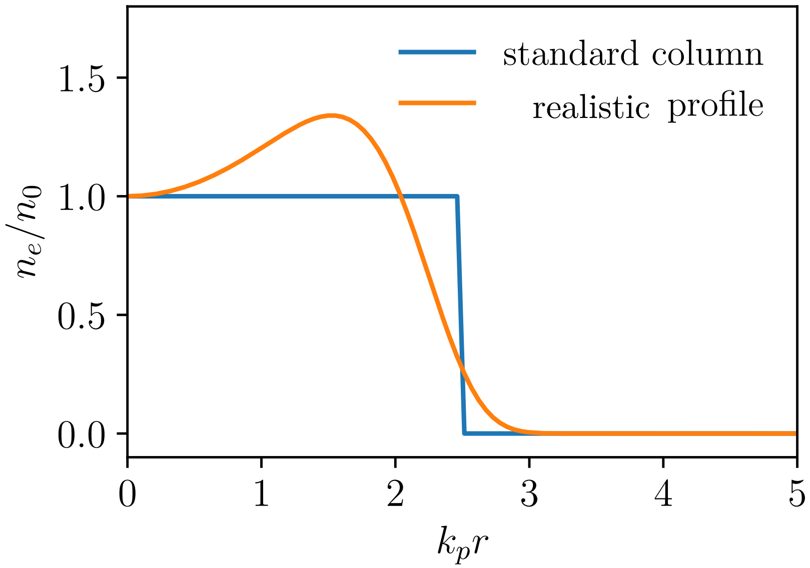
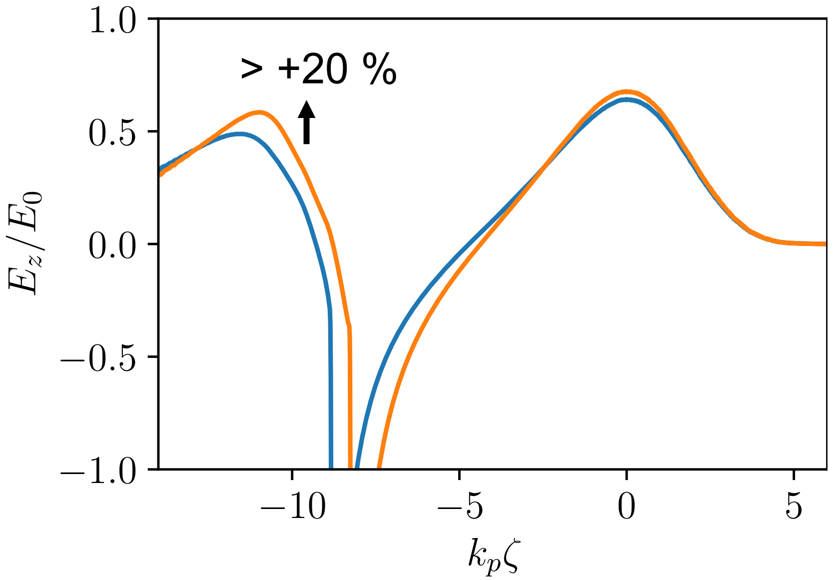
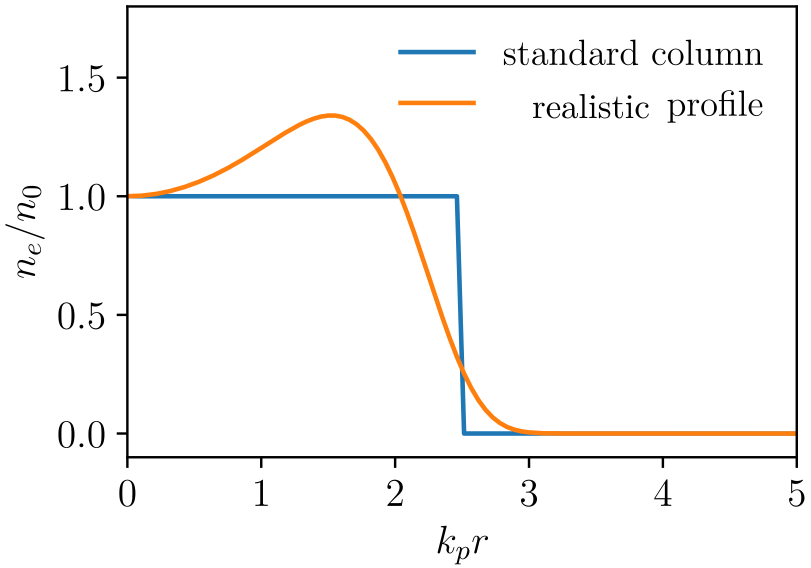
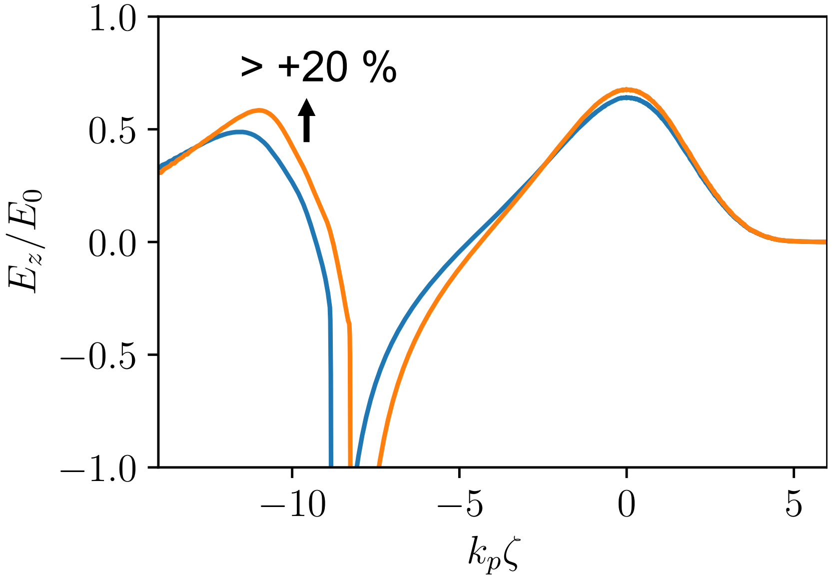
Realistic plasma profiles increase the accelerating gradient





Realistic plasma profiles increase the accelerating gradient





Efficiency can be further increased by tailoring drive beam profile (Roussel PRL 2020, Loisch PRL 2018)

A lot of room for improvement of the efficiency

Other schemes to generate electron filaments

Statements on **stability**, **temperature effects**, and **tweaks for improvement** translate to other concepts using electron filaments

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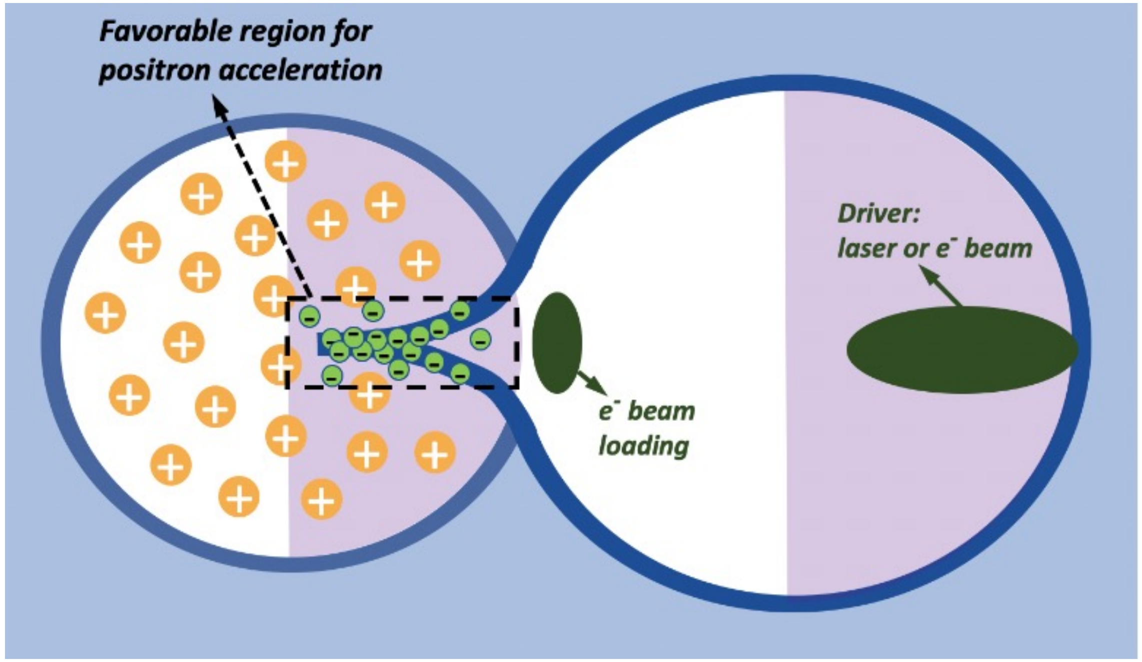
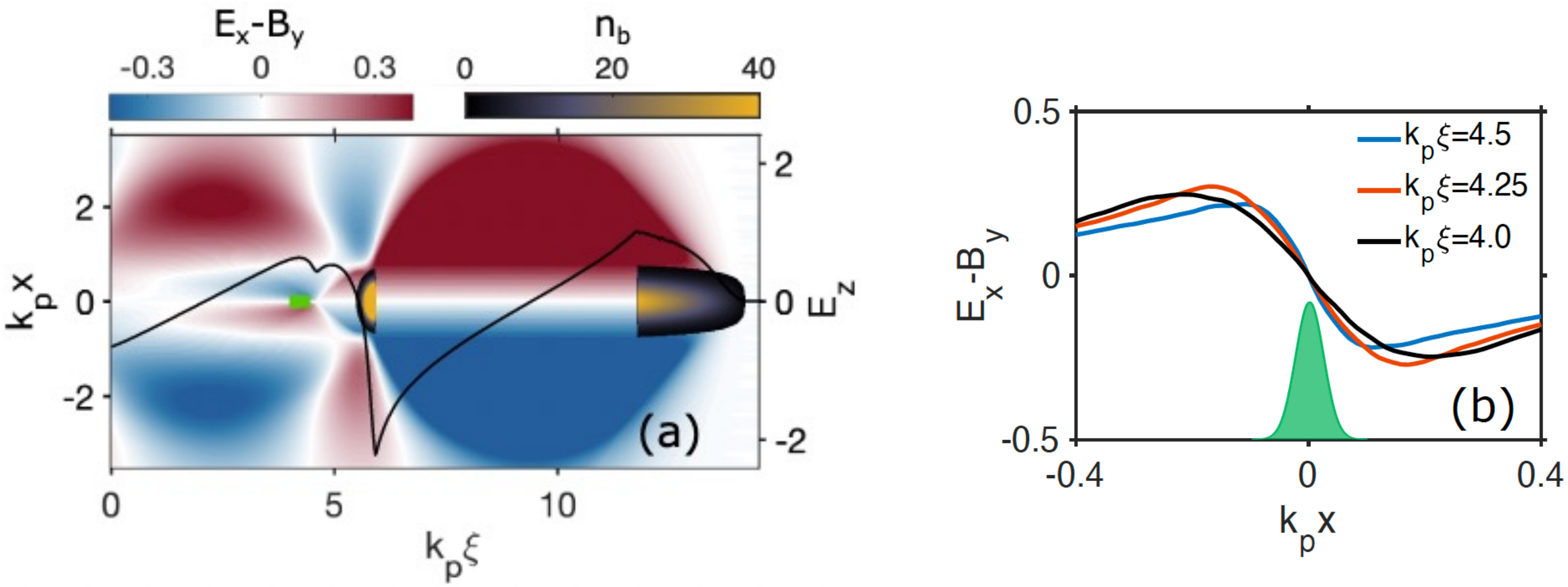
Electron witness bunch elongates plasma electron spike



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



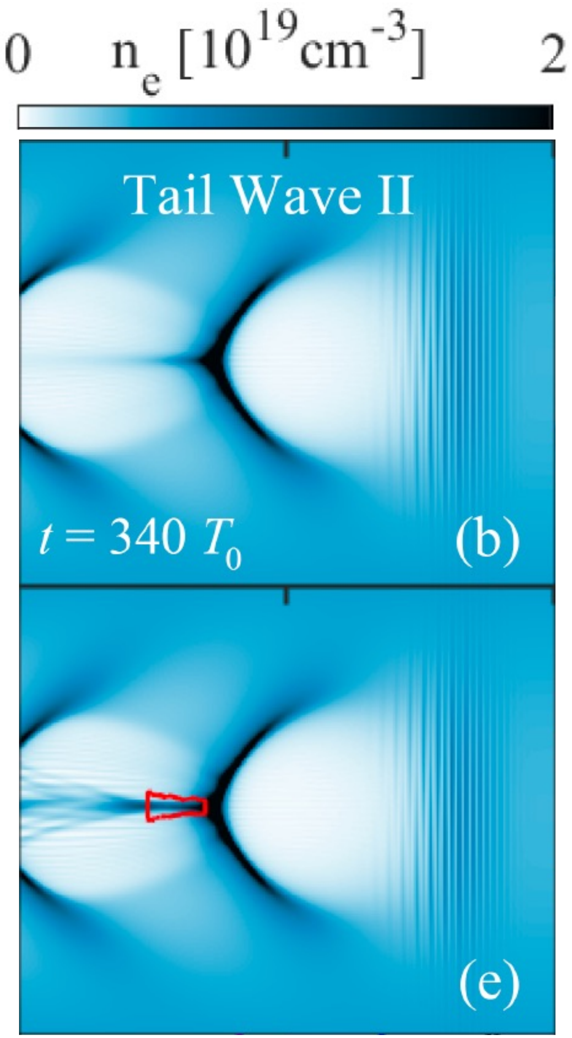
Linear focusing fields!
=> emittance preserved < 0.9 µm

1.4% rms energy spread
without beamloading

A lot of potential for optimization!

Wang et al. (arXiv. 2110.10290 2021)

Similar setting with laser driver demonstrated



Liu et al. (arXiv 2207.14749 2022)

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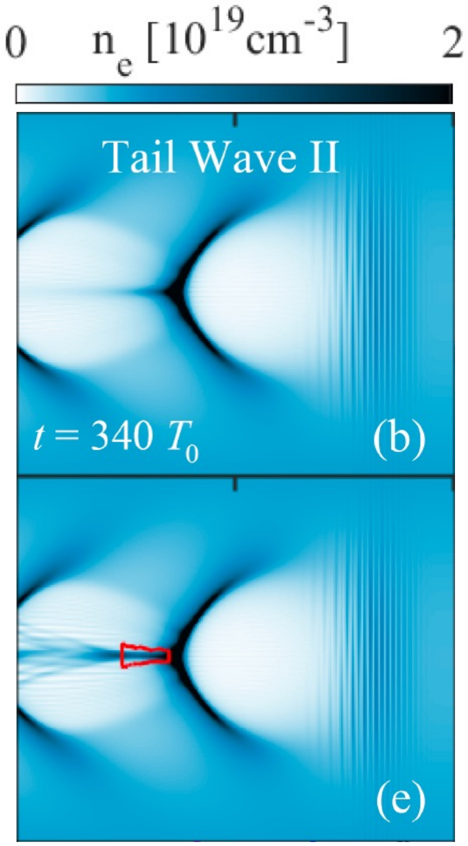
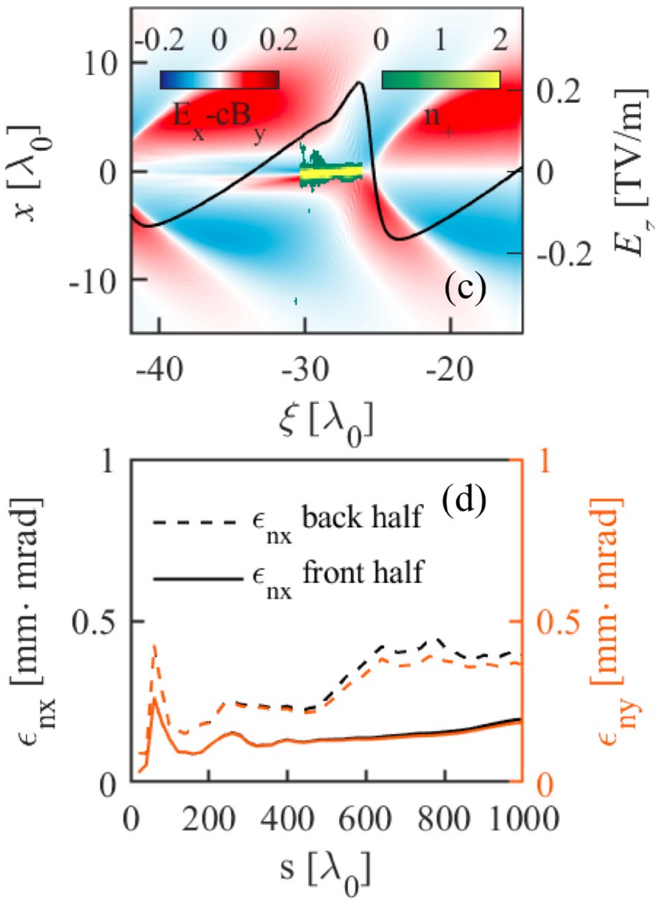
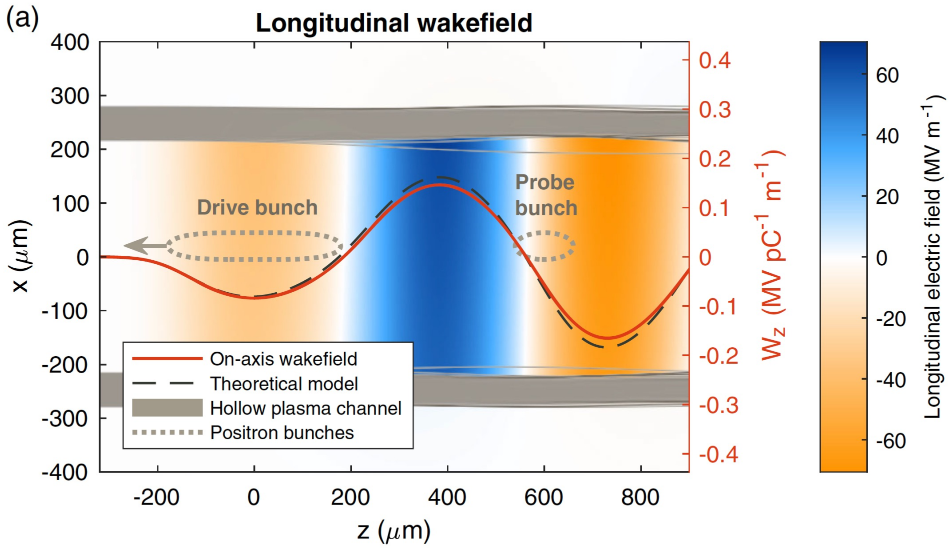




- Very simple setup
- High gradients: 100 GV/m fields
- A lot of potential for optimization

Liu et al. (arXiv 2207.14749 2022)

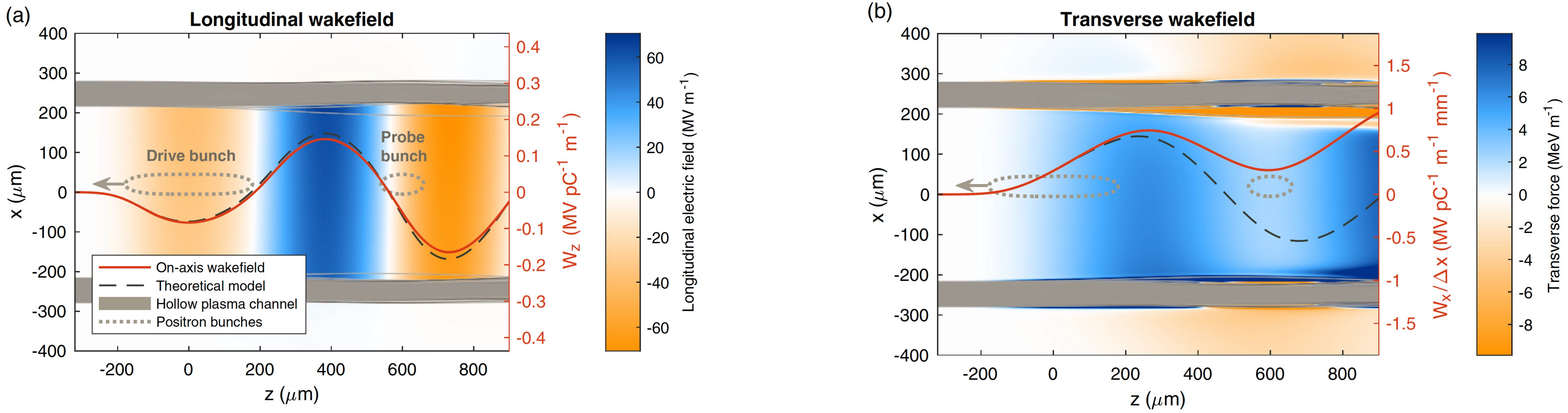
If ions defocus, let's ignore them altogether: Hollow core plasma accelerator



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)

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



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

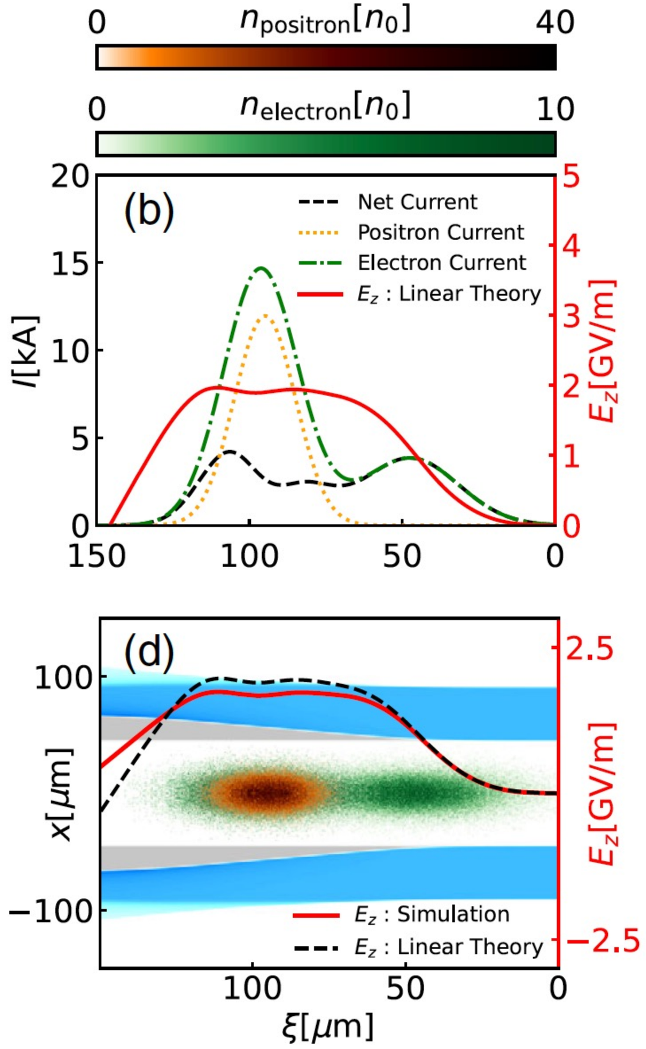
Misaligned beams are deflected

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)

Double loaded hollow core plasma channel yields extraordinary beam quality

$\sim$ nC charge
$\sim$ GV/m gradient
$\lesssim$ 0.5% induced energy spread
$\sim$ 50% energy transfer efficiency

Zhou et al. (PRAB 25, 091303 2022)



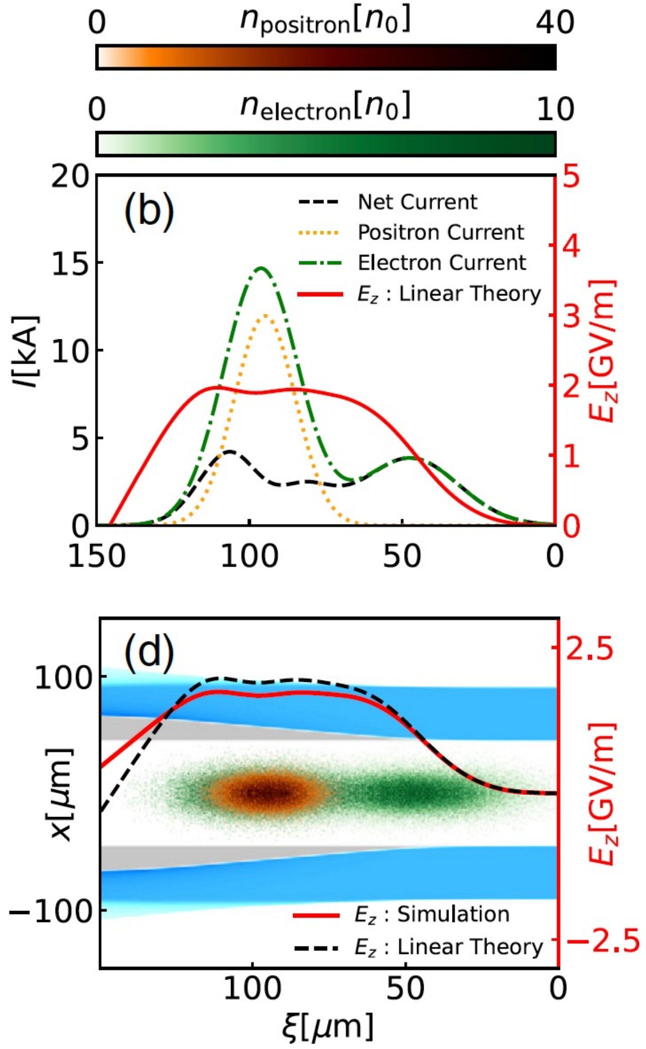
Double loaded hollow core plasma channel yields extraordinary beam quality

$\sim$ nC charge
$\sim$ GV/m gradient
$\lesssim$ 0.5% induced energy spread
$\sim$ 50% energy transfer efficiency

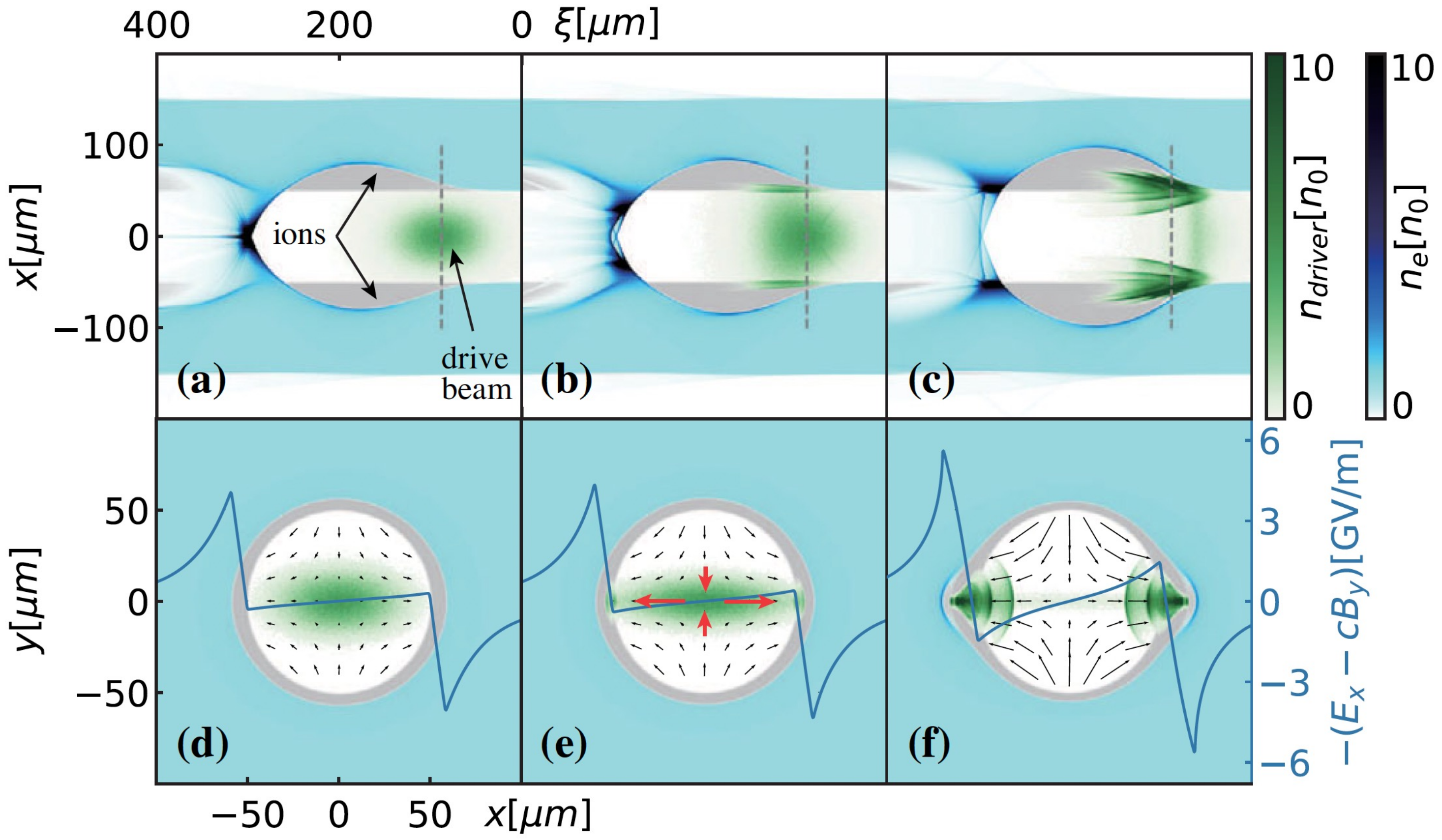
Stability?

External focusing needs to be demonstrated

Zhou et al. (PRAB 25, 091303 2022)



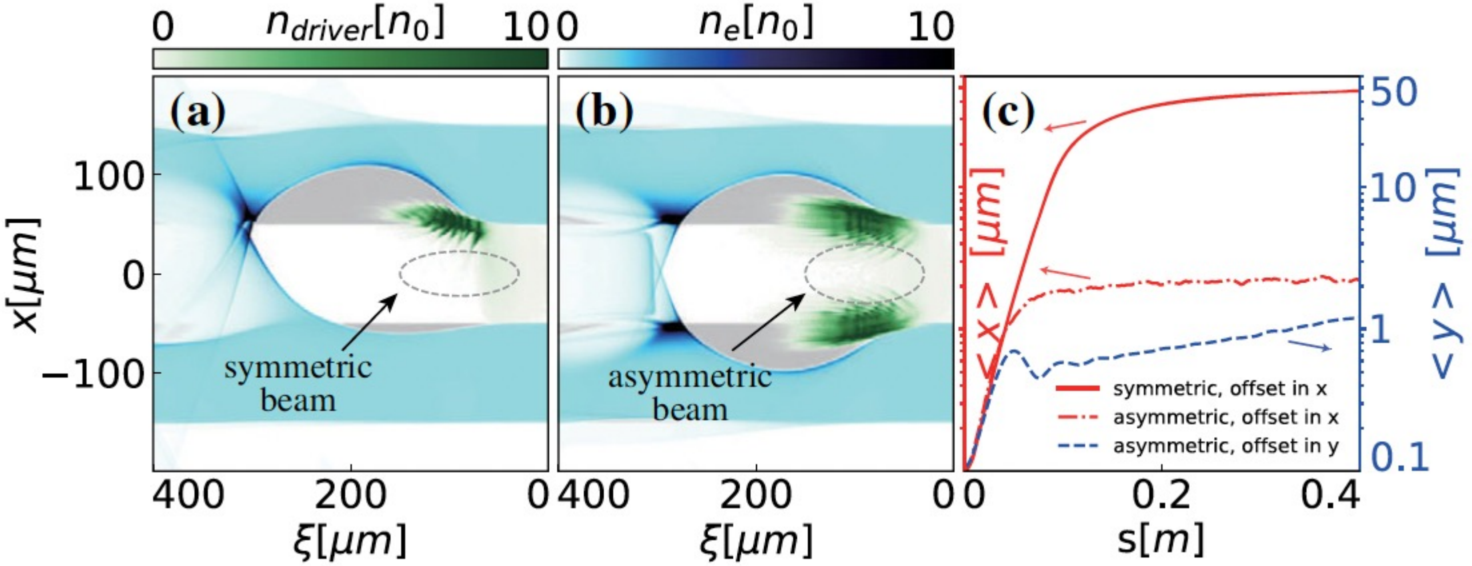
Asymmetric drive beams stabilize hollow core plasma accelerator



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

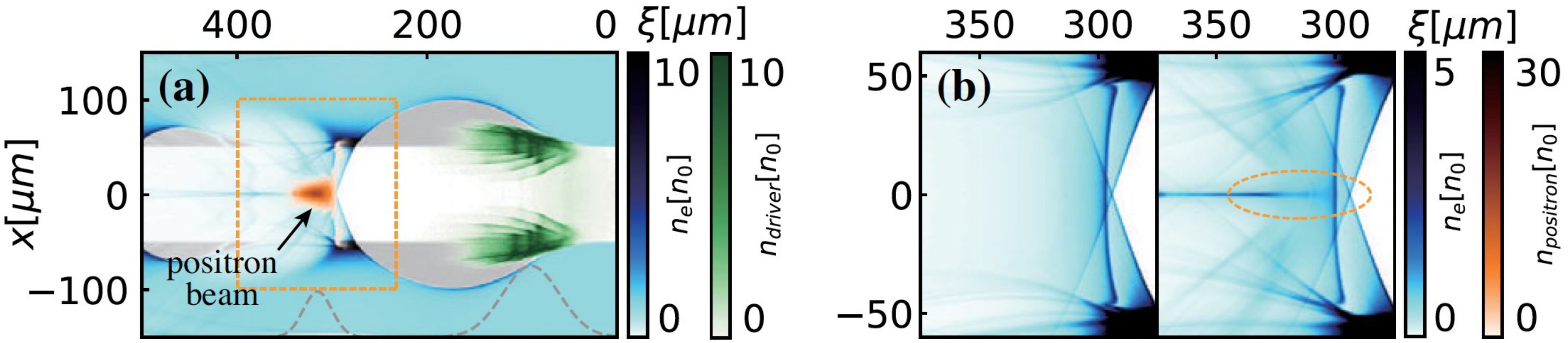


Quadrupole moment:
Drive beam hits channel wall
in a **controlled** manner

Stabilizes drive beam in hollow core channel!

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

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



Electron filament **stabilizes witness**

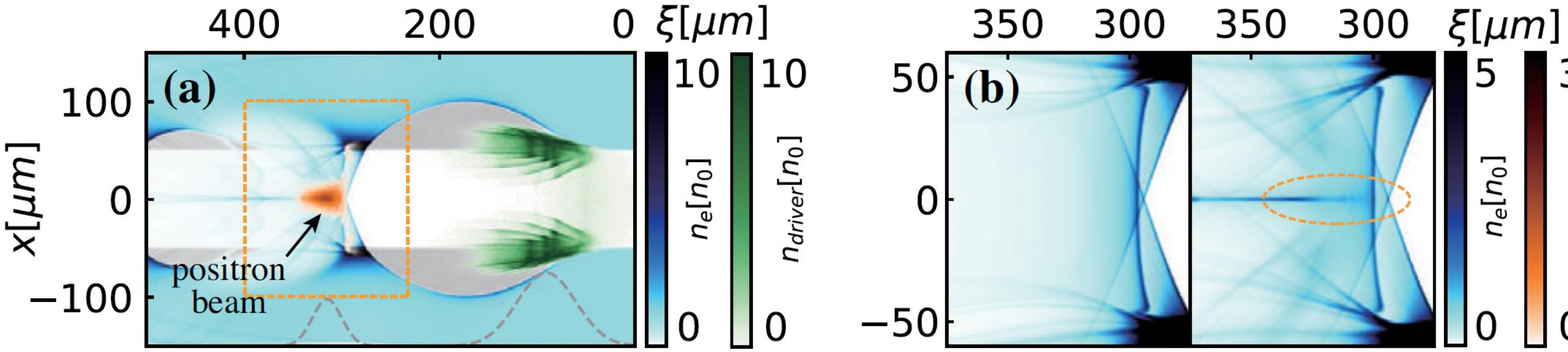
Zhou et al., PRL 127, 174801 (2021)

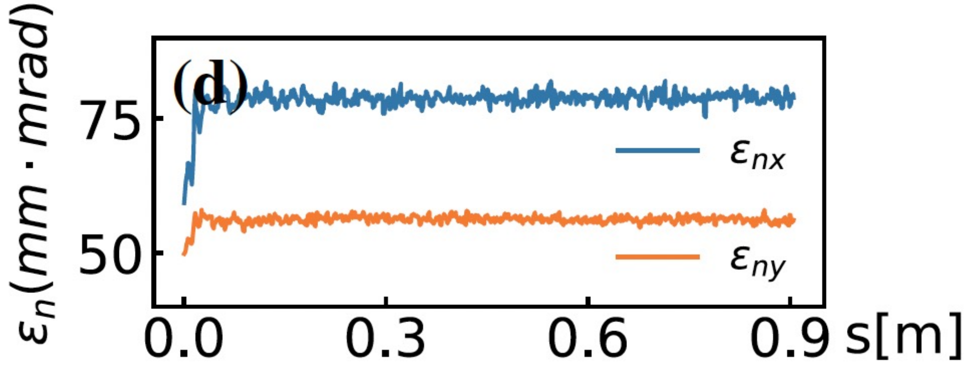
High-charge, low energy spread positron acceleration shown

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)

High-charge, low energy spread positron acceleration shown

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> 50 μm central slice emittance

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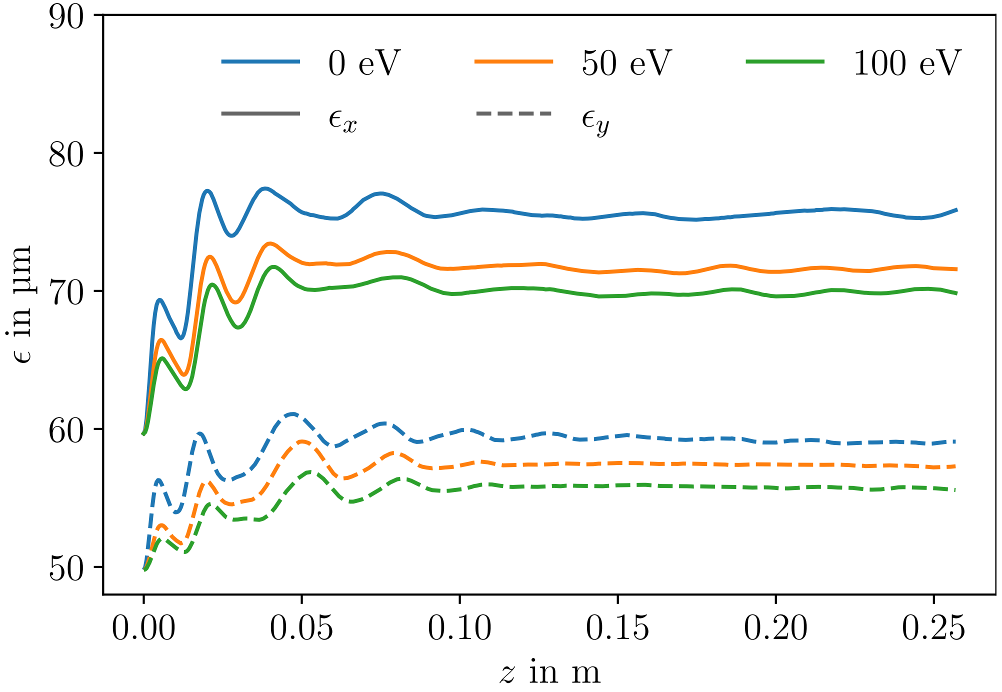
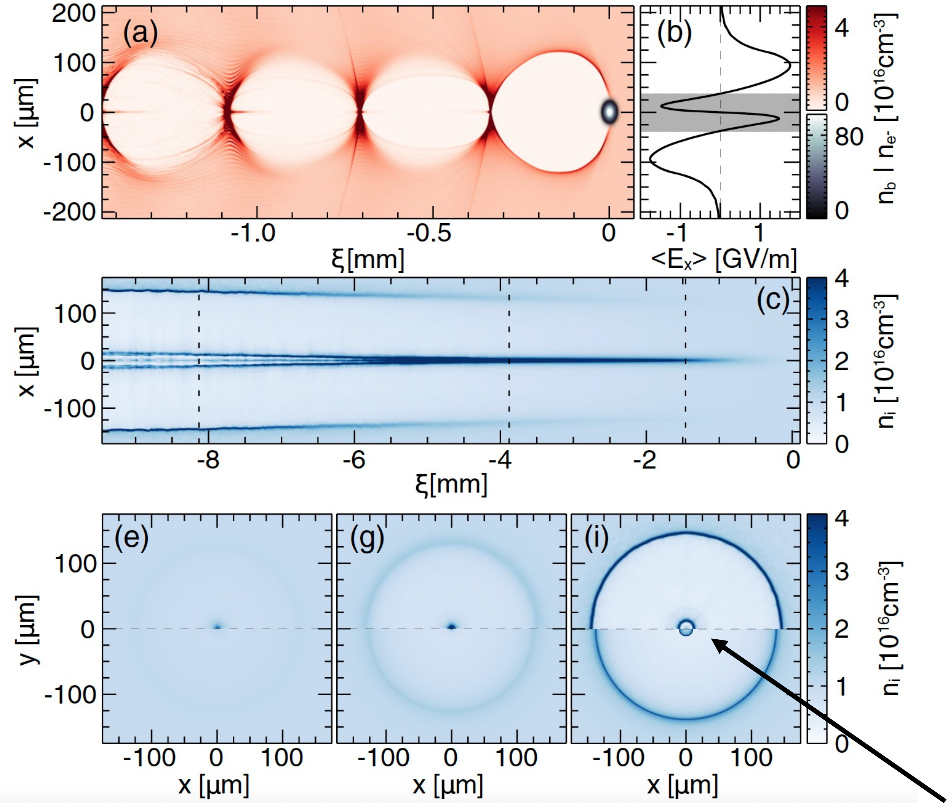
Temperature mitigates emittance growth



Zhou et al., PRL 127, 174801 (2021)
Diederichs et al. (in preparation)

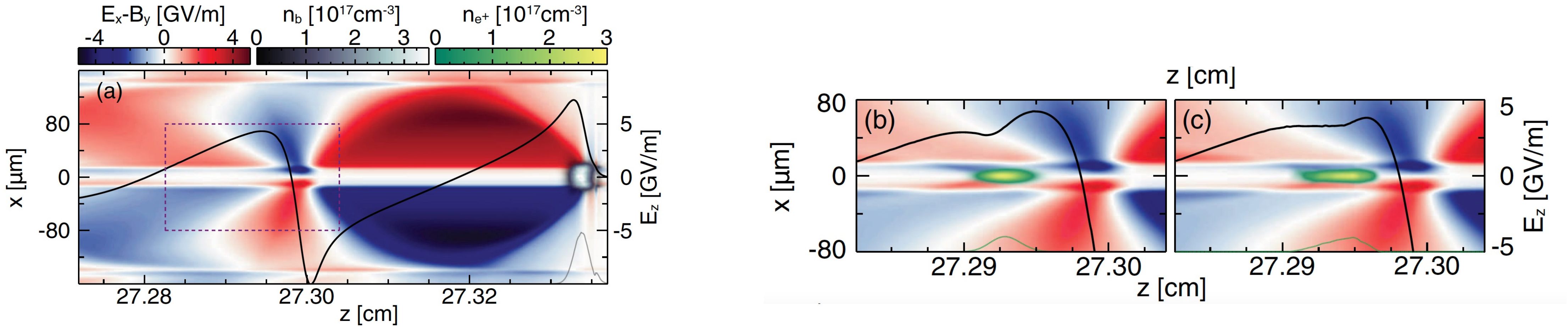
Blowout aftermath generates on-axis plasma filament



generates quasi-hollow
plasma channel

Silva et al., PRL 127, 104801 (2021)

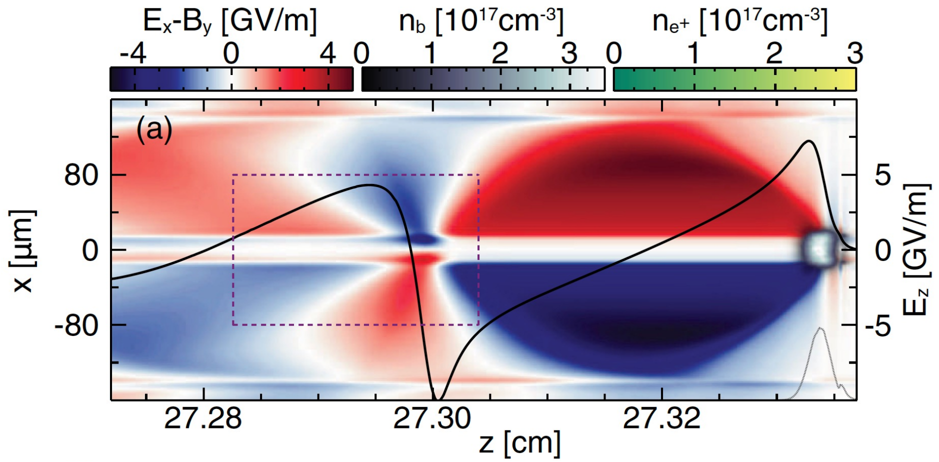
Blowout aftermath generates quasi-hollow plasma channel

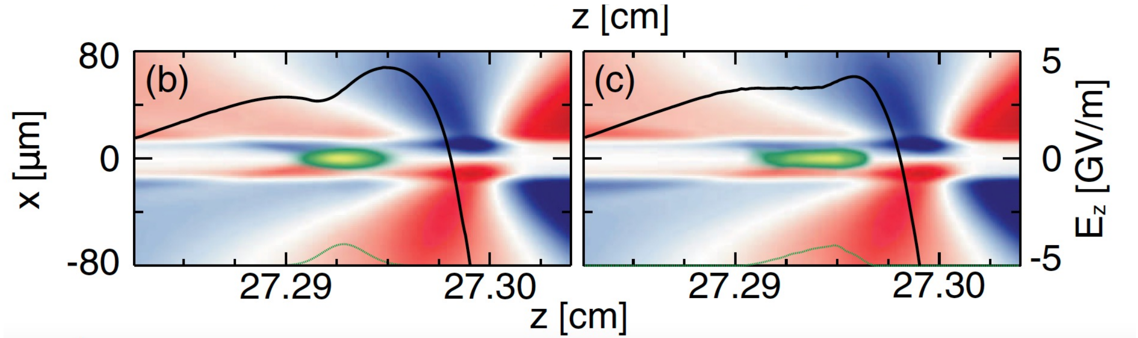


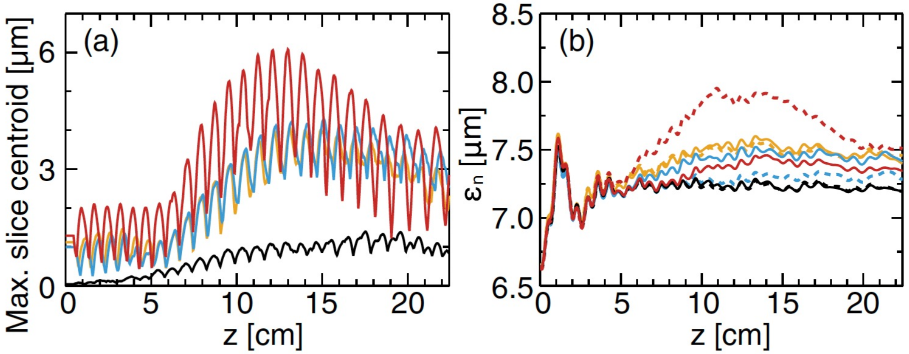
3.5 GV/m gradient
< 5% energy spread

Silva et al., PRL 127, 104801 (2021)

Blowout aftermath generates quasi-hollow plasma channel







3.5 GV/m gradient
< 5% energy spread
< 10μm emittance
Stability demonstrated

A lot of potential for optimization!

Silva et al., PRL 127, 104801 (2021)

There are more positron acceleration schemes…

Scheme	Highlights / Challenges	References
• (Quasi)-Linear wakes	Simple setup, high-charge, high beam quality challenging	Hue PRR 2022, Blue PRL 2003
• Long proton bunch	high, single-stage energy gain, emittance not yet studied	Lotov PPCF 2021
• Short proton bunch in hollow channel	high, single-stage energy gain, short proton bunches not yet available	Yi PRSTAB 2013, Yi Sci Rep 2014
• Ring-shaped drivers	Stability of driver challenging	Vieira PRL 2014, Jain PRL 2015 Hue PRR 2021
• Double column structure	Ring-shaped witness beams, emittance preservation unclear	Reichwein PRE 2022

Promising advances for plasma-based positron acceleration

Many **new concepts** have been developed!

1. Using electron filaments:

- **Low-emittance, low-energy-spread positron acceleration** is possible
- Longitudinally varying focusing fields **provide stability** via BNS damping
- **Temperature effects** are required for numerical convergence and improve emittance preservation
- All schemes can be optimized for **higher efficiency**

2. Hollow core plasmas are promising, realistic design with external focusing has highest priority

We need to perform the simulation study to reach the deliverable for the ESPP!