Positron acceleration in plasmas

S. Diederichs

Deutsches Elektronen-Synchrotron DESY, Germany
Lawrence Berkeley National Laboratory, USA
University of Hamburg, Germany

Advanced Accelerator Concepts Workshop
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A paradigm shift is needed in the accelerator technology

Snowmass 2021: **10+ TeV colliders** desired!

Conventional accelerators limited to
~100 MV/m accelerating gradient

Higgs Factories are already big!
ILC at 0.5 TeV: 31 km

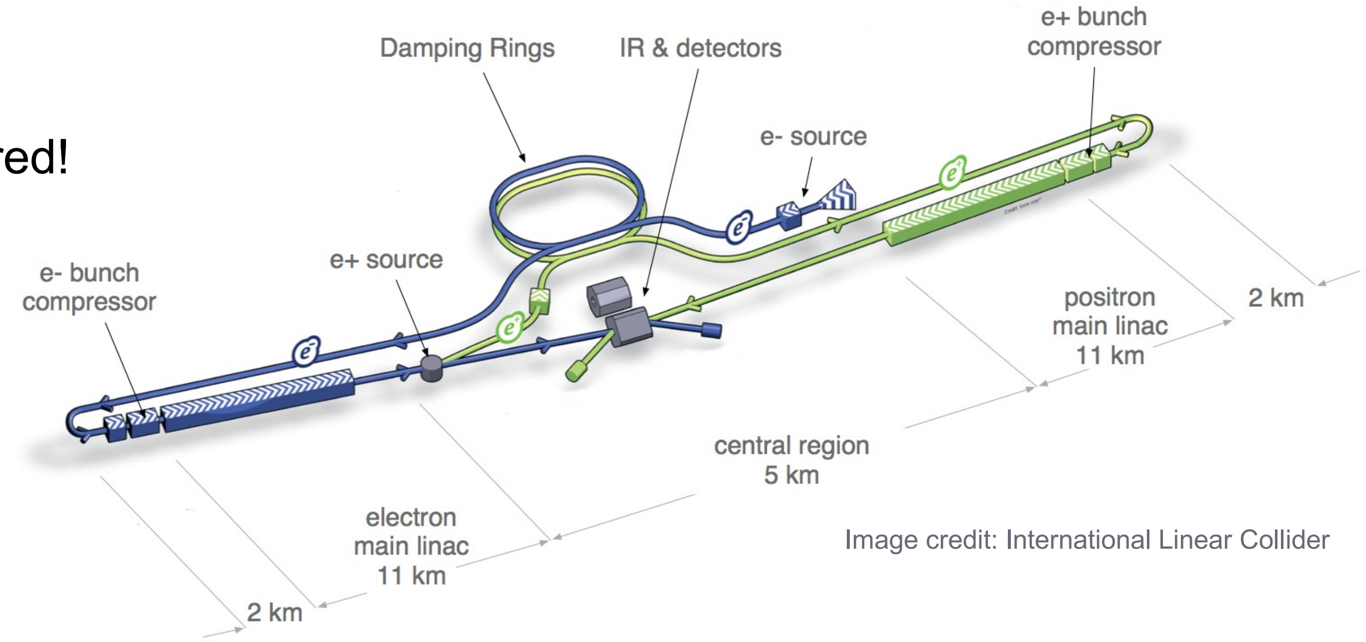


Image credit: International Linear Collider

New accelerator technologies will be needed for the 10-TeV scale!

Plasma accelerators provide extreme accelerating gradients

And potentially high-beam quality

A linear collider requires

1. High gradient (reduce the construction costs) $>$ GV/m
2. Low emittance (ability to focus the beam) $<$ 100 of nm
3. Low energy spread (ability to focus the beam) $<$ 1%
4. Stability
5. High wall-plug efficiency (reduce run time costs) $>$ 20%

Plasma accelerators provide extreme accelerating gradients

And potentially high-beam quality for electrons

A linear collider requires

			Electrons
1. High gradient (reduce the construction costs)	> GV/m	→	Gonsalves PRL 2019: 40 GV/m
2. Low emittance (ability to focus the beam)	< 100 of nm	→	Plateau PRL 2012: ~ 100 nm
3. Low energy spread (ability to focus the beam)	< 1%	→	Lindstrøm PRL 2021: < 1%
4. Stability		→	Maier PRX 2020
5. High wall-plug efficiency (reduce run time costs)	> 20%	→	Lindstrøm PRL 2021: > 40% wake-to-beam efficiency

Plasma accelerators provide extreme accelerating gradients

But preserving beam quality is challenging for positrons

A linear collider requires

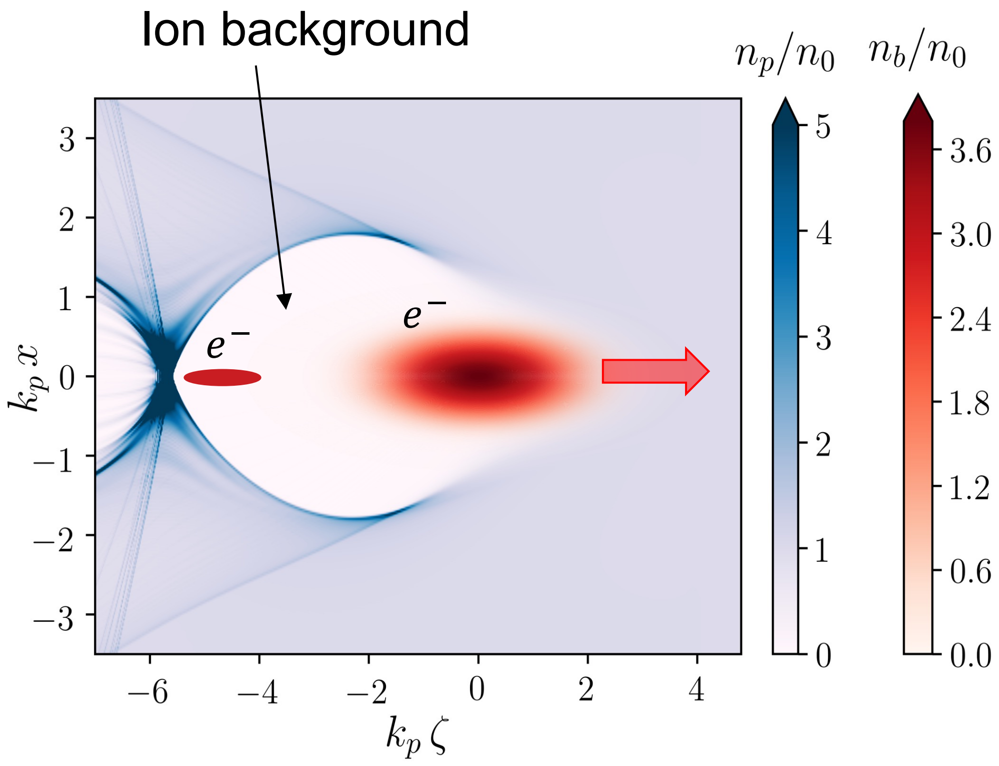
			Positrons
1. High gradient (reduce the construction costs)	$>$ GV/m	$\rightarrow$	Corde Nature 2015: $>$ 3.8 GV/m
2. Low emittance (ability to focus the beam)	$<$ 100 of nm	$\rightarrow$	✗
3. Low energy spread (ability to focus the beam)	$<$ 1%	$\rightarrow$	Doche Sci. Rep. 2017: ~ few %
4. Stability		$\rightarrow$	Lindstrøm PRL 2018 ✗
5. High wall-plug efficiency (reduce run time costs)	$>$ 20%	$\rightarrow$	Doche Sci. Rep. 2017: $>$ 30% wake-to-beam efficiency

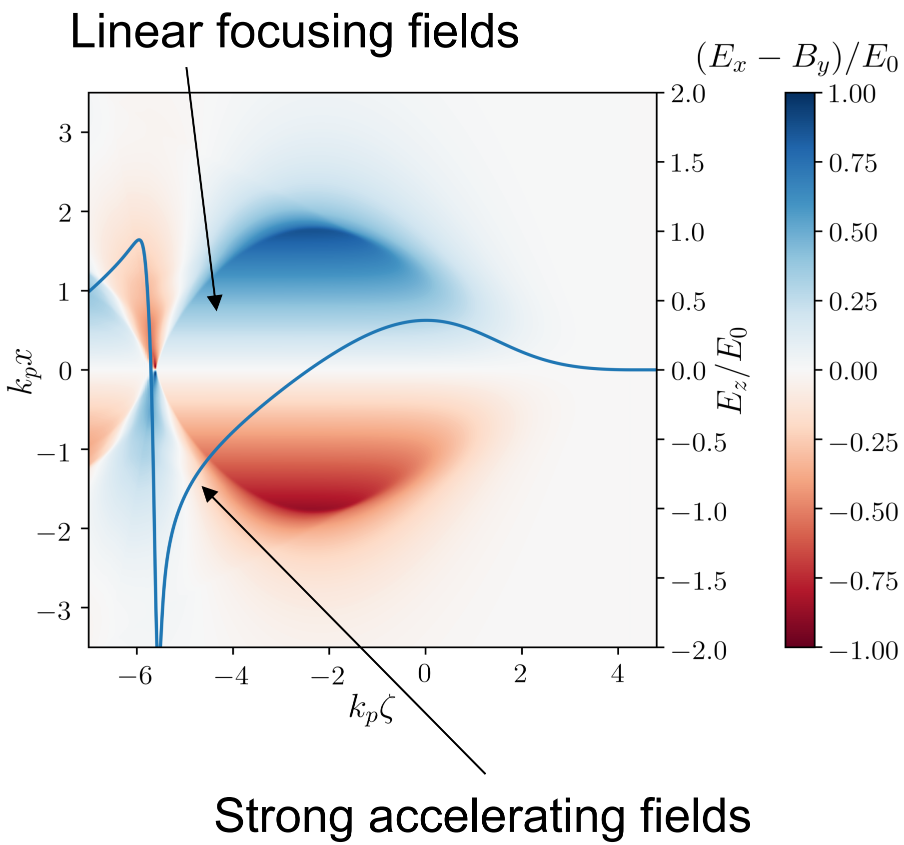
Emittance preservation challenging…
New concepts needed!

Outline

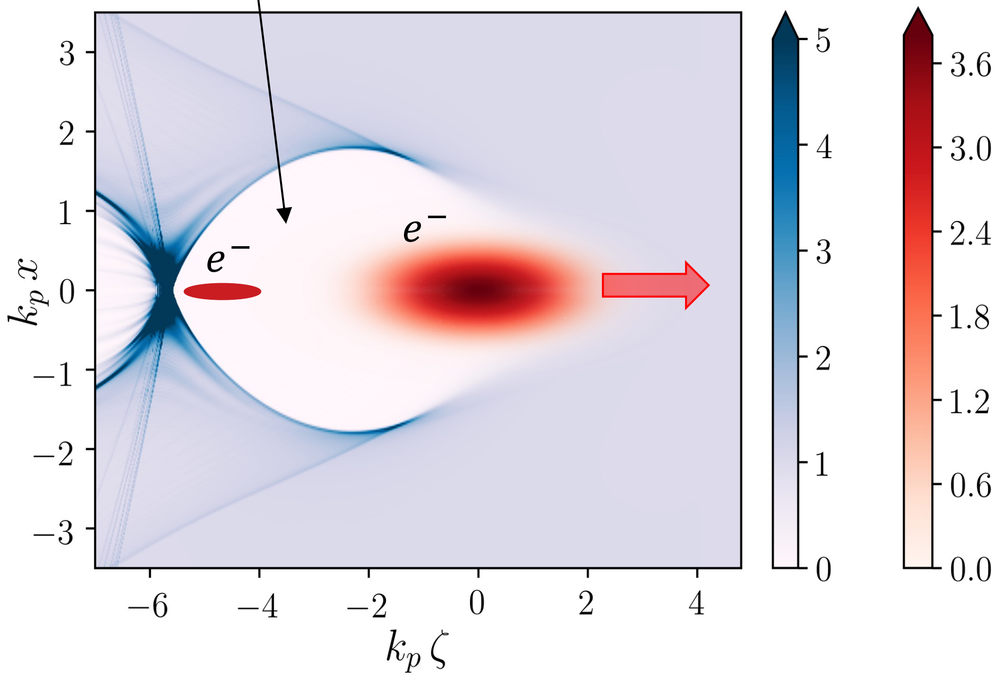
1. The challenge of positrons
2. Positron acceleration in electron filaments
3. Positron acceleration in hollow core plasmas
4. Conclusion and outlook

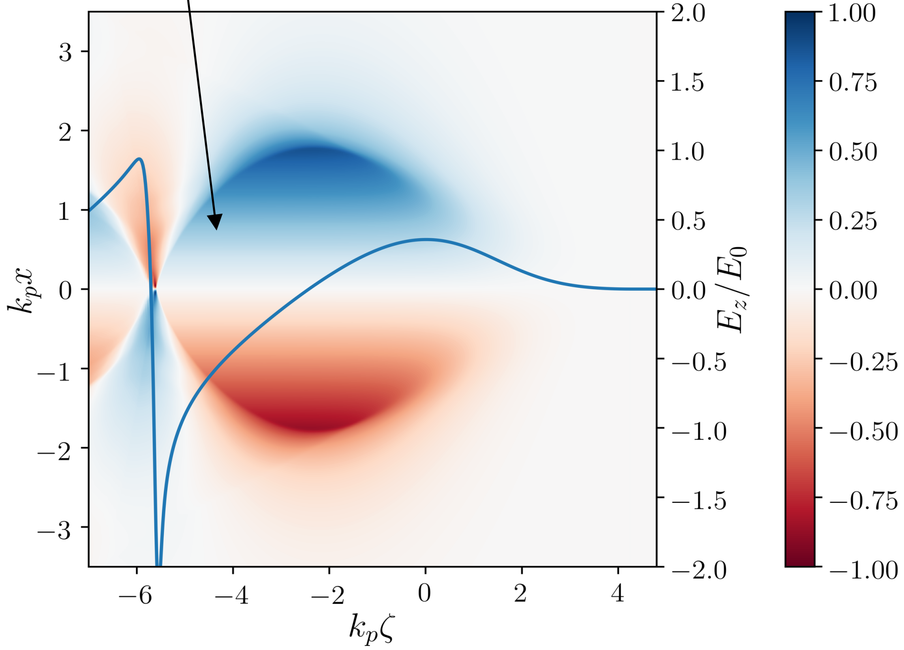
Plasma wakefield accelerators enable high-quality, high-gradient *electron* acceleration…





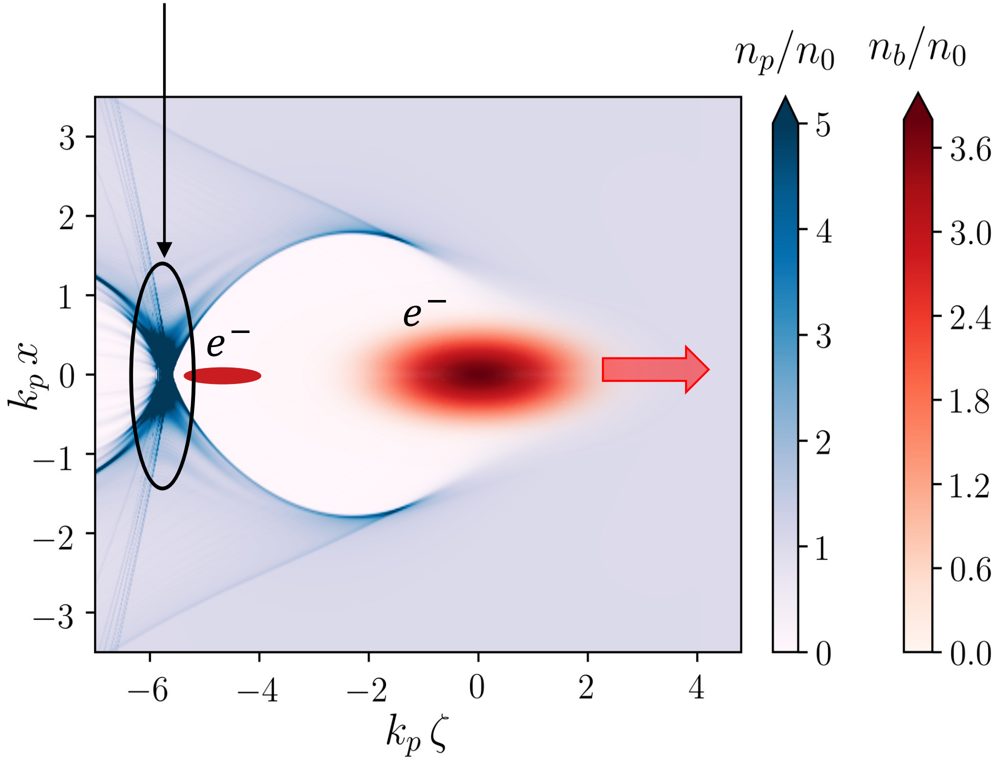
… but the ions defocus the positrons



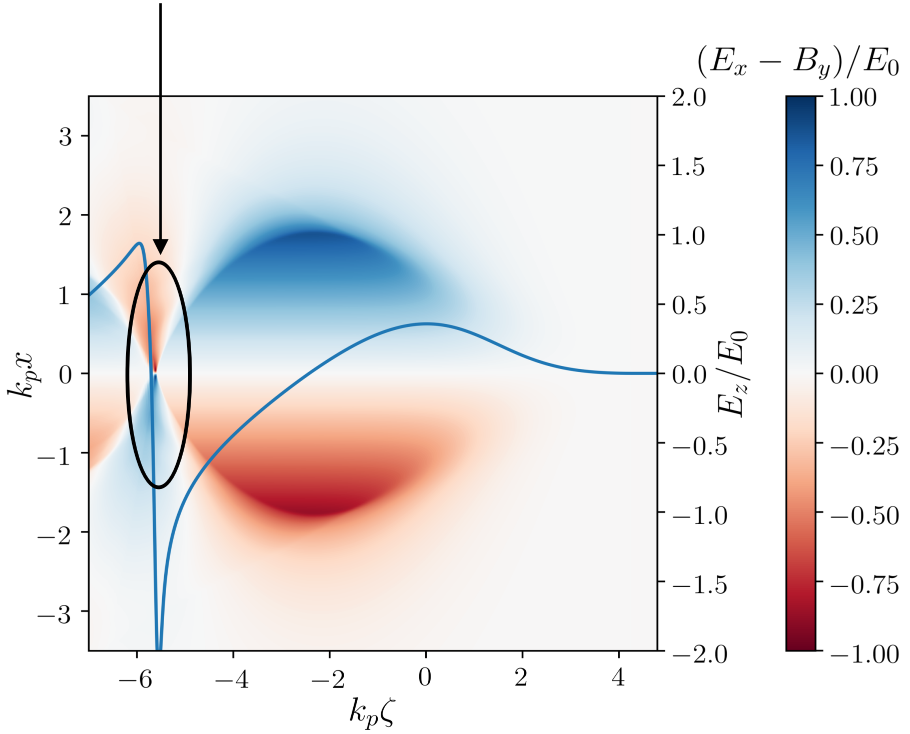


The electron spike at the back of the bubble enables positron acceleration

High density electron cusp



Focusing field for positrons



Positioning of the witness bunch challenging
Lotov, PoP 14, 023101 (2007)

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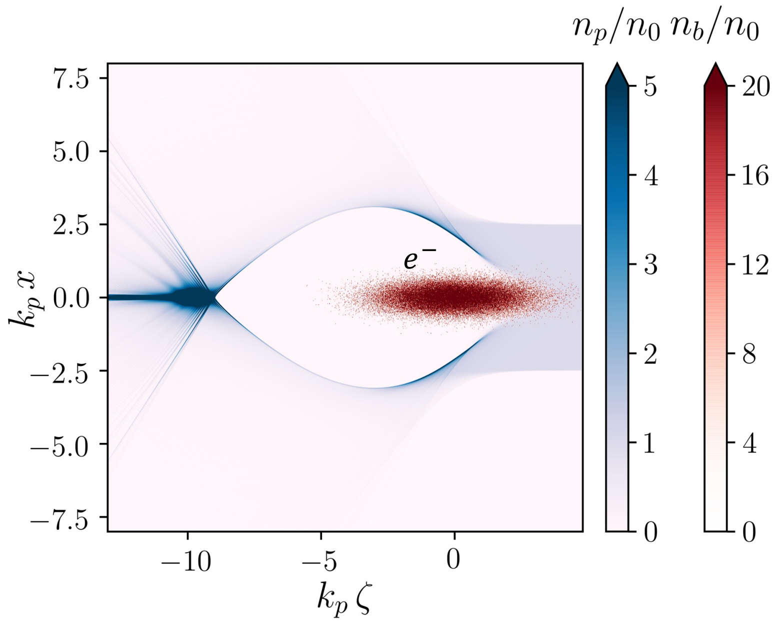
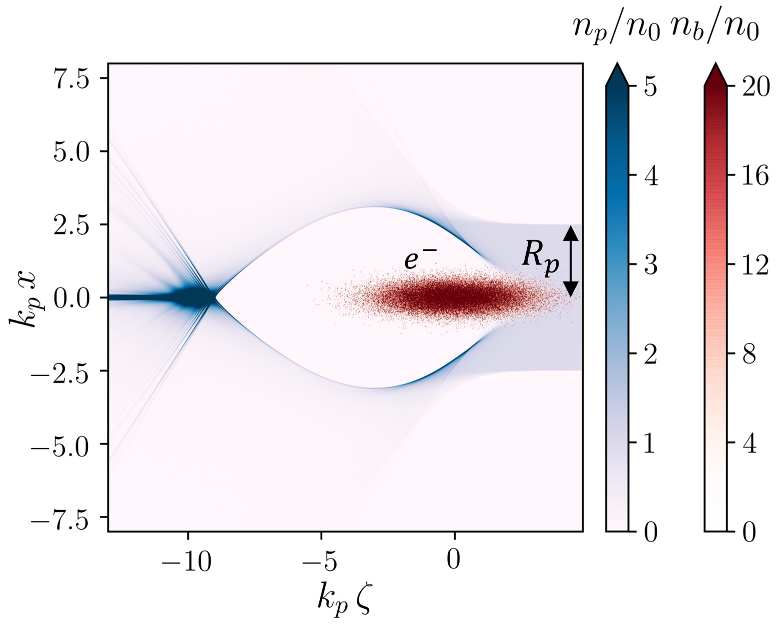


Elongated plasma electron trajectories induce positron acc. field

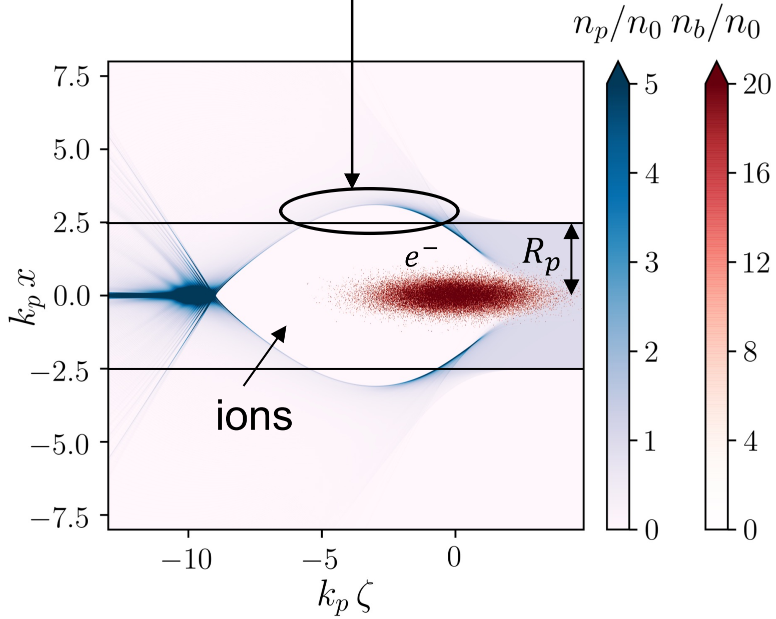
in pre-ionized plasma columns



Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns

1. Lack of ions outside the column



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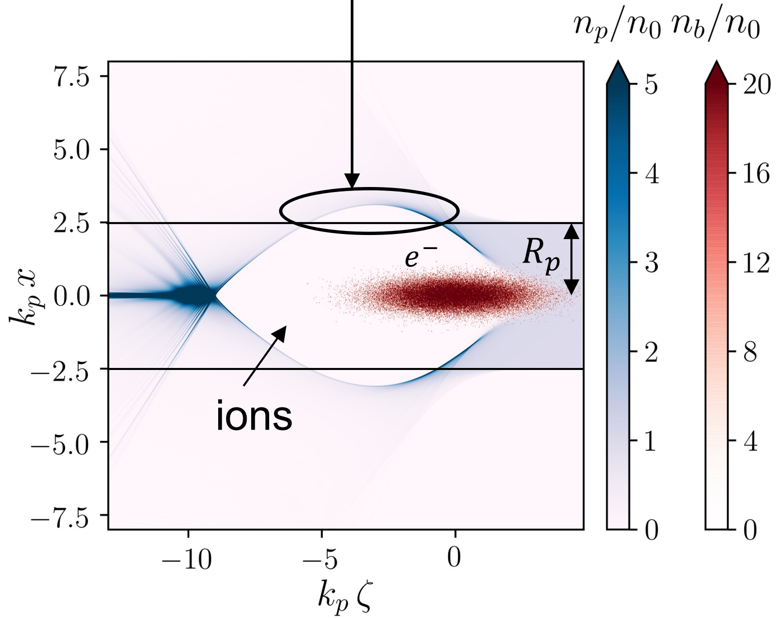
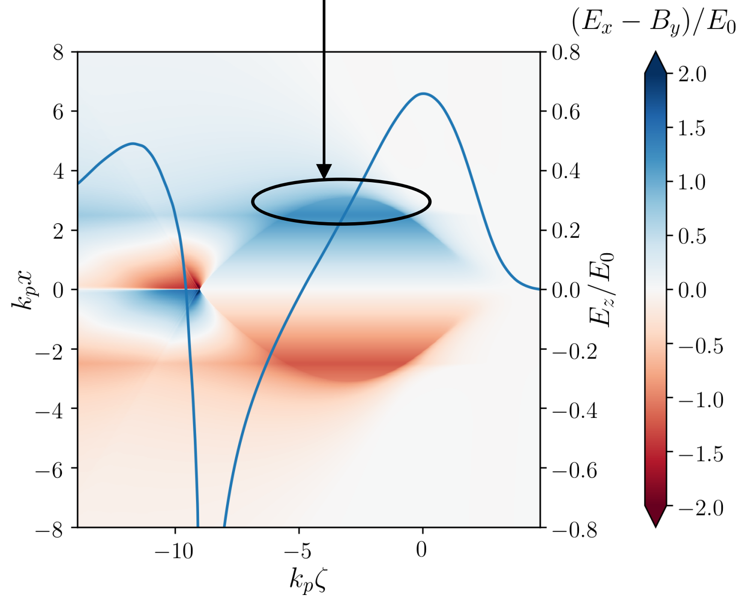


2. Reduced transverse wakefield



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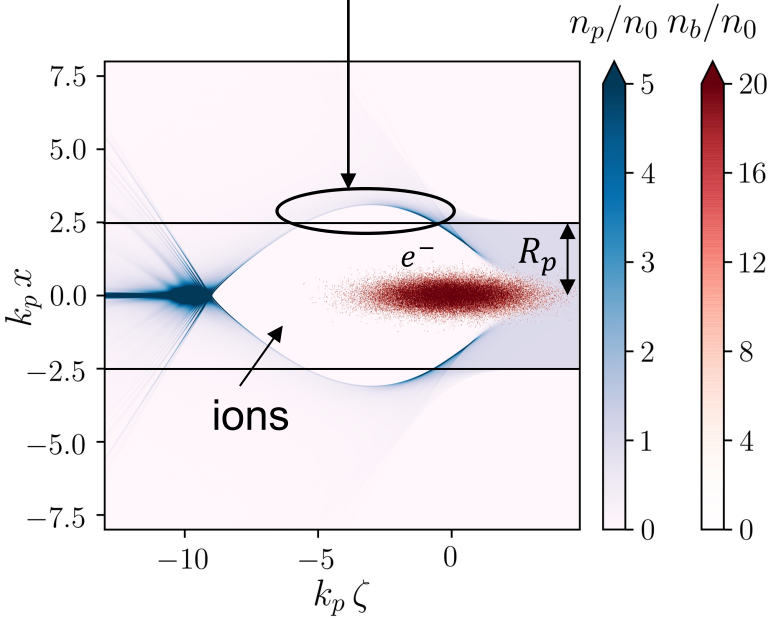

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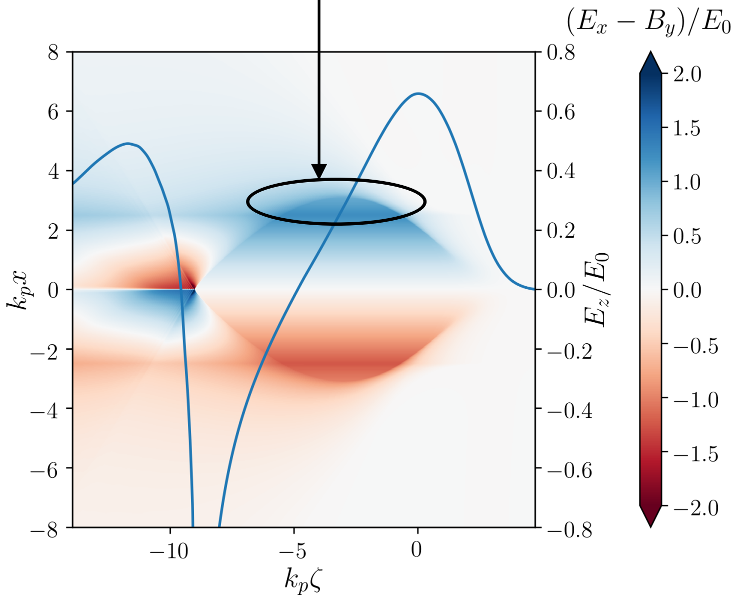
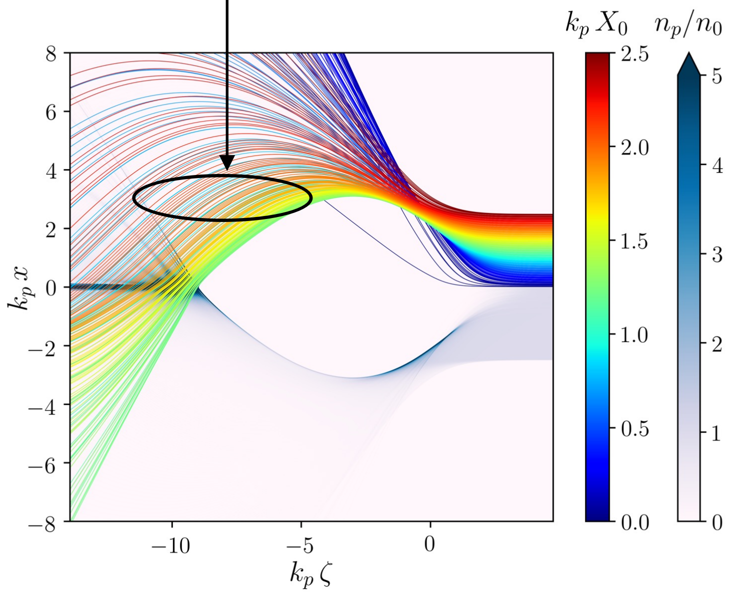


3. Elongated electron trajectories



Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns

1. Lack of ions outside the column

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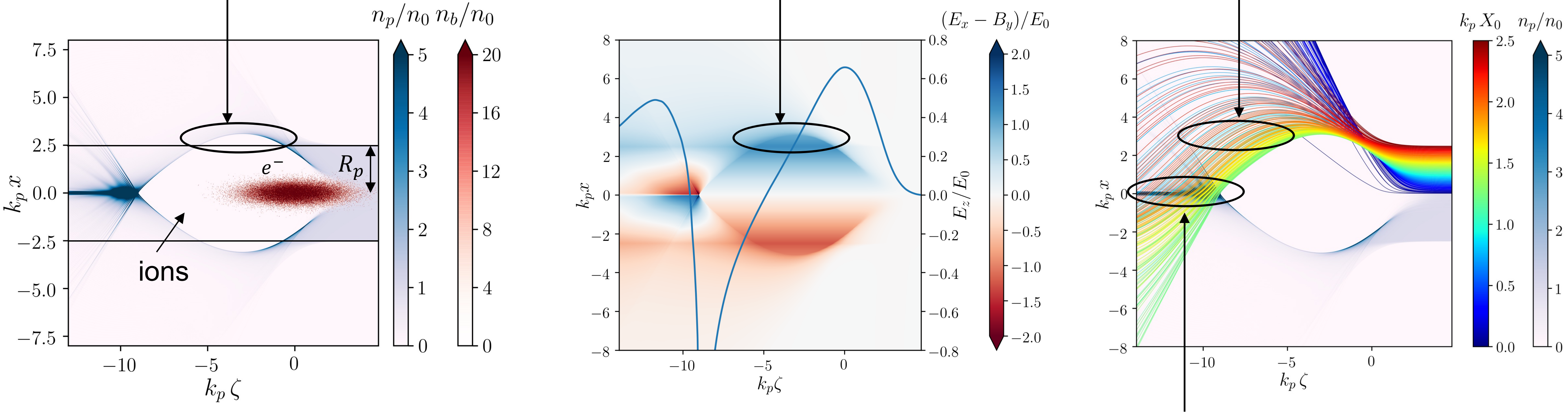
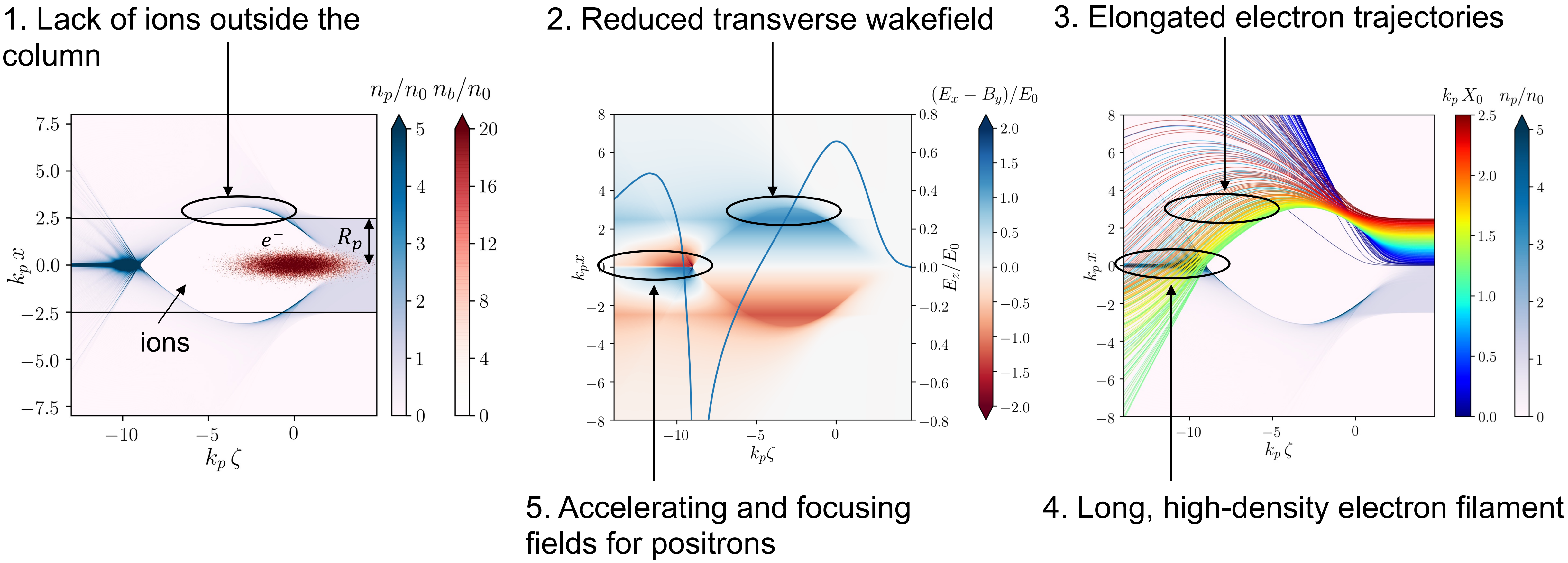
3. Elongated electron trajectories



4. Long, high-density electron filament

Elongated plasma electron trajectories induce positron acc. field

in pre-ionized plasma columns



Diederichs et al., PRAB 2019

Reminder: high beam quality demanded

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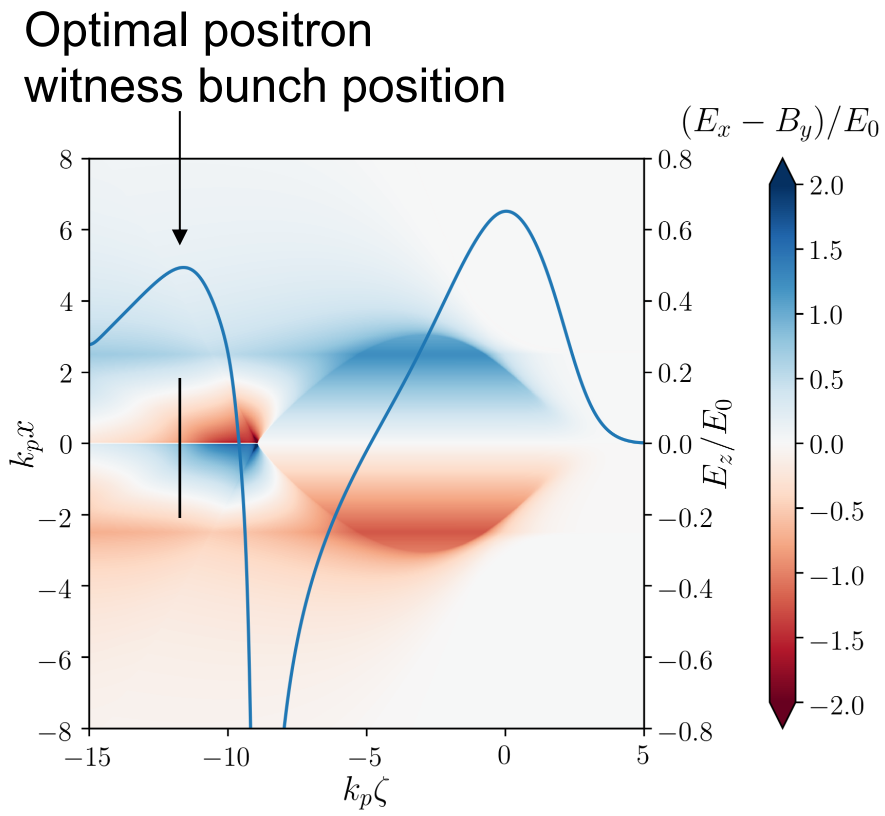
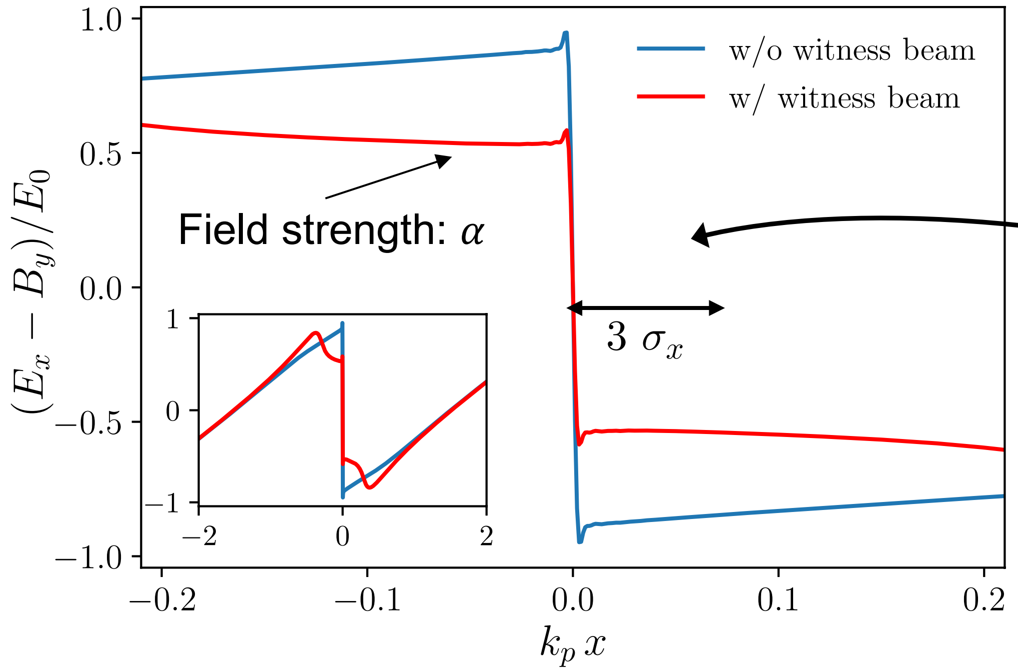
DESY. severin.diederichs@desy.de

Emittance preservation achievable with matched beams



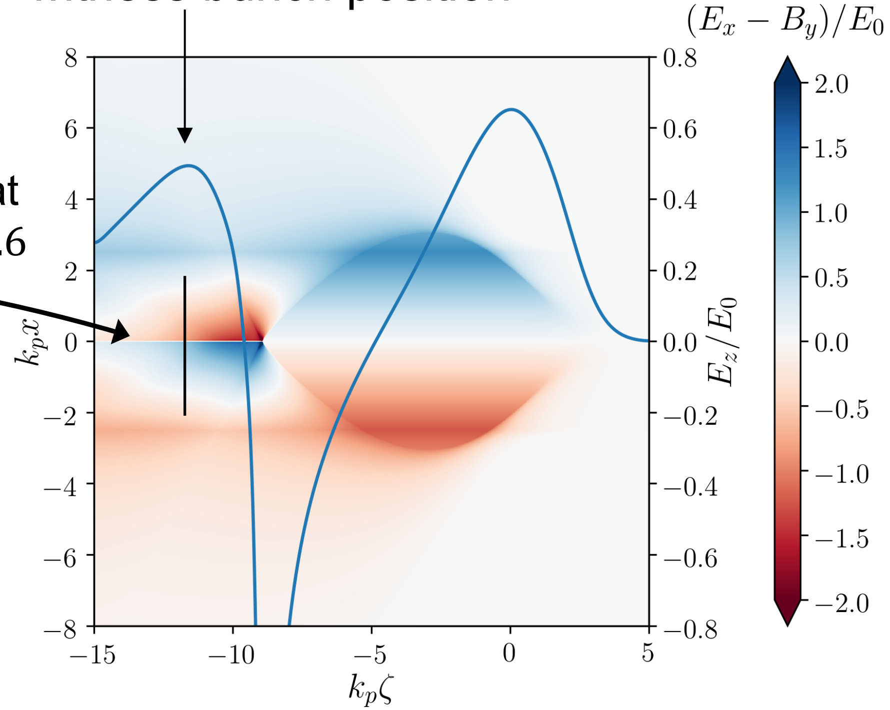
Emittance preservation achievable with matched beams

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?

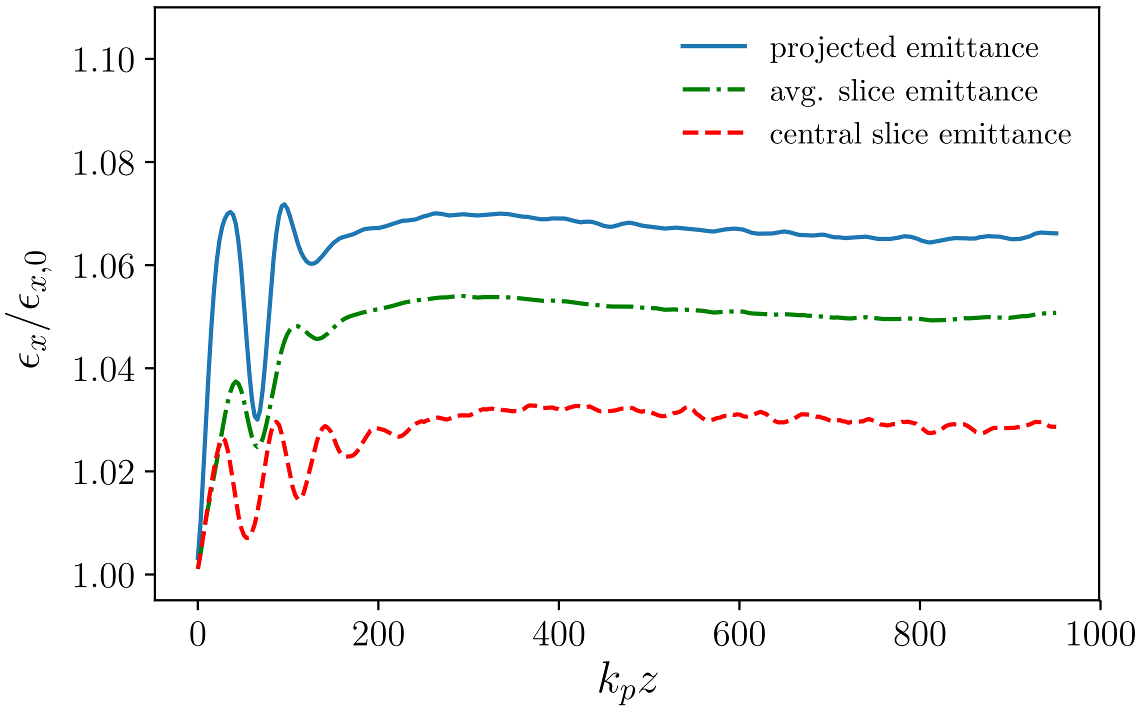
Demonstration of emittance-preserving positron acceleration

Results of PIC simulation

Emittance growth
Theory (2D): $\approx 2\%$
Simulation:
$\rightarrow$ quasi-matched central slice: $\approx 3\%$
$\rightarrow$ total (projected) bunch: $\approx 7\%$

At $n_0 = 5\times10^{17}\ \mathrm{cm}^3$: $\epsilon_{x,0} = 0.7\mu m$

Positron beam emittance evolution

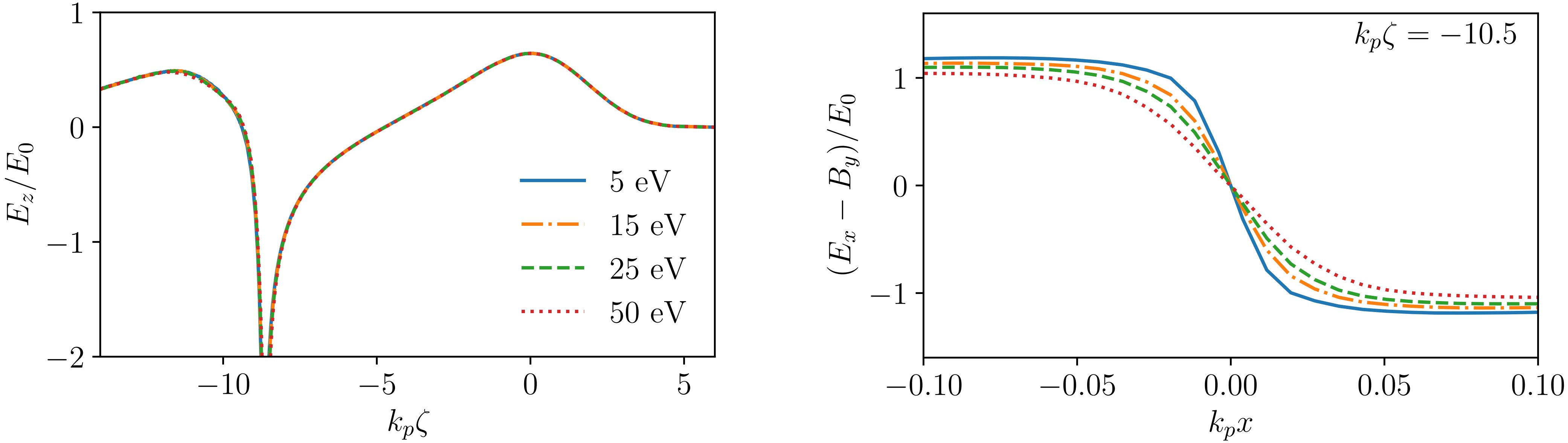


C. Benedetti et al., PRAB 2017
S. Diederichs et al., PRAB 2019

Finite temperature linearizes focusing field

Work in progress

High resolution simulation with HiPACE++ (3D)



Even better for emittance preservation!

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

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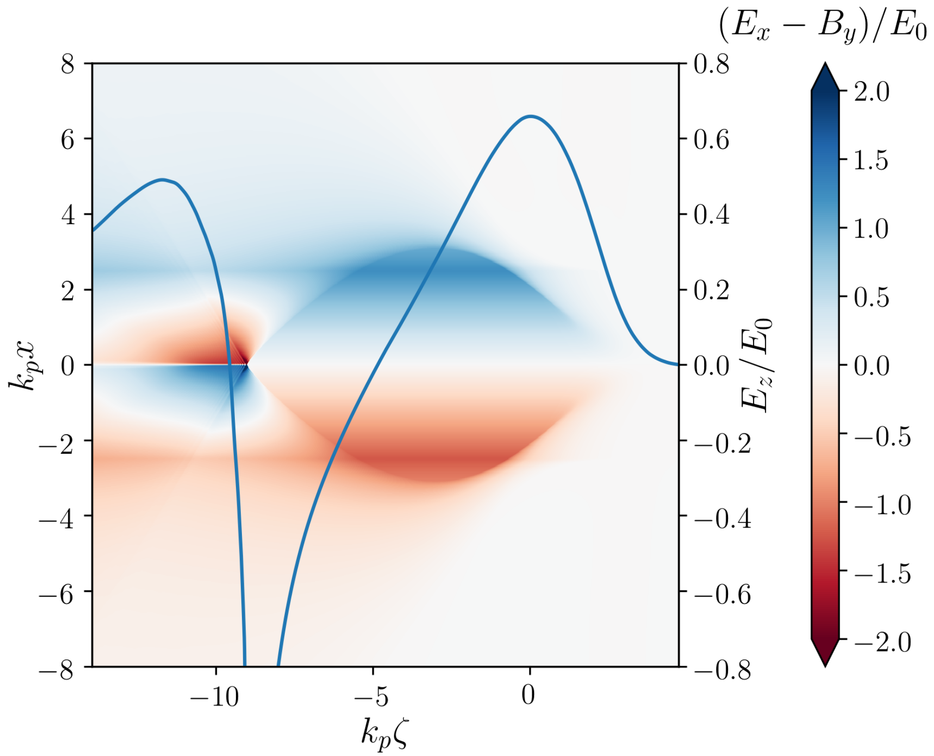
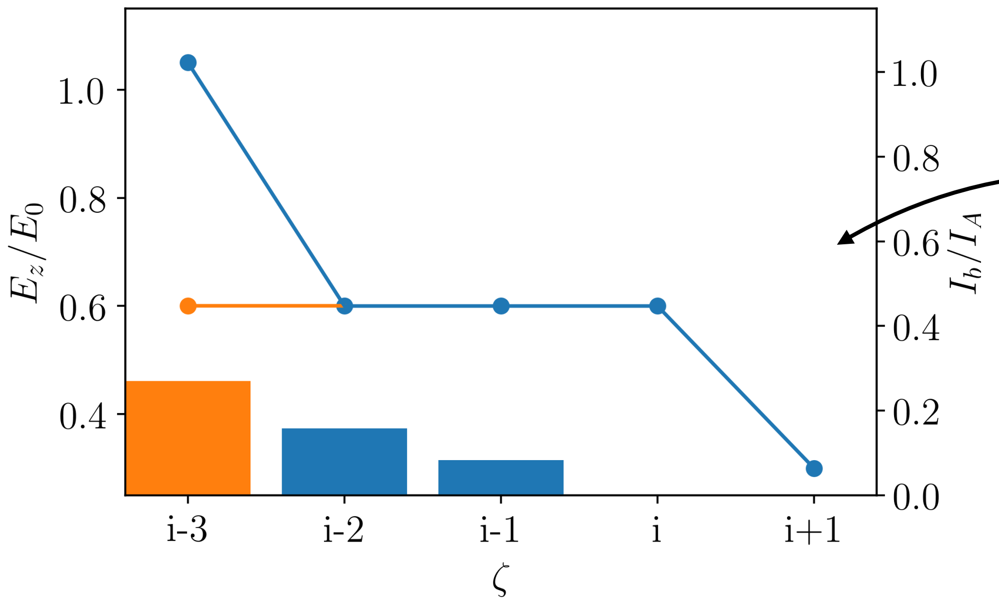
5. High wall-plug efficiency (reduce run time costs)	> 20%

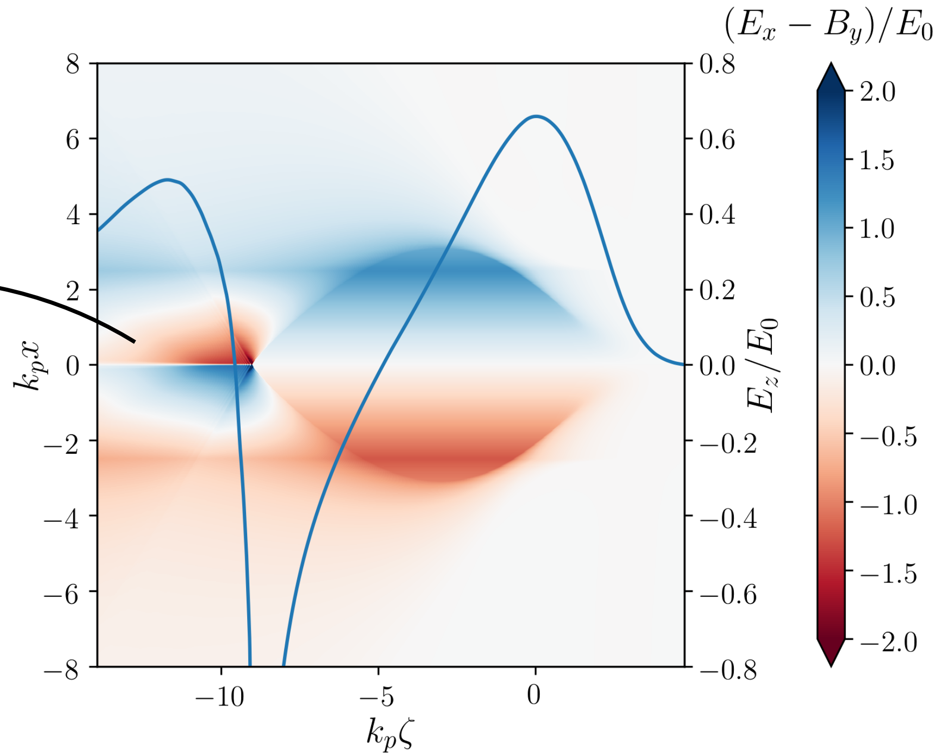
Positron accelerating field is non-uniform



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

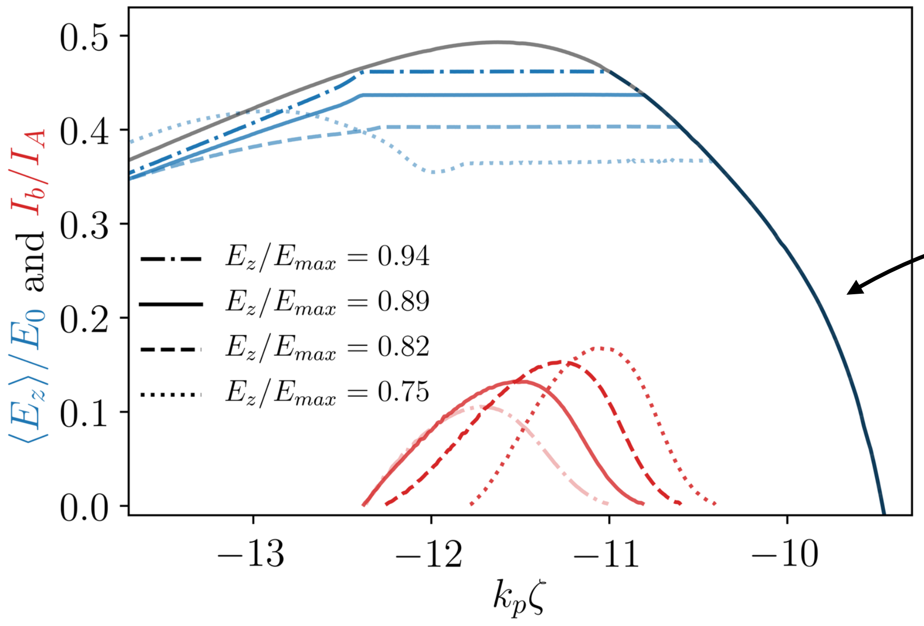
Slicing Advanced Loading Algorithm for Minimizing Energy spread (SALAME)



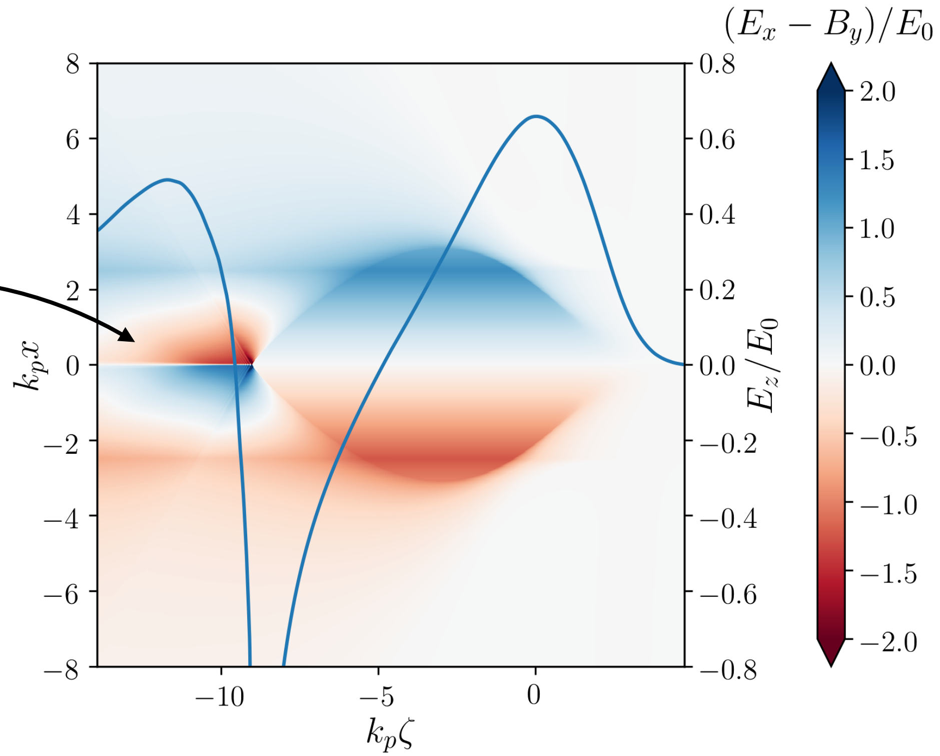


More information on the algorithm:
Diederichs et al., PRAB 2020
Lotov, PoP 12, 053105 (2005)
Lotov, PoP 14, 023101 (2007)

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



SALAME



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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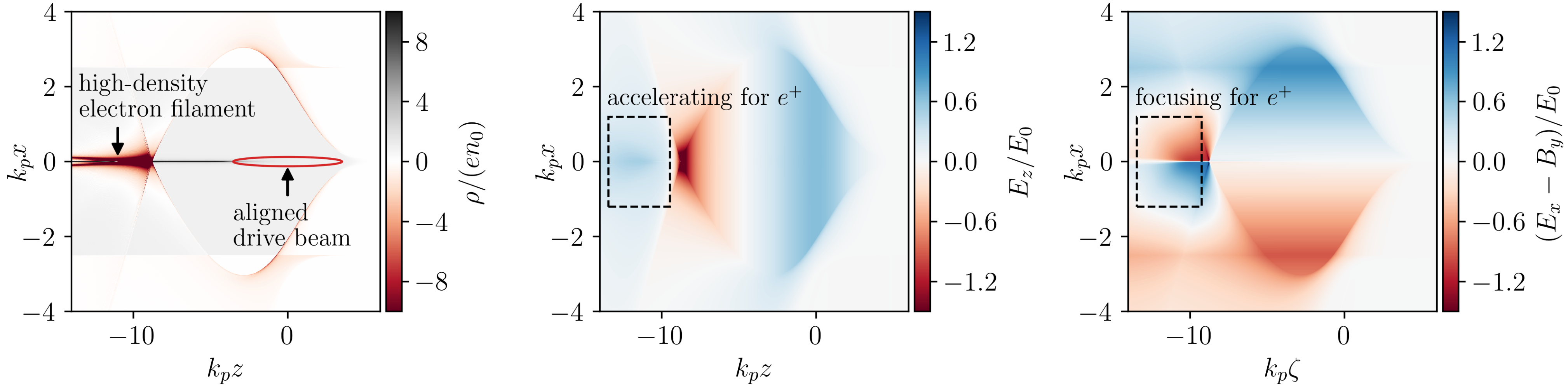
Beam stability is crucial because the scheme relies on cylindrical symmetry



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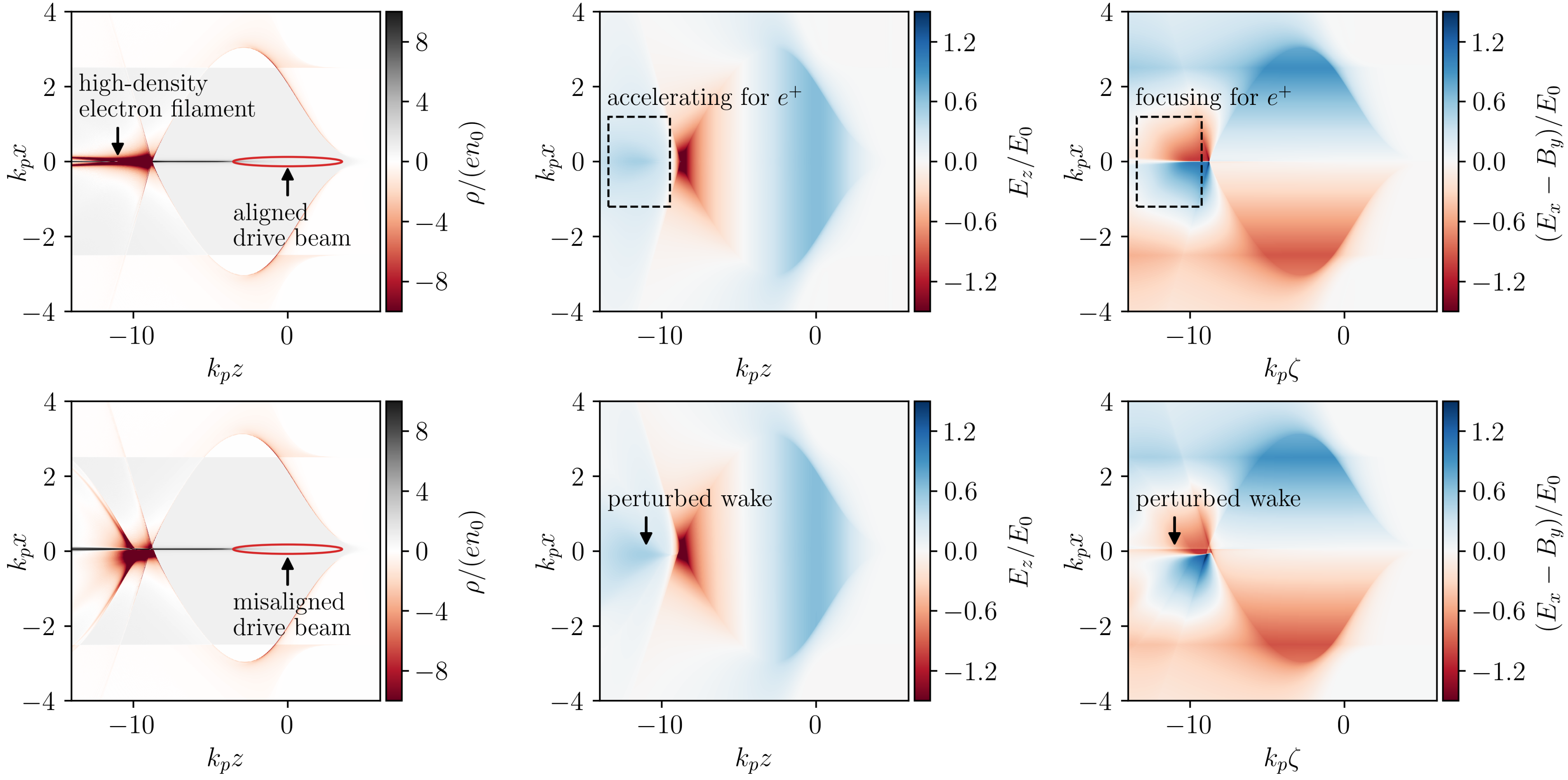
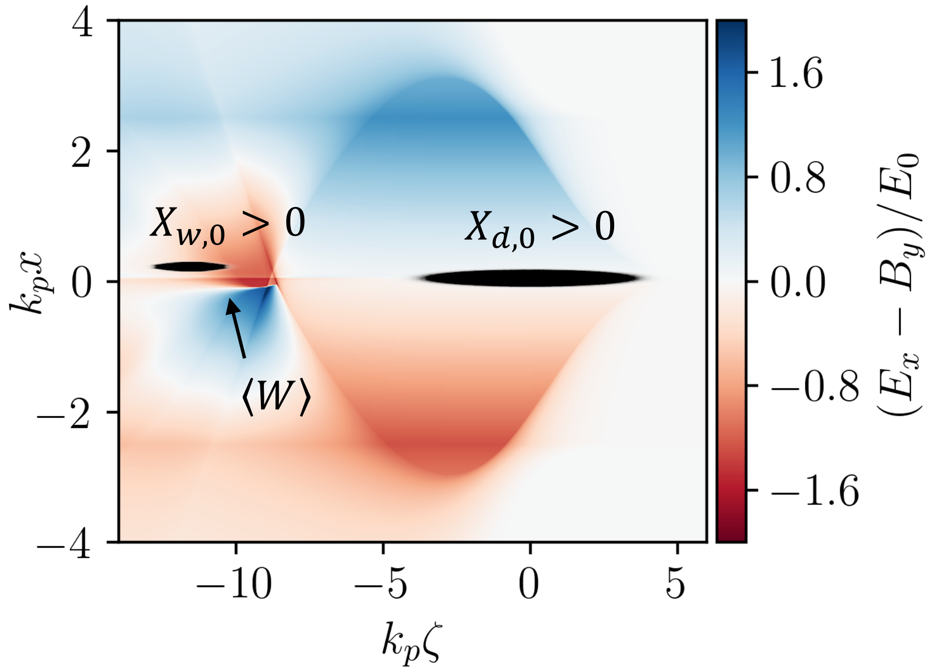
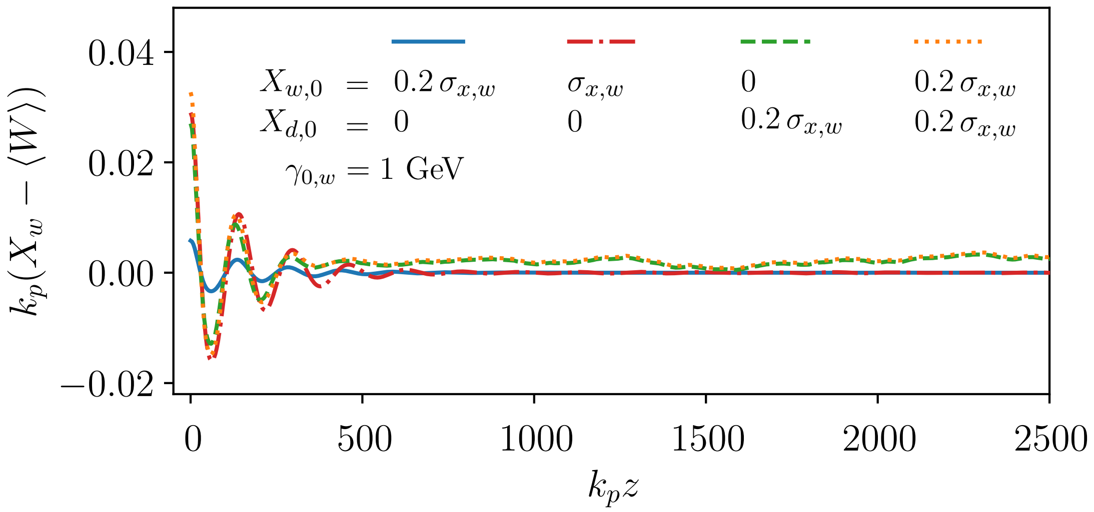


Witness beam is not susceptible to hosing





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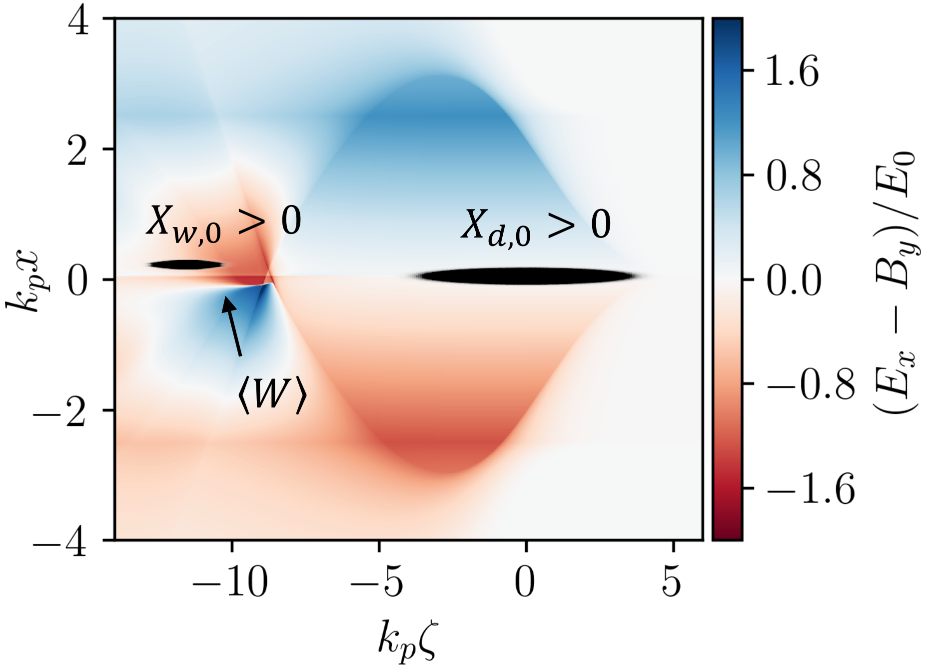
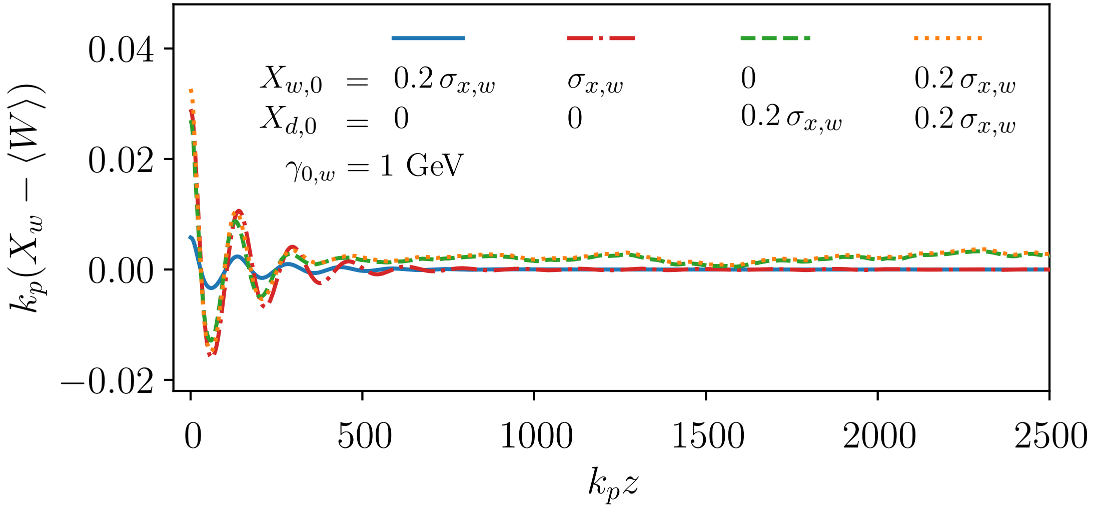
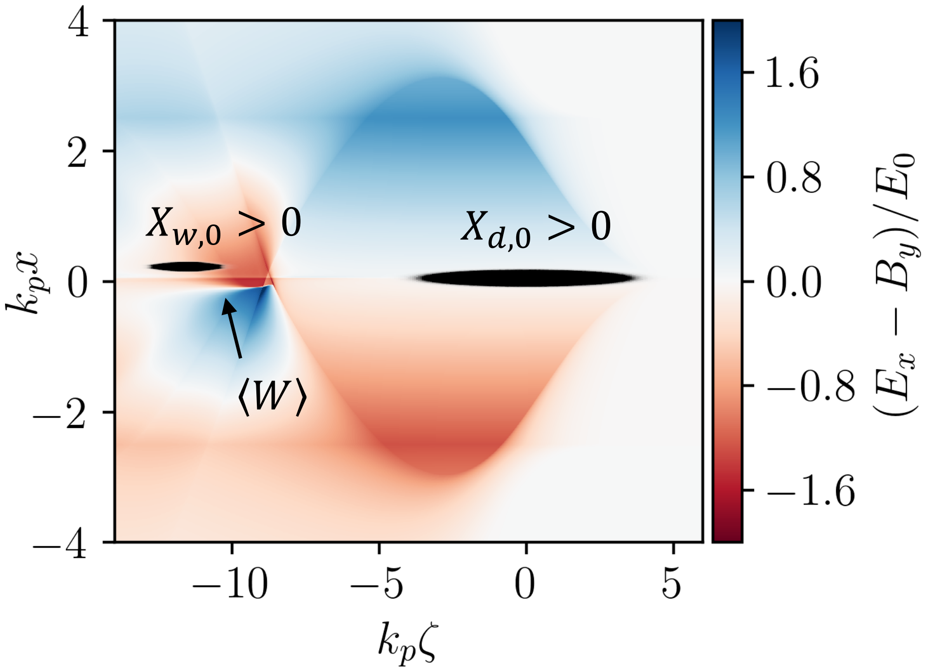




Hosing is prevented for 2 reasons:

1. **Longitudinally varying focusing field**
2. Phase-mixing per slice

Witness beam is not susceptible to hosing



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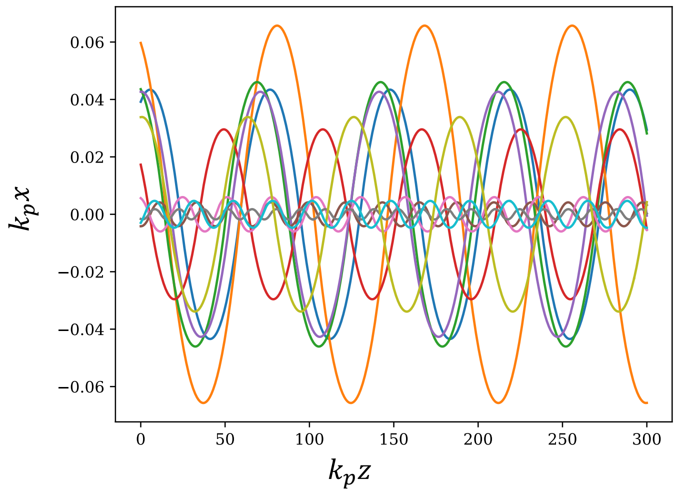
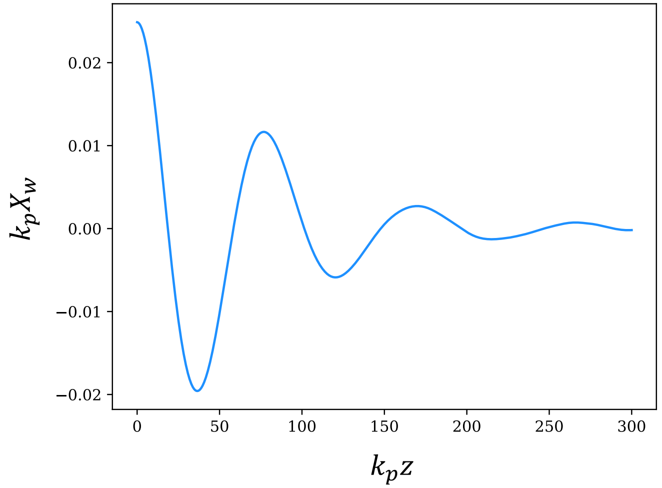
Single-particle trajectories



Bunch centroid trajectory

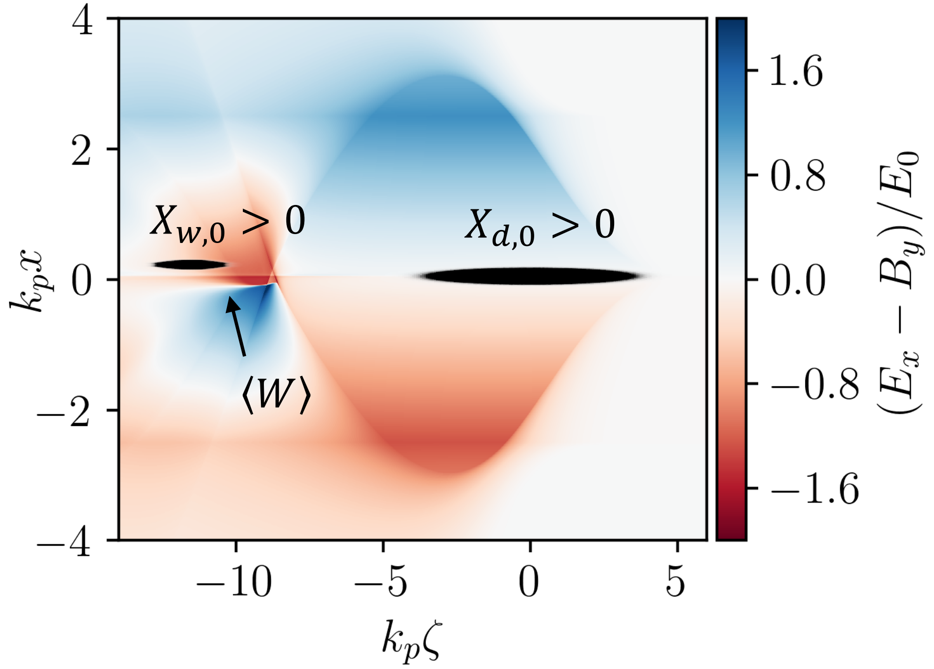


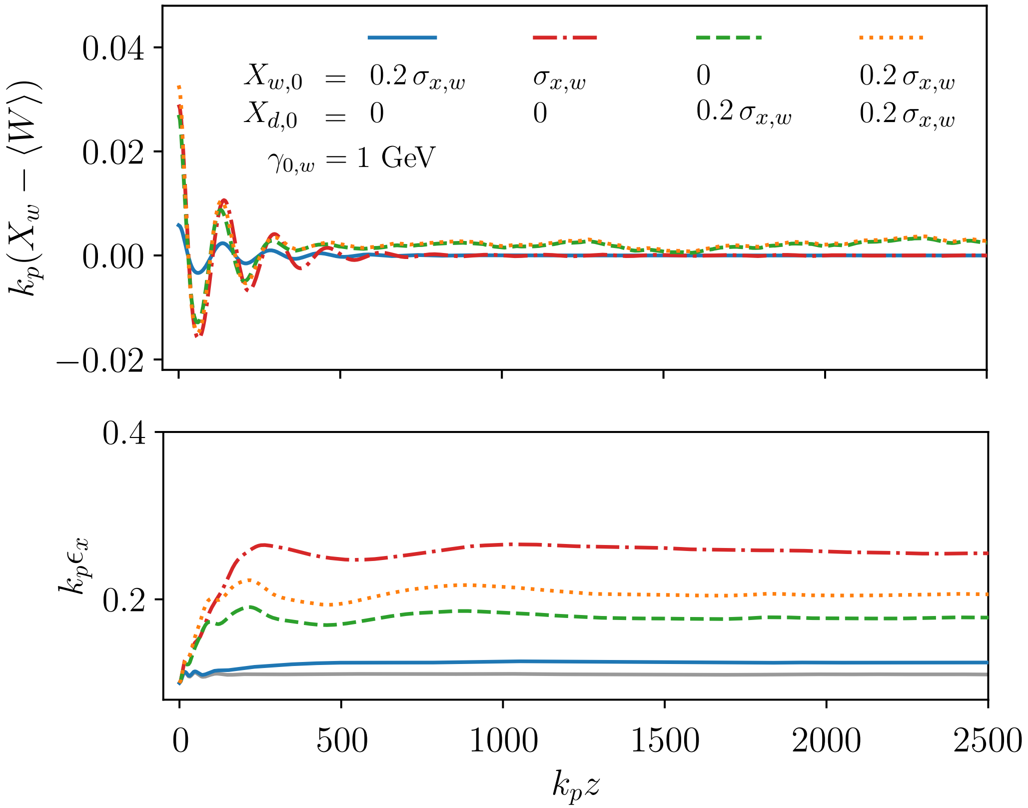
1D beam in step-like field with field strength α

Damping length:

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

Witness beam is not susceptible to hosing



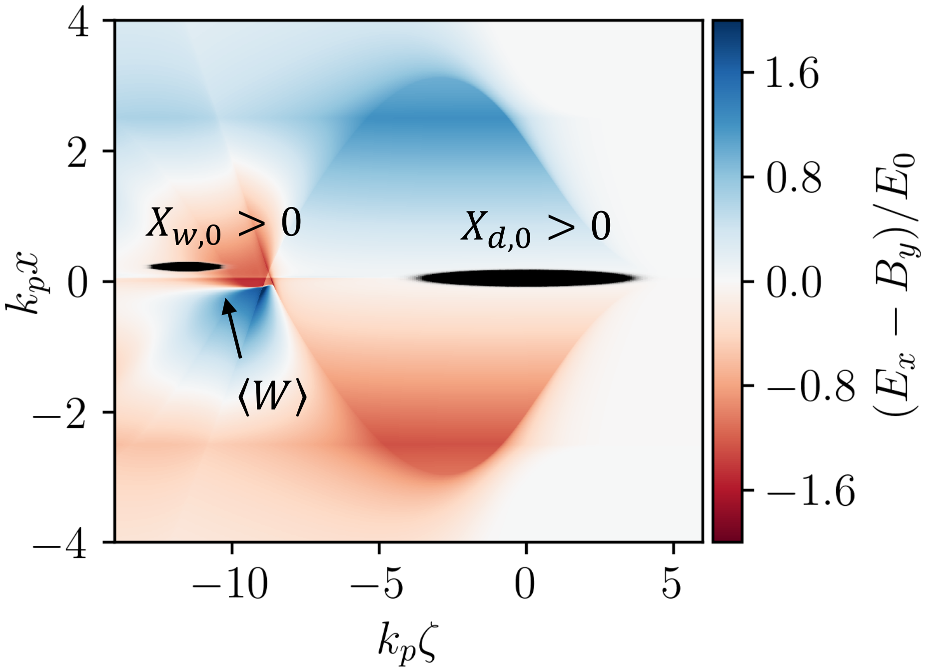


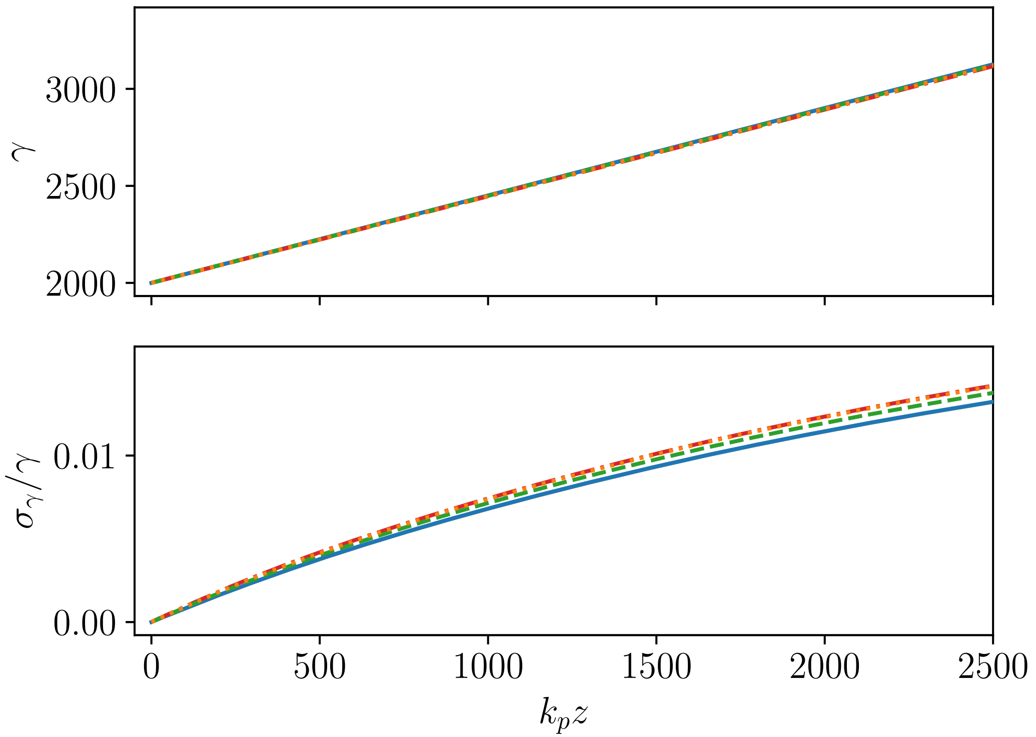
Hosing is prevented for 2 reasons:

1. Longitudinally varying focusing field
2. **Phase-mixing per slice**

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

Witness beam is not susceptible to hosing





Energy-gain and spread hardly affected

Diederichs et al., PRAB 2022

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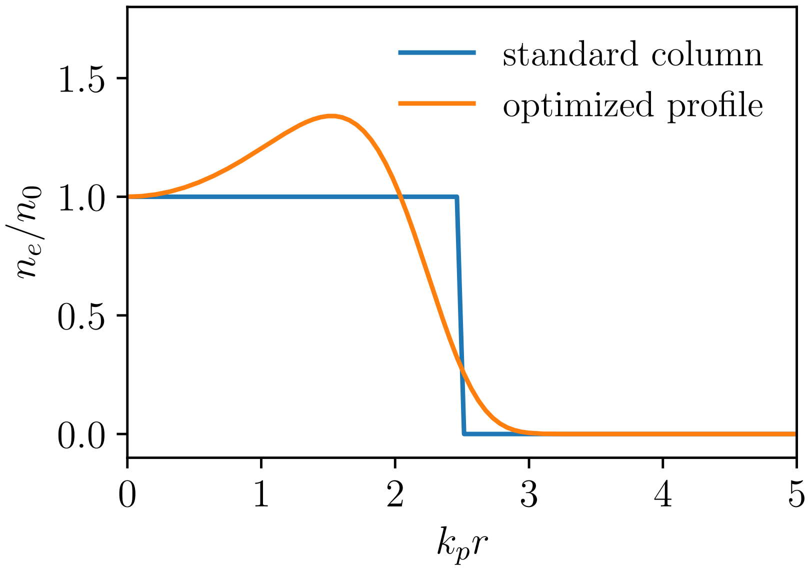
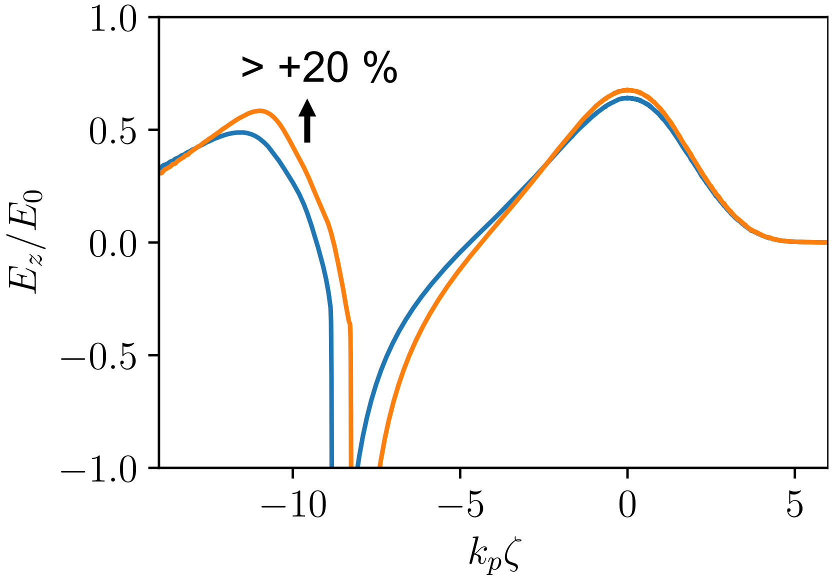
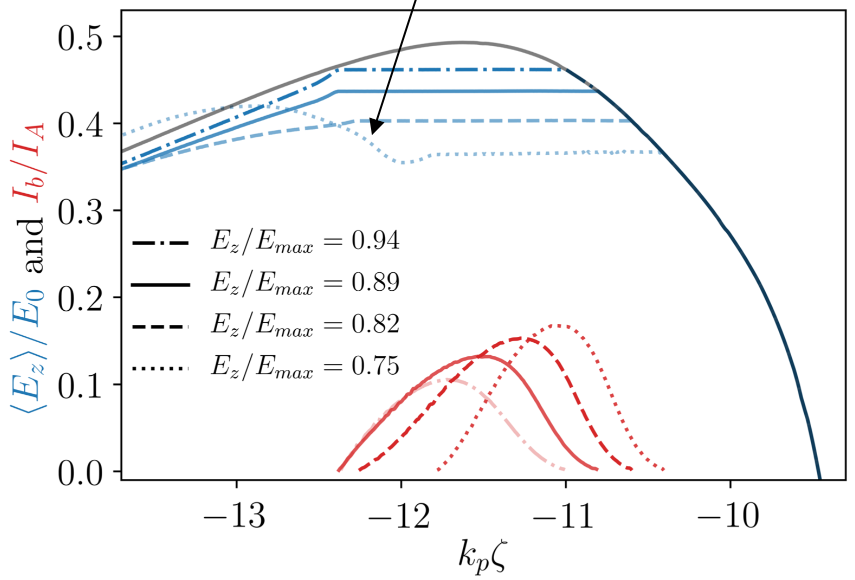
Optimized profiles can increase the accelerating gradient

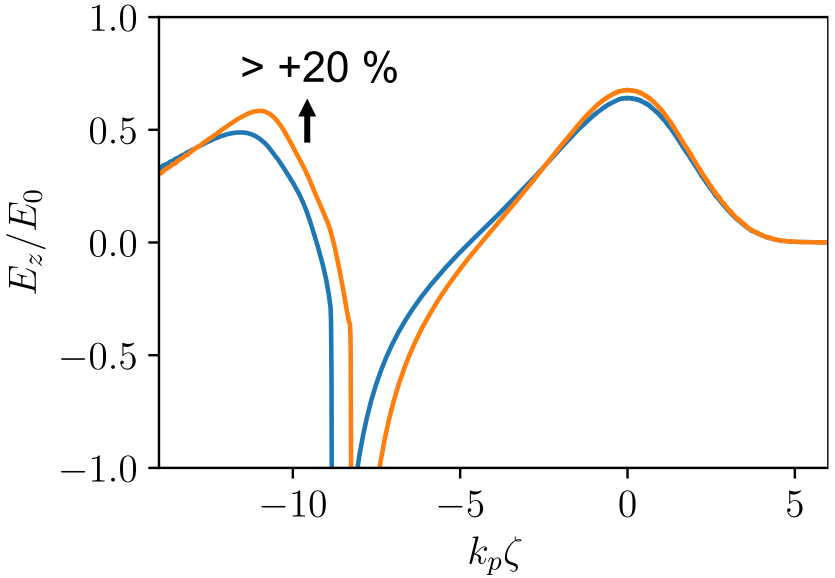




Optimized profiles can increase the accelerating gradient

20 % higher accelerating field could increase charge drastically





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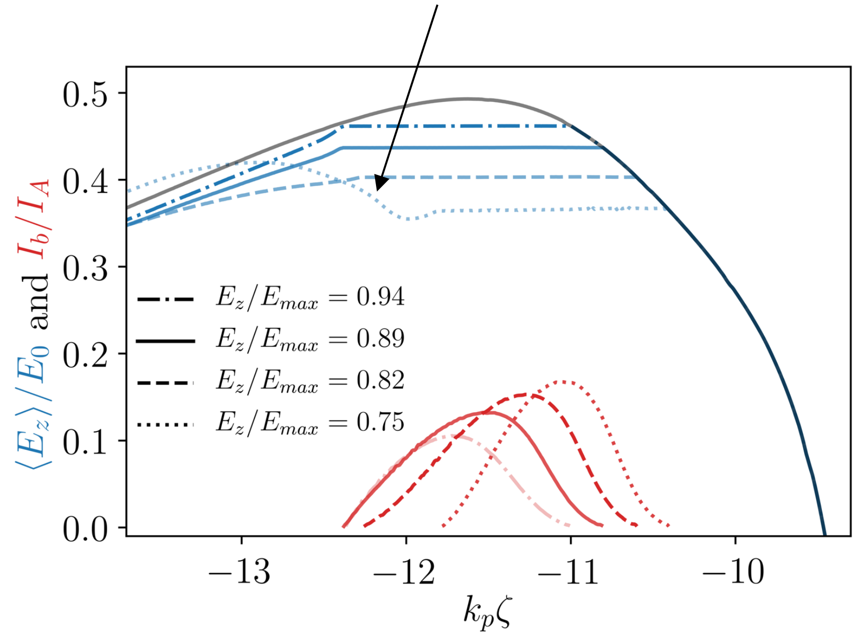
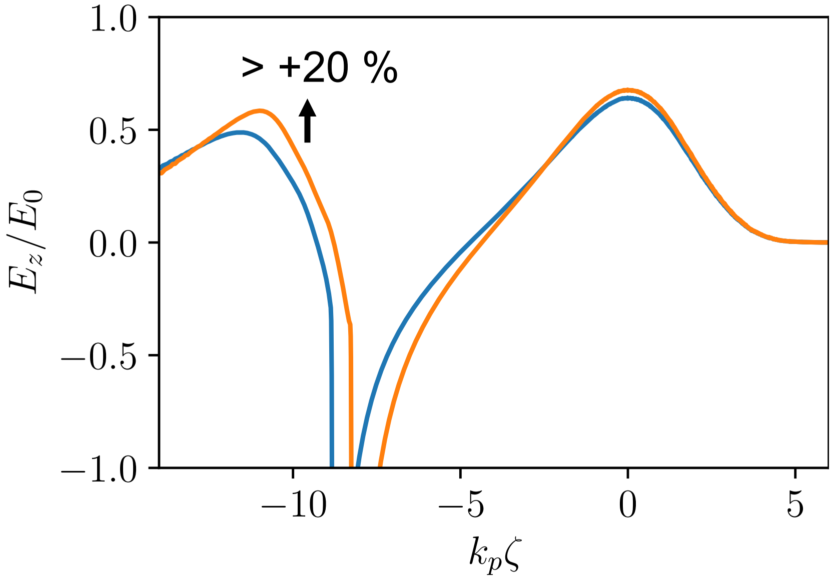




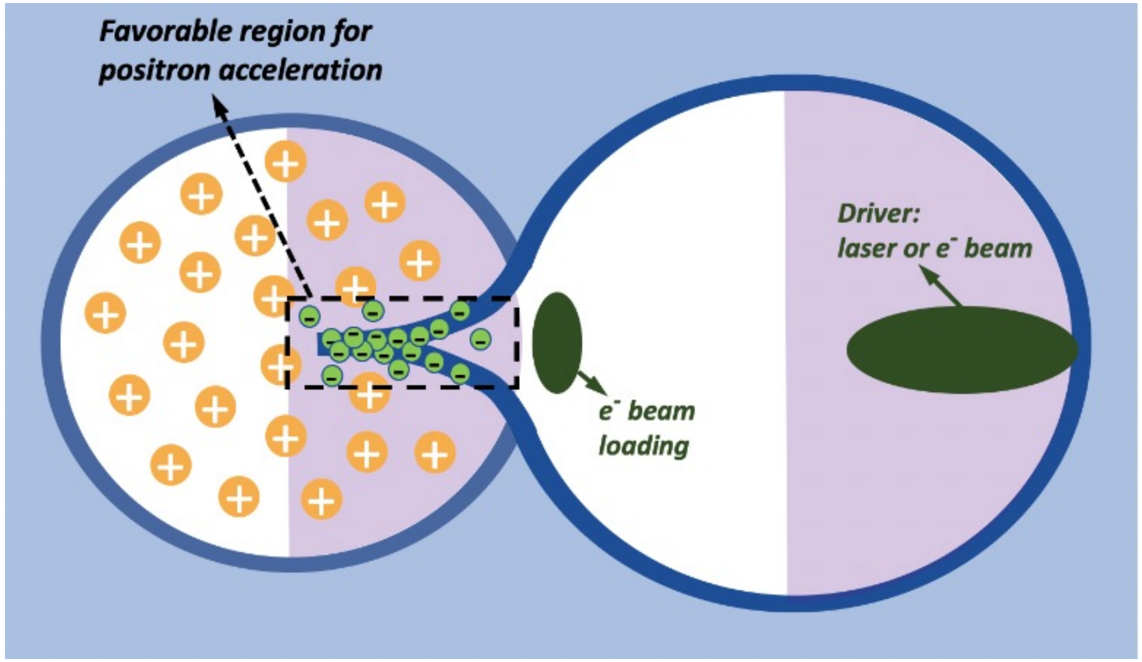
Efficiency can be further increased by tailoring drive beam profile (Roussel PRL 2020, Loisch PRL 2018)

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

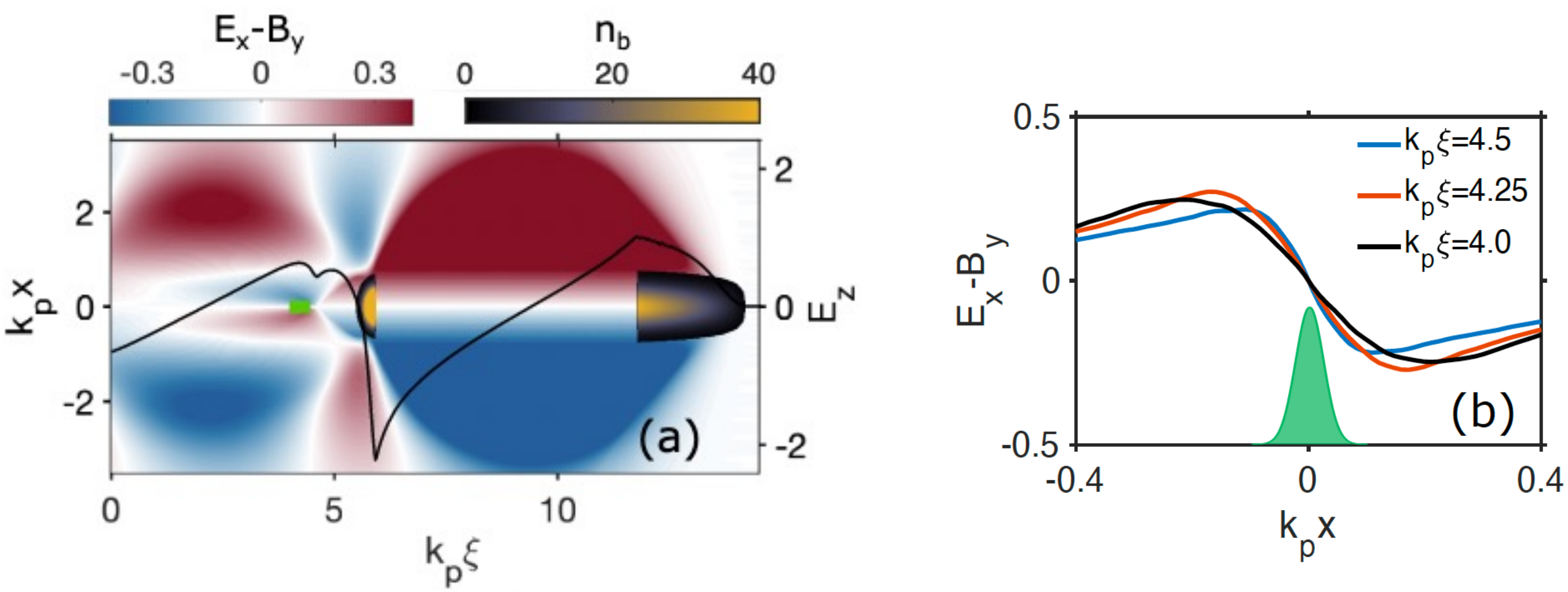
Electron witness bunch elongates plasma electron spike



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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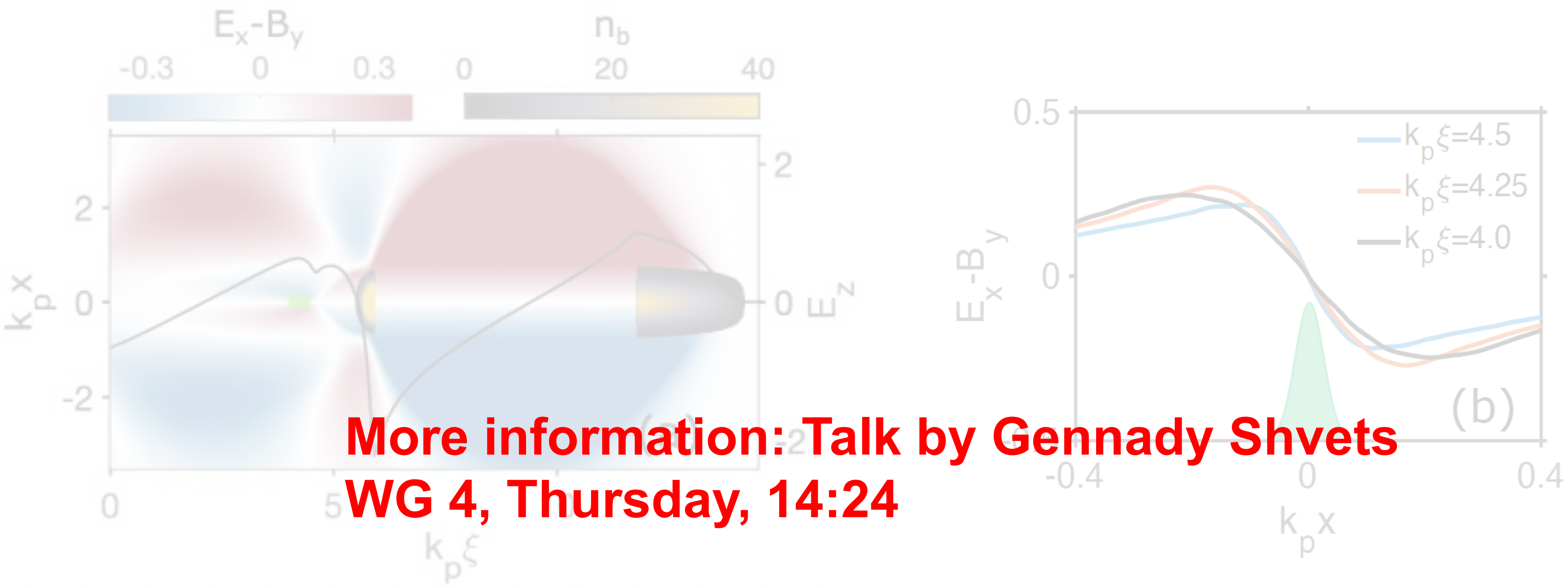

More information: Talk by Gennady Shvets
WG 4, Thursday, 14:24

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with test particles

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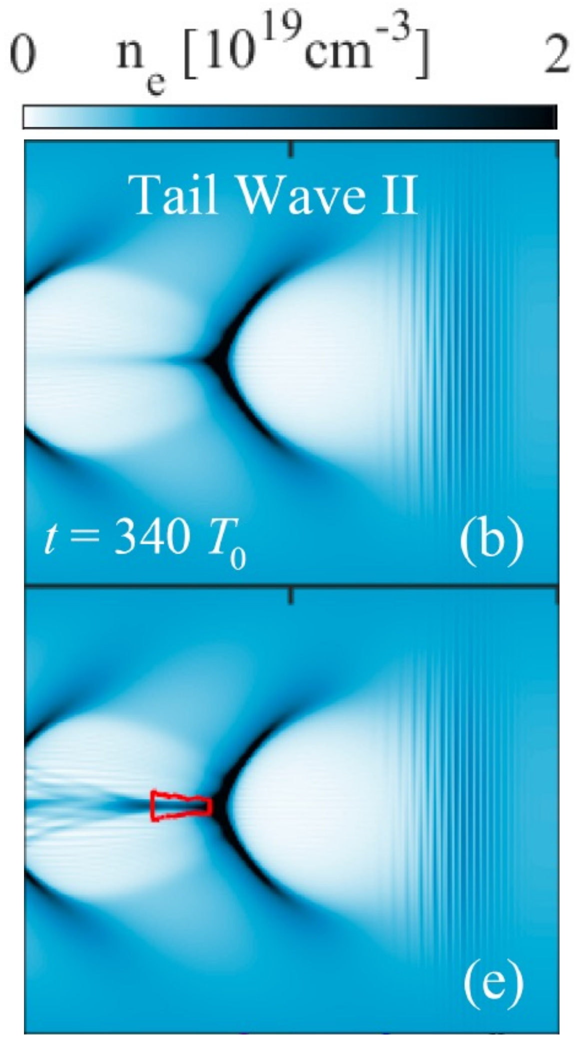
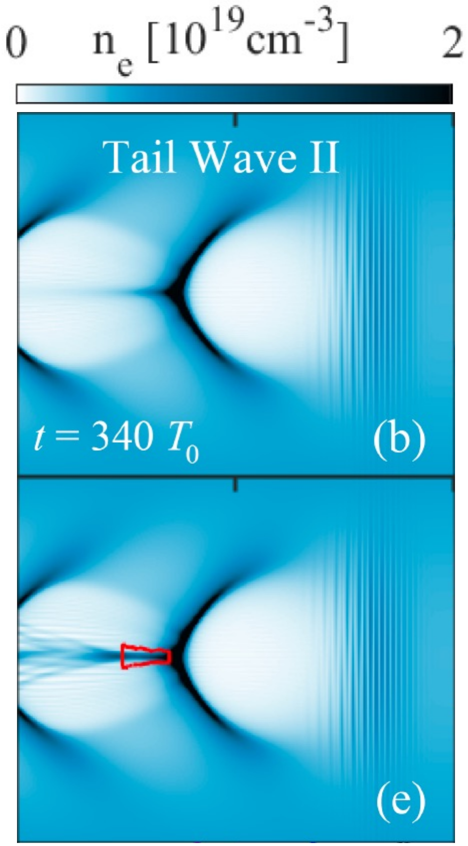
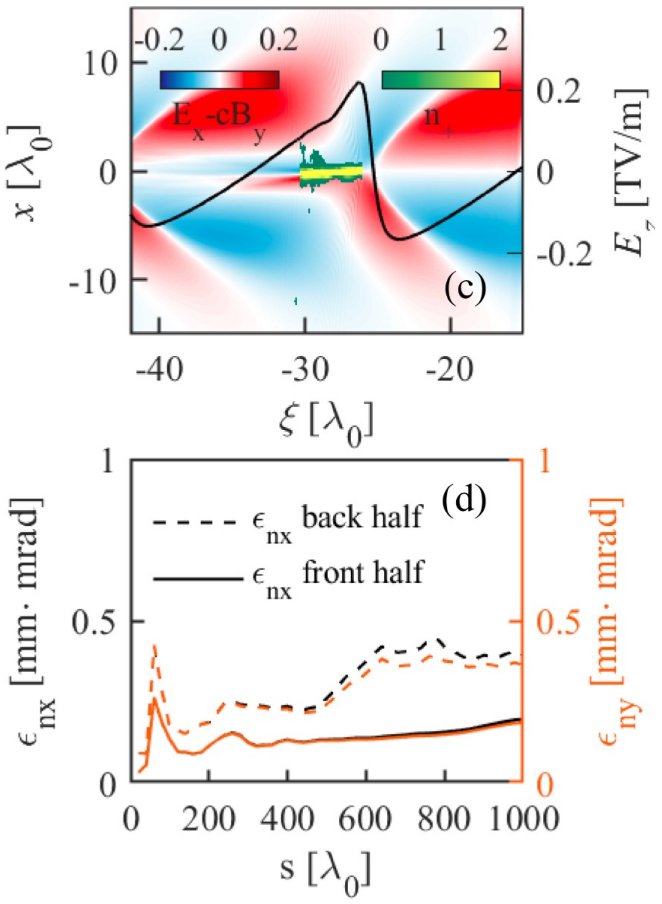
Similar setting with laser driver demonstrated



Liu et al. (arXiv 2207.14749 2022)

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)

Outline

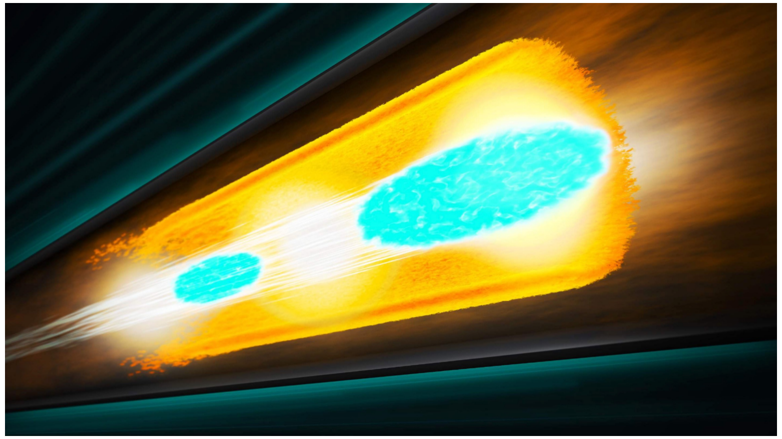
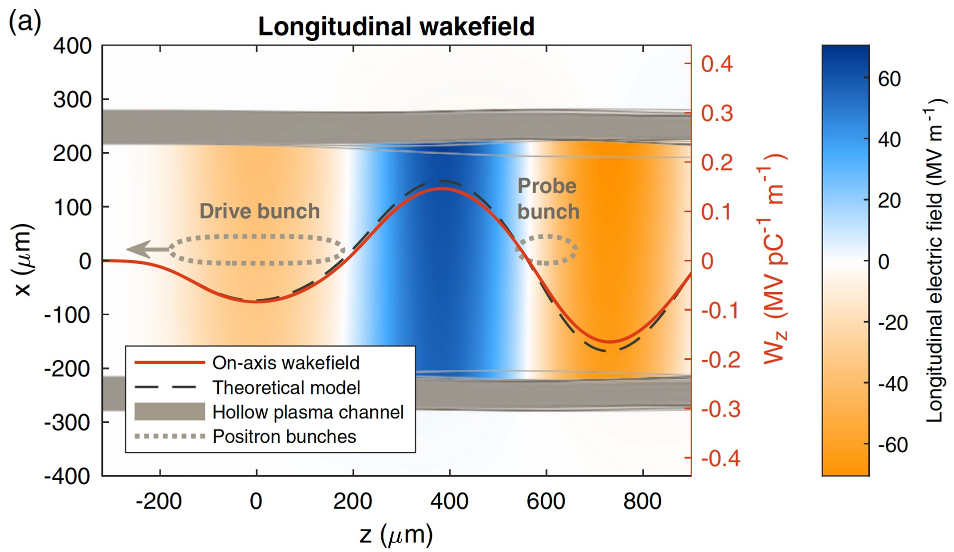


Image credit: SLAC National Accelerator Laboratory

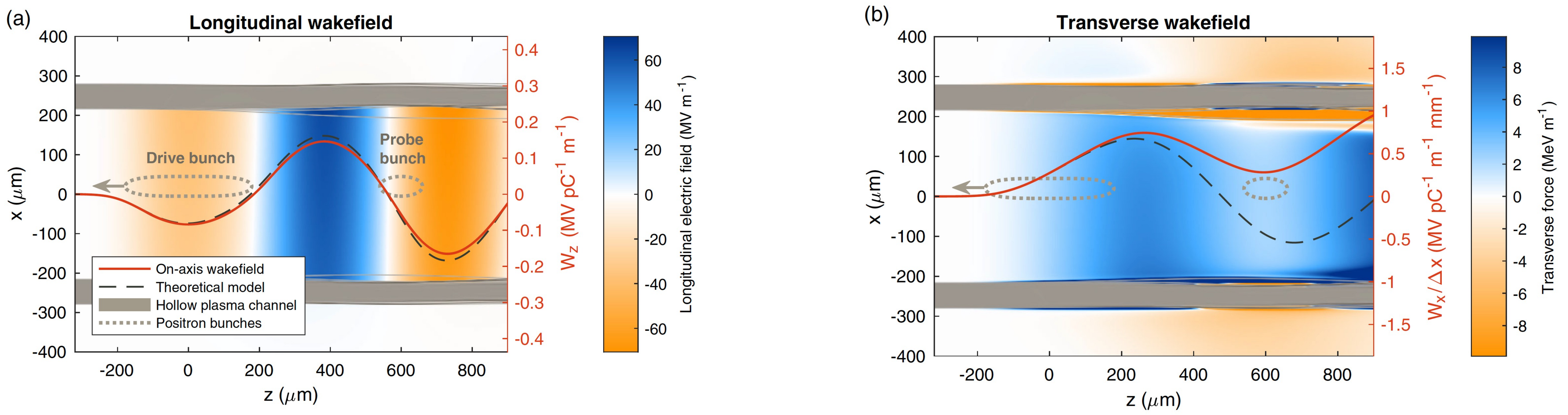
If ions defocus, let’s ignore them altogether: Hollow core plasma accelerator



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



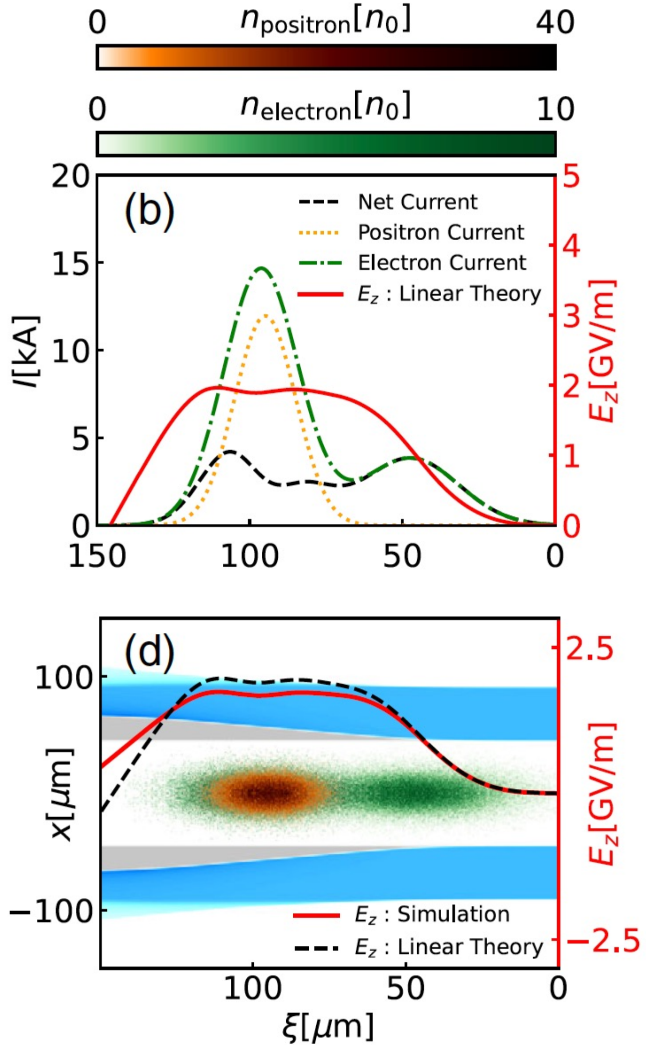
Hollow core plasma provides **accelerating, but no focusing fields**

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

- ~ nC charge
- ~ GV/m gradient
- ≲ 0.5% induced energy spread
- ~ 50% energy transfer efficiency



Zhou et al. (PRAB 25, 091303 2022)

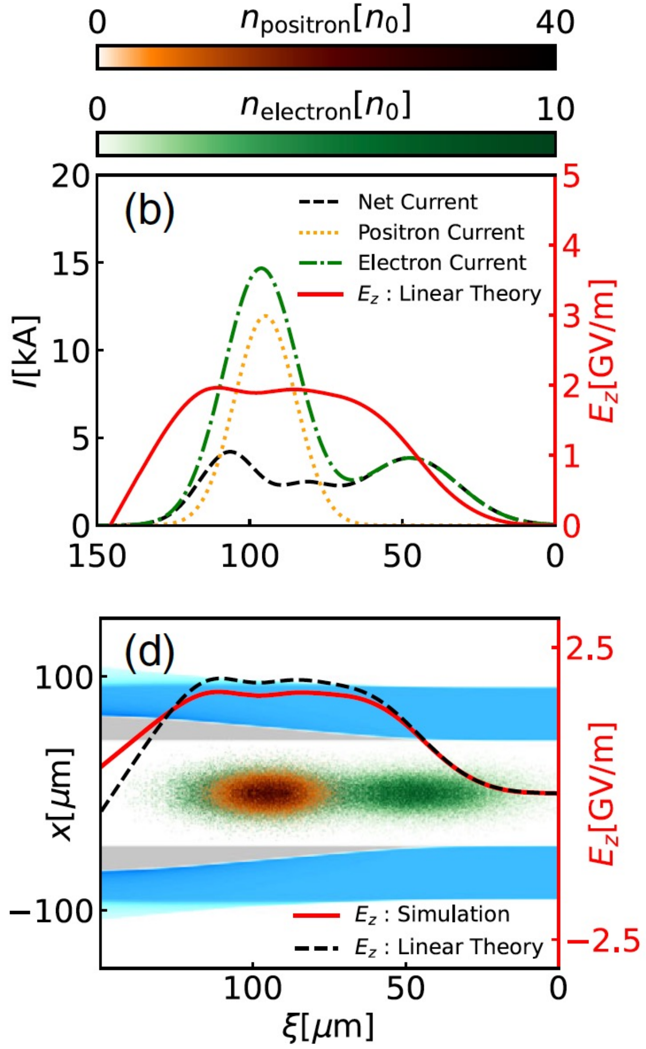
Double loaded hollow core plasma channel yields extraordinary beam quality

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

Stability?

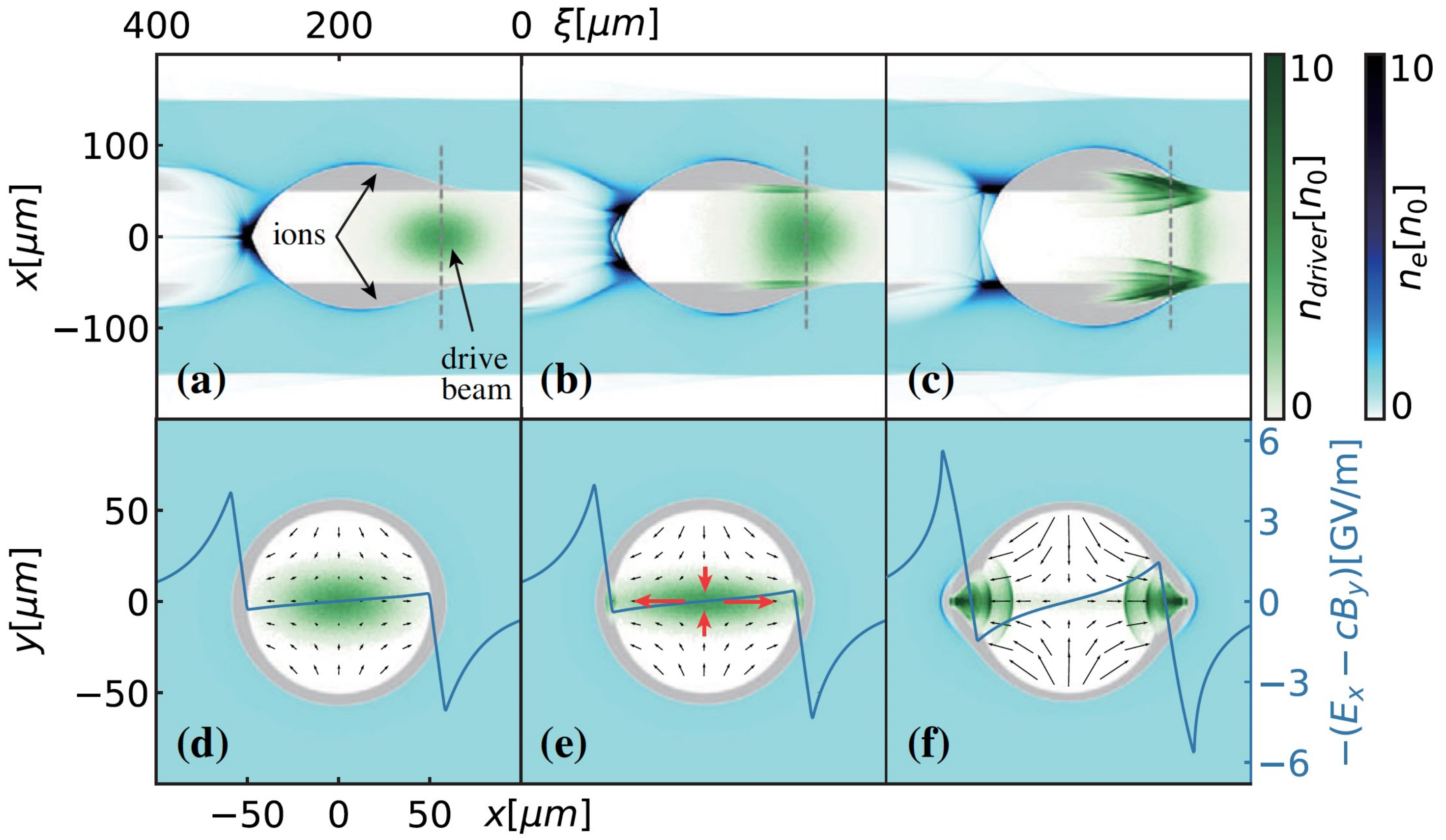
External focusing needs to be demonstrated

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

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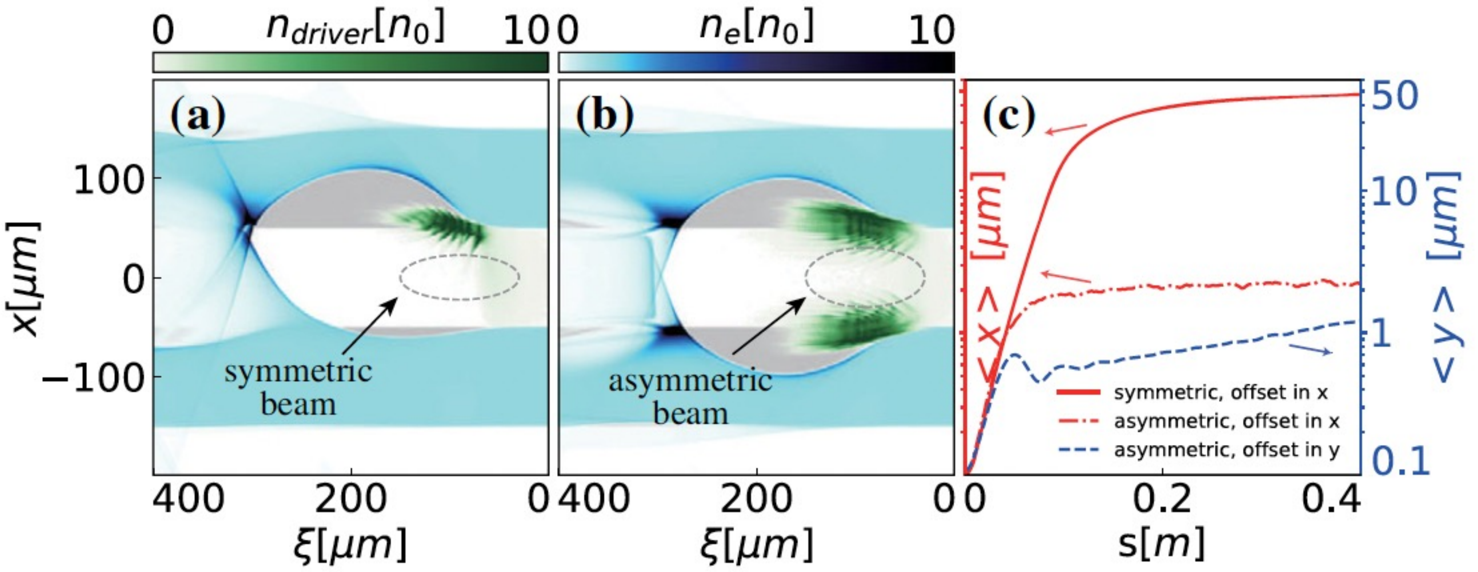
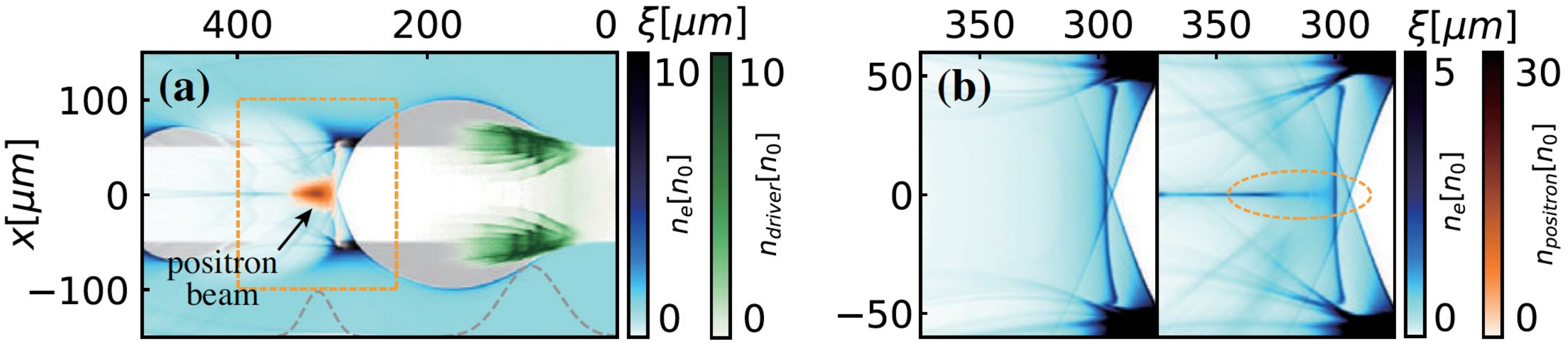


Stabilizes drive beam in hollow core channel!

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**

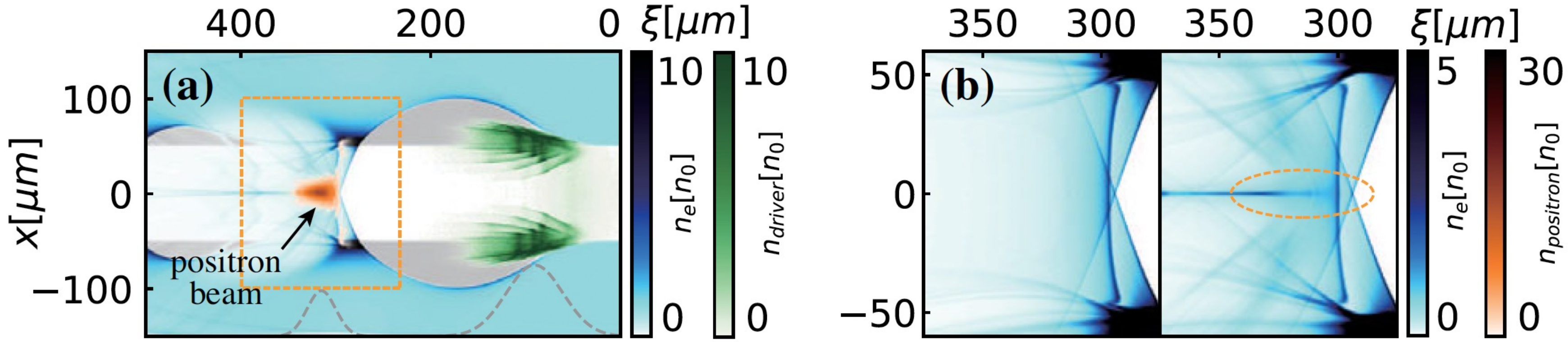
Zhou et al., PRL 127, 174801 (2021)

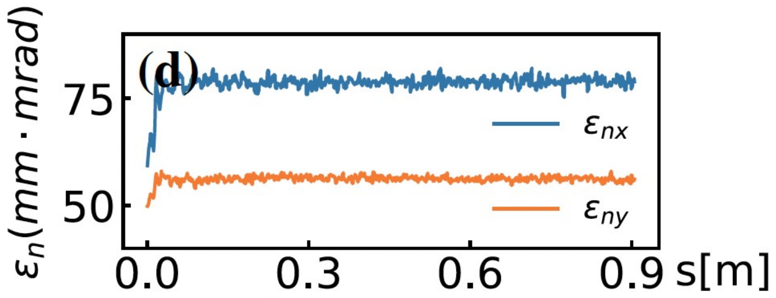
High-charge, low energy spread positron acceleration shown

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

> 50 µm emittance

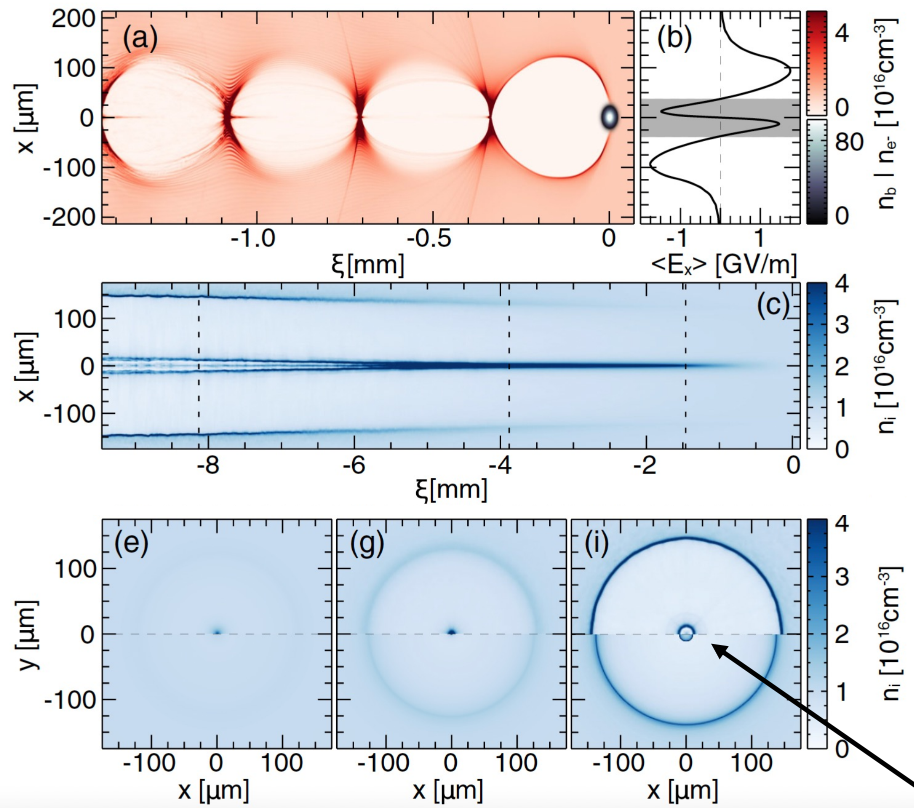
A lot of potential for optimization





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

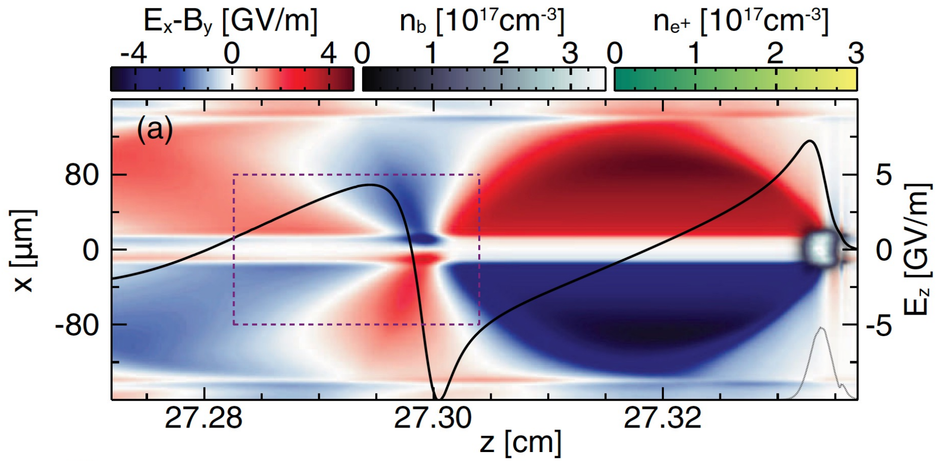
Blowout aftermath generates on-axis plasma filament

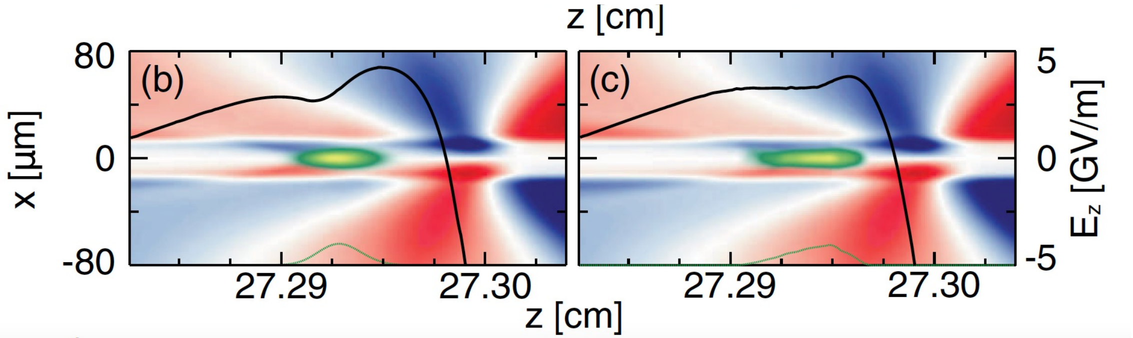


generates quasi-hollow plasma channel

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

Blowout aftermath generates quasi-hollow plasma channel

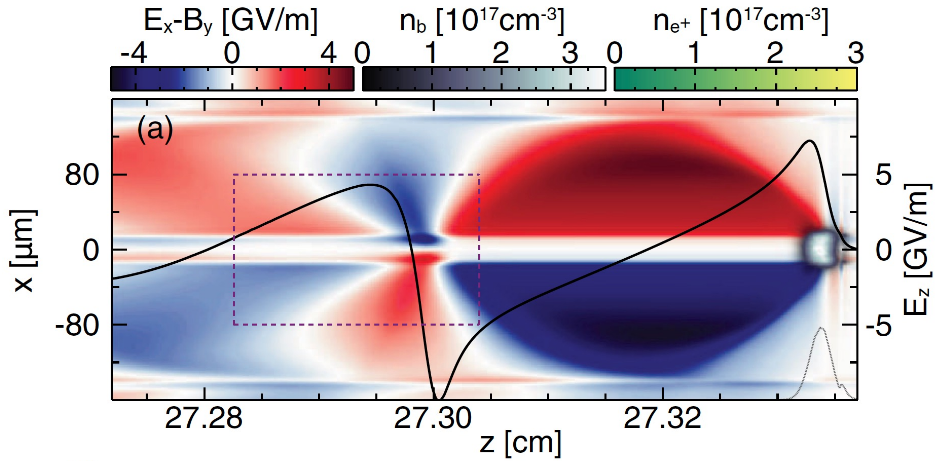


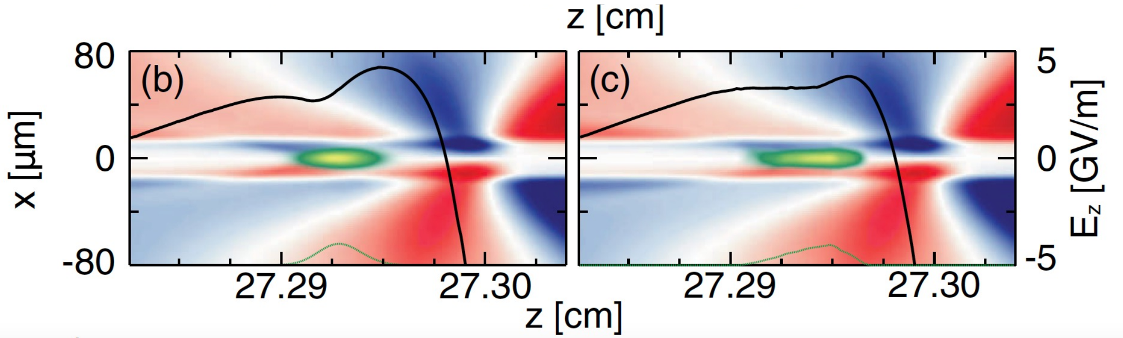


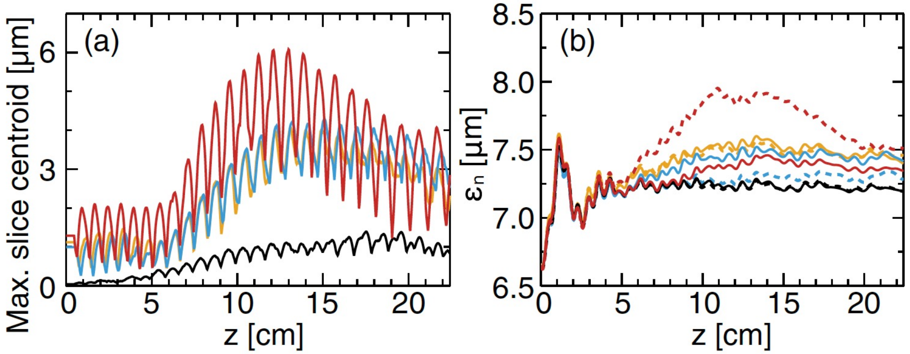
3.5 GV/m gradient
< 5% energy spread

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

Outline

1. The challenge of positrons
2. Positron acceleration in electron filaments
3. Positron acceleration in hollow core plasmas
4. Conclusion and outlook

Promising advances for plasma-based positron acceleration

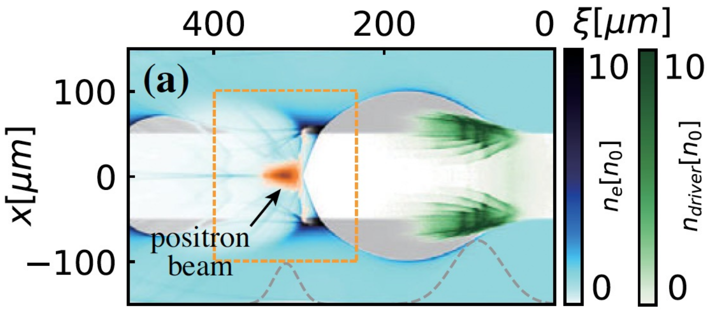
Many **new concepts** have evolved!

1. Using electron filaments:

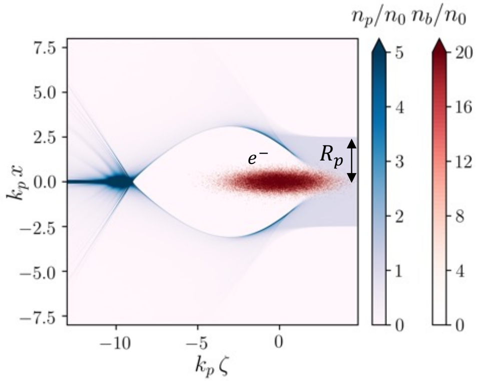
- **Low-emittance, low-energy-spread positron acceleration** is possible
- Longitudinally varying focusing fields **provide stability**
- **Temperature effects** are important, enable linear focusing fields
- All schemes can be optimized for **higher efficiency**

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

Game plan: Optimize each scheme properly, compare apples to apples!



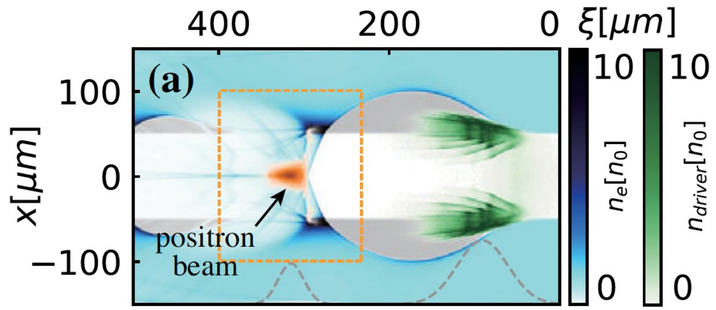
vs



50 μm emittance, 490 pC charge vs 0.5 μm emittance, 50 pC charge

We need a self-consistent **collider parameter set**

Game plan: Optimize each scheme properly, compare apples to apples!



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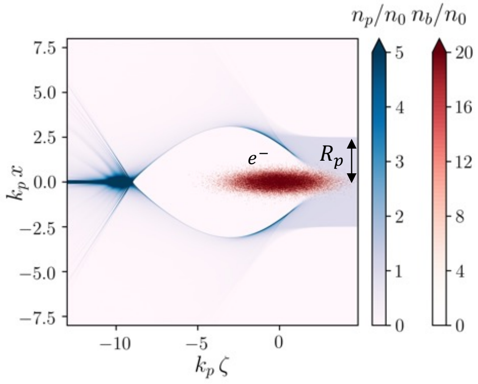
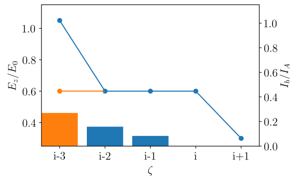


50 µm emittance, 490 pC charge vs 0.5 µm emittance, 50 pC charge

We need a self-consistent **collider parameter set**

Each scheme must

1. Be **optimized for efficiency**
2. Use the **same emittance** witness beam
3. **Optimally load the wake** using the SALAME



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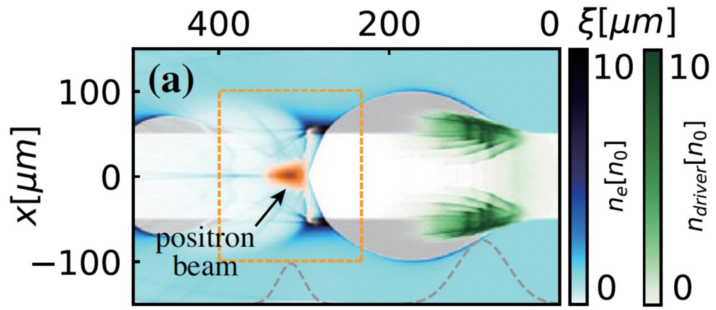

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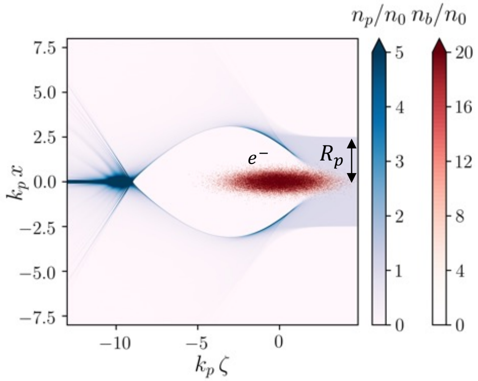

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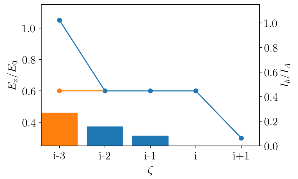


Europ. Strategy for Particle Physics Accelerator R&D Roadmap (due 2025)

WP:
e^+ Beam Performance Reach of Advanced Technologies (Simulation Results - Comparisons)

Most important part yet missing: Experiments!

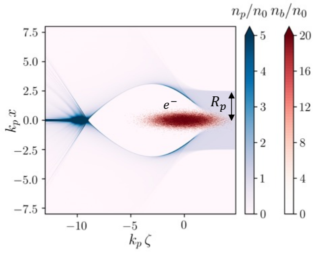
Real **progress only possible via experiments**

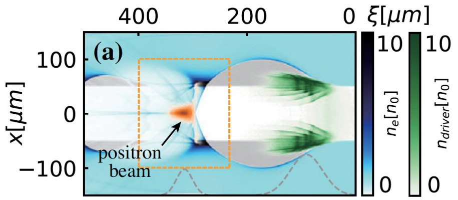
All PWFA positrons experiments have been conducted at SLAC

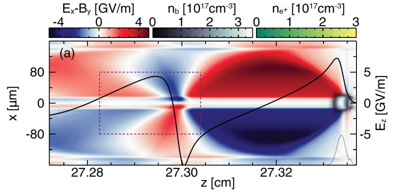
FACET-II positron upgrade planned

- Basic infrastructure for positron production exists
- Damping ring and beamline missing

Large international effort on various schemes:
SLAC, LBNL, DESY, UCLA, École Polytechnique,
CU Boulder, UT Austin, Tsinghua Uni., IST Portugal







Conclusion

1. A lot of promising progress on high-quality positron acceleration

2. There is a clear path to improve all schemes

3. Experiments are needed to confirm these new schemes

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