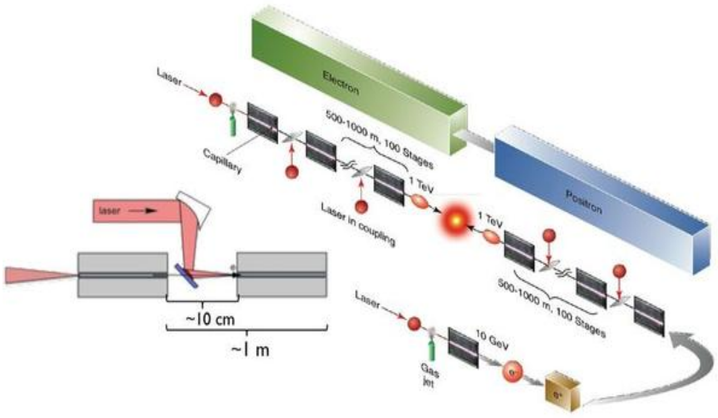
Plasma Wakefield Acceleration with Positron Beams

Spencer Gessner, SLAC

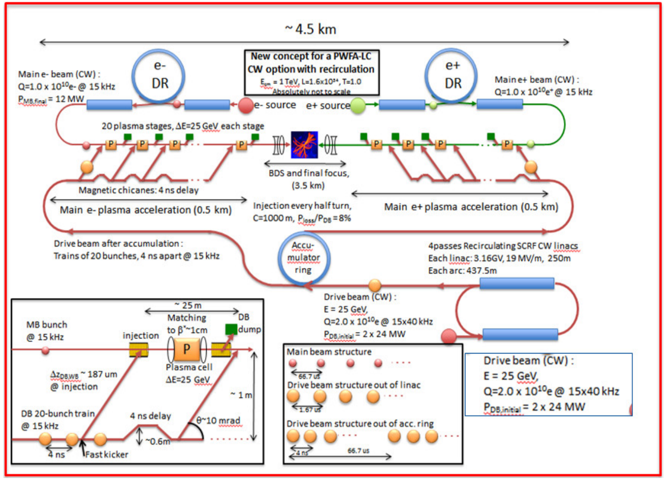
IAS Program on High Energy Physics

Plasma Acceleration Mini-Workshop, January 2020

The Plasma Linear Collider



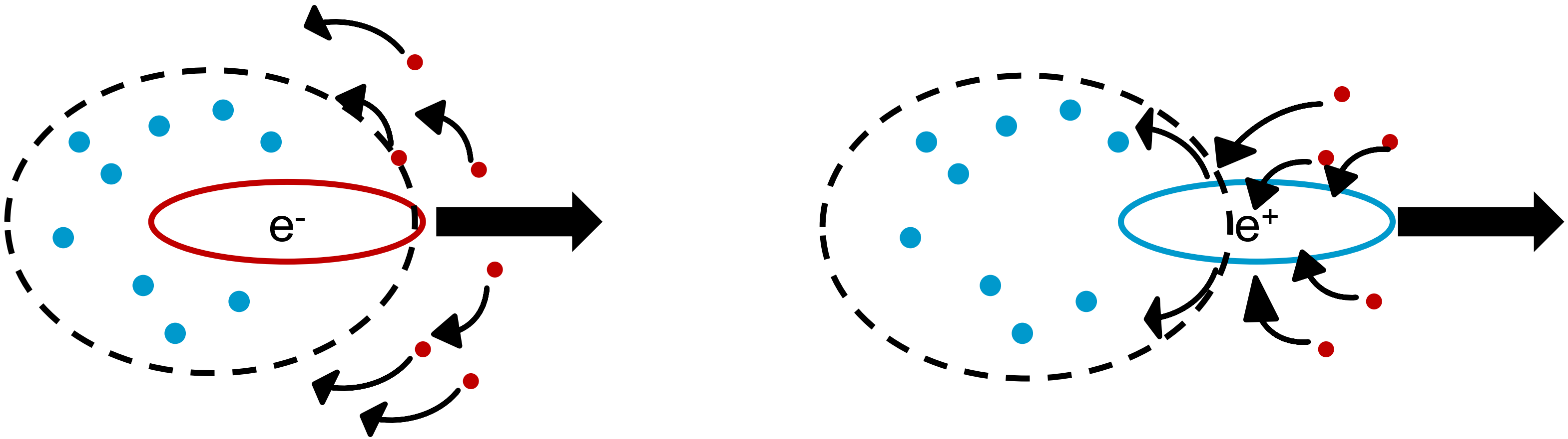
C. B. Schroeder *et. al*. Phys. Rev. ST Accel. Beams **13**, 101301



E. Adli *et. al*.,arXiv:1308.1145 [physics.acc-ph]

We are investigating plasma-based linear colliders (PLCs) as future energy-frontier machines in the context of Snowmass 2021. These machines collide electron and positron beams.

The Challenge

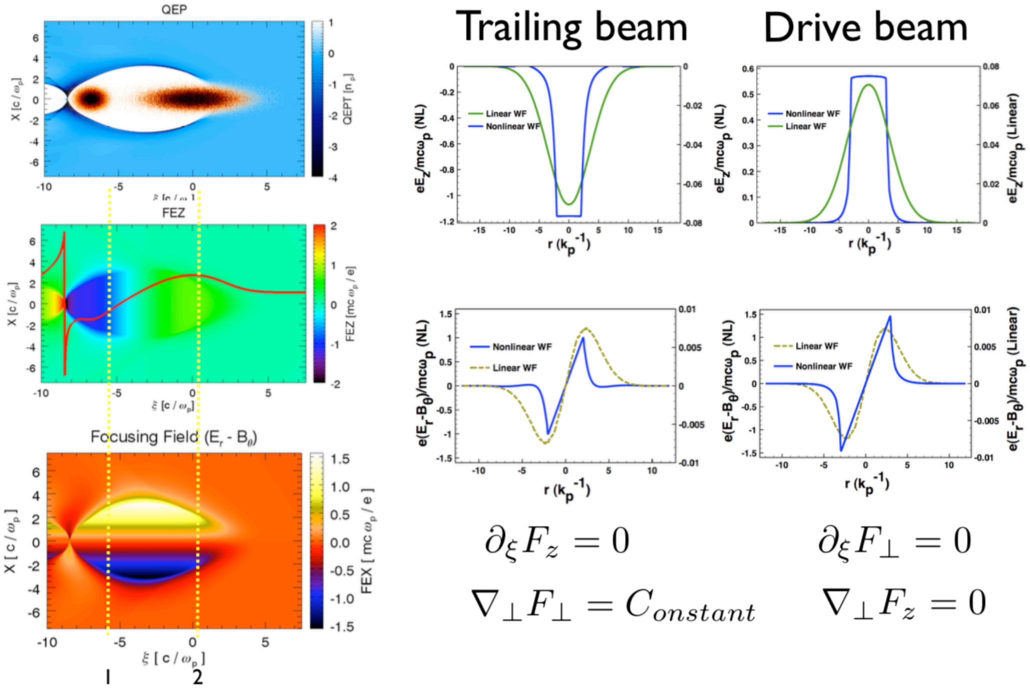


$$m_{ion} >> m_{elec}$$

The plasma electrons are mobile but the plasma ions are not. The plasma responds *asymmetrically* to beams of opposite charge. No other accelerating mechanism exhibits this behavior!

The Case for Electron Acceleration

Nonlinear wakefield is IDEAL for accelerating/focusing electrons
Trailing beam does not modify focusing fields of wake



$$\partial_\xi F_z = 0 \qquad \partial_\xi F_\perp = 0$$

$$\nabla_\perp F_\perp = C_{onstant} \qquad \nabla_\perp F_z = 0$$

Plasma Response to Positron Beams

PHYSICS OF PLASMAS **12**, 063101 (2005)

Limits of linear plasma wakefield theory for electron or positron beams

W. Lu, C. Huang, and M. M. Zhou
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W. B. Mori
Department of Electrical Engineering, University of California, Los Angeles, Los Angeles, California 90095 and Department of Physics and Astronomy, University of California, Los Angeles, Los Angeles, California 90095

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(Received 2 November 2004; accepted 16 March 2005; published online 26 May 2005)

The validity and usefulness of linear wakefield theory for electron and positron bunches is investigated. Starting from the well-known Green's function for a cold-fluid plasma, engineering

For electron drivers, the useful accelerating fields agree with linear theory up to $n_b/n_p \approx 10$, and then becomes smaller than linear theory, while the decelerating field agrees with linear theory only up to $n_b/n_p \approx 1$.

For positron drivers, both the peak accelerating fields and the peak decelerating fields agree with linear theory up to $n_b/n_p \approx 1$.

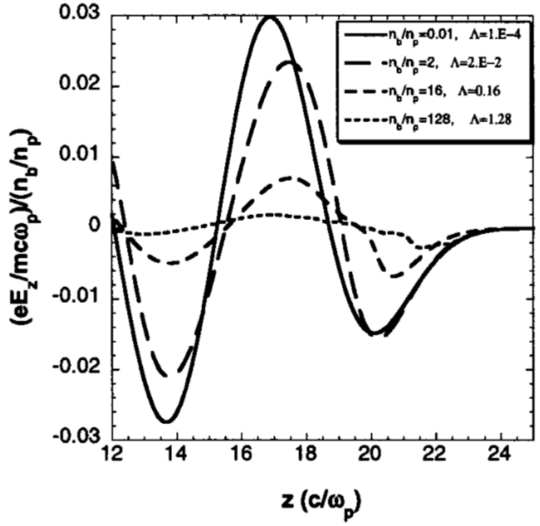
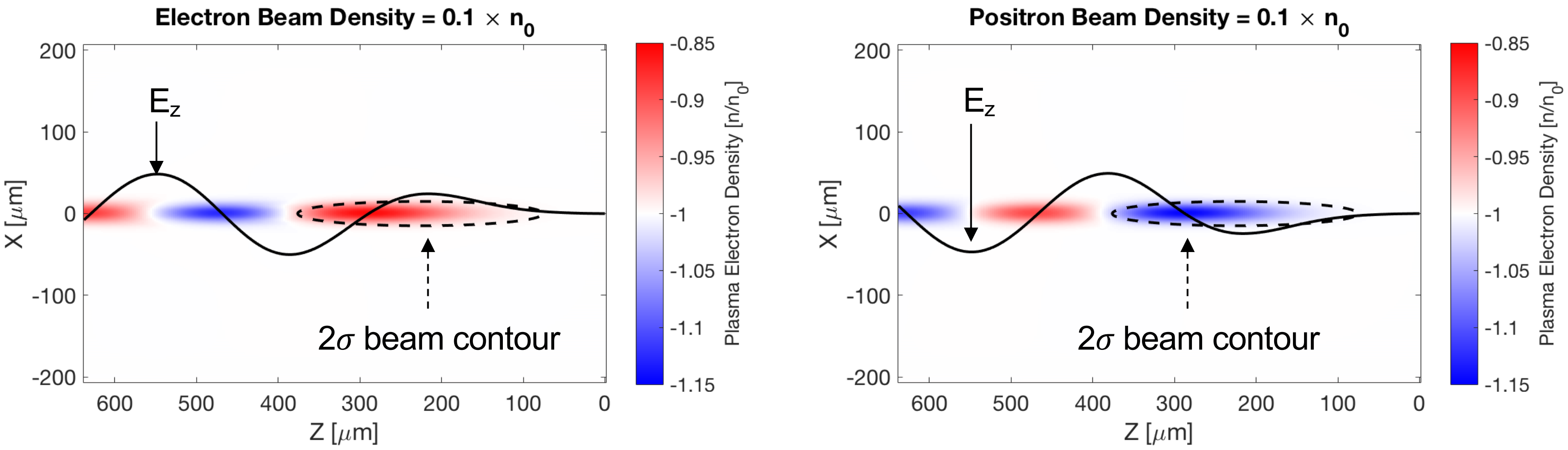


FIG. 7. Wake structure for positron drivers: we plot the ratio of normalized electric field over n_b/n_p, as a function of distance behind the wake, for $k_p\sigma_z=\sqrt{2}$ and $k_p\sigma_r=0.1$ (the beam center is at $z=20c/\omega_p$).

Positron-driven wakes become complicated in the mildly nonlinear regime.

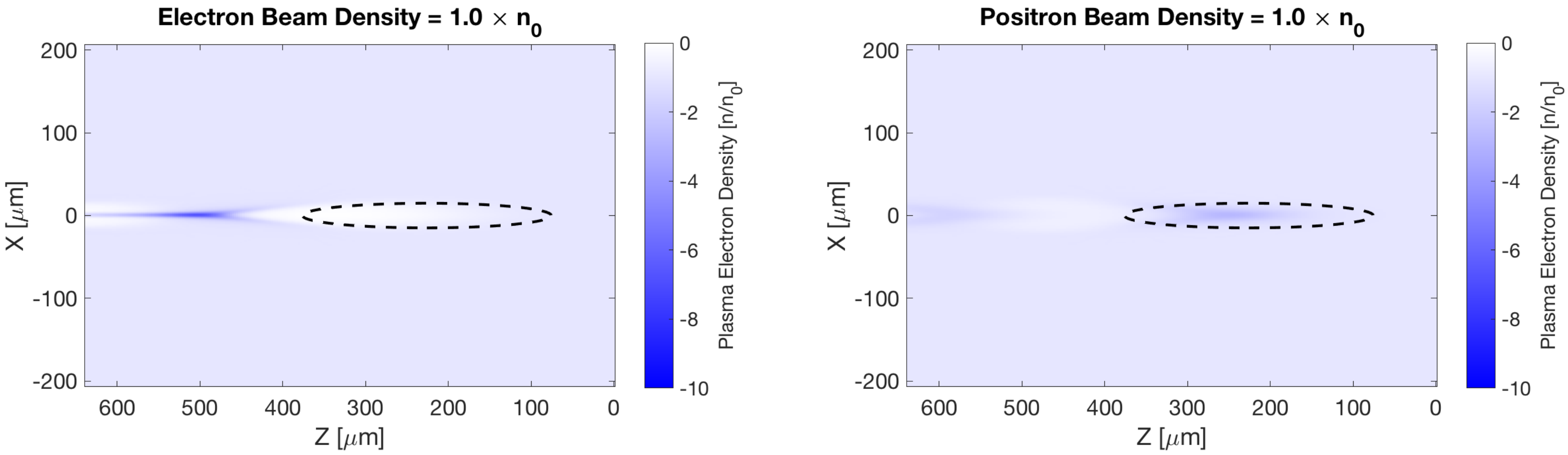
Plasma Response to Beams of Opposite Charge



In the linear regime, the response is symmetric.

QuickPIC Simulation run on Hoffman2 at UCLA

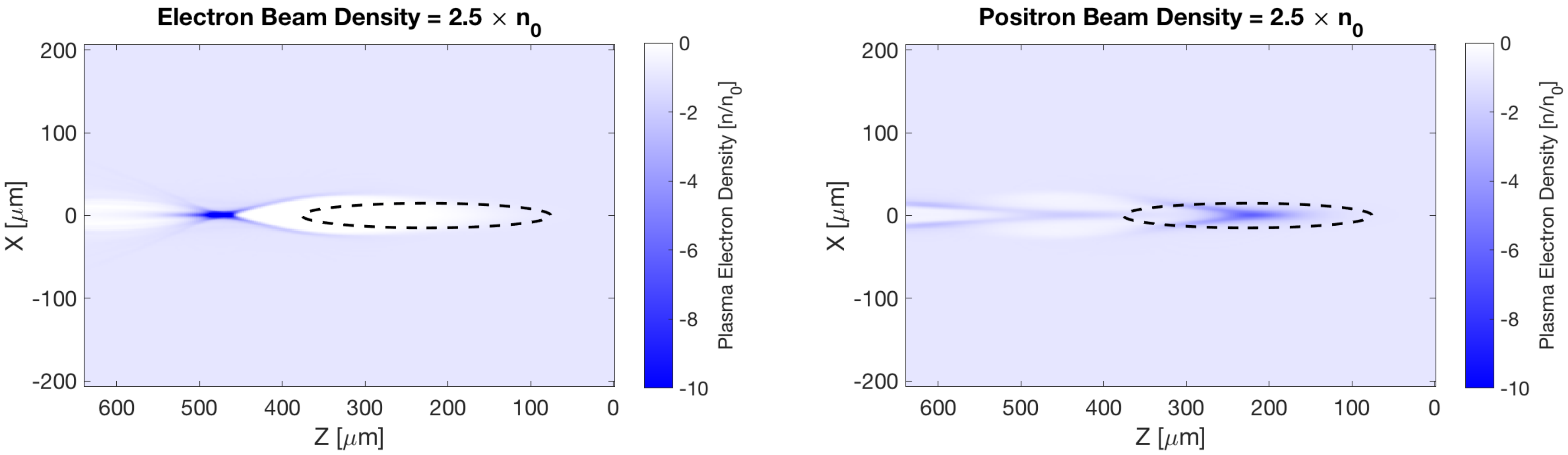
Plasma Response to Beams of Opposite Charge



As we increase the beam charge, the asymmetry becomes more pronounced.

QuickPIC Simulation run on Hoffman2 at UCLA

Plasma Response to Beams of Opposite Charge



As we increase the beam charge, the asymmetry becomes more pronounced.

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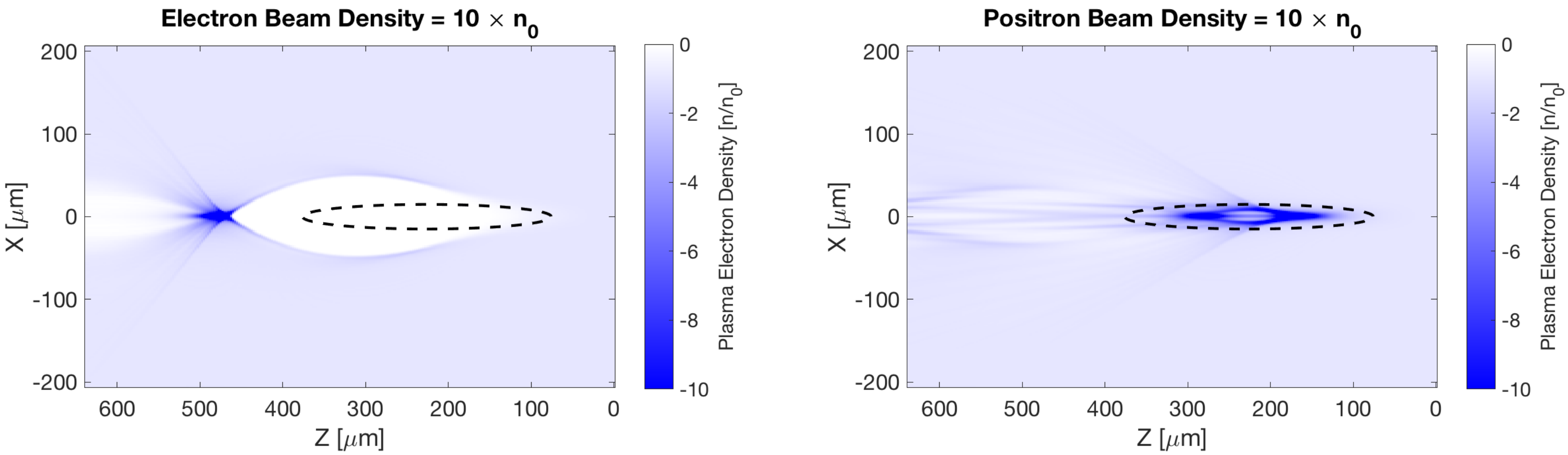
Plasma Response to Beams of Opposite Charge



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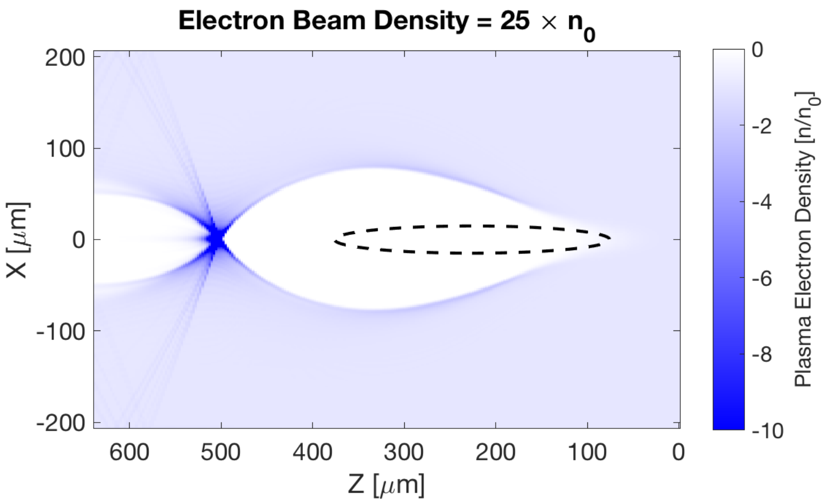
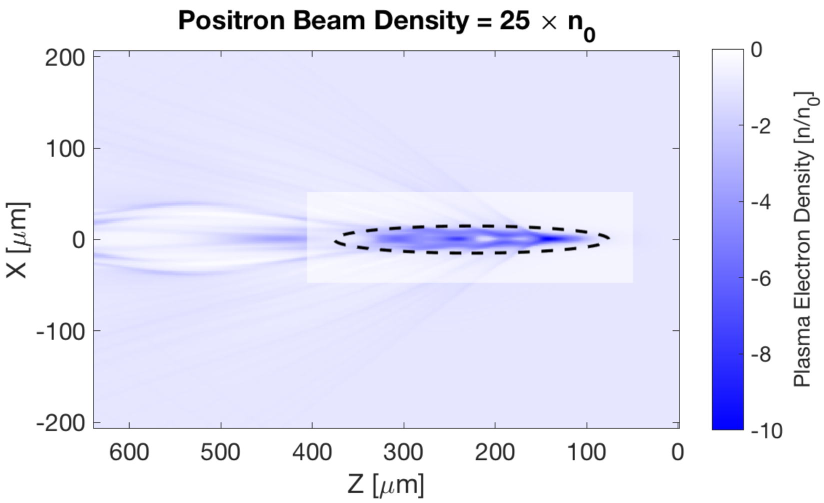
Plasma Response to Beams of Opposite Charge





As we increase the beam charge, the asymmetry becomes more pronounced.

And more complicated.

QuickPIC Simulation run on Hoffman2 at UCLA

Experiments at FACET

Image Credit: W. An, UCLA

Positron Acceleration in Nonlinear Regime

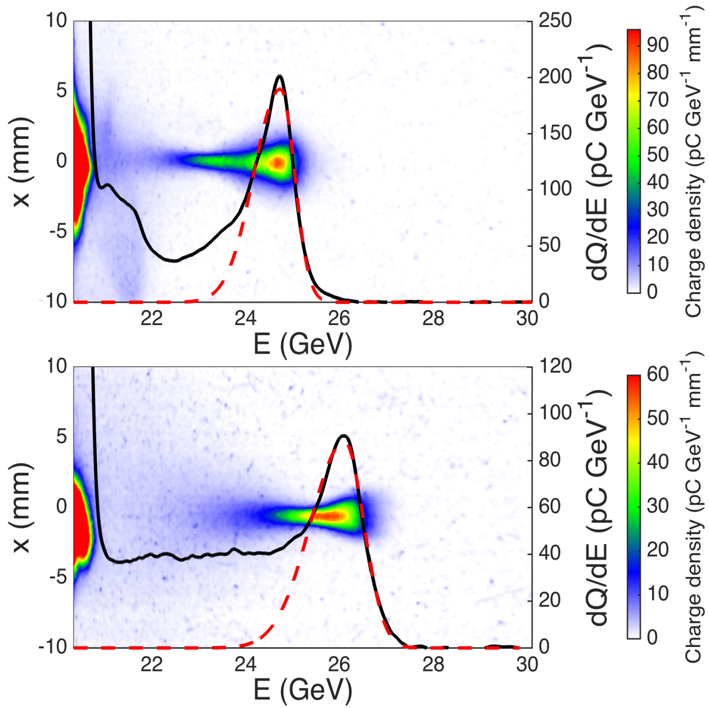
FACET was able to provide high-density, compressed positron beams for non-linear PWFA experiments.

This led to new observations:

- Accelerated positrons form a spectrally-distinct peak with an energy gain of 5 GeV.
- Energy spread can be as low as 1.8% (r.m.s.).

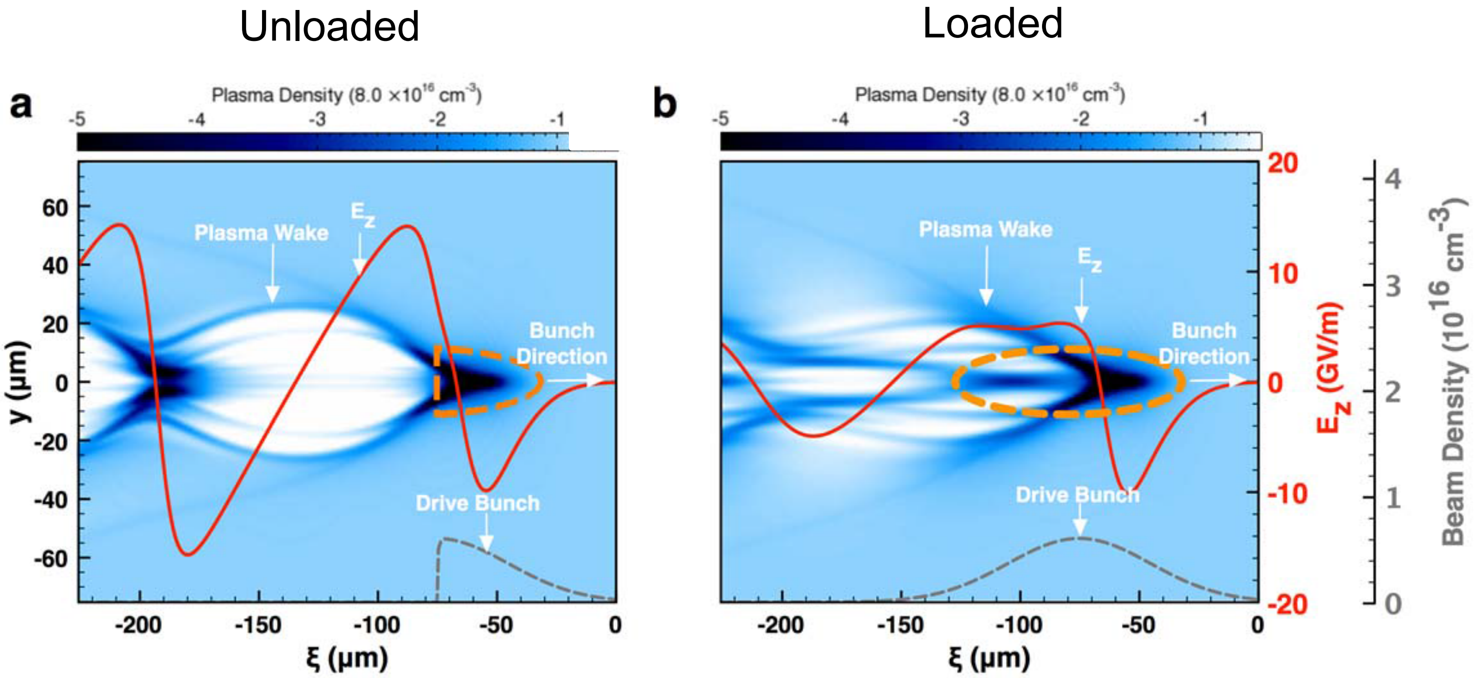
An unexpected result!

Experimental results in 1.3 m plasma



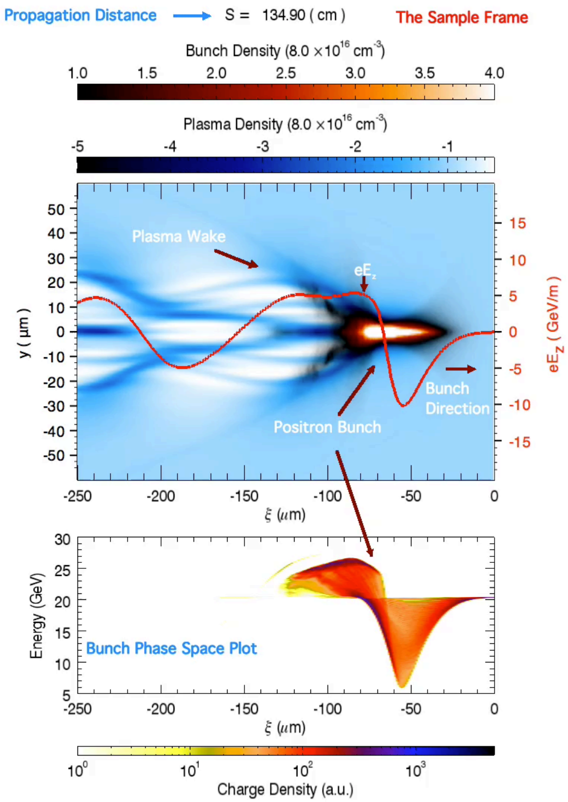
S. Corde *et al.*, Nature **524**, 442 (2015)

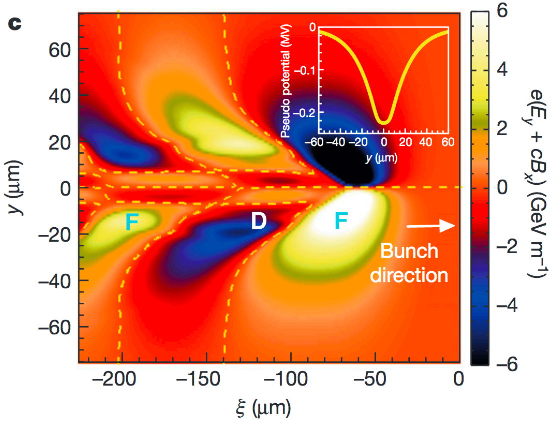
Positron Acceleration in Nonlinear Regime



S. Corde *et al.*, Nature **524**, 442 (2015)

Positron Acceleration in Nonlinear Regime





Key questions:

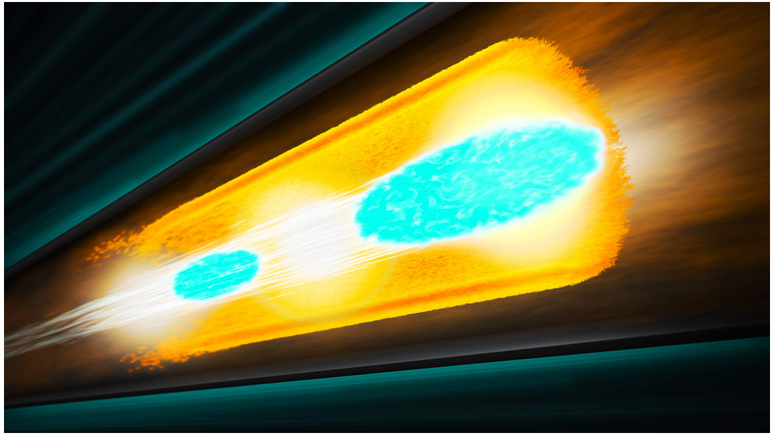
Is there an equilibrium emittance, or is the emittance growth continuous?

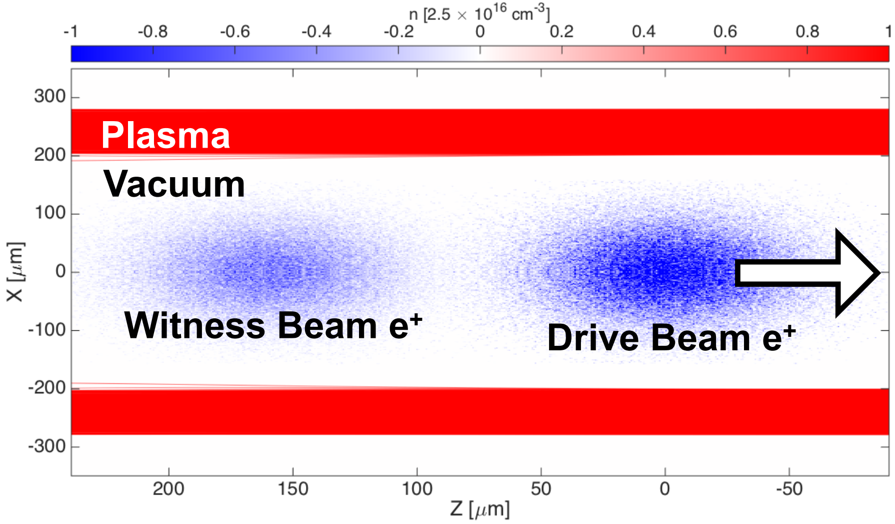
What does the equilibrium beam distribution look like in both physical and momentum space?

S. Corde *et al.*, Nature **524**, 442 (2015)

Hollow Channel Plasma Acceleration

SLAC

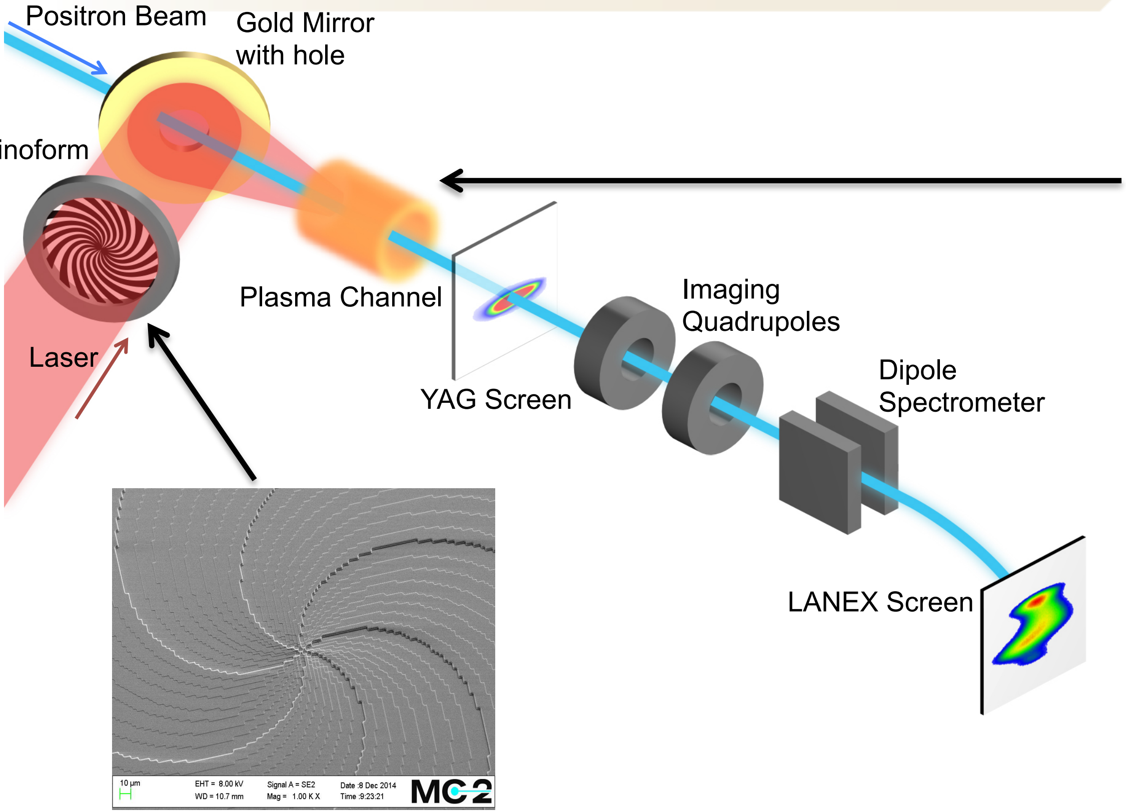


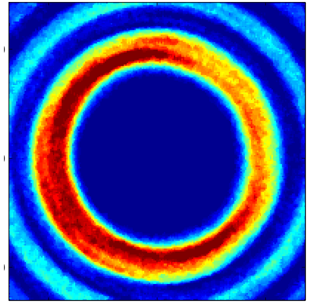


The Hollow Channel Plasma is a *structure* that symmetrizes the response of the plasma to electron and positron beams.

There is no plasma on-axis, and therefore no focusing/defocusing force from plasma ions.

Hollow Channel Plasma Acceleration





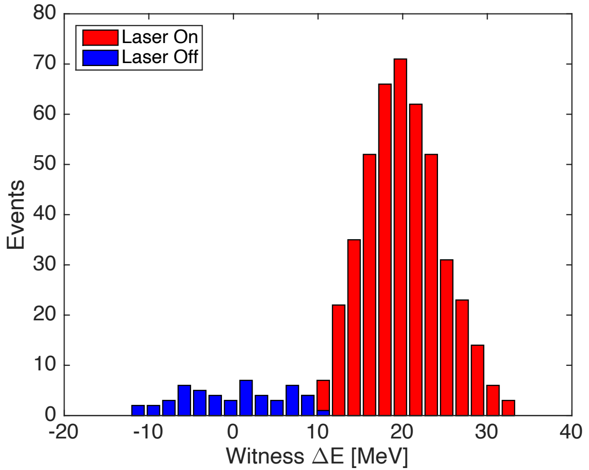
$$I(r,z) \propto k_z z J_m^2(k_\perp r)$$

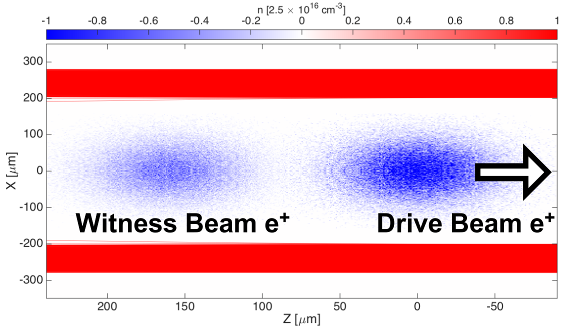
$$\Psi_m = k_\perp r + m\phi$$

S. Gessner et. al. *Nat. Comm.* 7, 11785

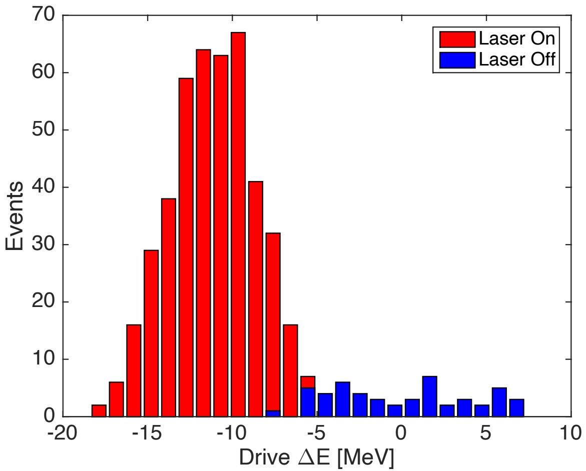
Hollow Channel Plasma Acceleration

Mean <ΔE> = 19.9 MeV





Mean <ΔE> = -11.0 MeV

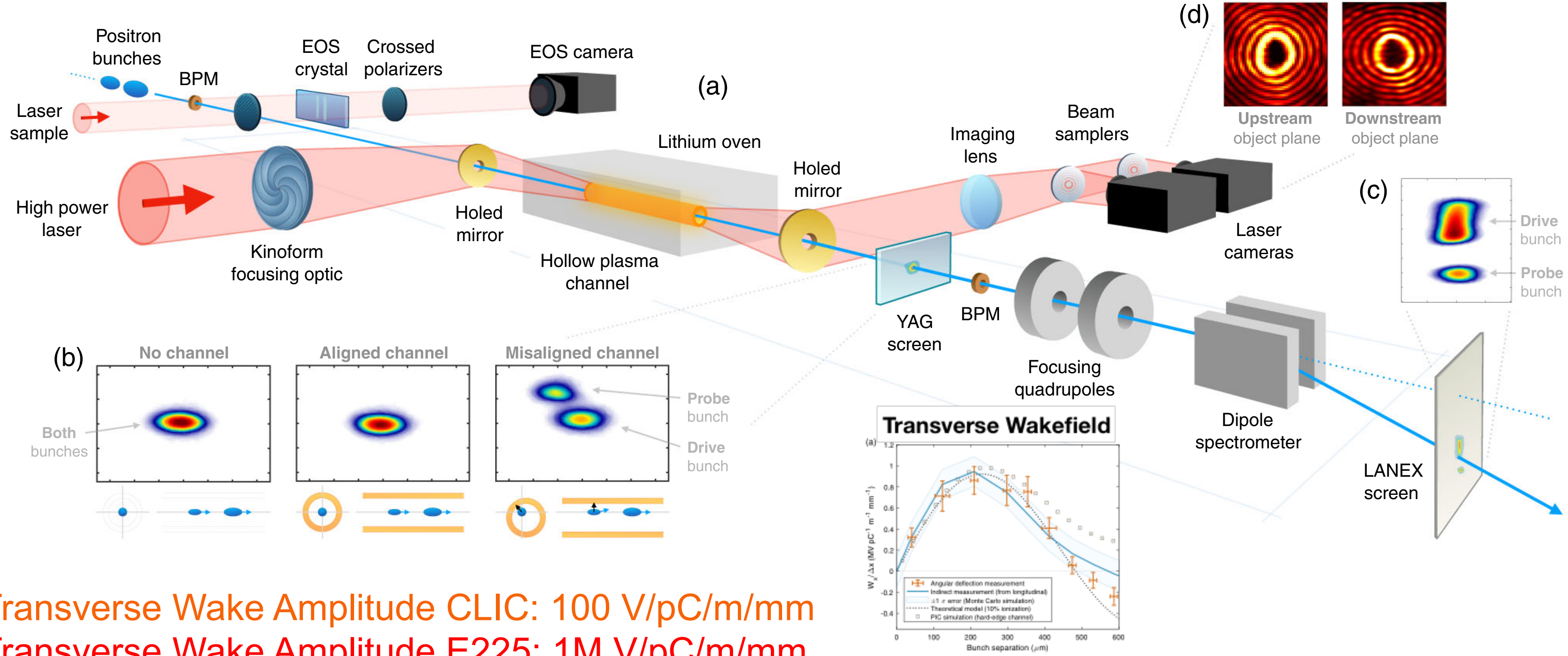


Witness beam gains energy from the wake.

Drive beam transfers energy to witness beam.

S. Gessner Ph.D. Thesis, SLAC-R-1073

Off-Axis Beams

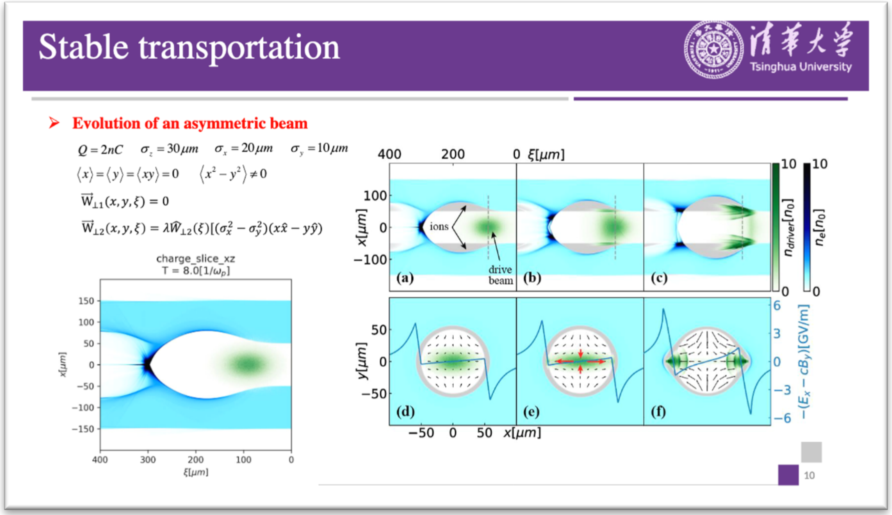


Transverse Wake Amplitude CLIC: 100 V/pC/m/mm

Transverse Wake Amplitude E225: 1M V/pC/m/mm

C. A. Lindstrøm et. al. *Phys. Rev. Lett.* 120 124802 (2018).

Addressing Stability in Hollow Channel Plasmas



Talk by Shiyu Zhou in MW-PA-D1-S3:
https://indico.cern.ch/event/971970/contributions/4161275/attachments/2171475/3666202/Positron_Acc_Shiyu_Zhou.pdf

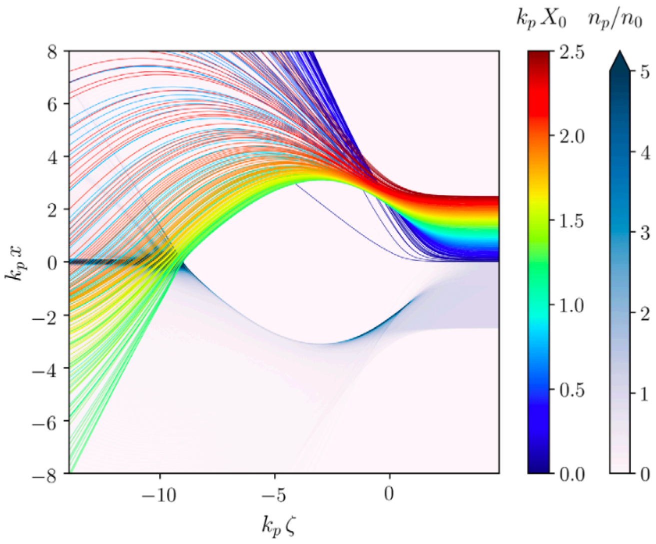
Where do we go from here?

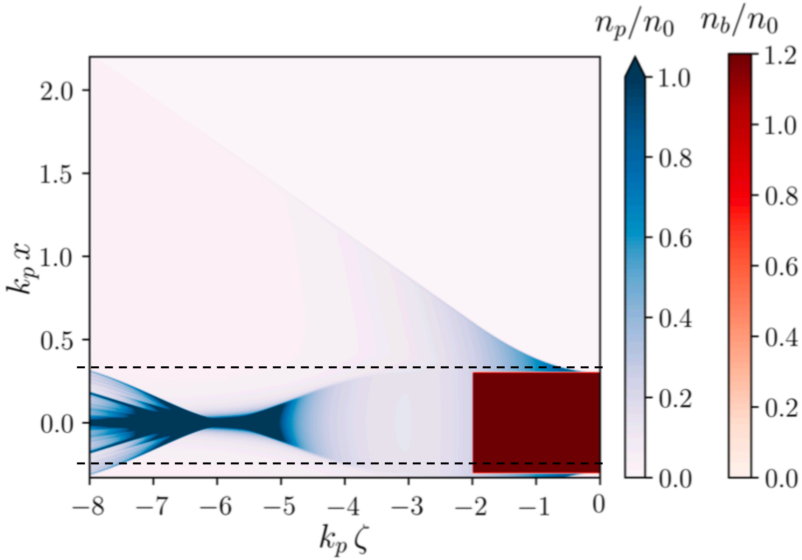
Image Credit: W. An, UCLA

Transversely Tailored Plasmas

S. Diederichs et. al. *Phys. Rev. Accel. Beams* **22** 081301 (2019)

S. Dietrichs. M.S.c. Thesis, DESY

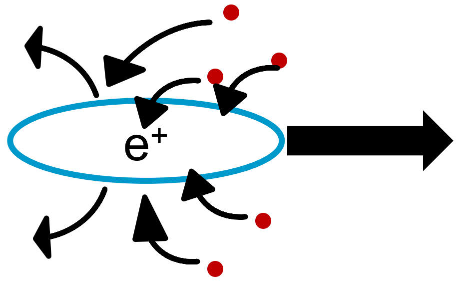




By driving a wakefield in a plasma filament, you can create a region of uniform focusing and acceleration for positrons at the back of the wake.

Transverse plasma electron motion appears to be an important factor.

Goals for Transverse Tailoring



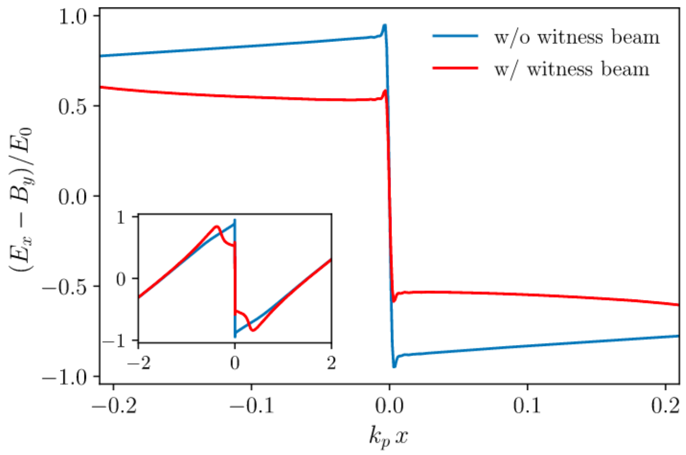
$$\partial_\xi F_z \approx 0 \qquad \partial_\xi F_\perp \approx 0$$

$$\nabla_\perp F_\perp \approx C_{onstant} \qquad \nabla_\perp F_z \approx 0$$

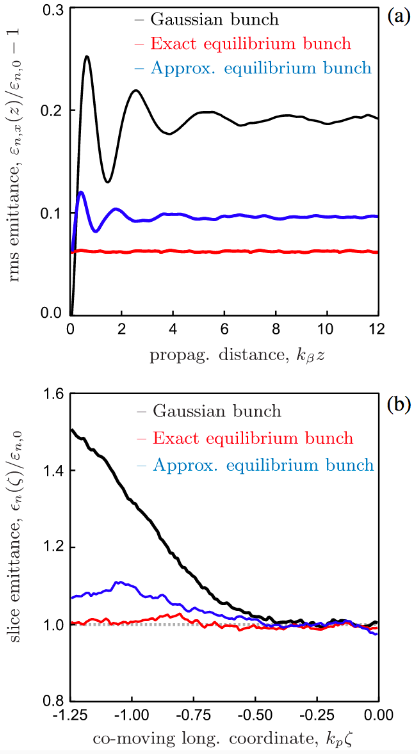
Can we create conditions where the plasma electron density in the vicinity of the positron beam roughly recreates the “ideal” equations?

All scenarios have beam matching challenges

S. Diederichs et. al. *Phys. Rev. Accel. Beams* **22** 081301 (2019)



Focusing fields in general will not be perfectly linear, but approximate matching to minimize emittance growth is still possible.



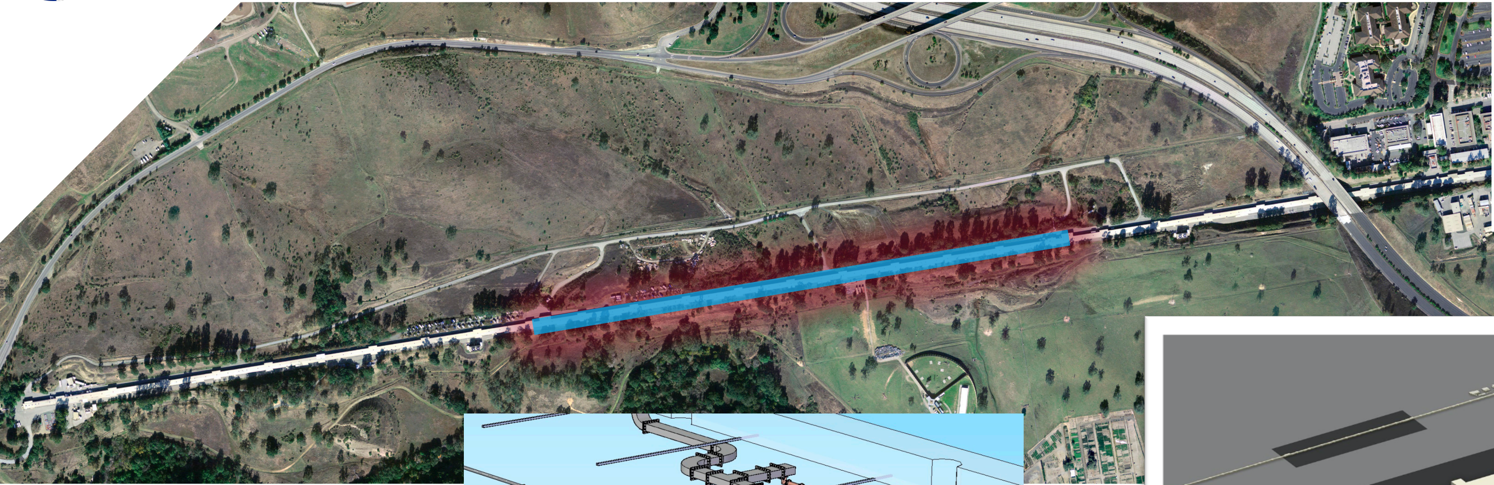
C. Benedetti et. al. *Phys. Rev. Accel. Beams* **20** 111301 (2017)

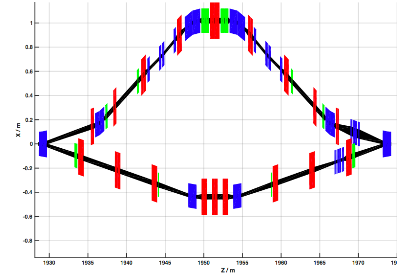
Positron Beams at FACET-II

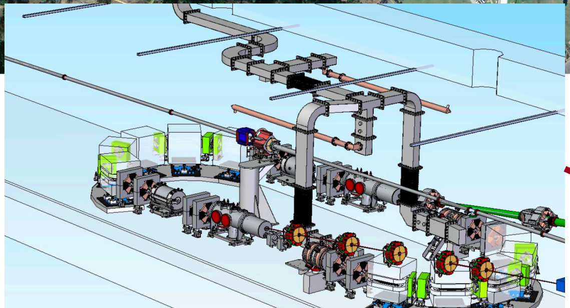
SLAC

FACET-II

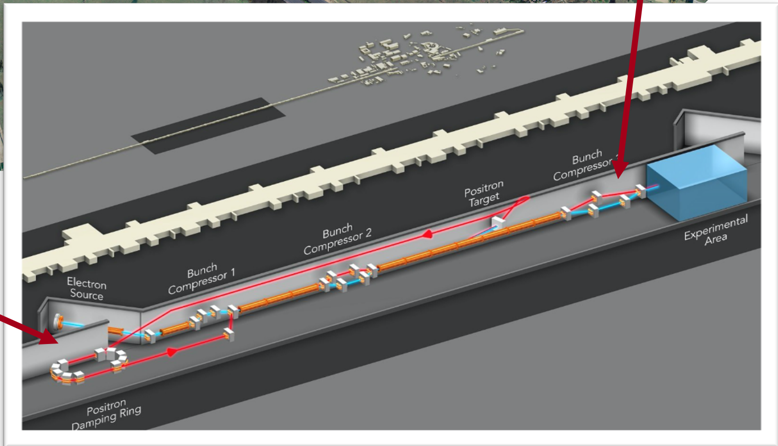
Facility for Advanced Accelerator Experimental Tests



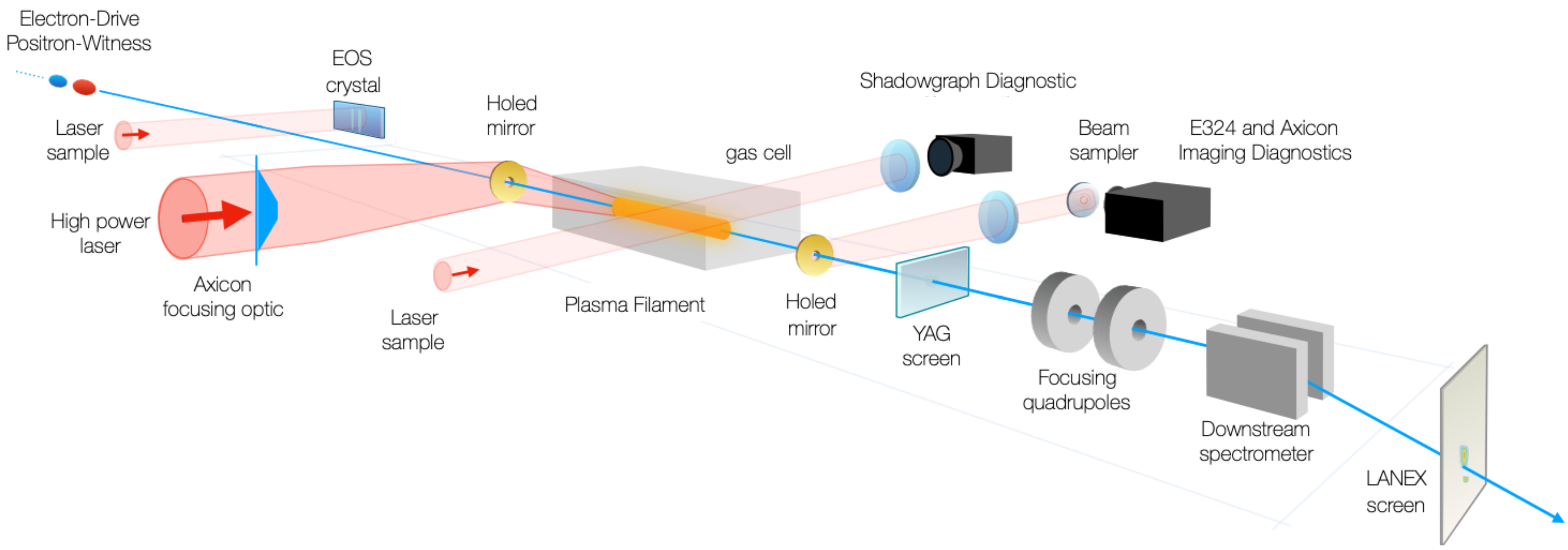




- 2.9 m diameter ring



Experimental Layout



Filament Plasma Wakefield Experiment E333 approved for FACET-II!

Thank You!

E333 Collaboration

SLAC: S. Gessner, J. Allen, C. Clarke, H. Ekerfelt, C. Emma, M. Hogan, B. O'Shea, D. Storey, X. Xu, V. Yakimenko

S. Diederichs, J. Osterhoff, M. Thévenet

C. Schroeder, C. Benedetti, E. Esarey

S. Corde, M. Gilljohann

M. Litos, R. Ariniello, C. Doss, K. Hunt-Stone, V. Lee

M. Downer, J. Brooks, R. Zgadzaj

UCLA: C. Joshi, K. Marsh, W. Mori, H. Fujii, J. Yan, N. Zan, C. Zhang

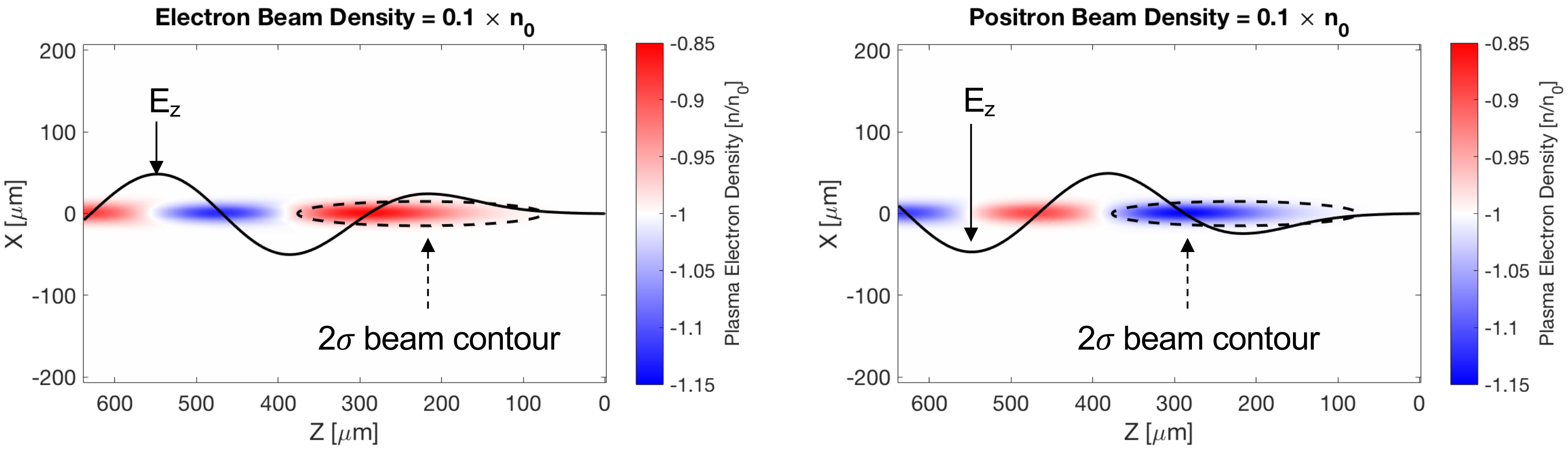
Recent Results on Positron PWFA

1. The non-linear regime is full of surprises.
   - S. Corde *et al.*, Nature **524**, 442 (2015)
2. Hollow channel PWFA is possible, but challenging.
   - S. Gessner et. al. *Nat. Comm.* **7** 11785 (2016), C. A. Lindstrøm et. al. *Phys. Rev. Lett.* **120** 124802 (2018)
3. The linear to quasi-linear regime is *not suitable* for collider-quality positron acceleration.
   - A. Doche et. al. *Nat. Sci. Rep.* **7** 14180 (2017), W. An, ALEGRO Positron PWFA Mini-Workshop (2018), S. Yu, EAAC (2019)
4. Ion motion is both a problem and a solution. Can the same be said about electron motion?
   - V. Lebedev et. al. *Phys. Rev. Accel. Beams* **20** 121301 (2018), W. An et. al. *Phys. Rev. Lett.* **118**, 244801 (2017), V. Lebedev et. al. arXiv:1808.03860v2 [physics.acc-ph] (2018), T. Mehrling et. al. *Phys. Rev. Lett.* **121**, 264802 (2018)
5. Transversely tailored plasmas and drivers open up a huge parameter space.
   - S. Diederichs et. al. *Phys. Rev. Accel. Beams* **22** 081301 (2019), J. Vieira et. al. *Phys. Rev. Lett.* **112**, 215001 (2014), N. Jain et. al. *Phys. Rev. Lett.* **115**, 195001 (2015), T. Silva, EAAC (2019)

Backup

Positron PWFA in Linear Regime

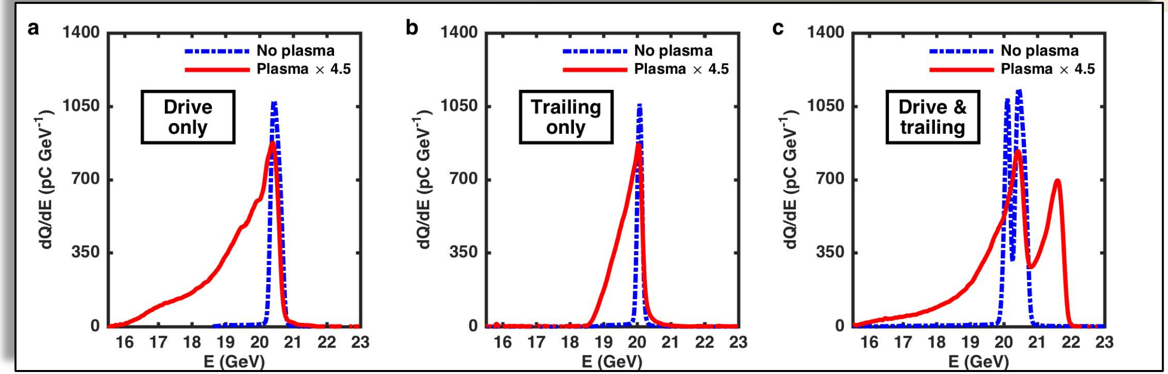
Positron Acceleration in the Linear Regime?

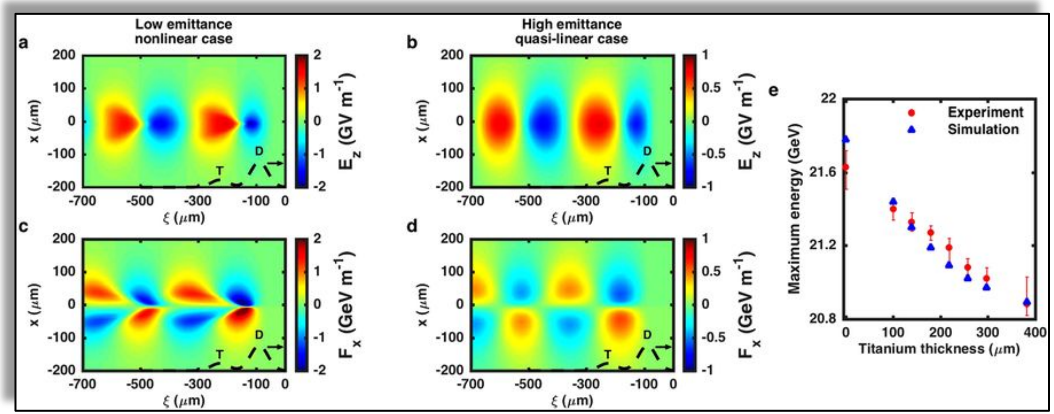


In the linear regime, the response is symmetric.

QuickPIC Simulation run on Hoffman2 at UCLA

Positron Acceleration in the Linear Regime





A. Doche *et al.*, Nat. Sci. Rep. 7, 14180 (2017)

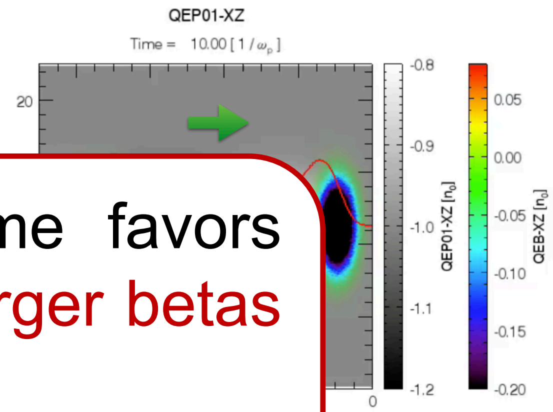
Beam Matching in the Linear Regime

Conditions for matching in the linear regime:

$$\frac{d^2\sigma_r}{dz^2} = -K\sigma_r + \frac{\epsilon^2}{\ldots} \quad \text{(envelope equation)}$$

n_b

Drive Beam (Electron):
N =1.25 x 10^{10} (2.0 nC), I_{peak}=15 kA
σ_z = 16 μm, E = 10 GeV
σ_r = 100.0 μm, ε_N = 1000 μm rad



Constraints ... = 10^{18} cm^{-3}:

$n_{\text{trailing}} =$ ... 000

... kA

- Emittance = 10 nm

$$\sigma_r = \sqrt{\frac{\beta\varepsilon_n}{\gamma}} \implies \beta_{\text{trailing}} = \gamma\frac{\sigma_r^2}{\epsilon_n} > \frac{\gamma I}{2\pi e c\, n_0\, \epsilon_n}$$

$\beta = 330$ m, $\lambda_\beta = 2$ km

Beam matching in the linear regime favors **lower charge, higher emittance, or larger betas** as the beam energy increases.

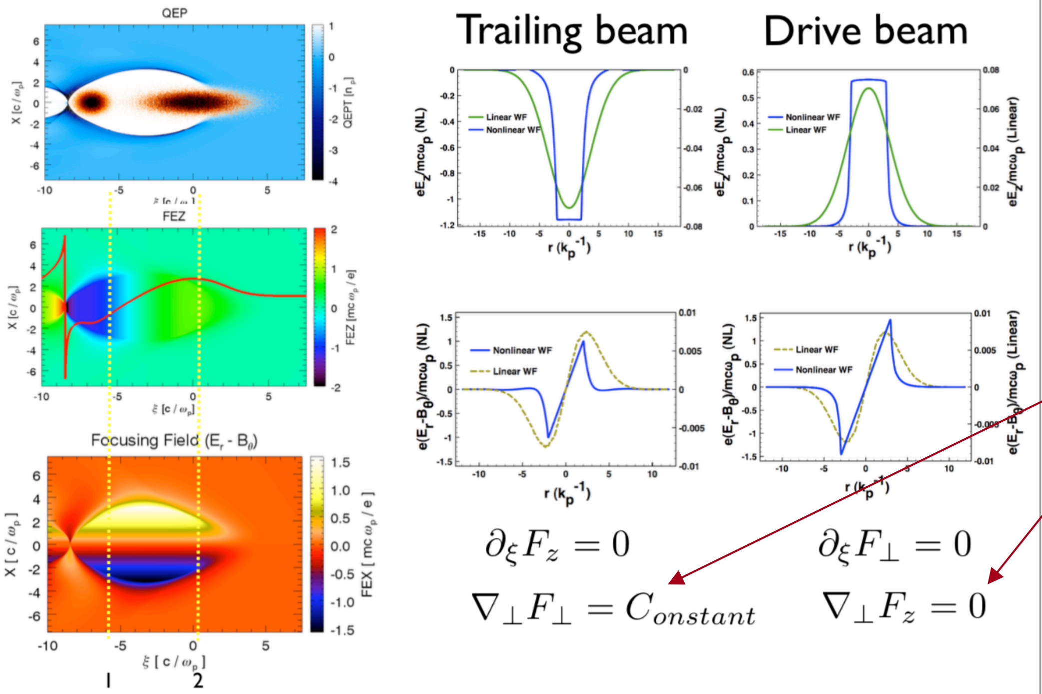
Not acceptable for a linear collider!

S. Corde, Royal Society Workshop

W. An, ALEGRO Positron PWFA Mini-Workshop

The Ideal Case

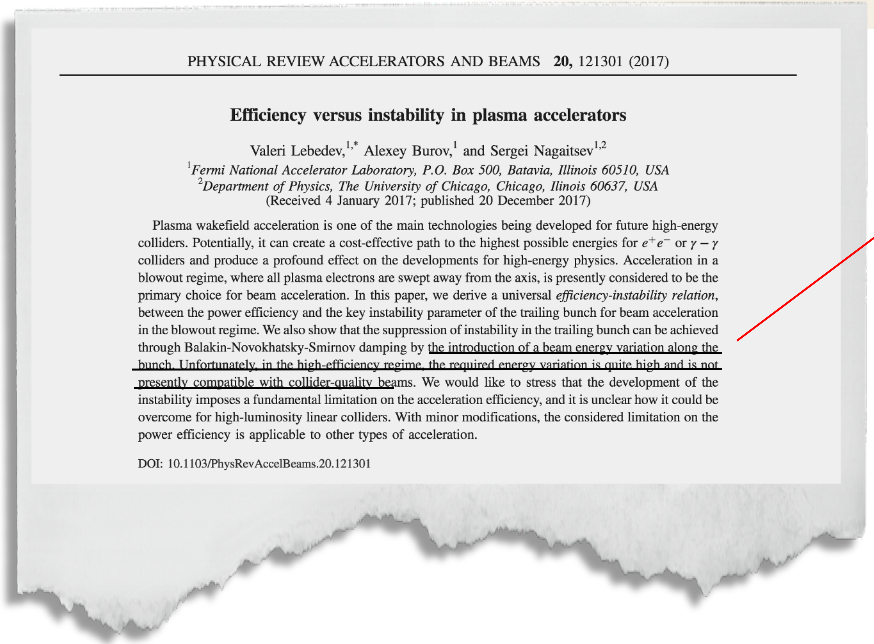
Nonlinear wakefield is IDEAL for accelerating/focusing electrons
Trailing beam does not modify focusing fields of wake



Not true in the linear regime

W. Mori, PAC 2011 Tutorial

Is the blow-out regime "ideal" for electrons?



PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 121301 (2017)

Efficiency versus instability in plasma accelerators

Valeri Lebedev,[1,*] Alexey Burov,[1] and Sergei Nagaitsev[1,2]
[1]*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA*
[2]*Department of Physics, The University of Chicago, Chicago, Ilinois 60637, USA*
(Received 4 January 2017; published 20 December 2017)

Plasma wakefield acceleration is one of the main technologies being developed for future high-energy colliders. Potentially, it can create a cost-effective path to the highest possible energies for e^+e^- or $\gamma-\gamma$ colliders and produce a profound effect on the developments for high-energy physics. Acceleration in a blowout regime, where all plasma electrons are swept away from the axis, is presently considered to be the primary choice for beam acceleration. In this paper, we derive a universal *efficiency-instability relation*, between the power efficiency and the key instability parameter of the trailing bunch for beam acceleration in the blowout regime. We also show that the suppression of instability in the trailing bunch can be achieved through Balakin-Novokhatsky-Smirnov damping by the introduction of a beam energy variation along the bunch. Unfortunately, in the high-efficiency regime, the required energy variation is quite high and is not presently compatible with collider-quality beams. We would like to stress that the development of the instability imposes a fundamental limitation on the acceleration efficiency, and it is unclear how it could be overcome for high-luminosity linear colliders. With minor modifications, the considered limitation on the power efficiency is applicable to other types of acceleration.

DOI: 10.1103/PhysRevAccelBeams.20.121301

> We would like to stress that the development of the instability imposes a fundamental limitation on the acceleration efficiency, and it is unclear how it could be overcome for high-luminosity linear colliders.

Wake-to-beam power coupling efficiency

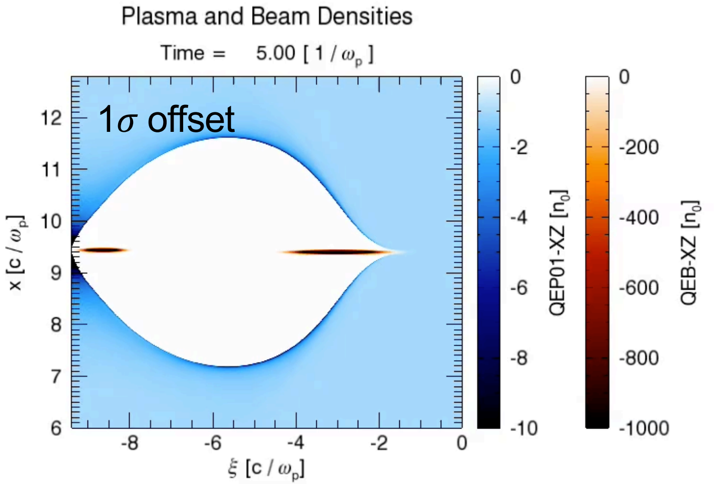
Instability growth rate

$$\eta_t \approx \frac{\eta_p^2}{4(1-\eta_p)}$$

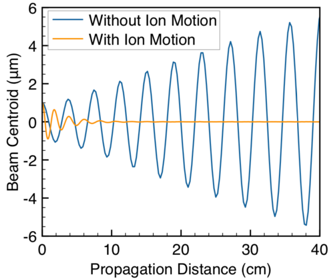
Highly efficient acceleration -> Strong coupling to the wake -> Drives transverse instability

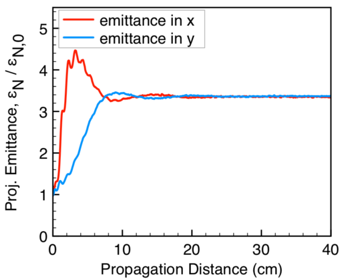
Solutions Proposed

SLAC

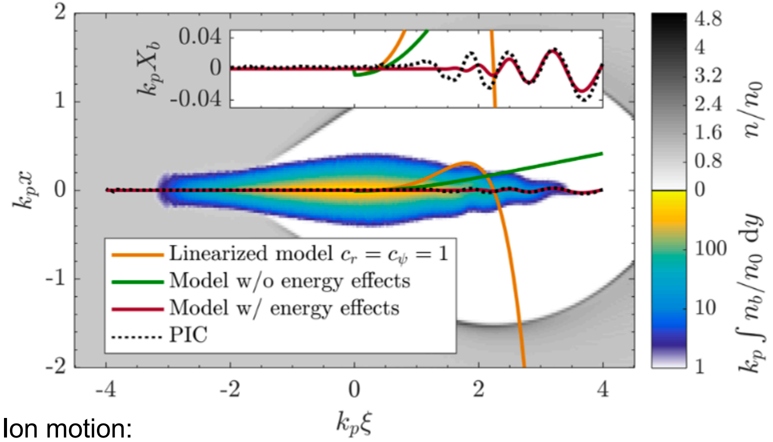


L. Hildebrand and W. An, AAC 2018





W. An, UCLA



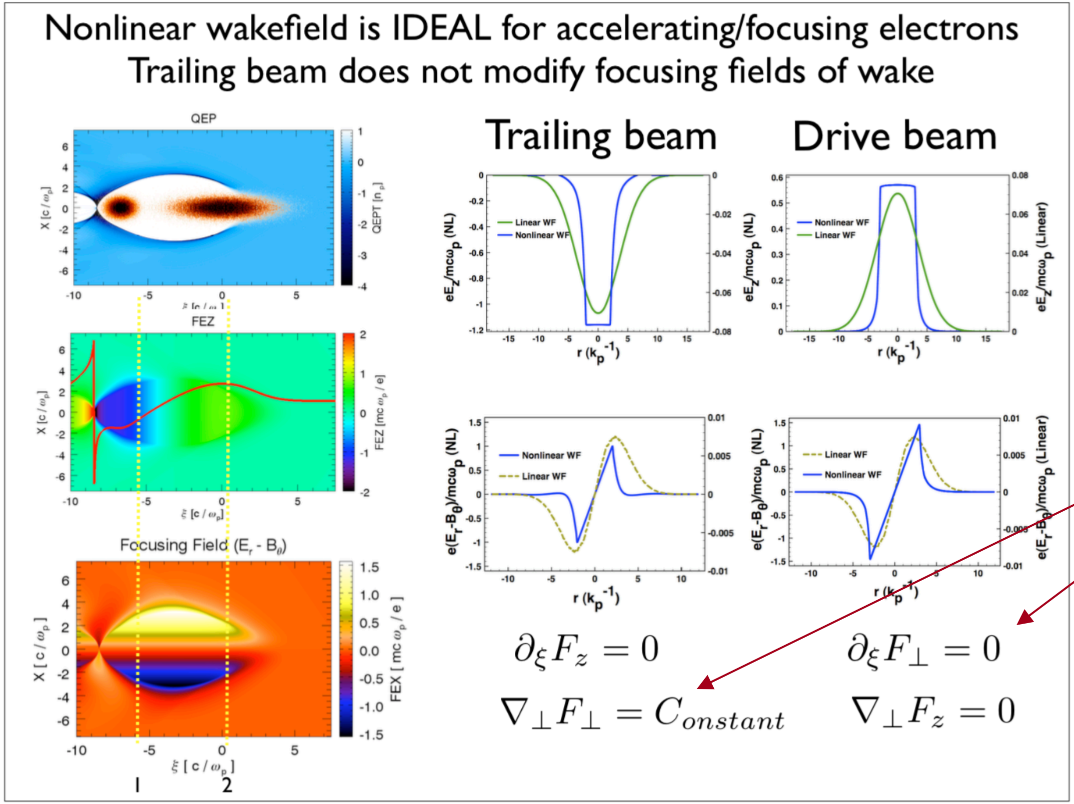
Ion motion:
W. An, et. al. Phys. Rev. Lett. 118, 244801 (2017)
T. J. Mehrling, et. al. Phys. Rev. Lett. 121, 264802 (2018)
V. Lebedev et. al. arXiv:1808.03860v2 [physics.acc-ph] (2018)

Energy spread:
T. J. Mehrling, et. al. Phys. Rev. Lett. 118, 174801(2017)

Quasi-linear focusing:
R. Lehe, et. al. Phys. Rev. Lett. 119, 244801 (2017)

Fat beams:
A. Martinez de la Ossa, et. al. Phys. Rev. Lett. 121, 064803 (2018)

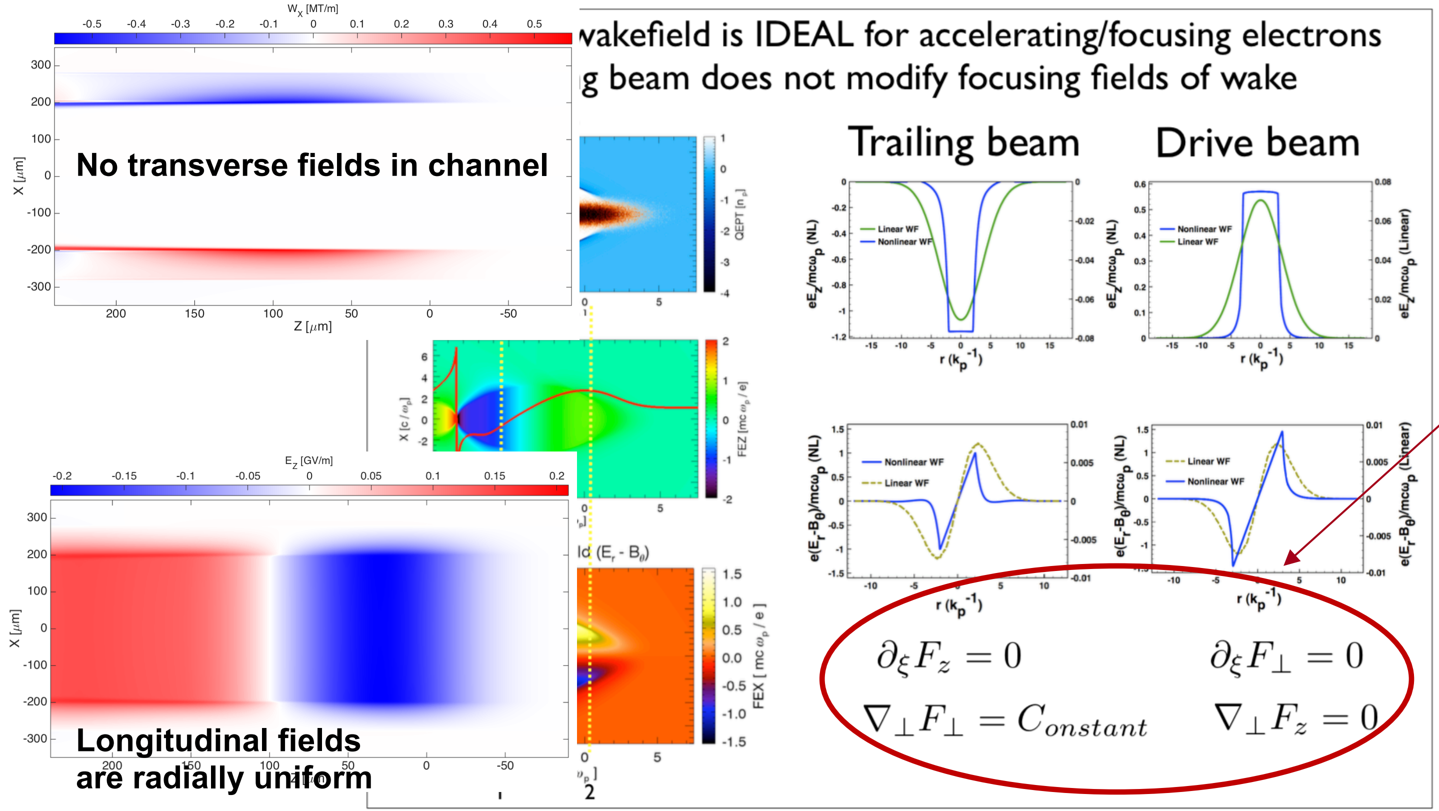
The Ideal Case?



Replace "=" with "≈"

W. Mori, PAC 2011 Tutorial

Fields "Ideal" for Hollow Channel



Still true in hollow channel

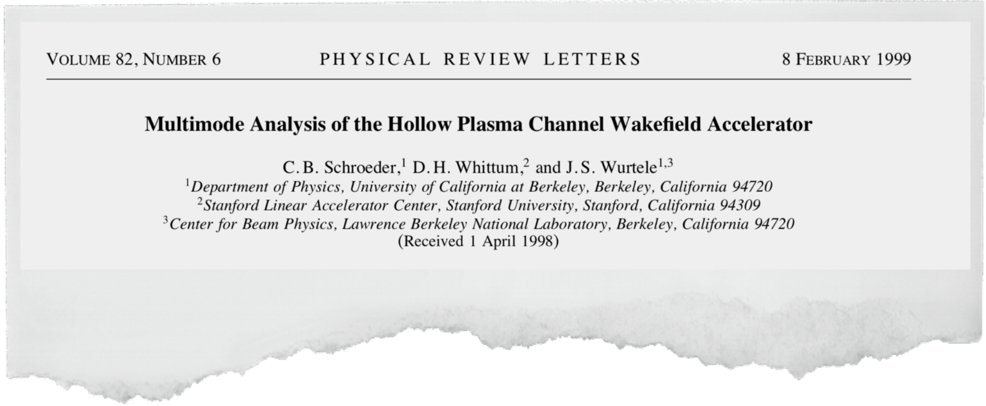
W. Mori, PAC 2011 Tutorial

Off-Axis Beams

What if the beam is off-axis in the channel?

The beam induces a transverse wakefield which deflects the tail of the bunch from the channel axis.

This wakefield is strong and drives a beam-breakup instability (BBU). The growth lengths of this instability is O(10 cm) for FACET-like parameters.



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Multimode Analysis of the Hollow Plasma Channel Wakefield Accelerator

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[2]*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*
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(Received 1 April 1998)

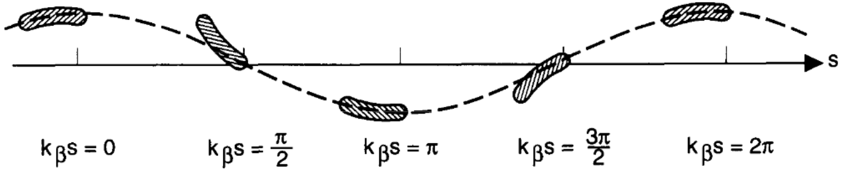
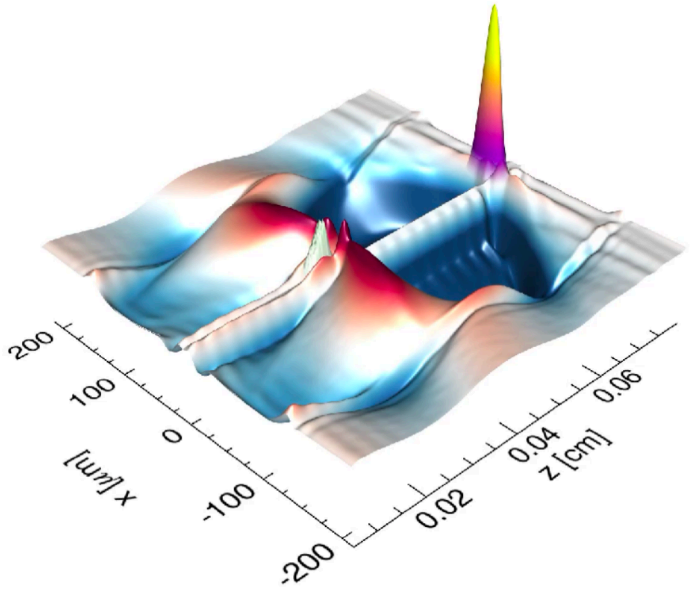


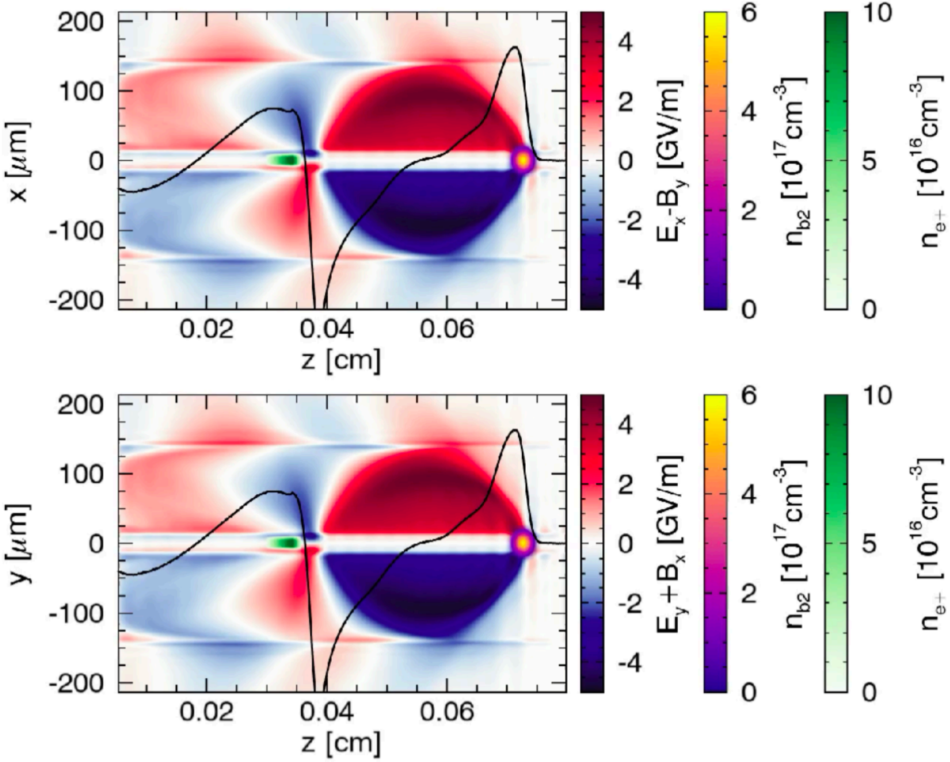
Figure 3.3. Sequence of snapshots of a beam undergoing dipole beam breakup instability in a linac. Values of $k_\beta s$ indicated are modulo 2π. The dashed curves indicate the trajectory of the bunch head.

Physics of Collective Beam Instabilities in High Energy Accelerators.
A. Chao, Wiley 1992

Other PWFA concepts

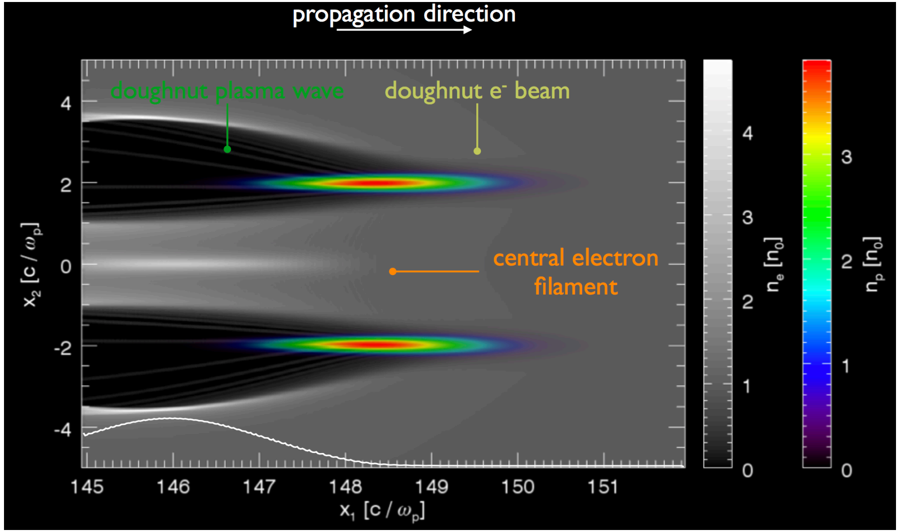
Beam-Shaped Plasmas



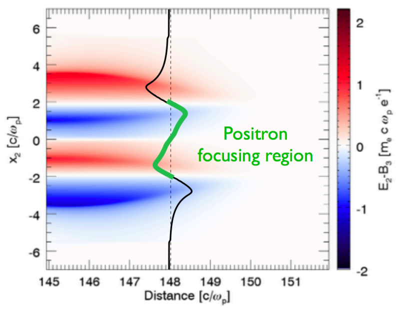


T. Silva, EAAC (2019)

Transversely Tailored Drivers

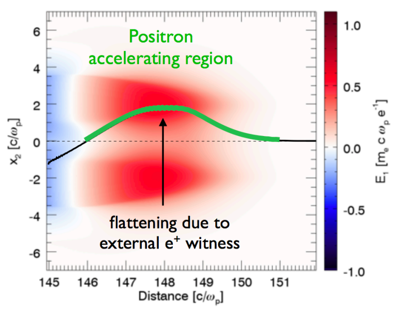


Focusing force



- **Linear focusing** force for e^+
- Width of linear focusing region on the order of the skin depth
- Focusing varies but **may not compromise divergence/emittance growth**

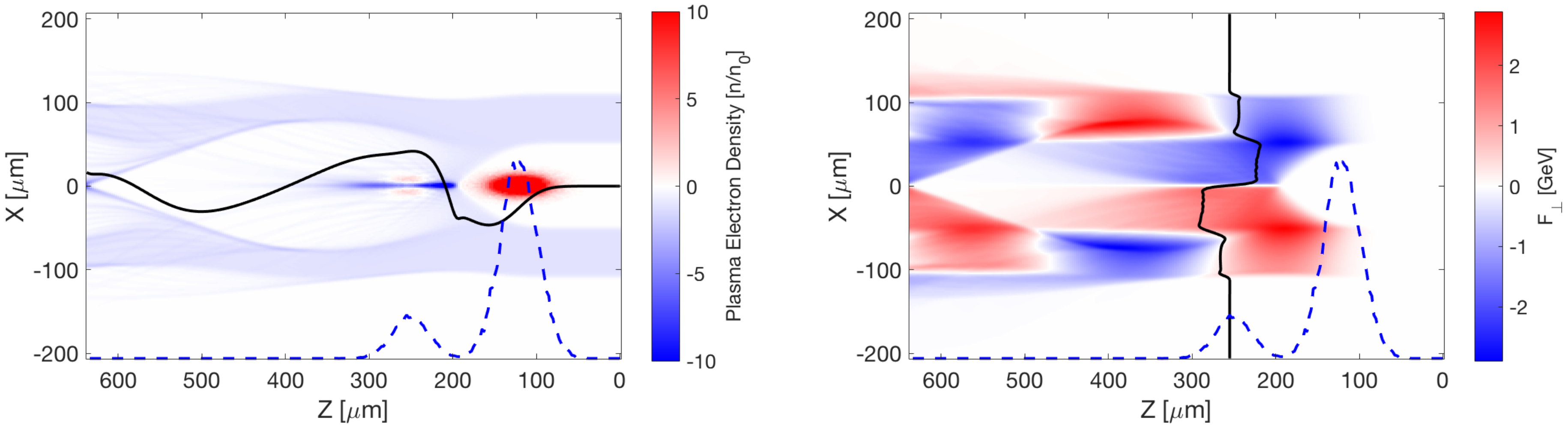
Accelerating force



- e+ can **accelerate at the front**
- **Beam loading** is possible
- **Energy spread** growth can be **controlled**

J. Vieira, et al. PRL 112 215001 (2014)
N. Jain et al. PRL 115 195001(2015)

Transverse Tailoring has a HUGE Parameter Space



It is possible to reproduce some features of the wake seen in the narrow plasma filament case by driving a non-linear wake in the hollow channel.