New Directions in Positron Plasma Acceleration Research

FACET-II Workshop

Spencer Gessner

October 31st, 2019

Experimental Positron PWFA by the Numbers

SLAC

1 Laboratory: SLAC

2 Facilities: FFTB, FACET

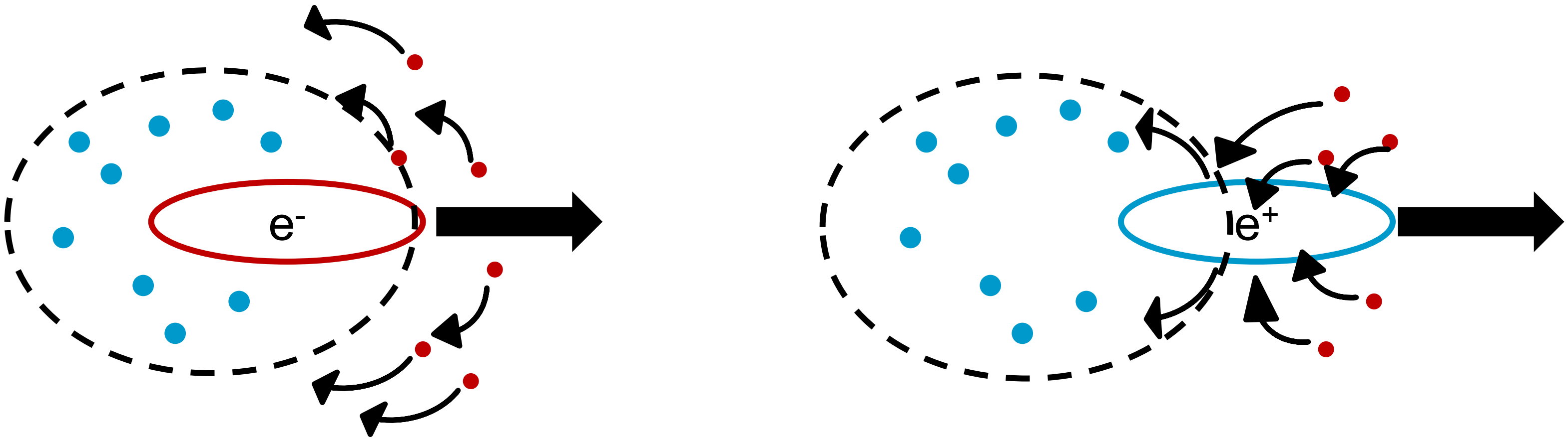
3 Experiments: E162, E200, E225

7 Publications:

Ultrarelativistic-Positron-Beam Transport through Meter-Scale Plasmas, M. J. Hogan et. al. *PRL.* 90 205002 (2003).
Plasma-Wakefield Acceleration of an Intense Positron Beam, B. Blue et. al. *PRL.* 90 214801 (2003).
Halo Formation and Emittance Growth of Positron Beams in Plasmas, P. Muggli et. al. *PRL.* 101 055001 (2008).
Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield, S. Corde et. al. *Nature.* 524 442445 (2015).
Demonstration of a positron beam-driven hollow channel plasma wakefield accelerator, S. Gessner et. al. *Nat. Comm.* 7 11785 (2016).
Acceleration of a trailing positron bunch in a plasma wakefield accelerator, A. Doche et. al. *Nat. Sci. Rep.* 7 14180 (2017).
Meas. of Trans. Wakes Induced by a Misaligned e^{+} Bunch in a HCPA, C.A. Lindstrøm et. al. *PRL.* 120 124802 (2018).

Positron acceleration is 50% of a PLC but only a small fraction of PWFA research.

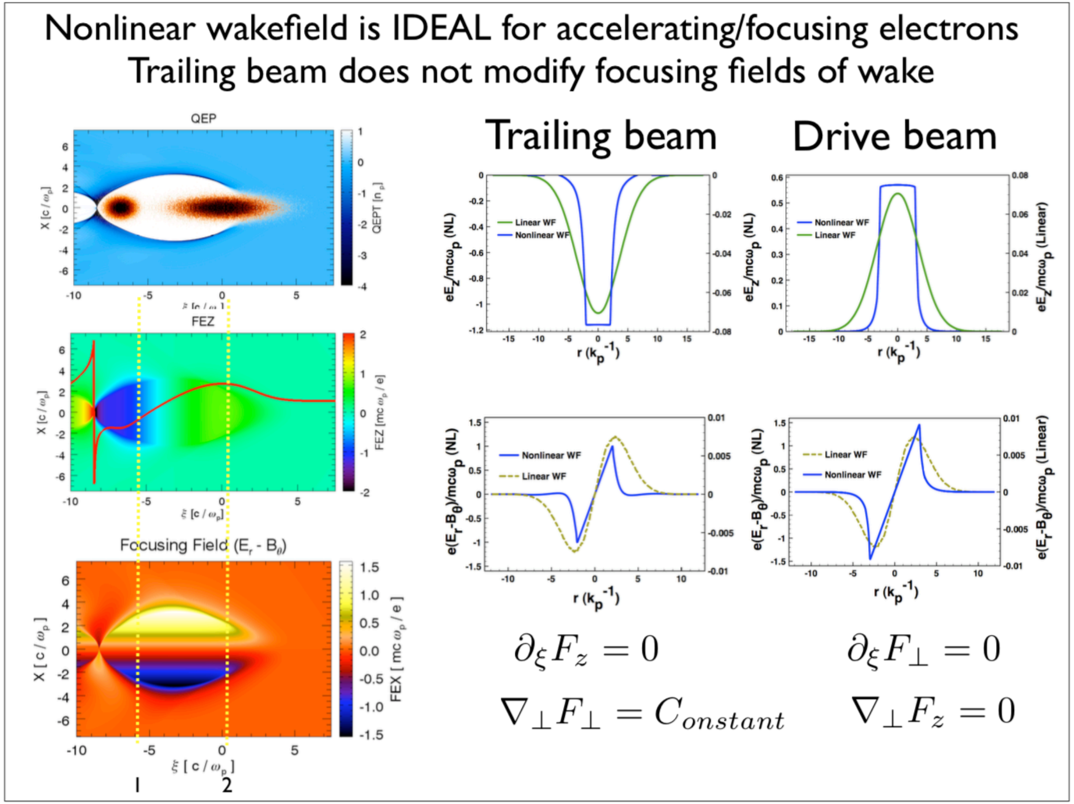
The Challenge



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

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



W. Mori, PAC 2011 Tutorial

Plasma Response to Positron Beams

SLAC

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
Department of Electrical Engineering, University of California, Los Angeles, Los Angeles, California 90095

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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Department of Electrical Engineering, University of South California, Los Angeles, California 90089

(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 $n_b/n_p \approx 1$.

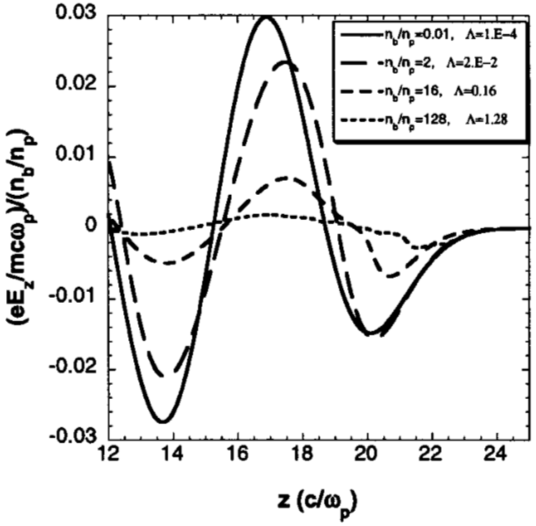
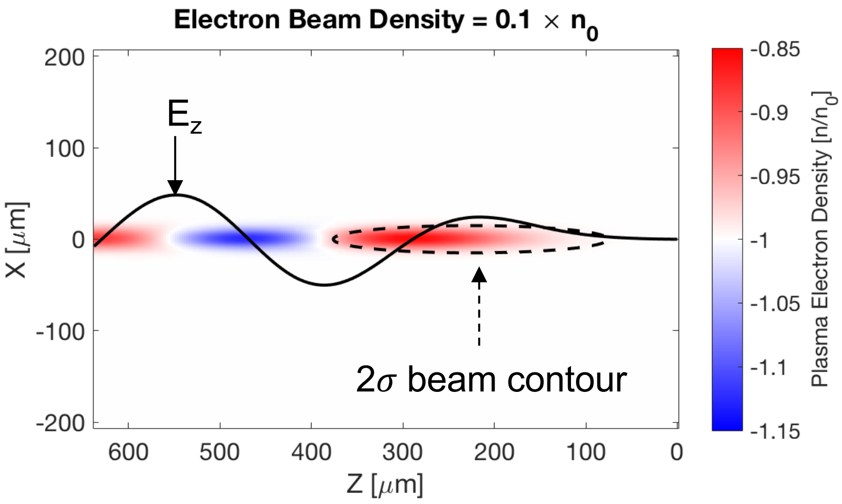
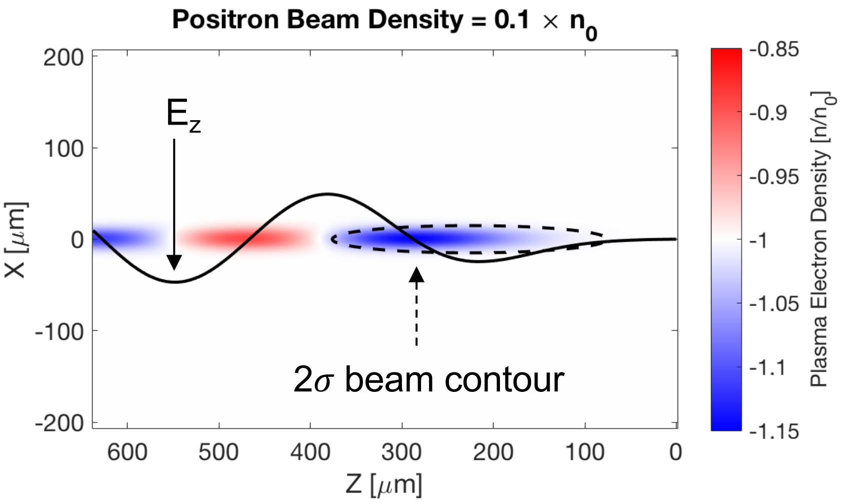


FIG. 7. Wake structure for positron drivers: we plot the ratio of normalized electric field over n_b/n_p, as a function of distance behind the wake, for $k_p\sigma_z=\sqrt{2}$ and $k_p\sigma_r=0.1$ (the beam center is at $z=20c/\omega_p$).

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

Plasma Response to Beams of Opposite Charge

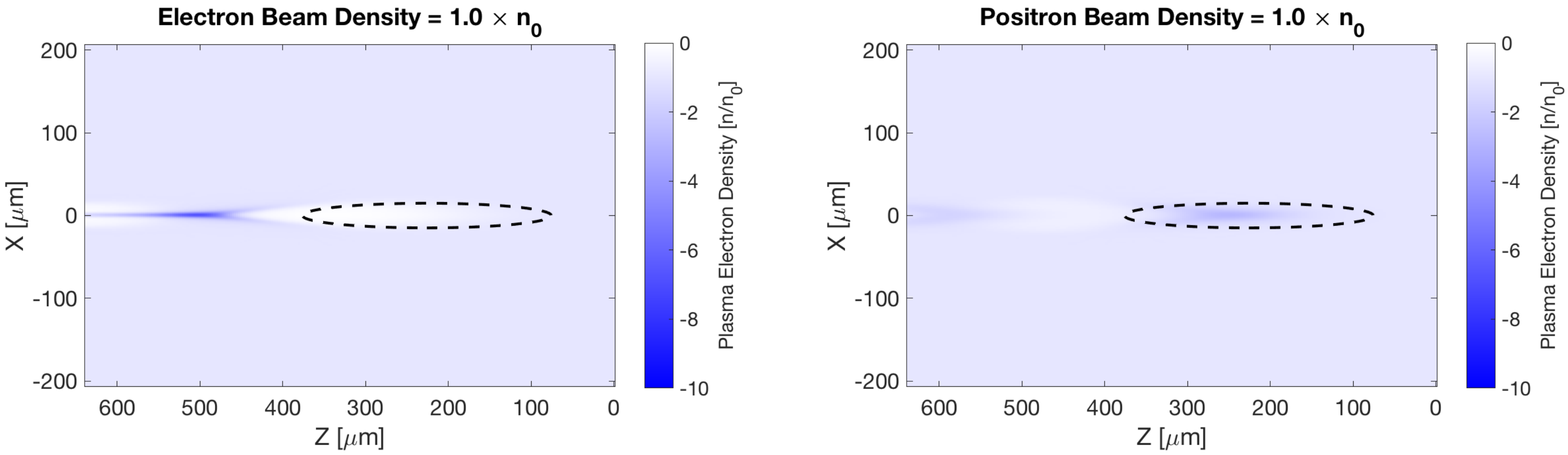




In the linear regime, the response is symmetric.

QuickPIC Simulation run on Hoffman2 at UCLA

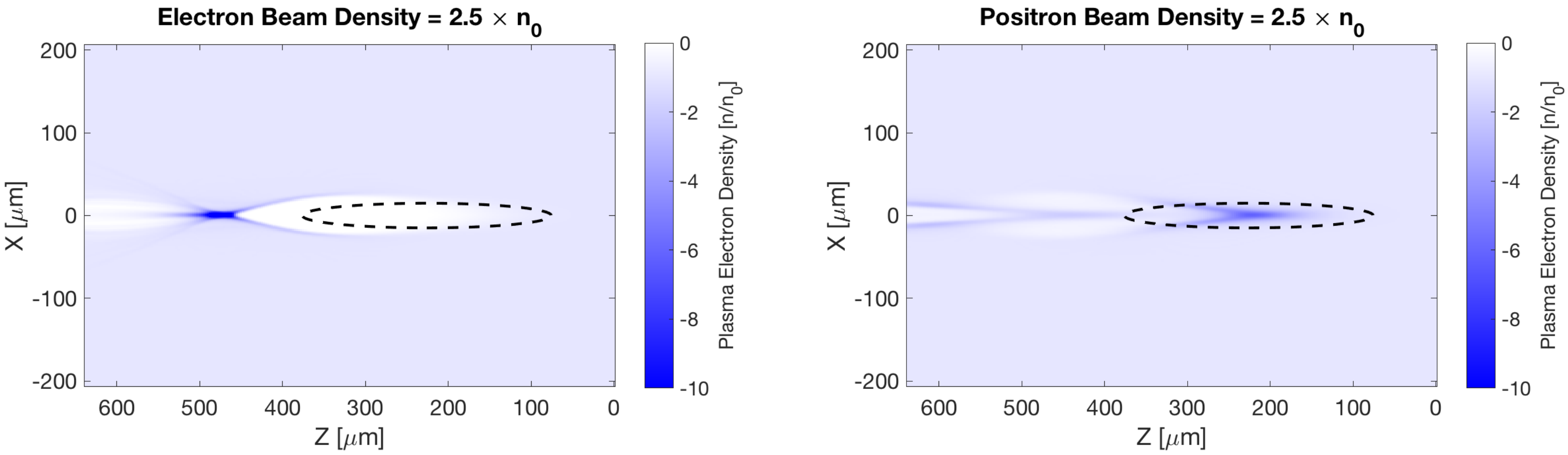
Plasma Response to Beams of Opposite Charge



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



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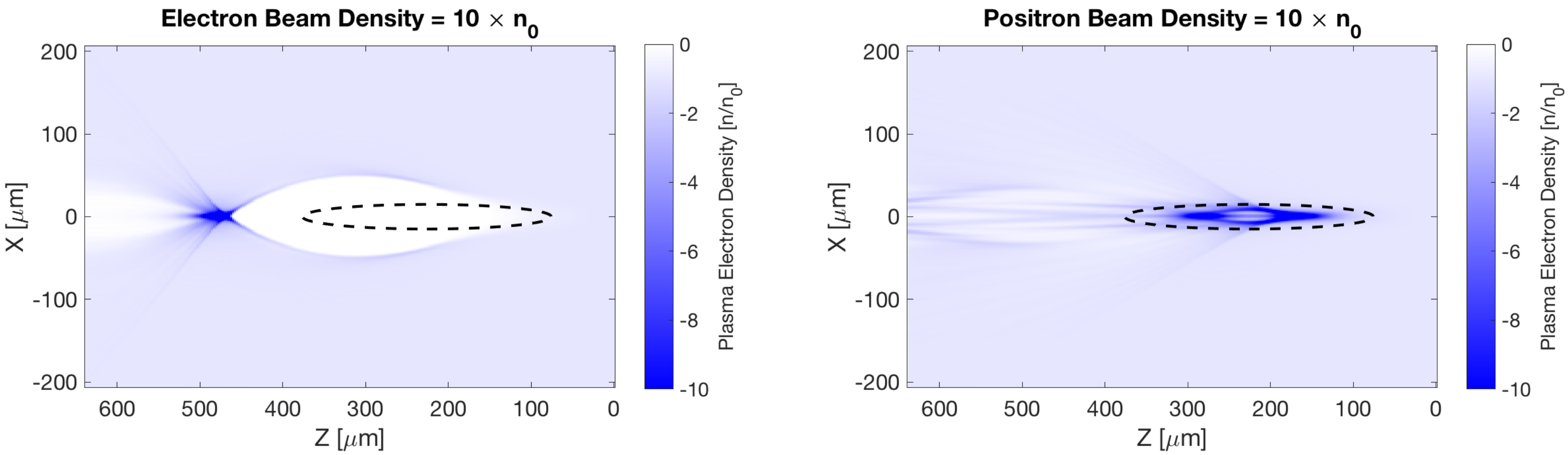
Plasma Response to Beams of Opposite Charge



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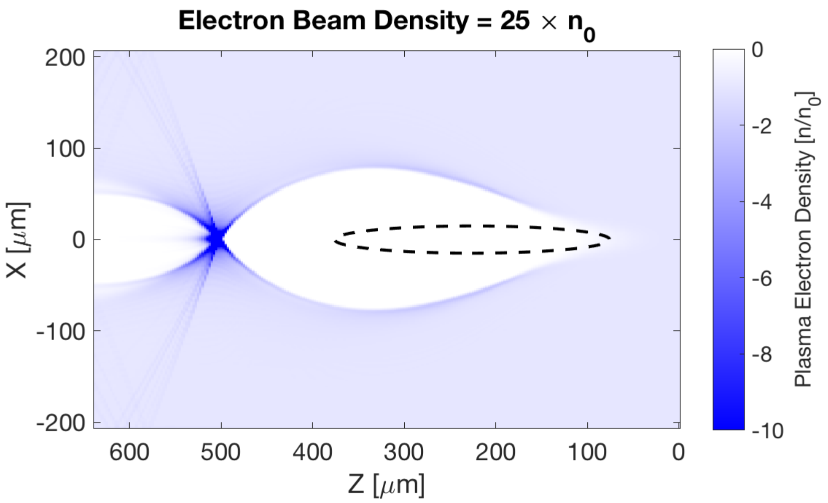
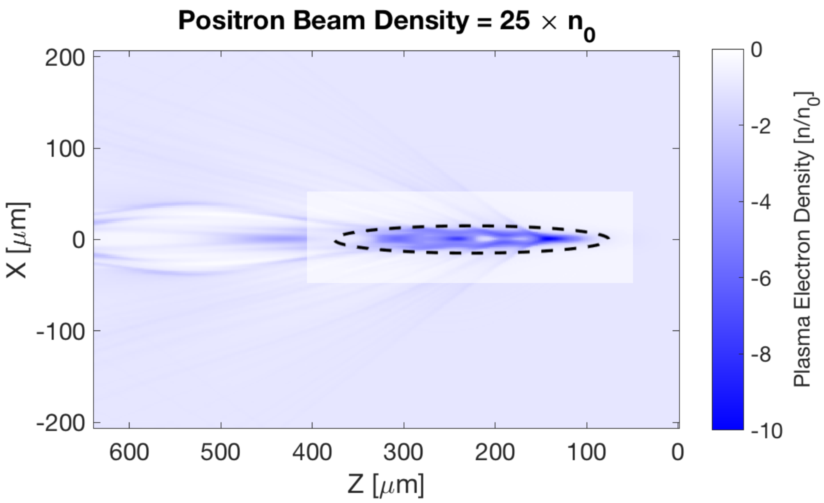
QuickPIC Simulation run on Hoffman2 at UCLA

Plasma Response to Beams of Opposite Charge





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

And more complicated.

QuickPIC Simulation run on Hoffman2 at UCLA

What have we learned in the past 5 years?

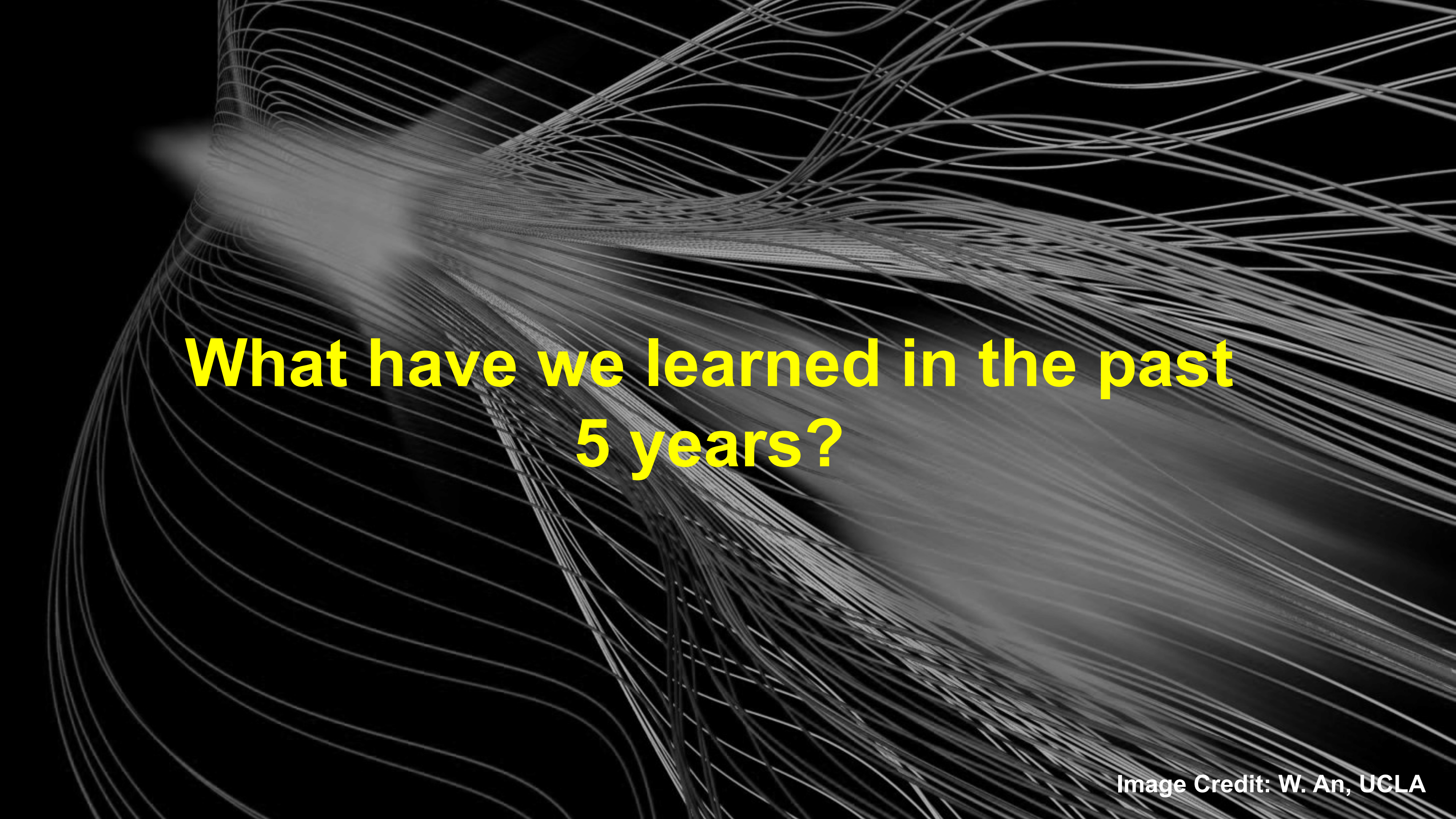


Image Credit: W. An, UCLA

What have we learned in the last 5 years?

SLAC

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)

Positron Acceleration in Nonlinear Regime

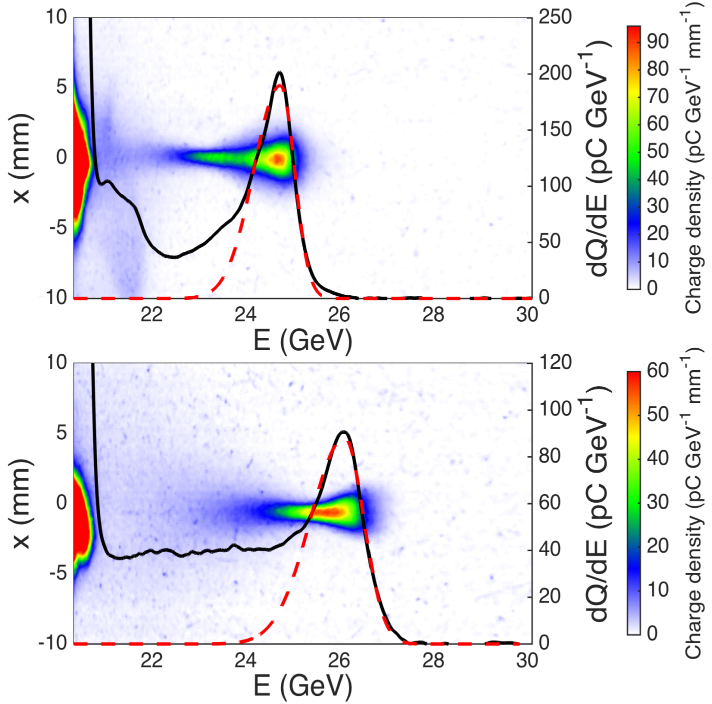
FACET was able to provide high-density, compressed positron beams for non-linear PWFA experiments.

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.).

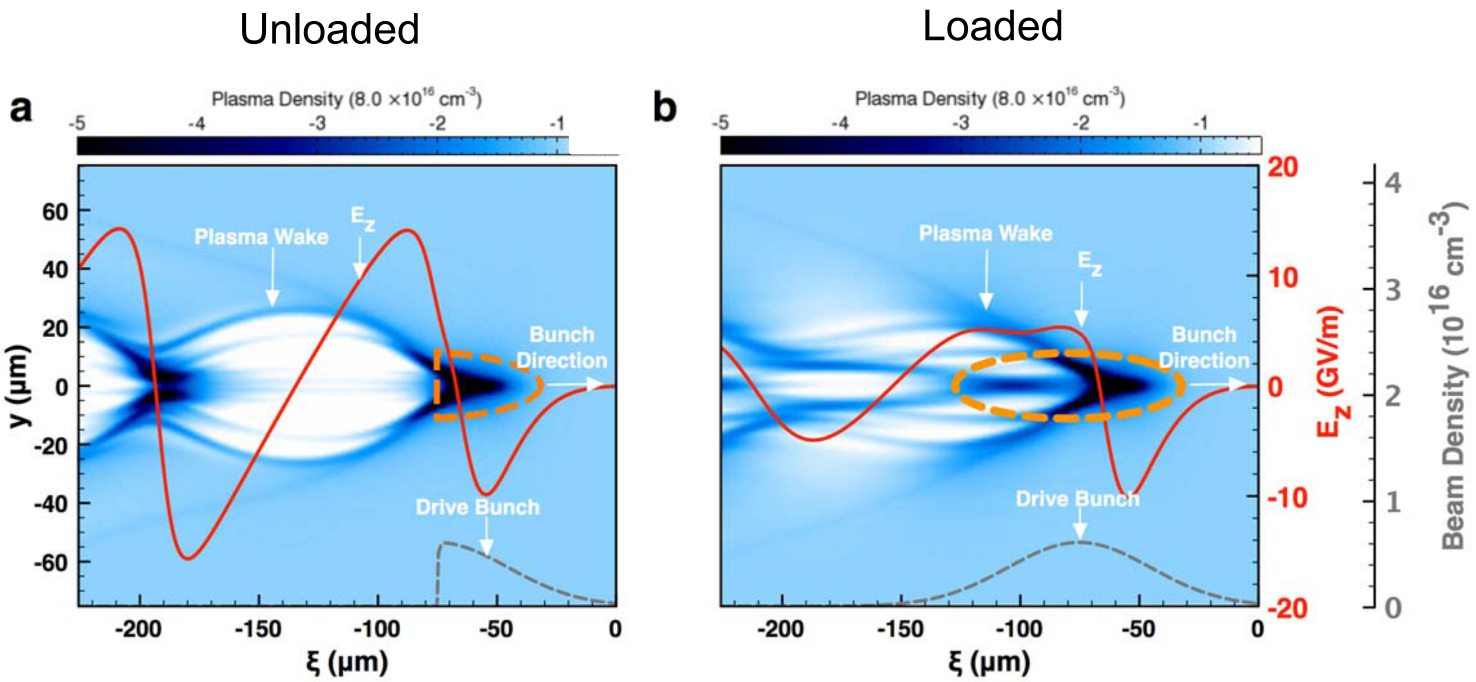
An unexpected result!

Experimental results in 1.3 m plasma



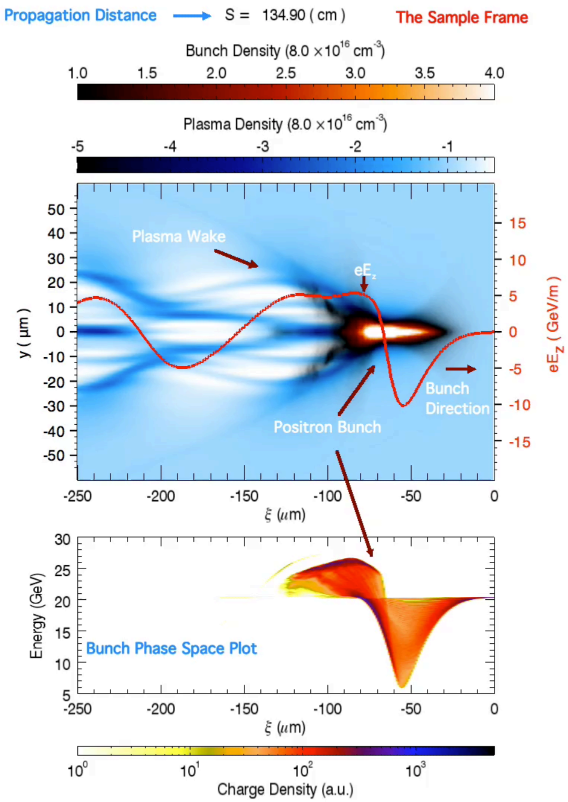
S. Corde *et al.*, Nature **524**, 442 (2015)

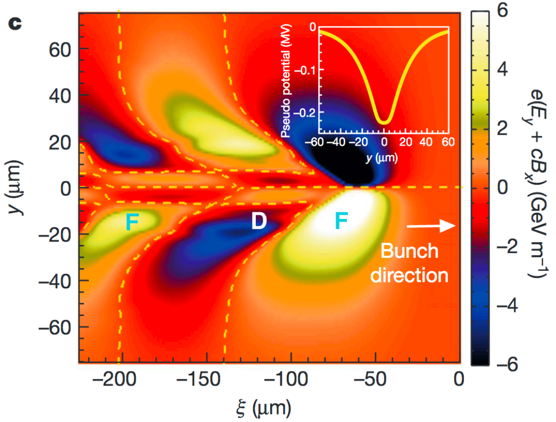
Positron Acceleration in Nonlinear Regime



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

Positron Acceleration in Nonlinear Regime





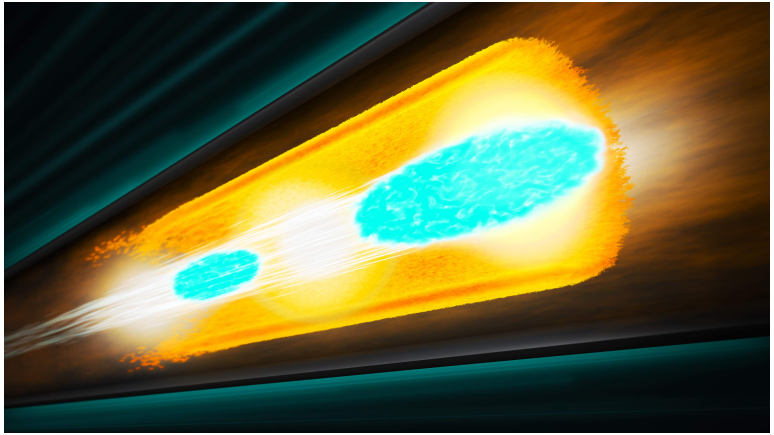
Key questions:

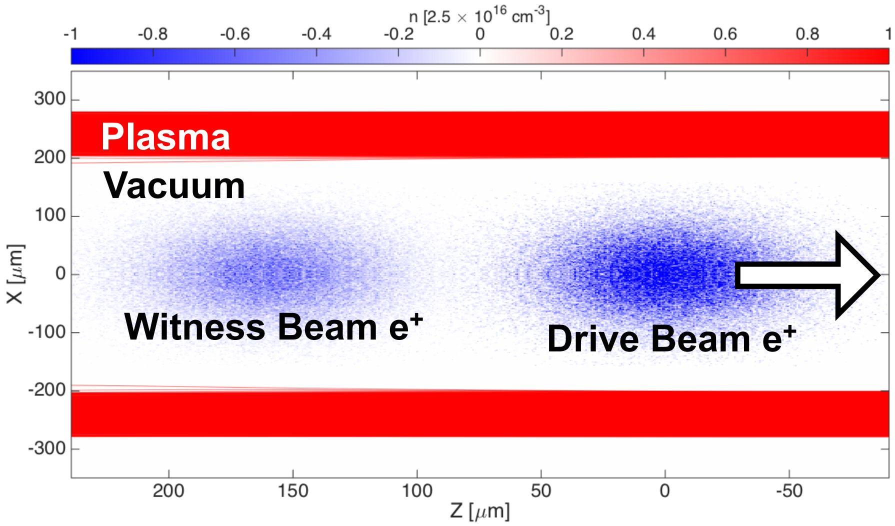
Is there an equilibrium emittance, or is the emittance growth continuous?

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

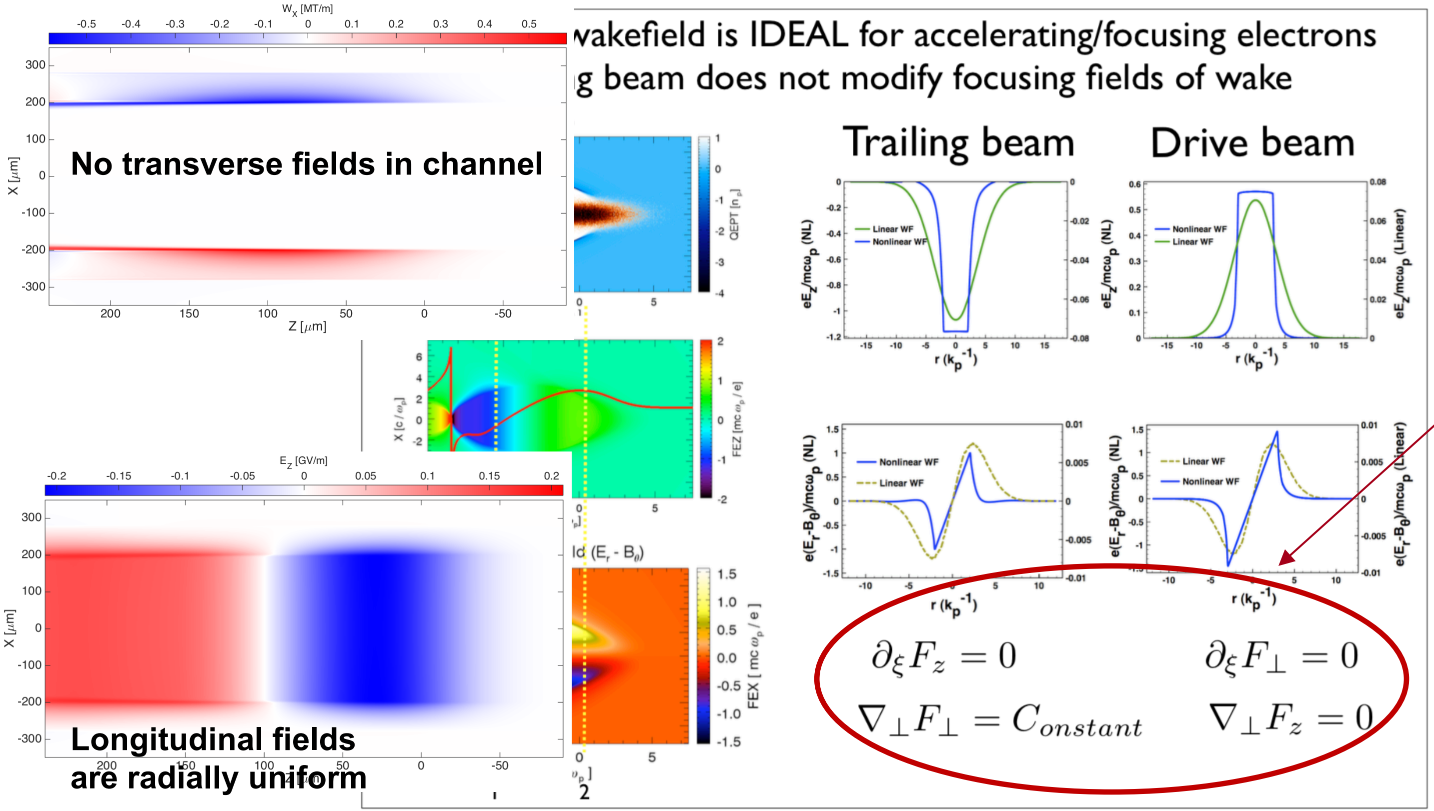




The Hollow Channel Plasma is a *structure* that symmetrizes the response of the plasma to electron and positron beams.

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

Fields "Ideal" for Hollow Channel



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

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

Still true in hollow channel

W. Mori, PAC 2011 Tutorial

Hollow Channel Plasma Acceleration

Laser wakefield acceleration & optical guiding in a hollow plas

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IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 24, NO. 2, APRIL 1996 351

VOLUME 81, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1998

VOLUME 82, NUMBER 6 PHYSICAL REVIEW LETTERS 8 FEBRUARY 1999

Multimode An

[1]Department
[2]Stanford L
[3]Center for Beam

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14,** 041301 (2011)

Hollow plasma channel for positron plasma wakefield acceleration

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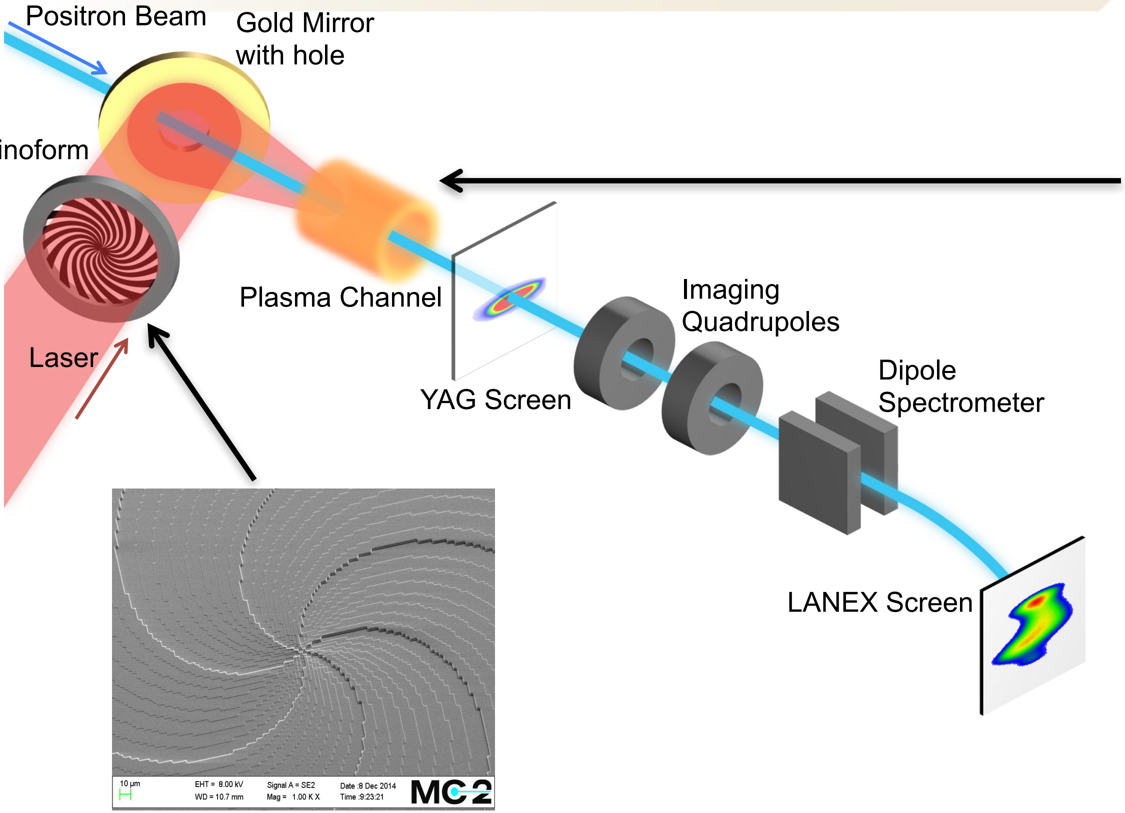
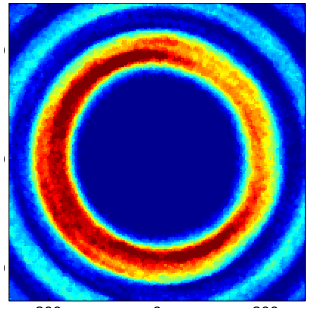
(Received 9 September 2010; published 18 April 2011)

Hollow Channel Plasma Acceleration





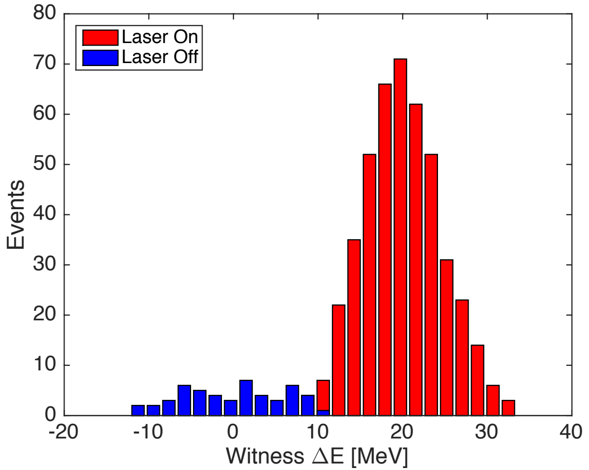
$$I(r,z) \propto k_z z J_m^2(k_\perp r)$$

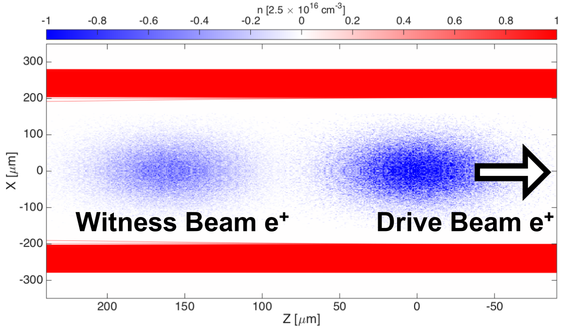
$$\Psi_m = k_\perp r + m\phi$$

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

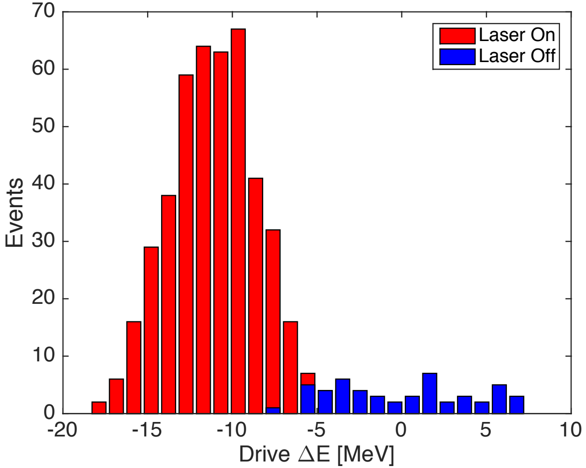
Hollow Channel Plasma Acceleration

Mean <ΔE> = 19.9 MeV





Mean <ΔE> = -11.0 MeV



Witness beam gains energy from the wake.

Drive beam transfers energy to witness beam.

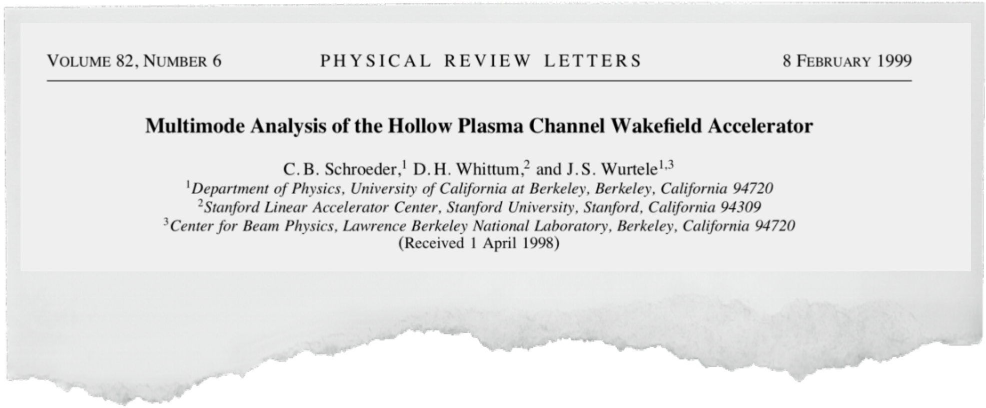
S. Gessner Ph.D. Thesis, SLAC-R-1073

Off-Axis Beams

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.


VOLUME 82, NUMBER 6 PHYSICAL REVIEW LETTERS 8 FEBRUARY 1999

Multimode Analysis of the Hollow Plasma Channel Wakefield Accelerator

C. B. Schroeder,[1] D. H. Whittum,[2] and J. S. Wurtele[1,3]
[1]Department of Physics, University of California at Berkeley, Berkeley, California 94720
[2]Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
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(Received 1 April 1998)

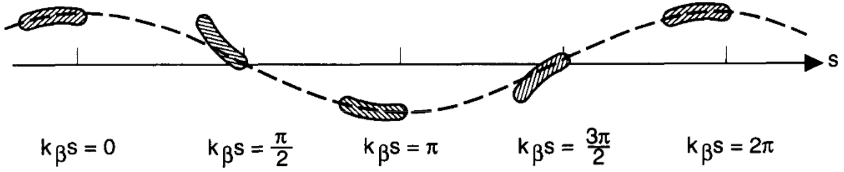
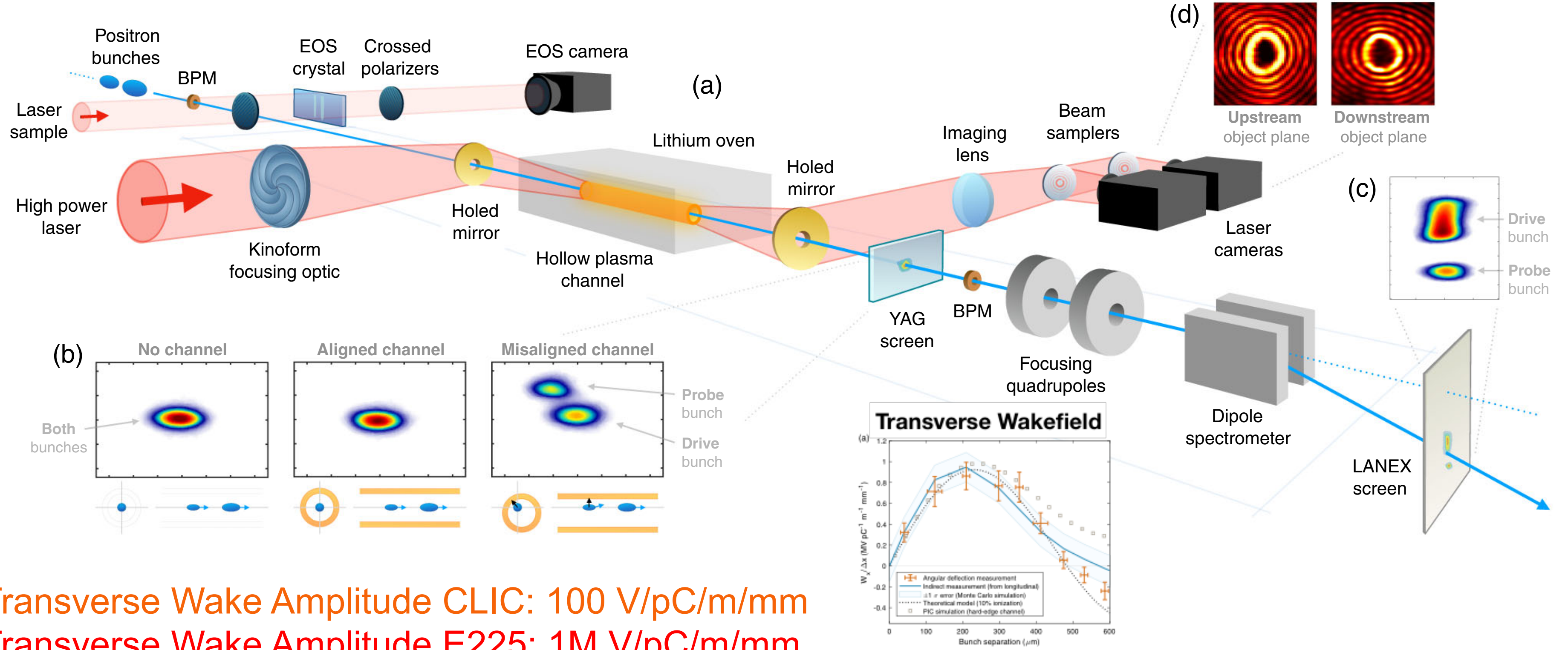


Figure 3.3. Sequence of snapshots of a beam undergoing dipole beam breakup instability in a linac. Values of $k_\beta s$ indicated are modulo 2π. The dashed curves indicate the trajectory of the bunch head.

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

Off-Axis Beams

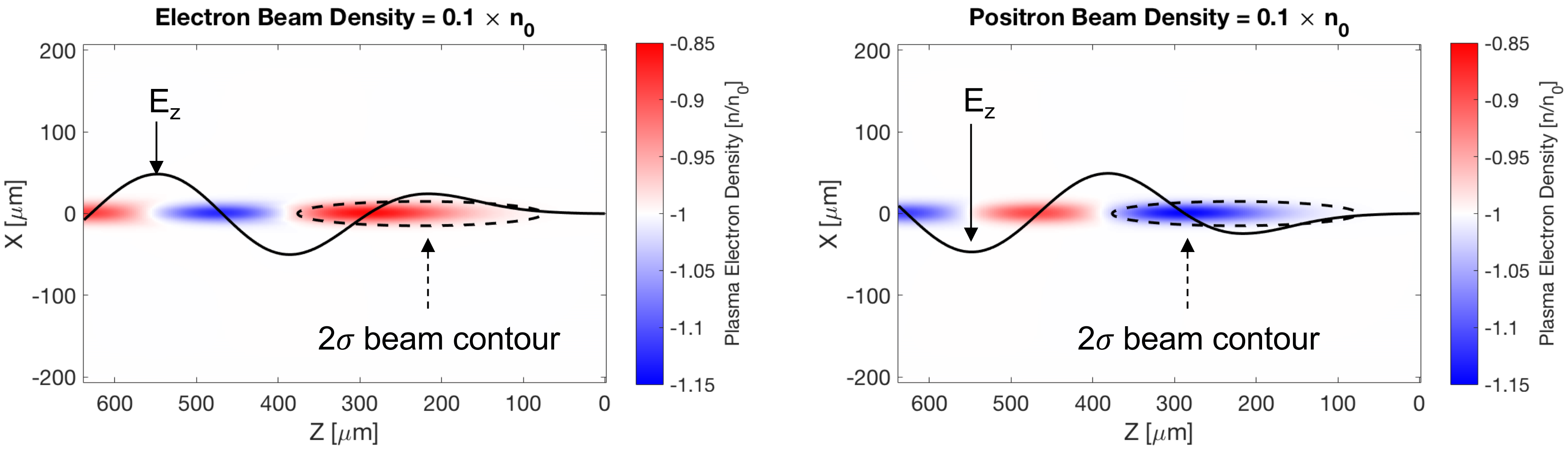


Transverse Wake Amplitude CLIC: 100 V/pC/m/mm

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

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

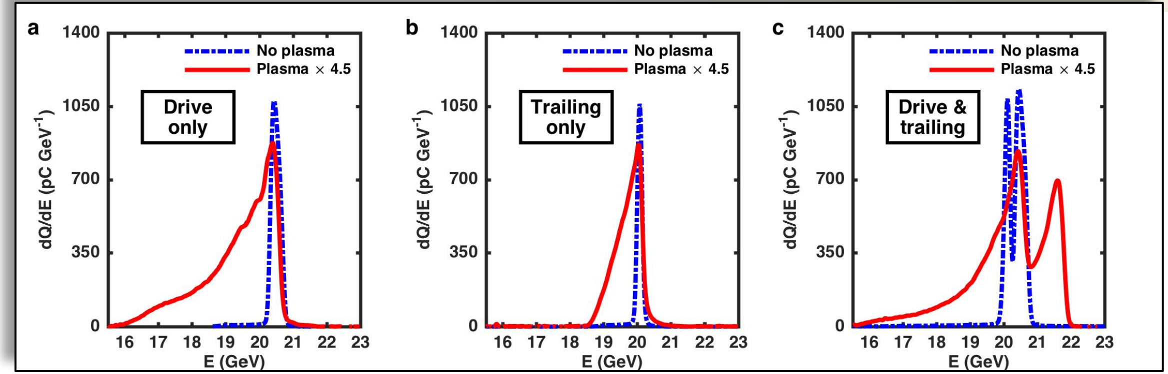
Positron Acceleration in the Linear Regime?

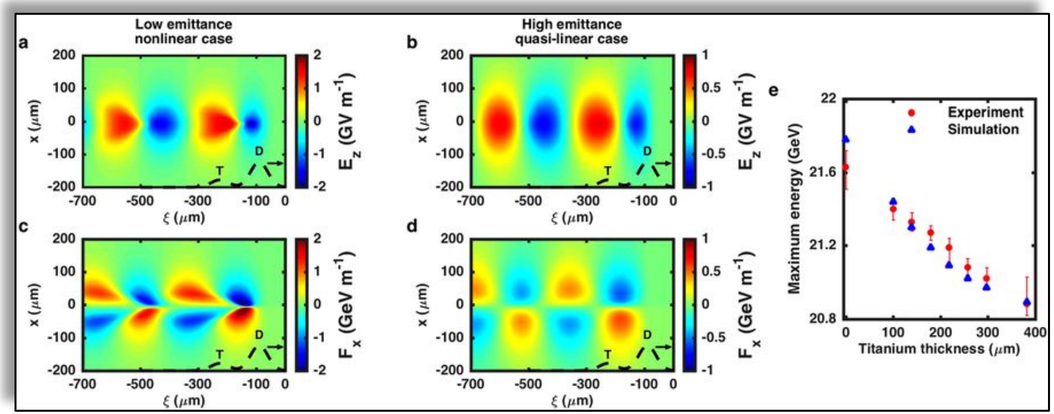


In the linear regime, the response is symmetric.

QuickPIC Simulation run on Hoffman2 at UCLA

Positron Acceleration in the Linear Regime





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

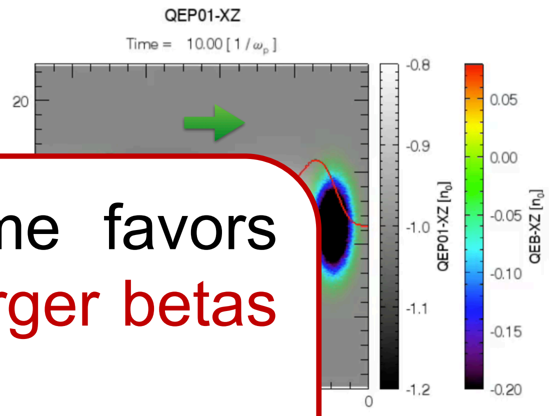
Beam Matching in the Linear Regime

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



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!

Constraints

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

$n_{\text{trailing}} =$

000

kA

- Emittance = 10 nm

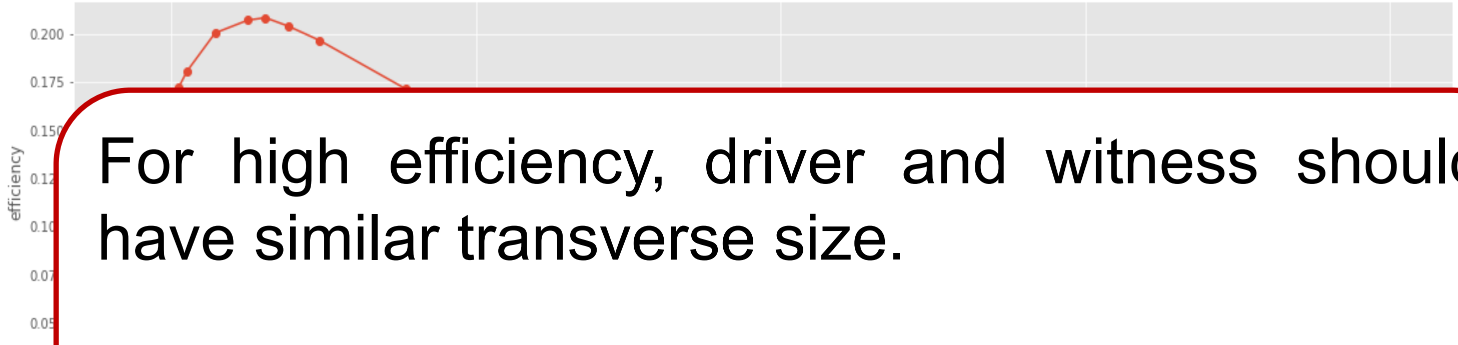
$$\sigma_r = \sqrt{\frac{\beta\varepsilon_n}{\gamma}} \implies \beta_{\text{trailing}} = \gamma\frac{\sigma_r^2}{\epsilon_n} > \frac{\gamma I}{2\pi e c\, n_0\, \epsilon_n}$$

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

S. Corde, Royal Society Workshop

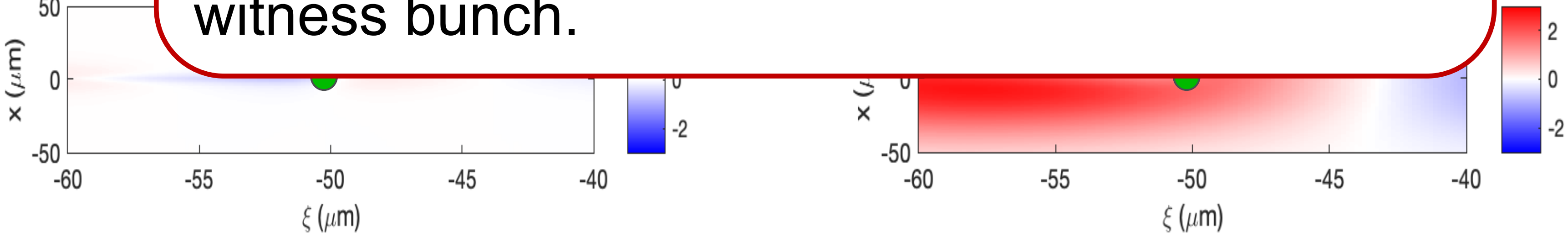
W. An, ALEGRO Positron PWFA Mini-Workshop

Beam Loading in the Linear Regime



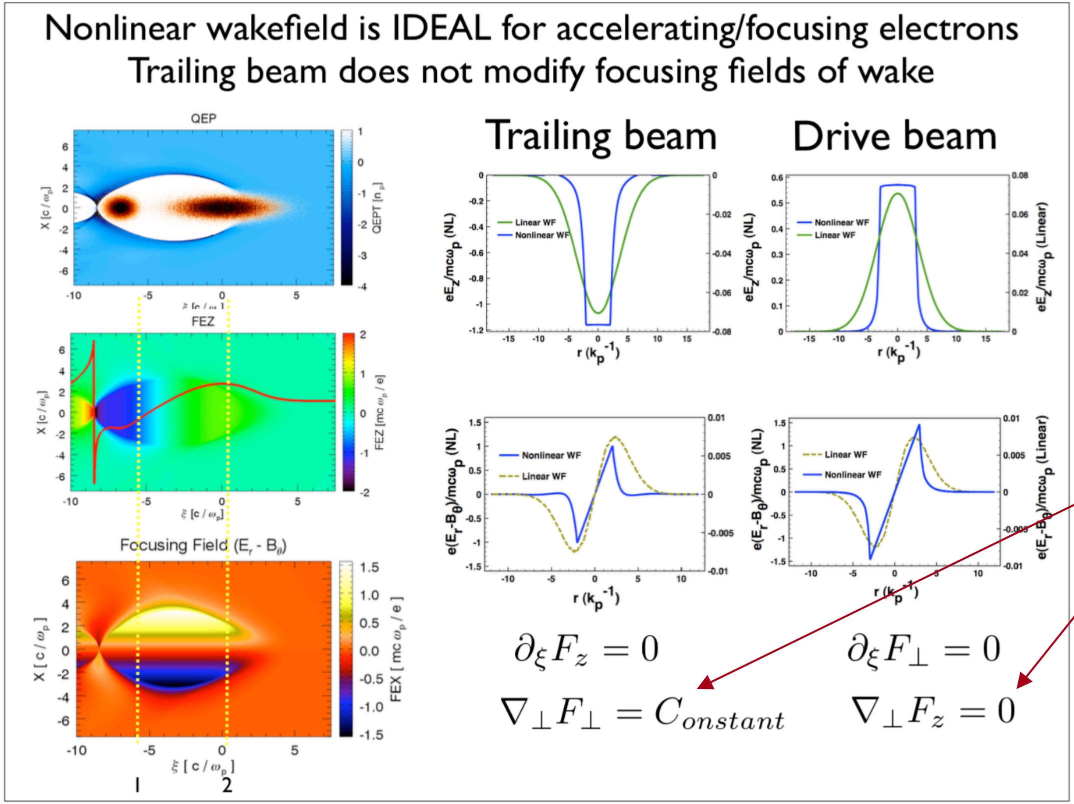
For high efficiency, driver and witness should have similar transverse size.

This leads to radial variation in E_z across the witness bunch.



S. Yu, EAAC (2019)

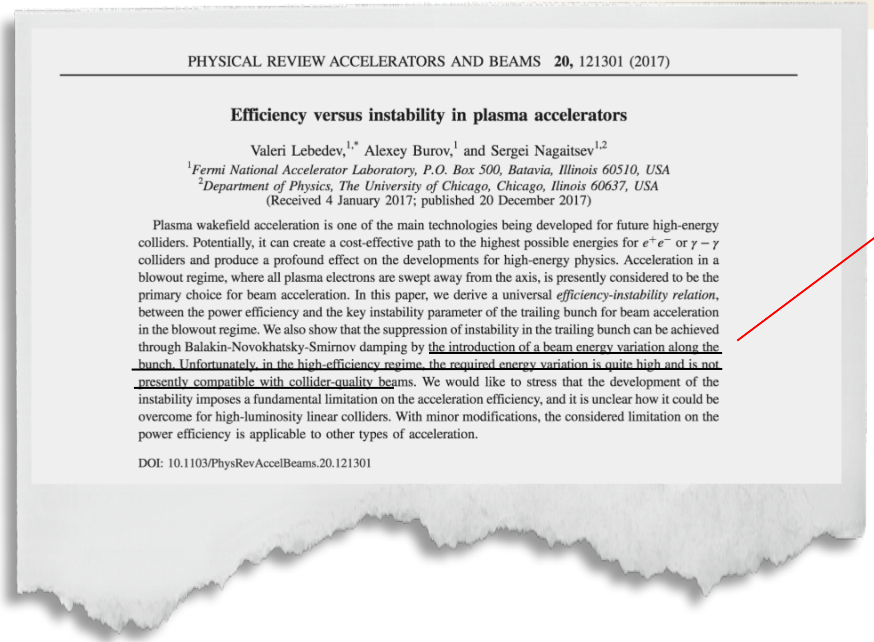
The Ideal Case



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.

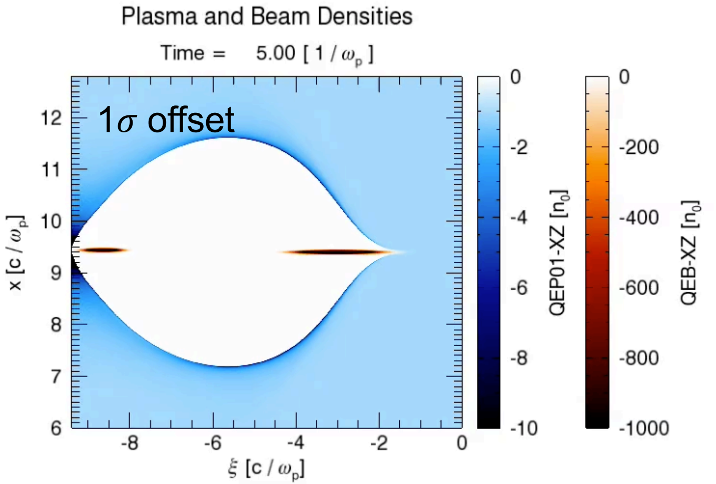
Wake-to-beam power coupling efficiency

Instability growth rate

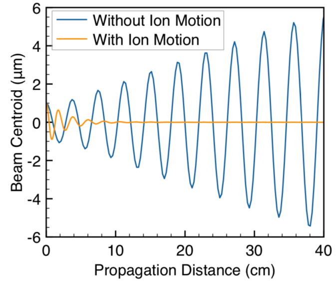
$$\eta_t \approx \frac{\eta_p^2}{4(1-\eta_p)}$$

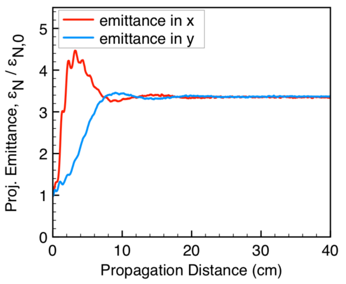
Highly efficient acceleration -> Strong coupling to the wake -> Drives transverse instability

Solutions Proposed

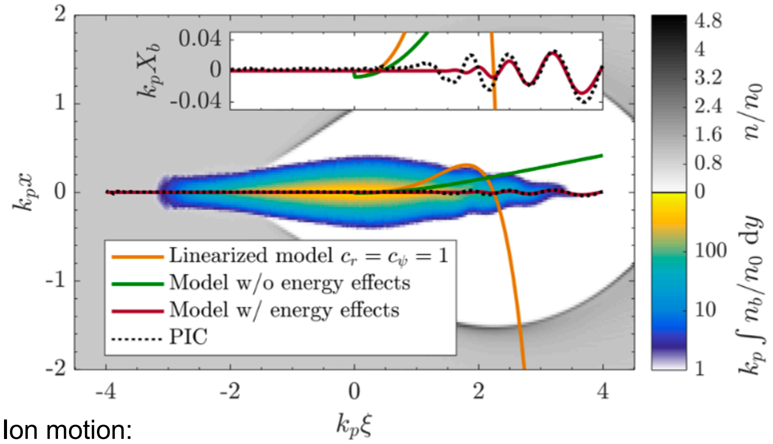


L. Hildebrand and W. An, AAC 2018





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)

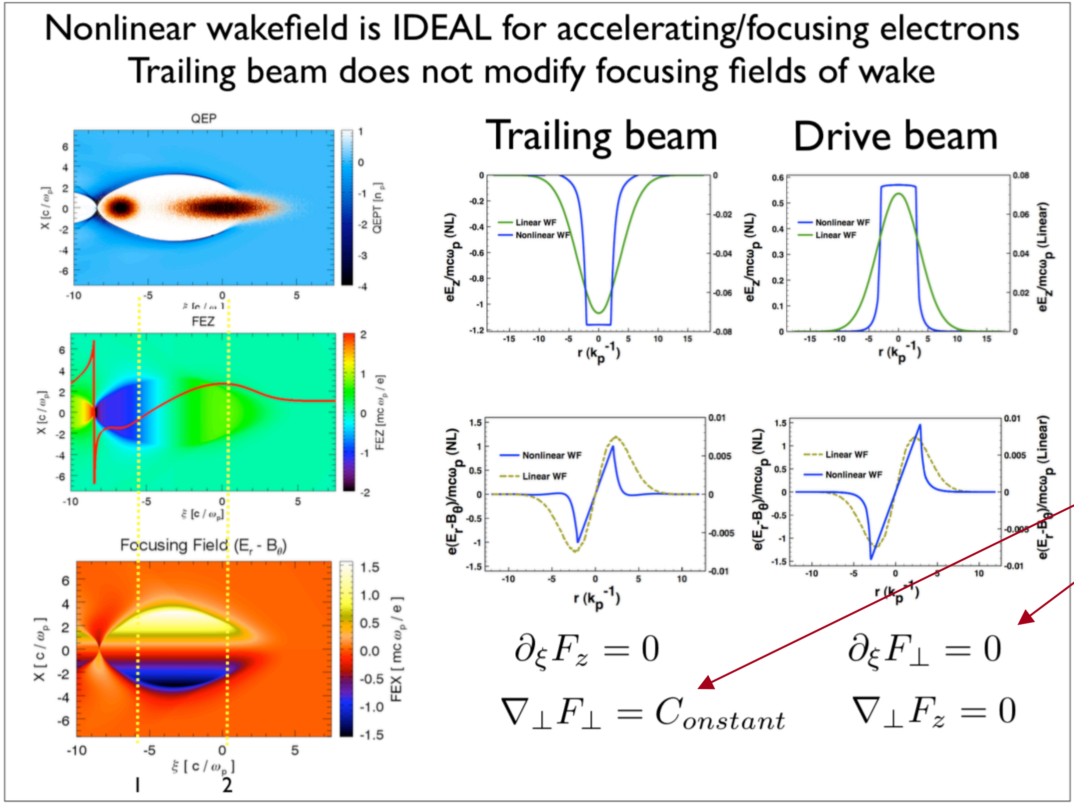
Energy spread:
T. J. Mehrling, et. al. Phys. Rev. Lett. 118, 174801(2017)

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?

SLAC



Replace "=" with "≈"

W. Mori, PAC 2011 Tutorial

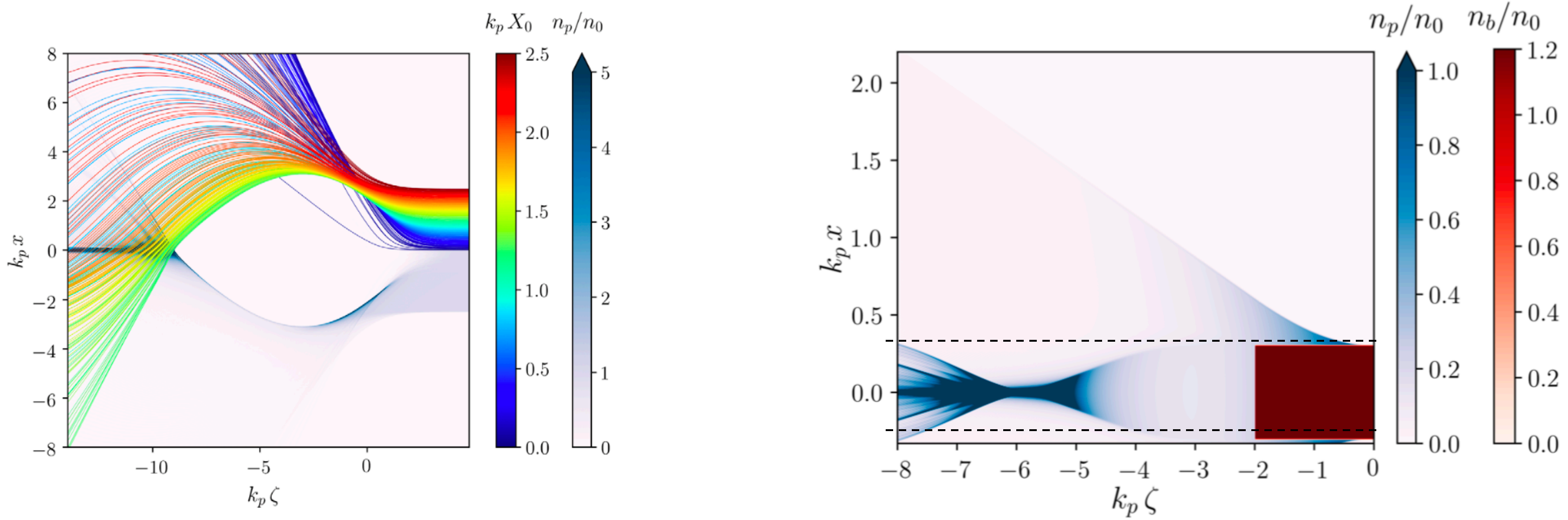
Where do we go from here?

Image Credit: W. An, UCLA

Transversely Tailored Plasmas

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

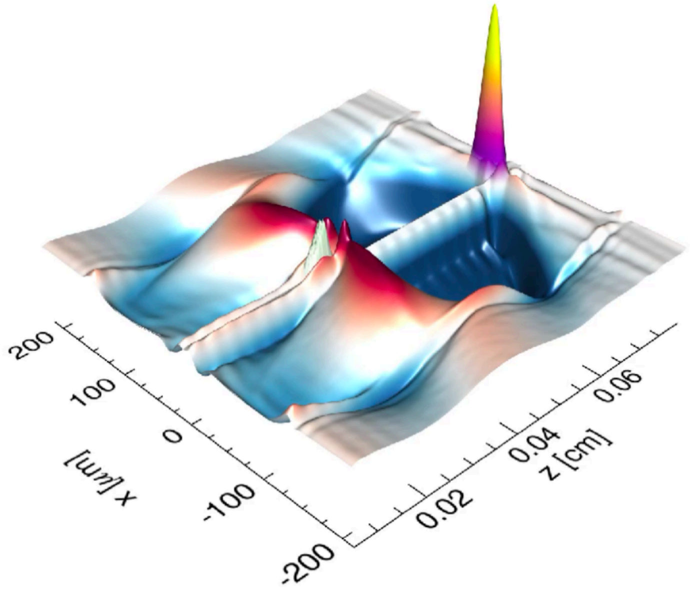
S. Dietrichs. M.S.c. Thesis, DESY

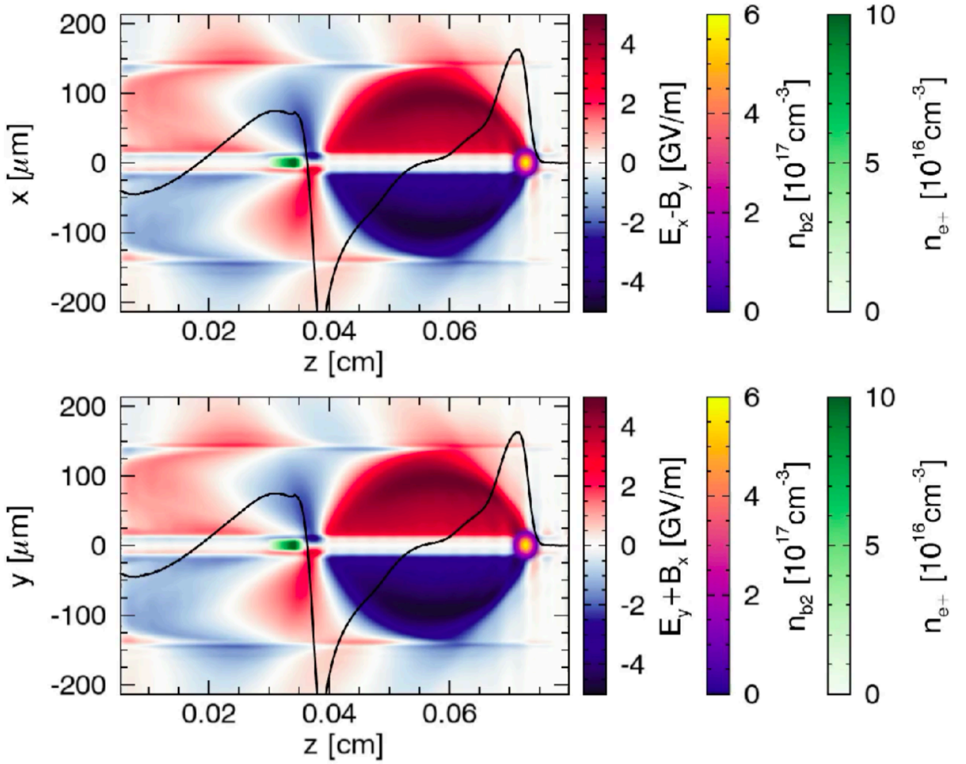


By driving a wakefield in a plasma filament, you can create a region of uniform focusing and acceleration for positrons at the back of the wake.

Transverse plasma electron motion appears to be an important factor.

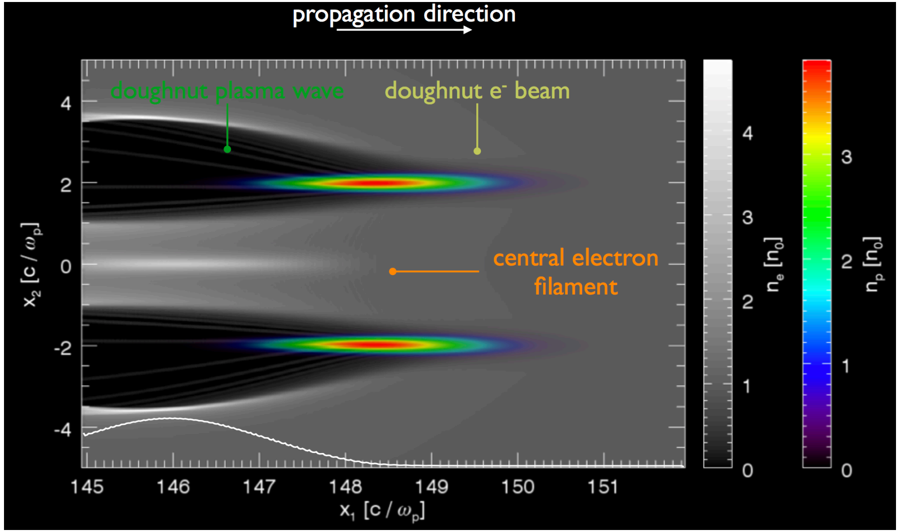
Beam-Shaped Plasmas



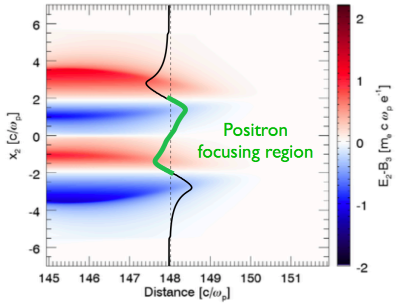


T. Silva, EAAC (2019)

Transversely Tailored Drivers

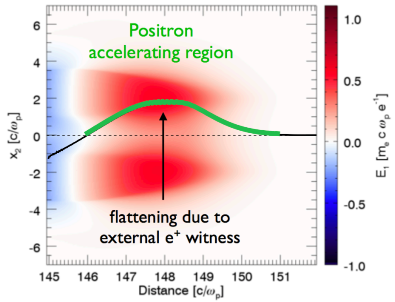


Focusing force



- **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**

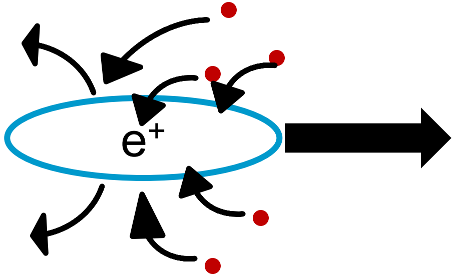
Accelerating force



- 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)

Goals for Transverse Tailoring

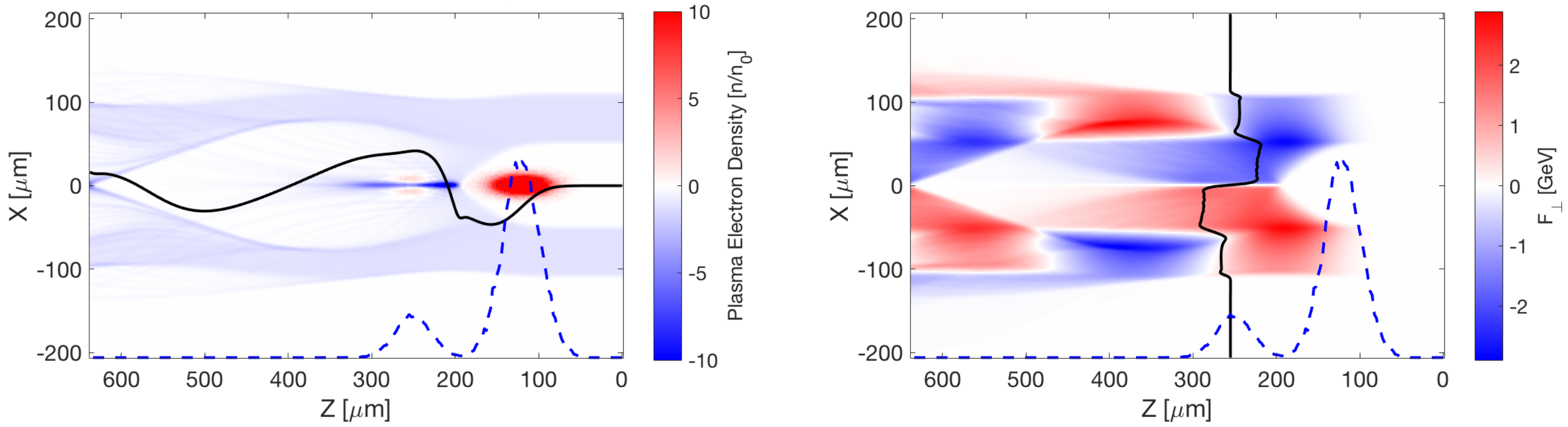


$$\partial_\xi F_z \approx 0 \qquad \partial_\xi F_\perp \approx 0$$

$$\nabla_\perp F_\perp \approx Constant \qquad \nabla_\perp F_z \approx 0$$

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

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.

All scenarios have beam matching challenges

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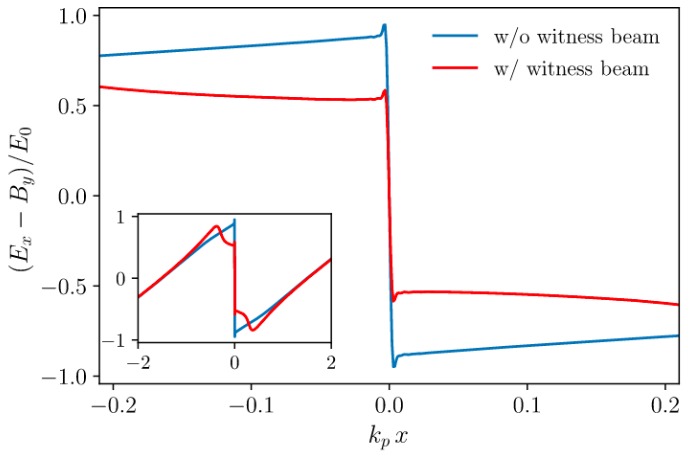
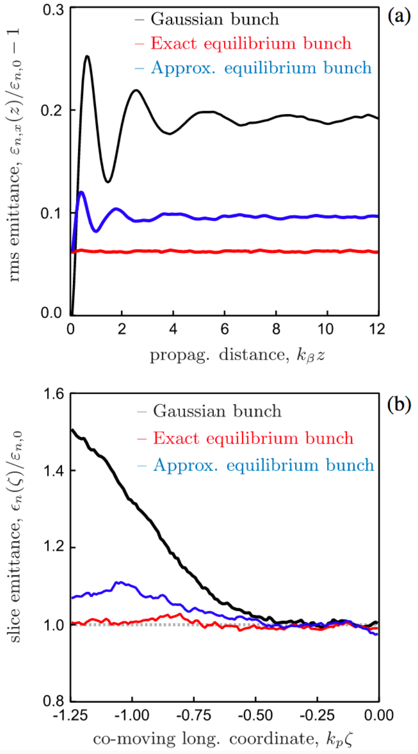


Focusing fields in general will not be perfectly linear, but approximate matching to minimize emittance growth is still possible.

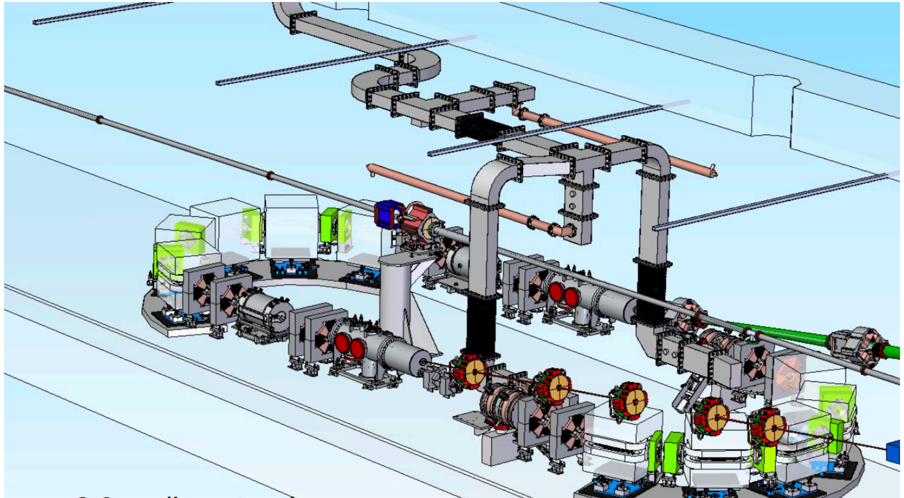


C. Benedetti et. al. *Phys. Rev. Accel. Beams* **20** 111301 (2017)

Positron Beams at FACET-II

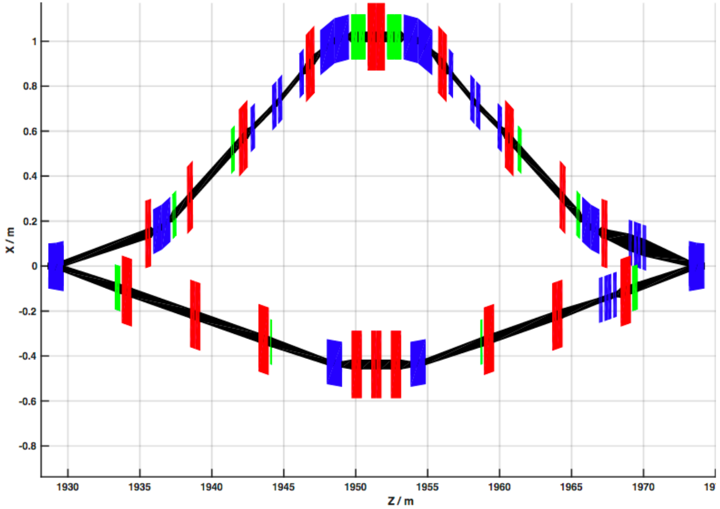
SLAC

New Positron Damping Ring



- 2.9 m diameter ring

New UFO e^+/e^- Chicane



Positron damping ring and UFO chicane will enable first electron beam-driven, positron witness PWFA experiments with externally injected e^+ beam.

Experiments at FACET-II

SLAC

1. E303: First positron acceleration in an electron beam-driven wake.

2. Linear regime studies: verification of scaling laws and matching conditions.

3. Transversely tailored plasmas: make use of advanced ionization optics by M. Litos's group:
   - Filament type plasmas
   - Hollow channel plasmas

4. Transversely tailored drivers:
   - Donut beams from injector
   - Donut laser after laser upgrade

5. Beam-driven ion channels.

Does not require FACET-II Positron Source

Requires FACET-II Positron Source

Conclusions

SLAC

- The last 5 years have seen big advances in our understanding of positron acceleration in plasma.
- Several new, promising avenues have emerged.
- Transversely tailored plasmas using advanced laser optics for filament ionization are readily-achievable at FACET-II.
- Most of the experiments mentioned can *only* be done at FACET-II.

Thank you!

SLAC

SLAC — J. M. Allen, C. I. Clarke, C. Emma, S. Gessner, S. Z. Green, M. Hogan, B. O'Shea, D. Storey, A. Sutherland, V. Yakimenko

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