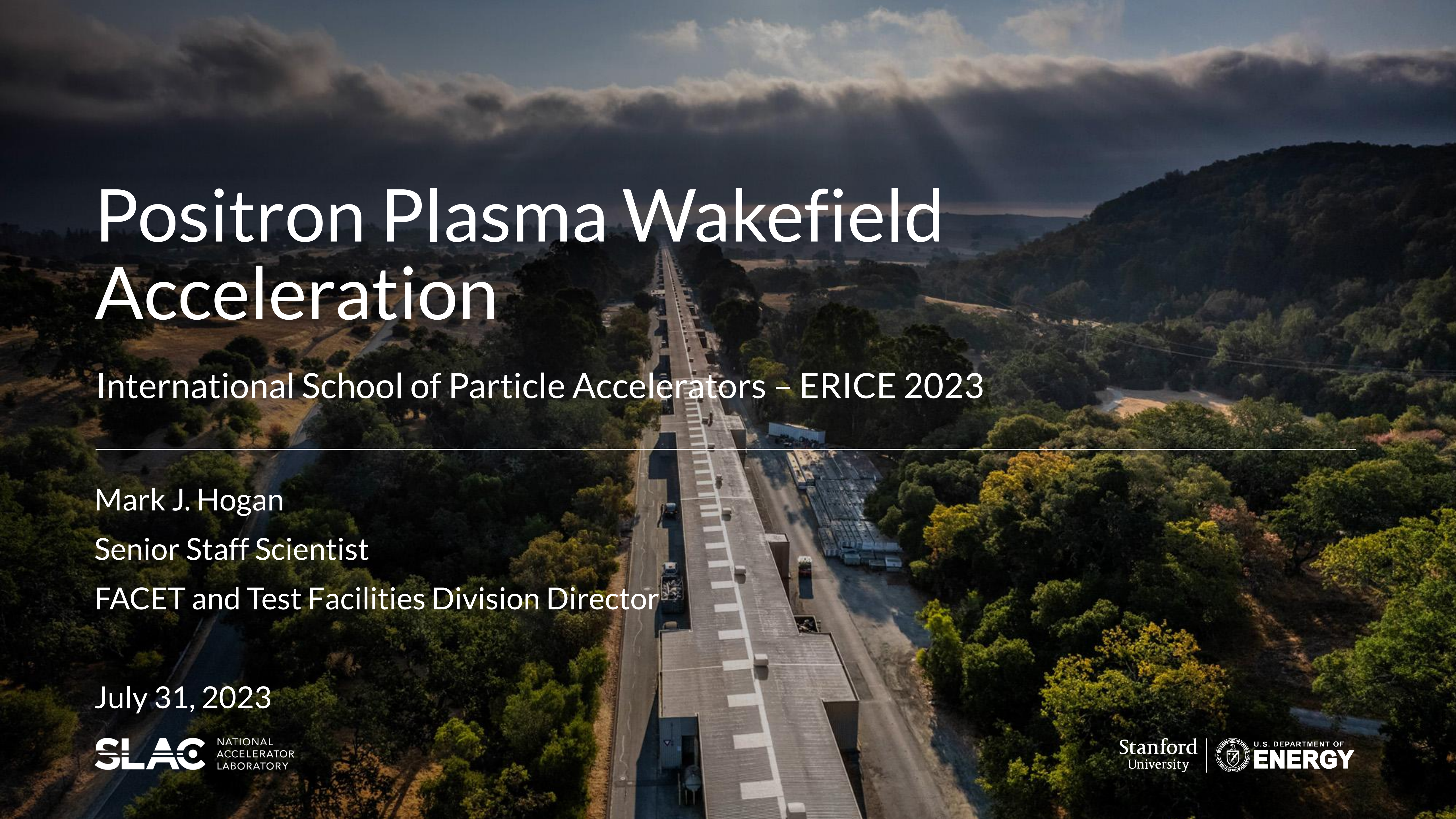


Positron Plasma Wakefield Acceleration

International School of Particle Accelerators – ERICE 2023

Mark J. Hogan

Senior Staff Scientist

FACET and Test Facilities Division Director

July 31, 2023

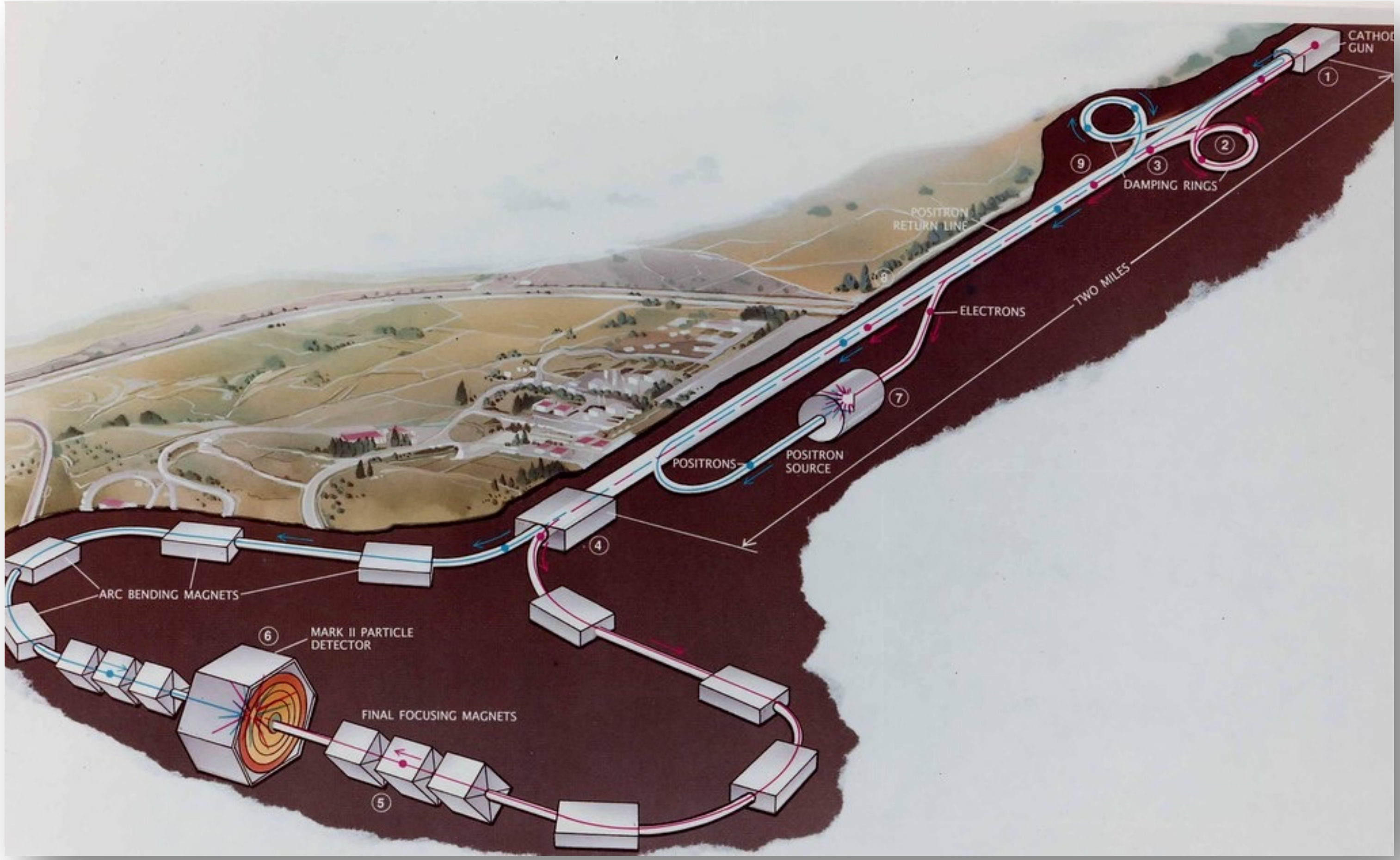
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Linear Colliders

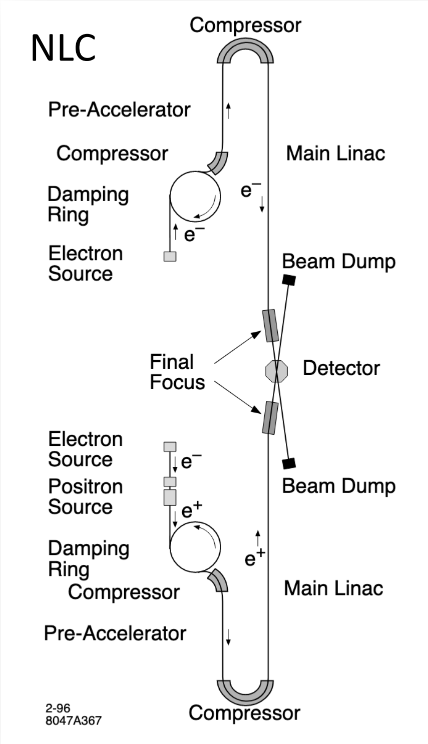
To date, there has only been one linear collider ever built:

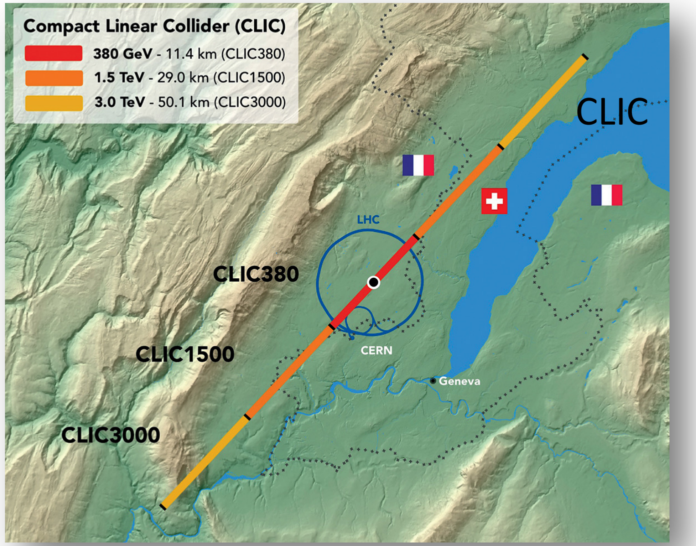
The SLAC Linear Collider (SLC) which operated from 1986-1998

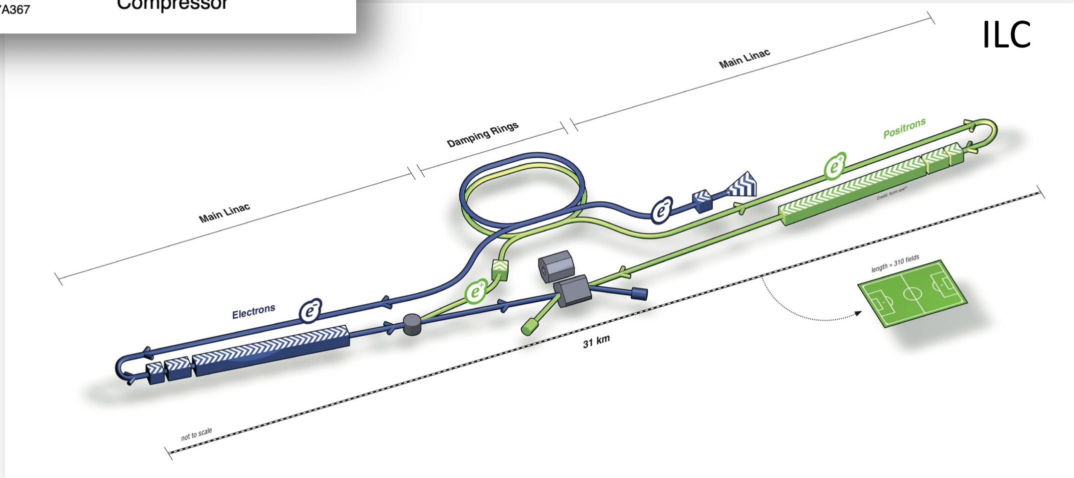


Linear Colliders

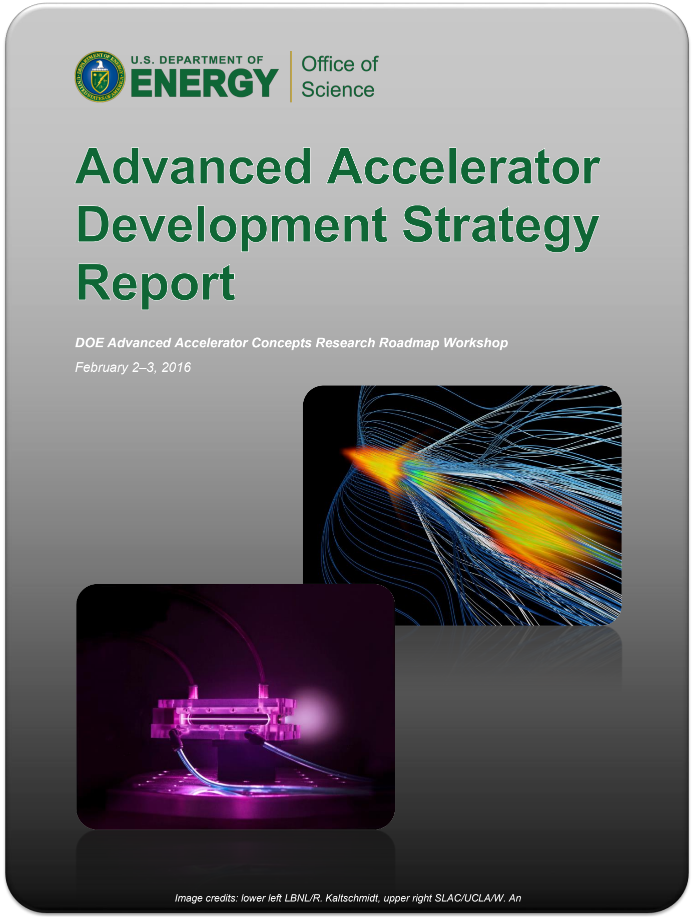
- Linear Colliders collide electron and **positron** beams
- They are used for precision particle physics studies
- There are several existing design concepts
- The total length of the machines are ~30km





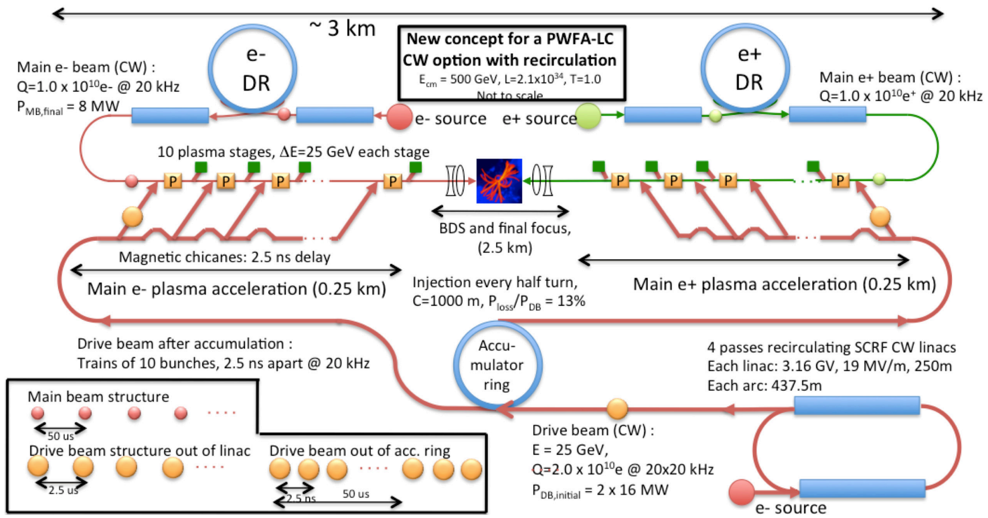


PWFA Experimental Program at FACET-II is Motivated by Roadmap for Future Colliders Based on Advanced Accelerators



http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Advanced_Accelerator_Development_Strategy_Report.pdf

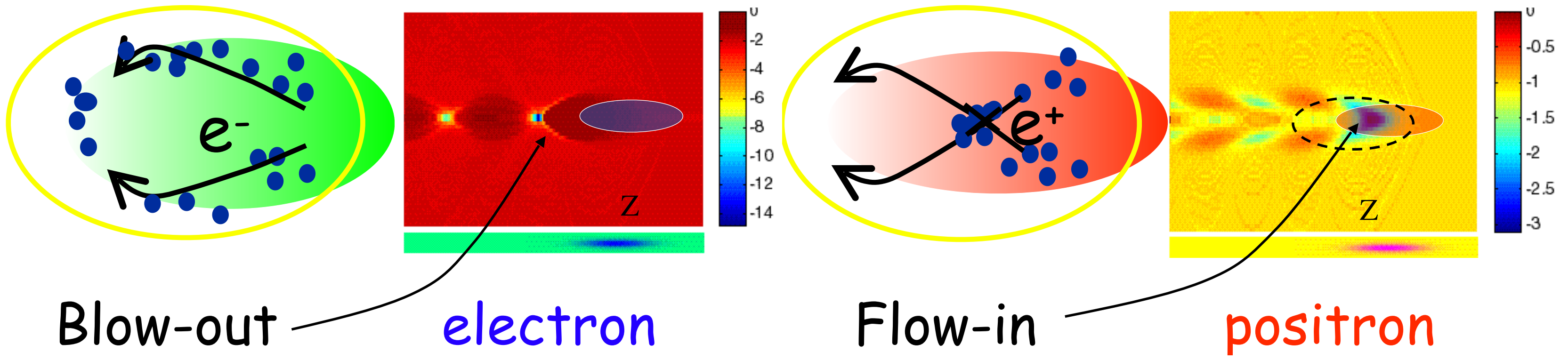
A Conceptual PWFA-LC



E. Adli et al., ArXiv 1308.1145
J. P. Delahaye et al., Proceedings of IPAC2014

- Collider concepts assume high degree of symmetry between electron and positrons
- **This is not a good assumption**
- Planning for FACET-II to offer ability to test concepts in collider relevant regimes

Plasma Response to Positron Beams



- 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!

PHYSICS OF PLASMAS 12, 063101 (2005)

Limits of linear plasma wakefield theory for electron or positron beams

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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 $n_b/n_p \approx 1$.

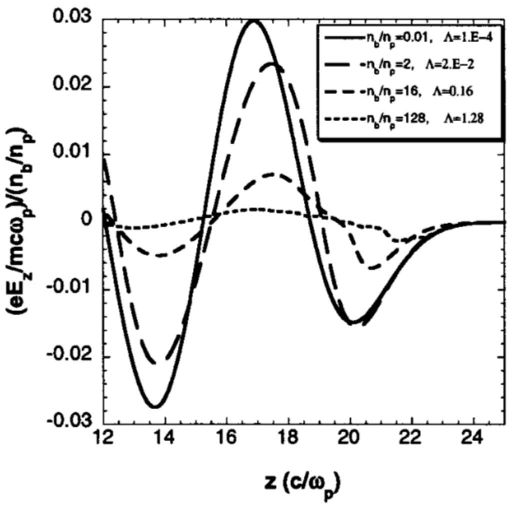


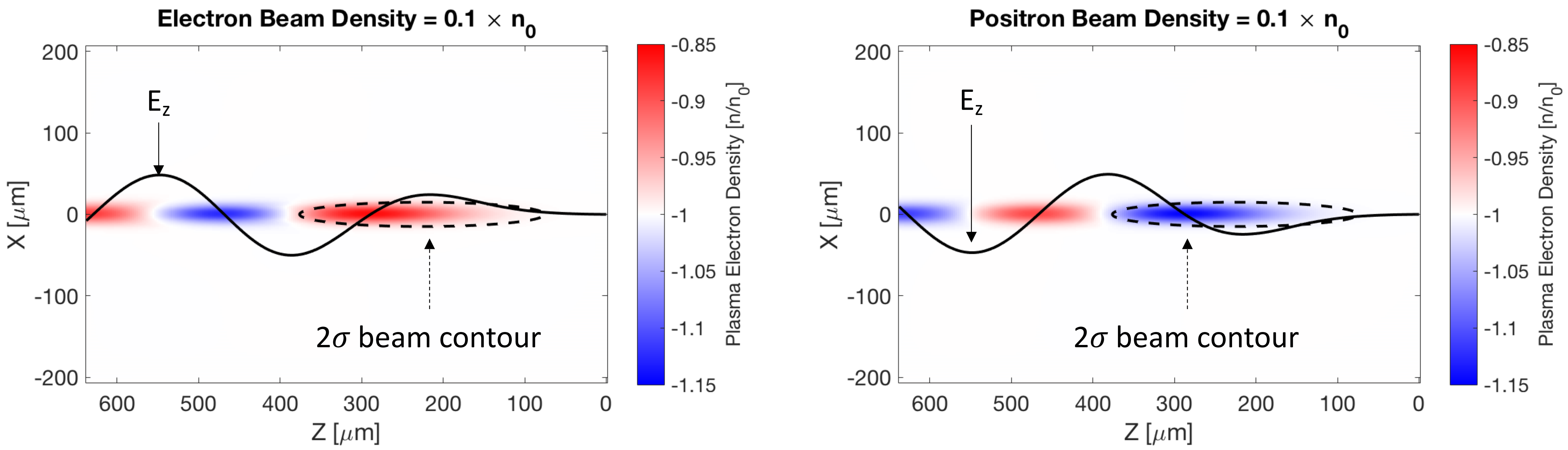
FIG. 7. Wake structure for positron drivers: we plot the ratio of normalized electric field over n_b/n_p, as a function of distance behind the wake, for $k_p\sigma_z=\sqrt{2}$ and $k_p\sigma_r=0.1$ (the beam center is at $z=20c/\omega_p$).

Positron-driven wakes become complicated in the mildly nonlinear regime

SLAC

Plasma Response to Beams of Opposite Charge

In the linear regime, the response is symmetric

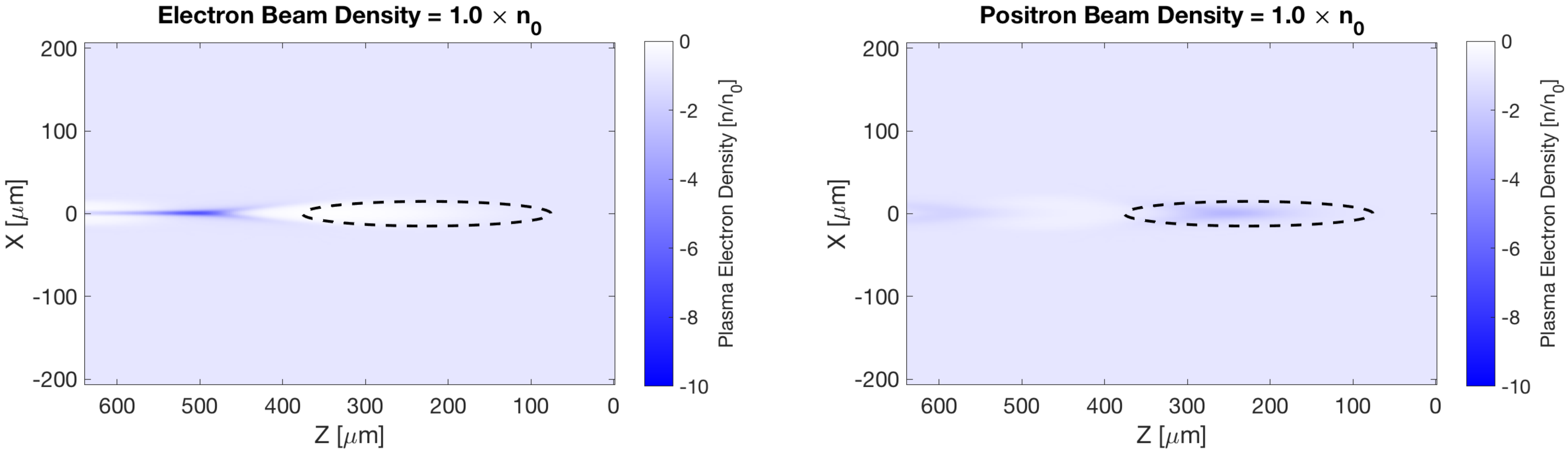


QuickPIC Simulation run on Hoffman2 at UCLA - courtesy of S. Gessner

SLAC

Plasma Response to Beams of Opposite Charge

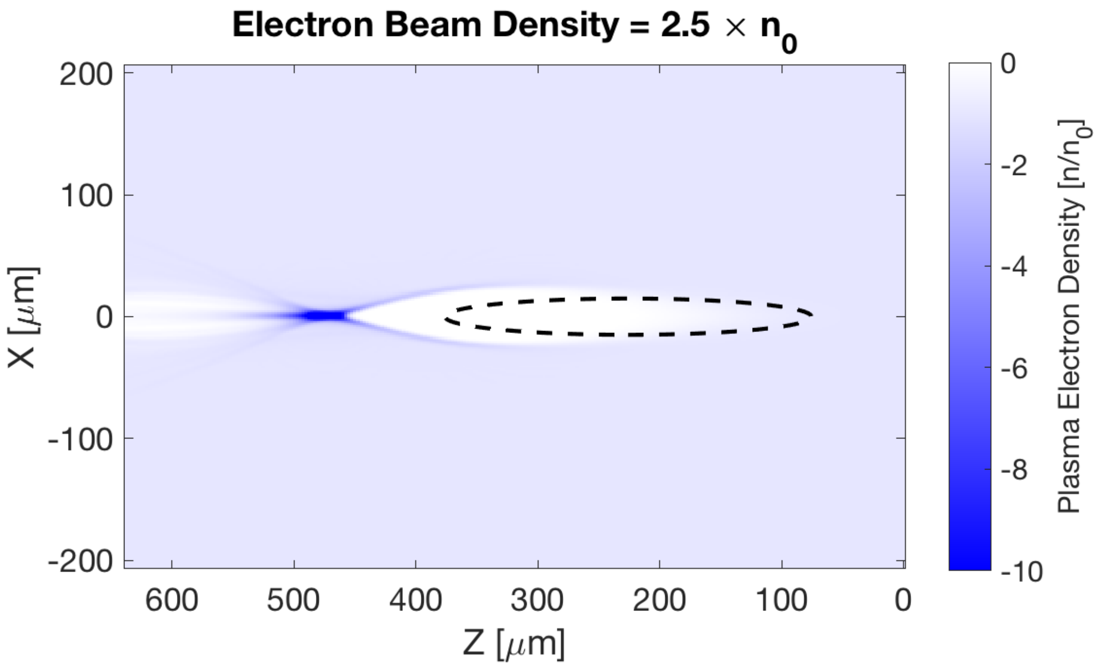
As we increase the beam charge (density), the asymmetry becomes more pronounced

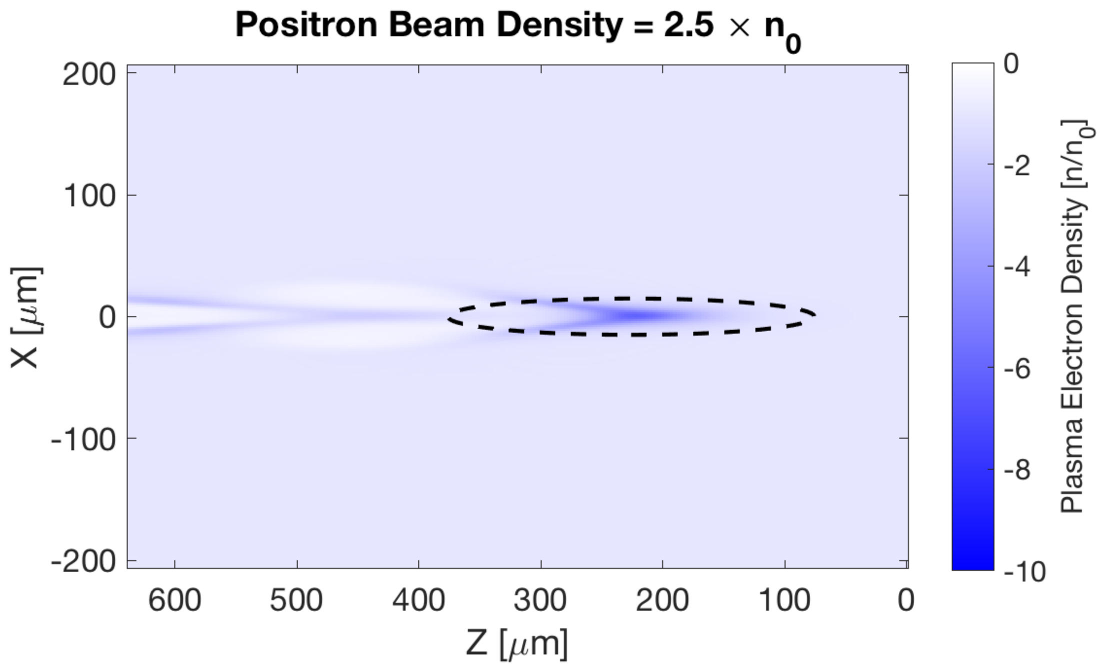


QuickPIC Simulation run on Hoffman2 at UCLA - courtesy of S. Gessner

Plasma Response to Beams of Opposite Charge

As we increase the beam charge (density), the asymmetry becomes more pronounced

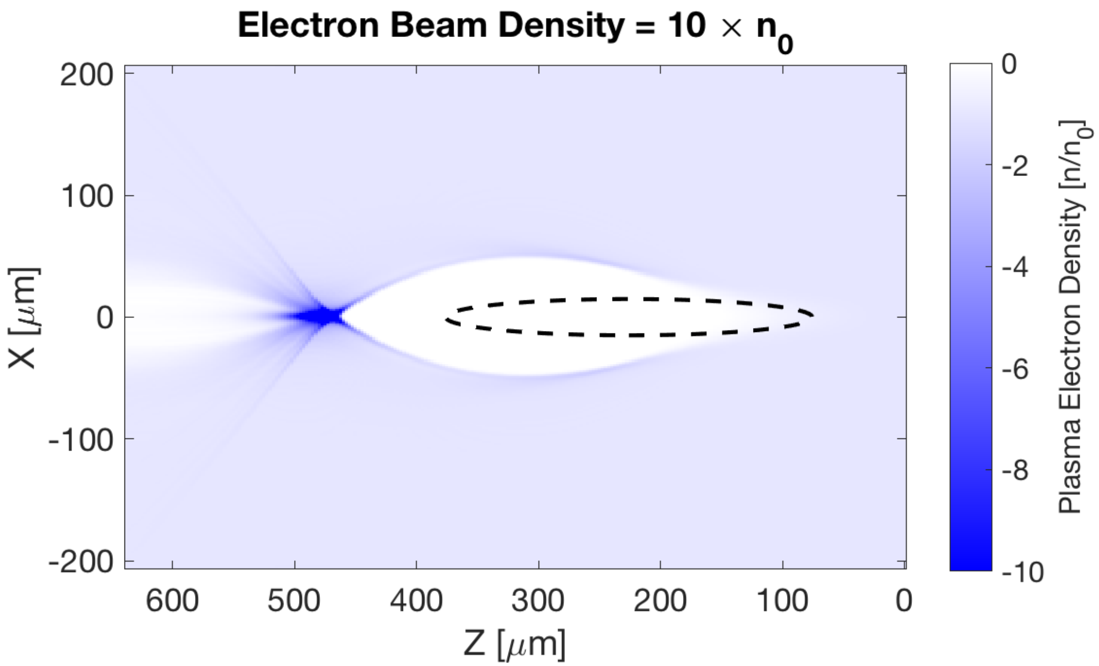


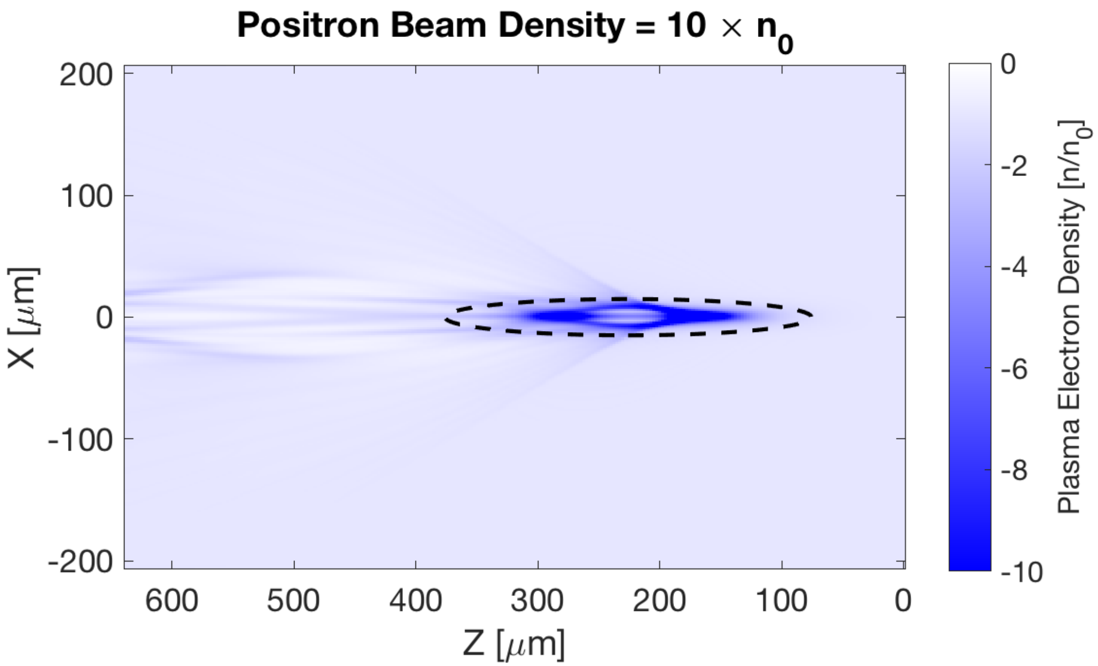


QuickPIC Simulation run on Hoffman2 at UCLA - courtesy of S. Gessner

Plasma Response to Beams of Opposite Charge

As we increase the beam charge (density), the asymmetry becomes more pronounced

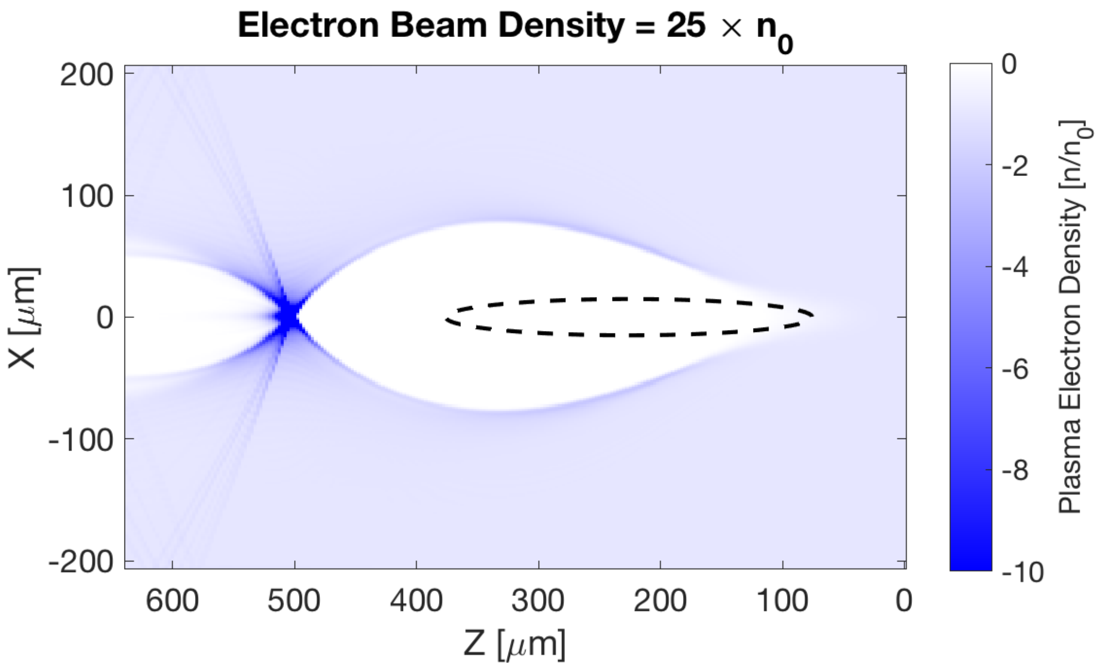


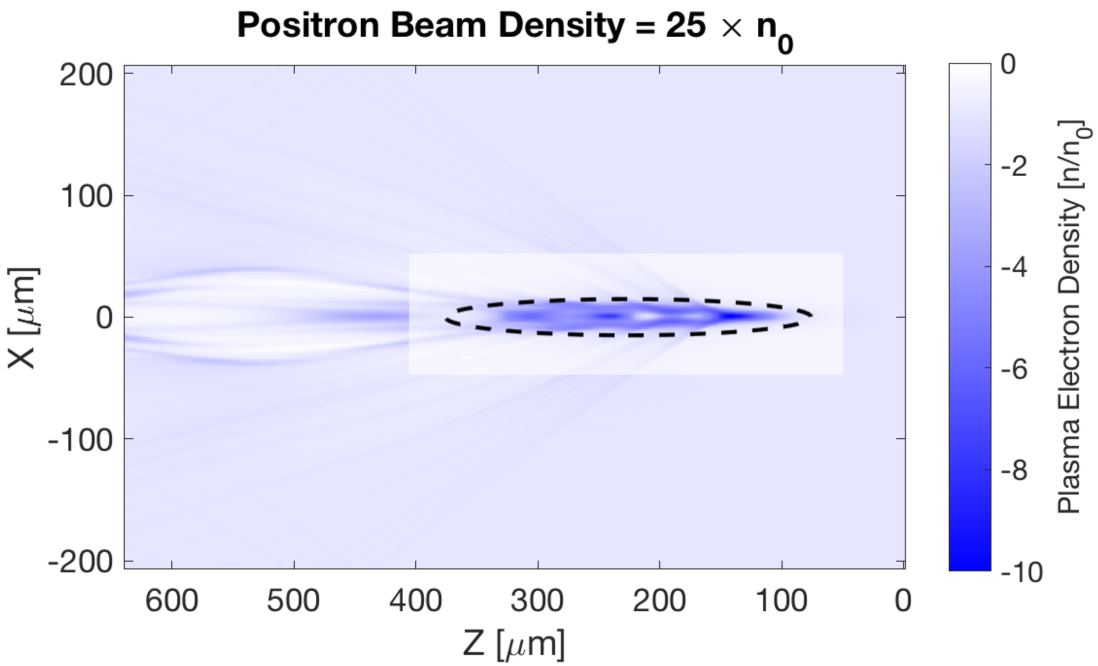


QuickPIC Simulation run on Hoffman2 at UCLA - courtesy of S. Gessner

Plasma Response to Beams of Opposite Charge

As we increase the beam charge (density), the asymmetry becomes more pronounced
…and more complicated





Blow-out regime has many great properties for accelerating electrons:

- Focusing is linear in r and constant in z
- Accelerating field is constant in r

QuickPIC Simulation run on Hoffman2 at UCLA - courtesy of S. Gessner

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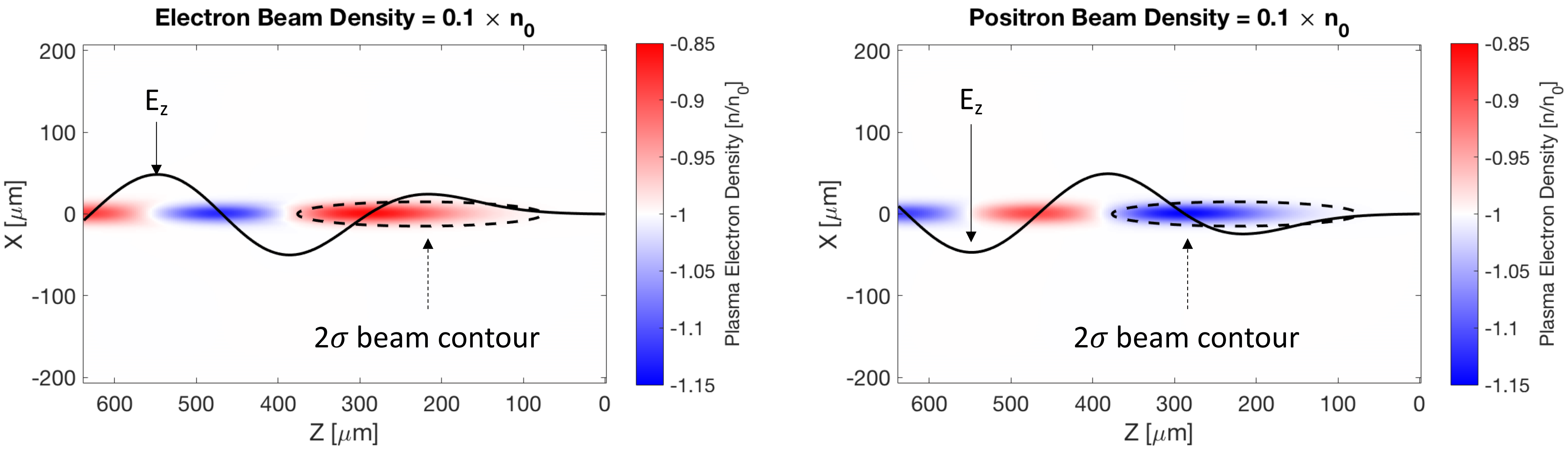
Positron Acceleration in the Linear Regime?

Why not operate in the linear regime then?

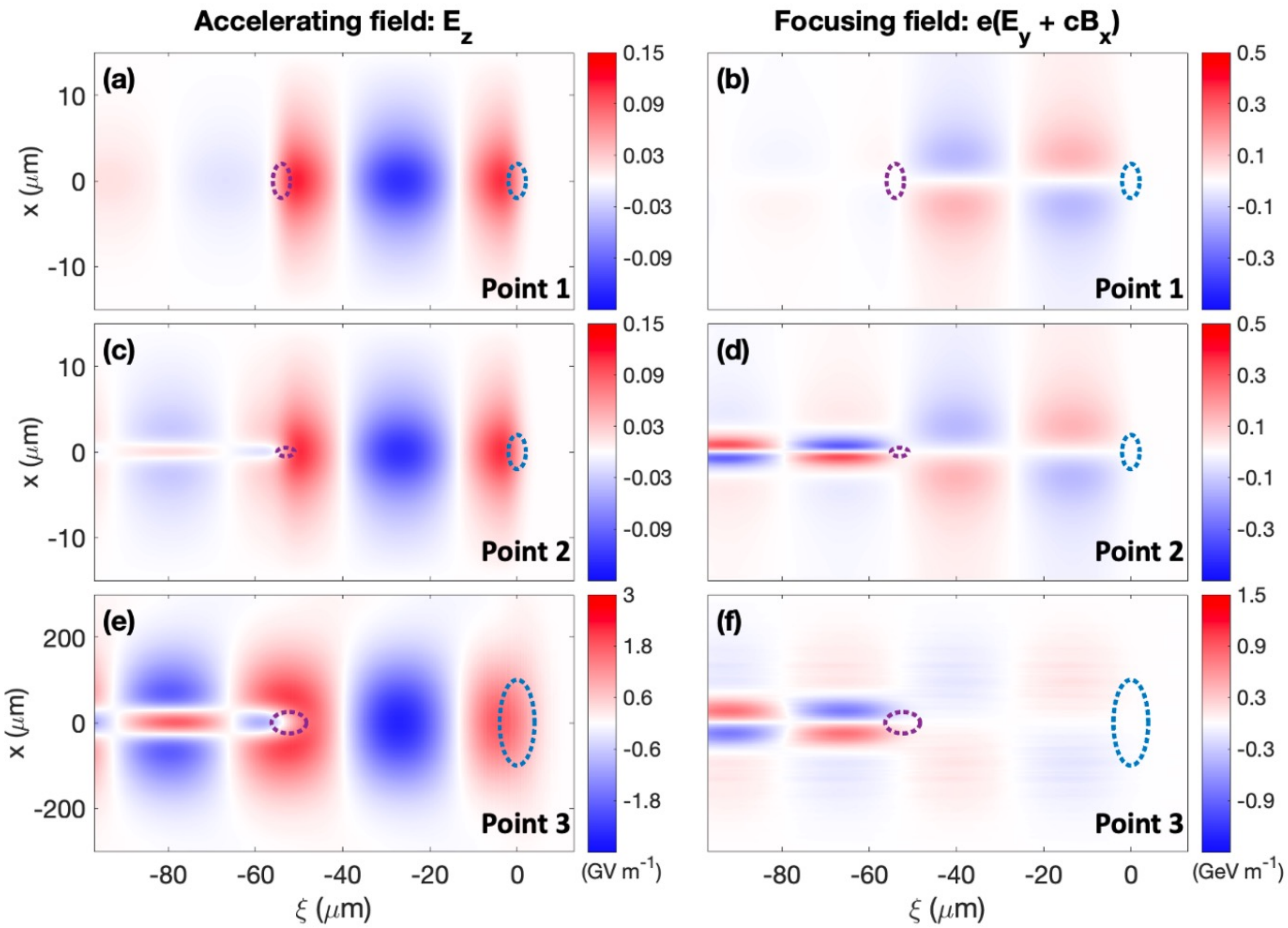


QuickPIC Simulation run on Hoffman2 at UCLA - courtesy of S. Gessner

Beam Loading in the Linear Regime

For positron acceleration in the linear regime, we must consider both beam quality and efficiency.

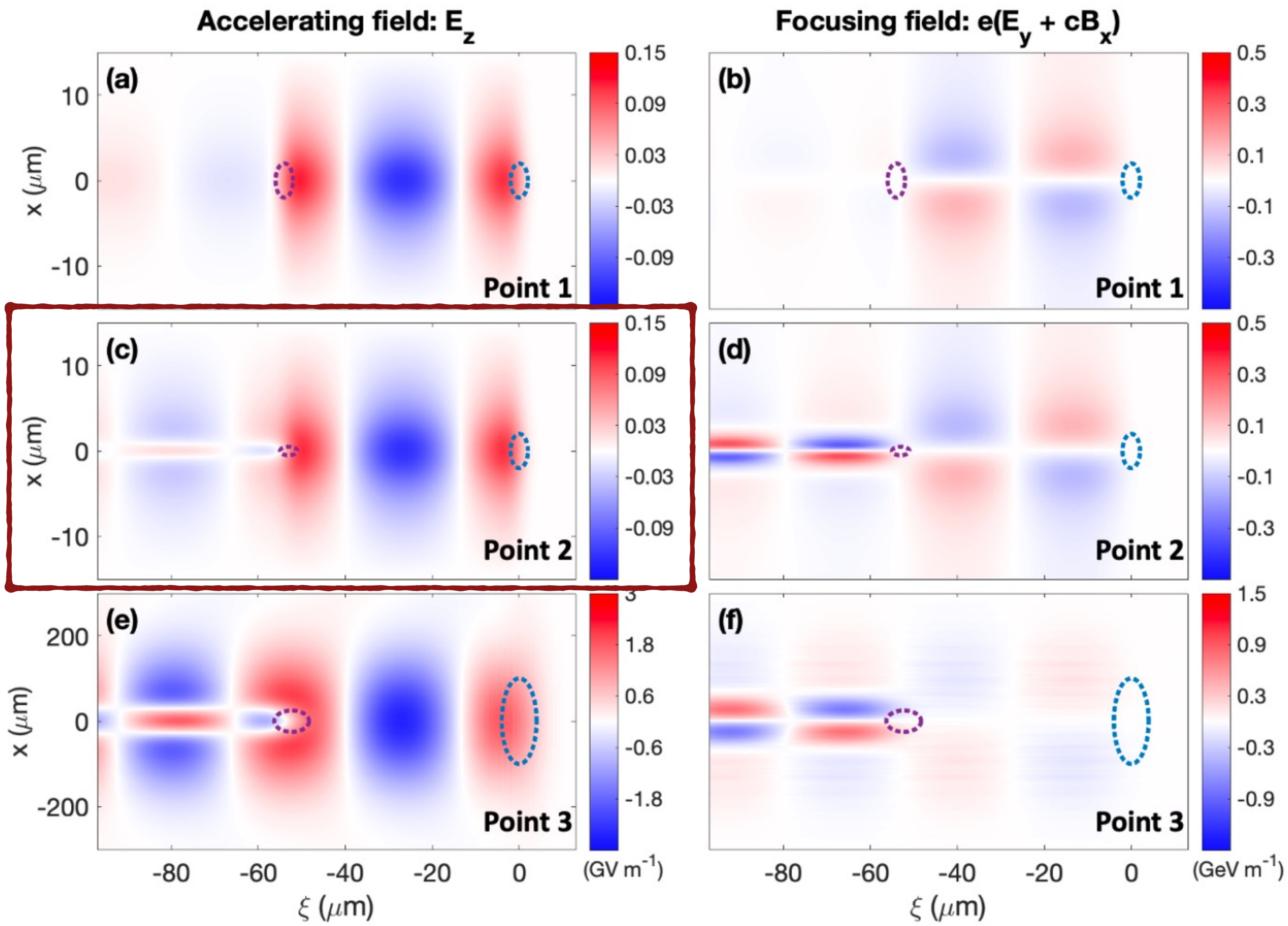
- What is the energy spread of the beam?
- Is the emittance maintained throughout acceleration?
- What is the transfer efficiency?



C. S. Hue et al, Phys. Rev. Research, 043063 (2021)

Beam Loading in the Linear Regime

- In general, a smaller witness beam samples less variation of a changing wakefield, and beam quality is higher
- However, it also absorbs less energy from the wake and efficiency is lower
- The problem becomes more severe with lower emittance beams



C. S. Hue et al, Phys. Rev. Research, 043063 (2021)

Beam Loading in the Linear Regime

If we insist on maintaining beam quality at a certain level, none of the options in the linear regime are particularly efficient

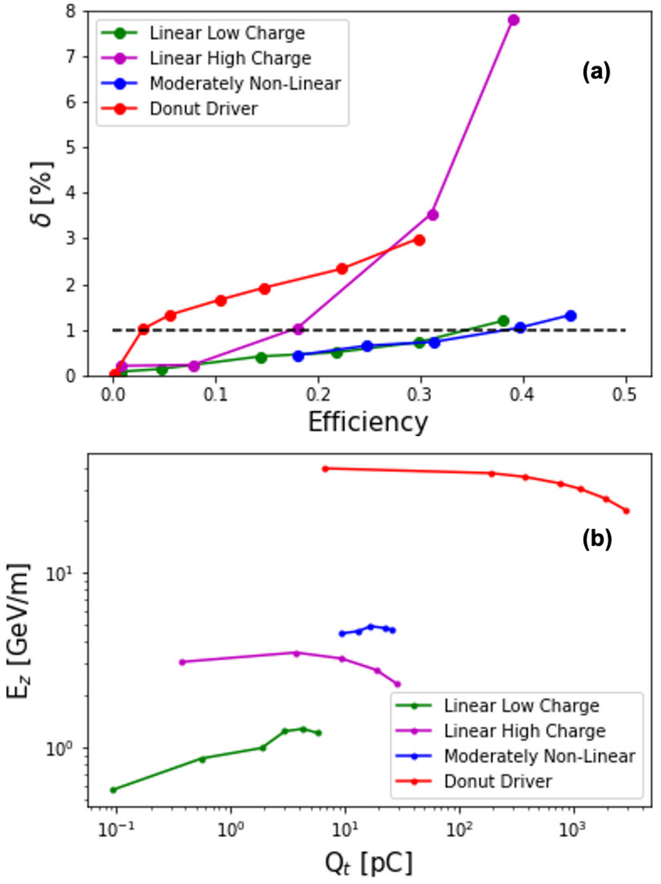
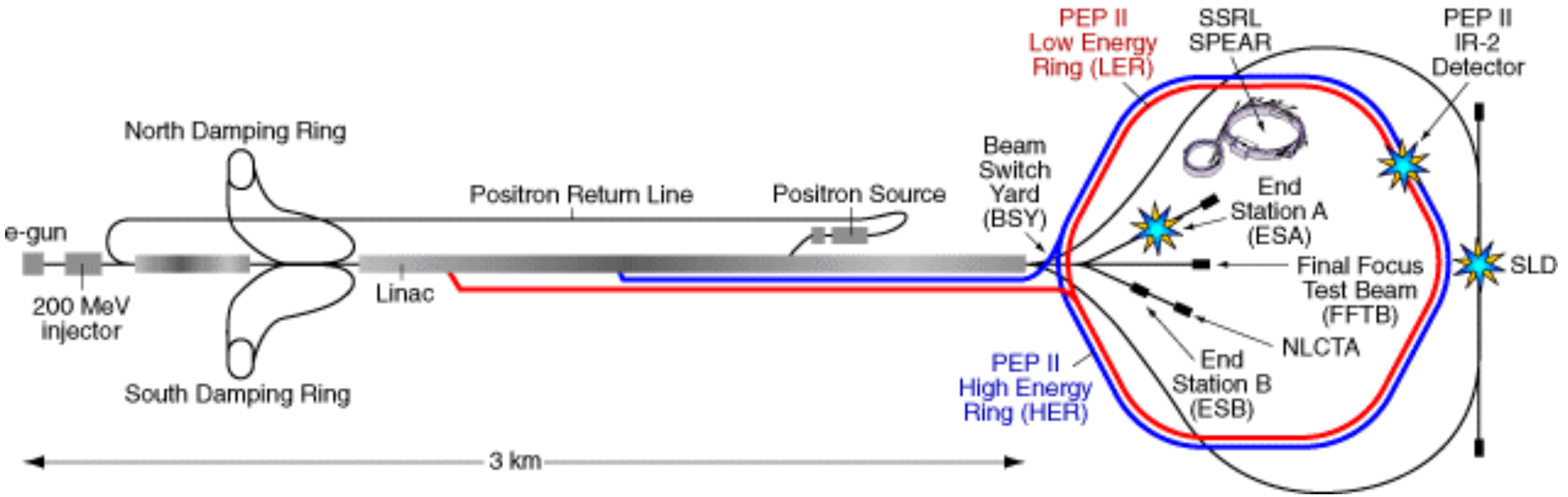
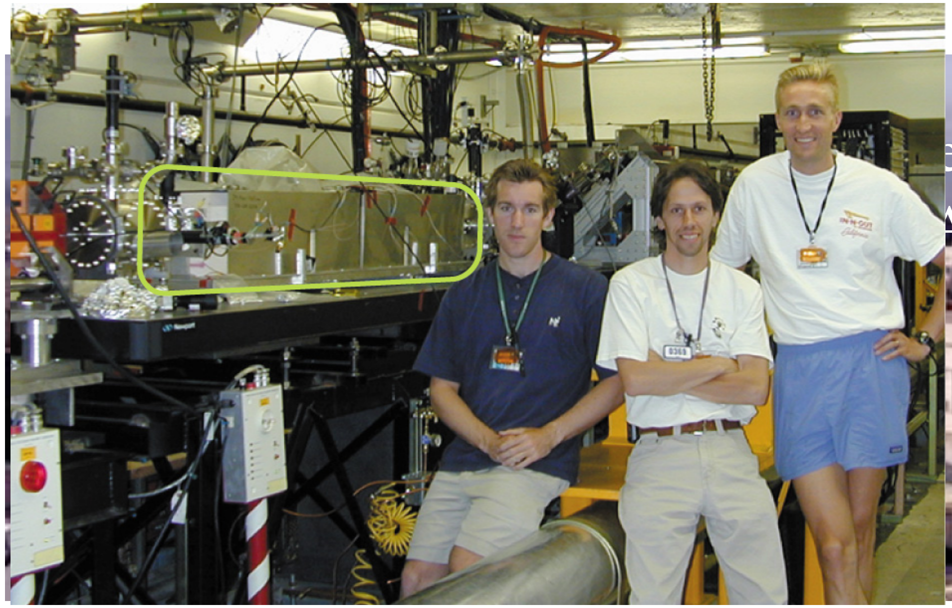


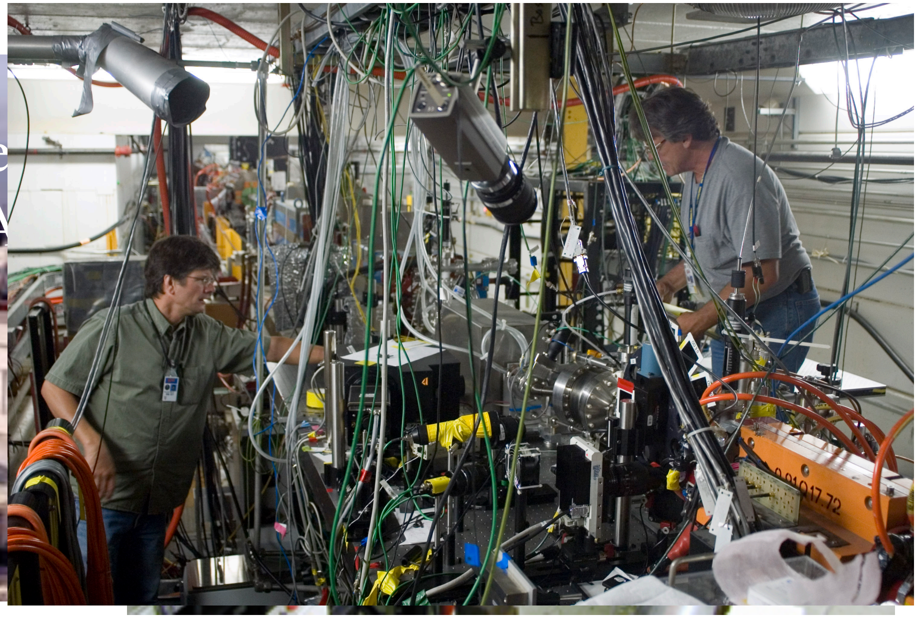
FIG. 8. (a) Uncorrelated-energy-spread-to-gain ratio δ vs energy-transfer efficiency η for different regimes of positron acceleration. The dashed black line depicts the constraint $\delta \lesssim 1\%$ explained in the text. For each regime, the different data points are obtained by increasing Q_t and optimizing the driver to minimize δ. (b) Loaded accelerating field E_z vs trailing positron charge Q_t for the same data points as in (a). Beam and plasma parameters or parameter range for these simulation results can be found in Table II.

C.S. Hue et al., Physical Review Research 3, 043063 (2021)

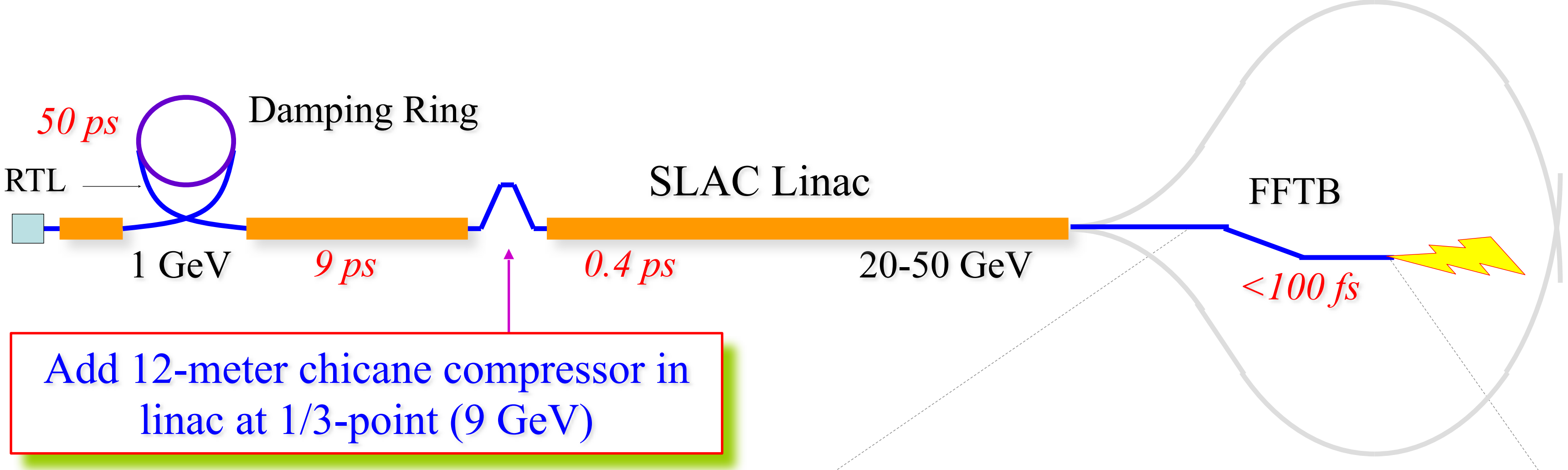
Plasma Wakefield Experiments at the SLAC FFTB (1998-2006)

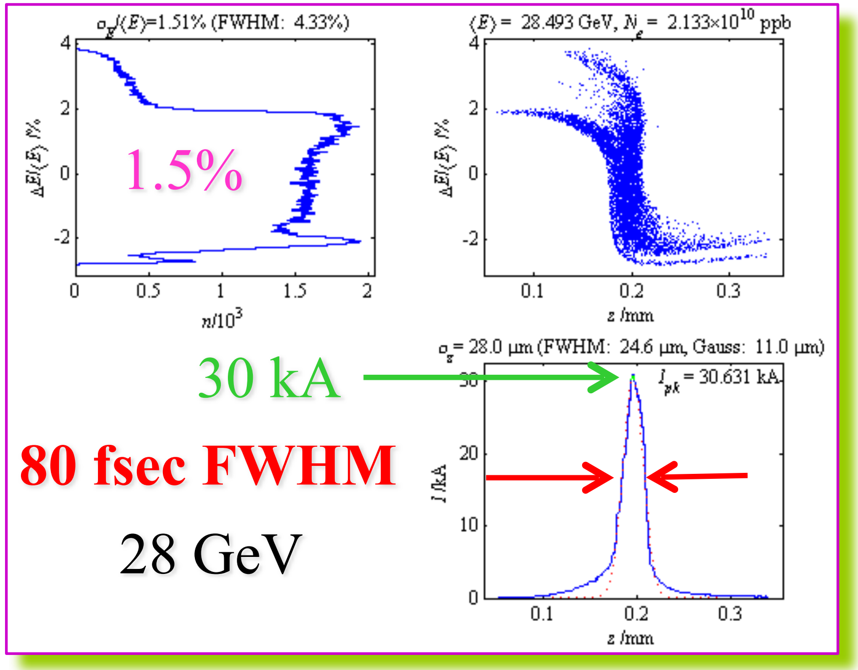


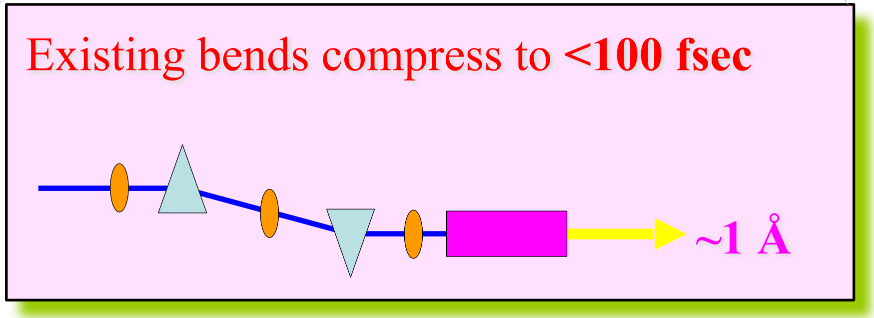




Short Bunch Generation In The SLAC Linac After 2002 – But Only for Electrons







- Bunch length/current profile is the convolution of an incoming energy spectrum and the magnetic compression
- Dial FFTB R56, measure incoming energy spectrum

First Acceleration of Positrons in Plasma

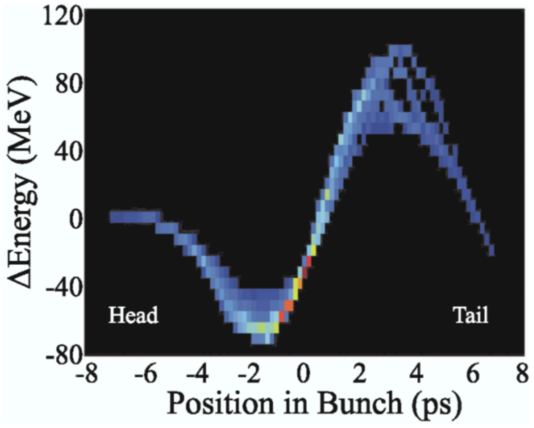
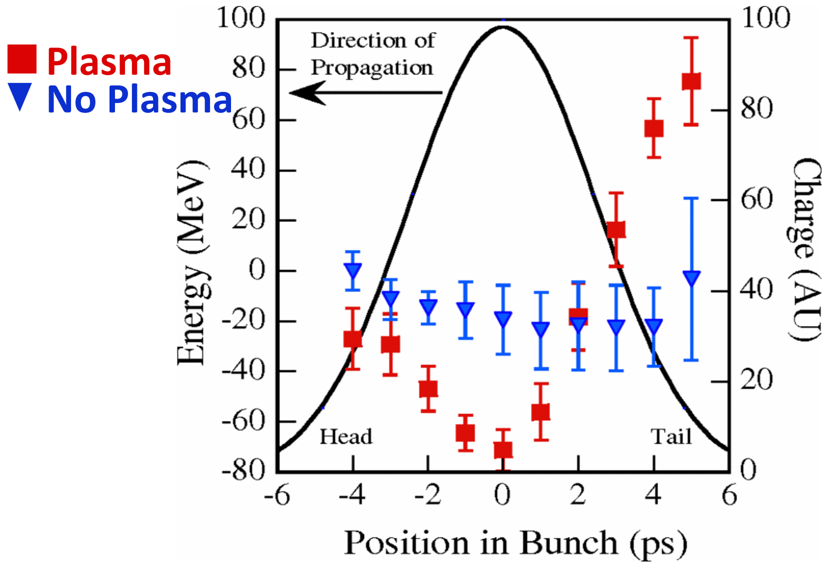


FIG. 2 (color). 3D particle-in-cell simulation of a positron beam in a plasma. The image depicts the phase space of the beam after it has traversed 1.4 m of plasma. Beam parameters in the simulation were identical to experimental parameters. The simulation predicts an energy loss of 64 MeV and an energy gain of 79 MeV.



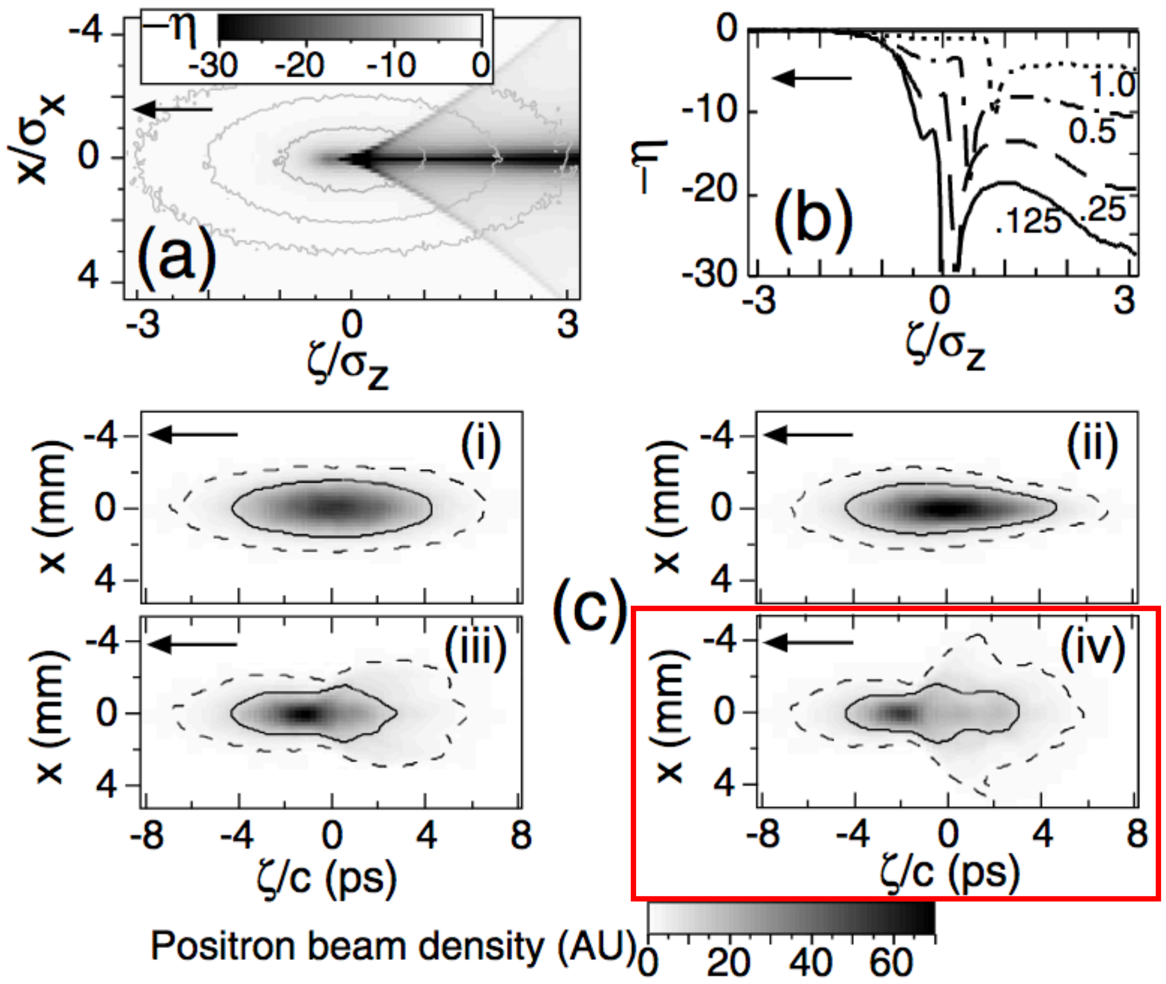
B. Blue et. al. *Phys. Rev. Lett.* 90 214801 (2003).

- First demonstration of positron acceleration in plasma!
- The E162 experiment operated in the linear regime
- A streak camera was used to measure the time-resolved energy spectrum

Transverse Dynamics of Positrons in Plasma

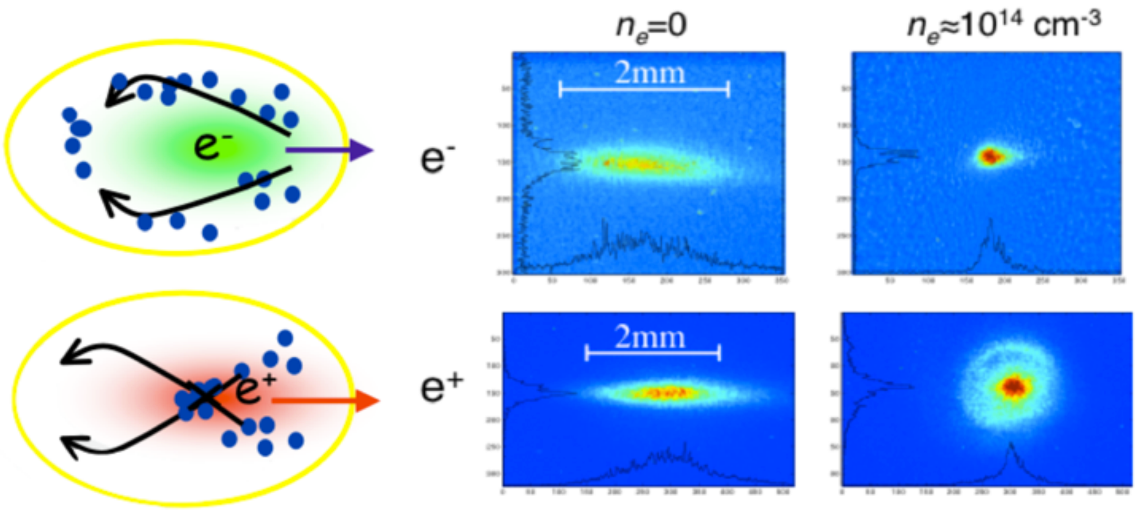
- When the positron beam is much denser than the background plasma, the nonlinearities become evident.

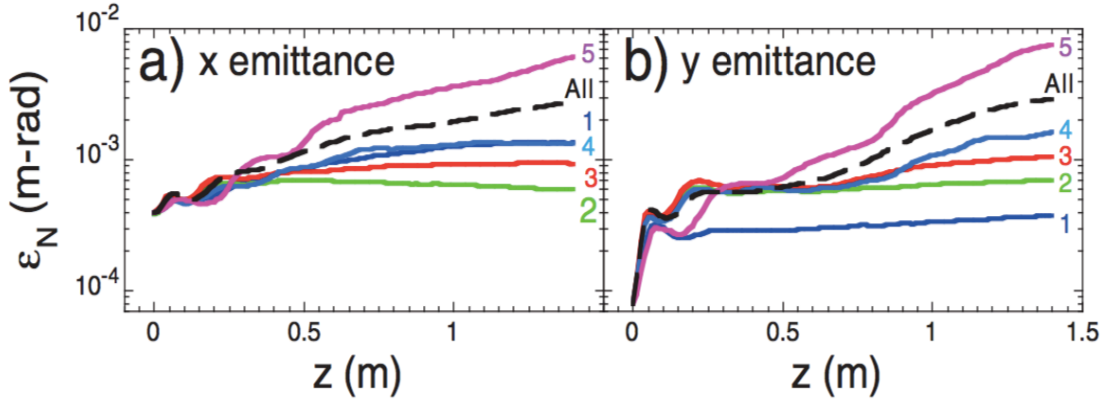
- Simulations of the ultra-relativisitic positron experiment show the formation of an "arrowhead" bunch.



M. J. Hogan et. al. *Phys. Rev. Lett.* 90 205002 (2003).

Transverse Dynamics of Positrons in Plasma

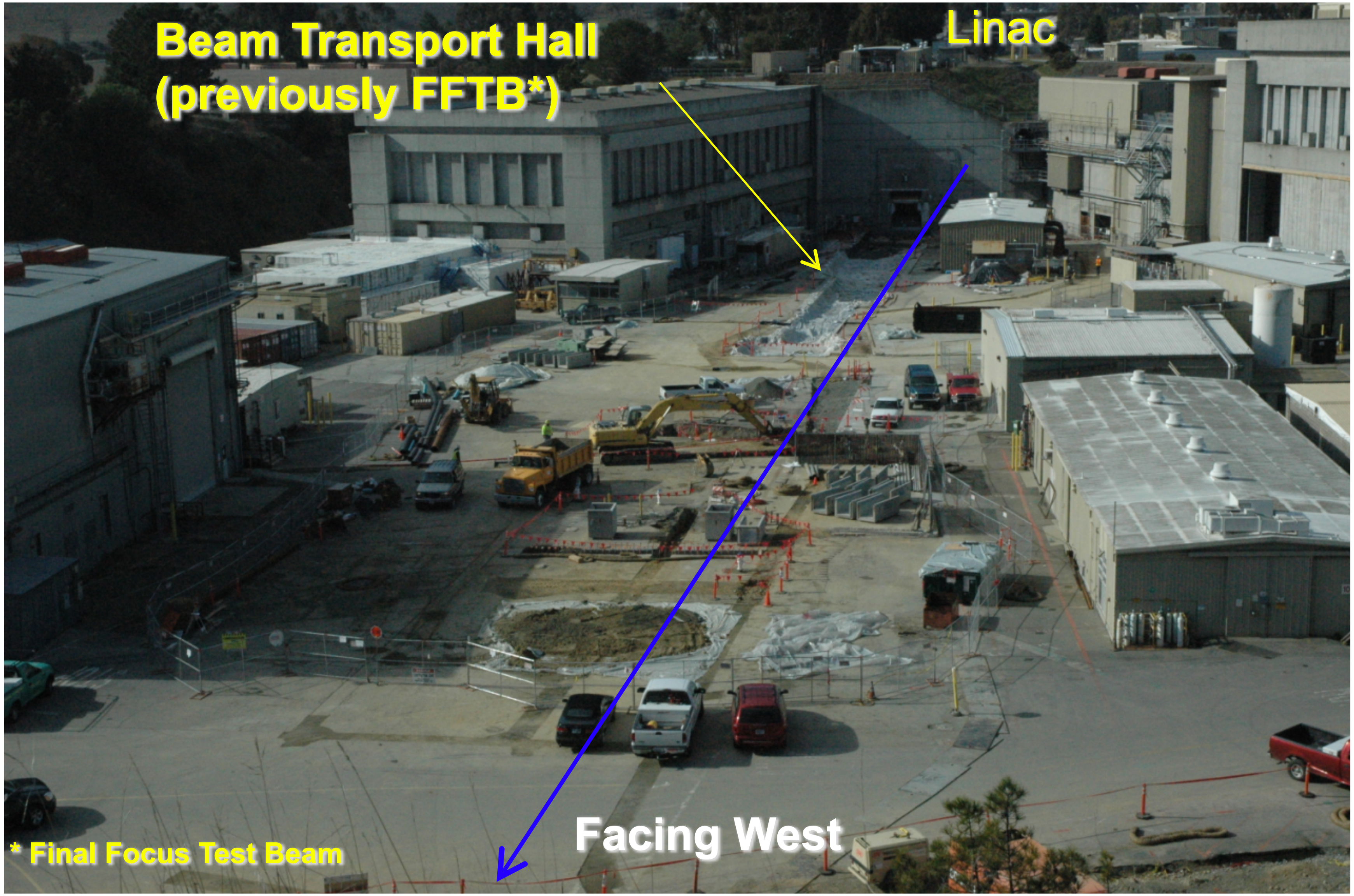




P. Muggli et. al. *Phys. Rev. Lett.* 101 055001 (2008).

- The question of positron beam evolution in the plasma important for understanding the final beam parameters
- A large, non-gaussian, beam halo is observed implying a large emittance
- Simulations show that the emittance grows rapidly along all longitudinal slices of the beam.

Future Experiments Would Require a New Facility – FACET



SLAC

FACET: A National User Facility (2012-2016)
based on high-energy beams and their interaction with plasmas and lasers

Primary Goal:

- Demonstrate a single-stage high-energy plasma accelerator for electrons

Timeline:

- Construction, Commissioning (2008-2011)
- Experimental program (2012-2016)

A National User Facility:

- Externally reviewed experimental program
- >200 Users, 25 experiments, 8 months/year operation

Key PWFA Milestones:

✓ Mono-energetic e- acceleration

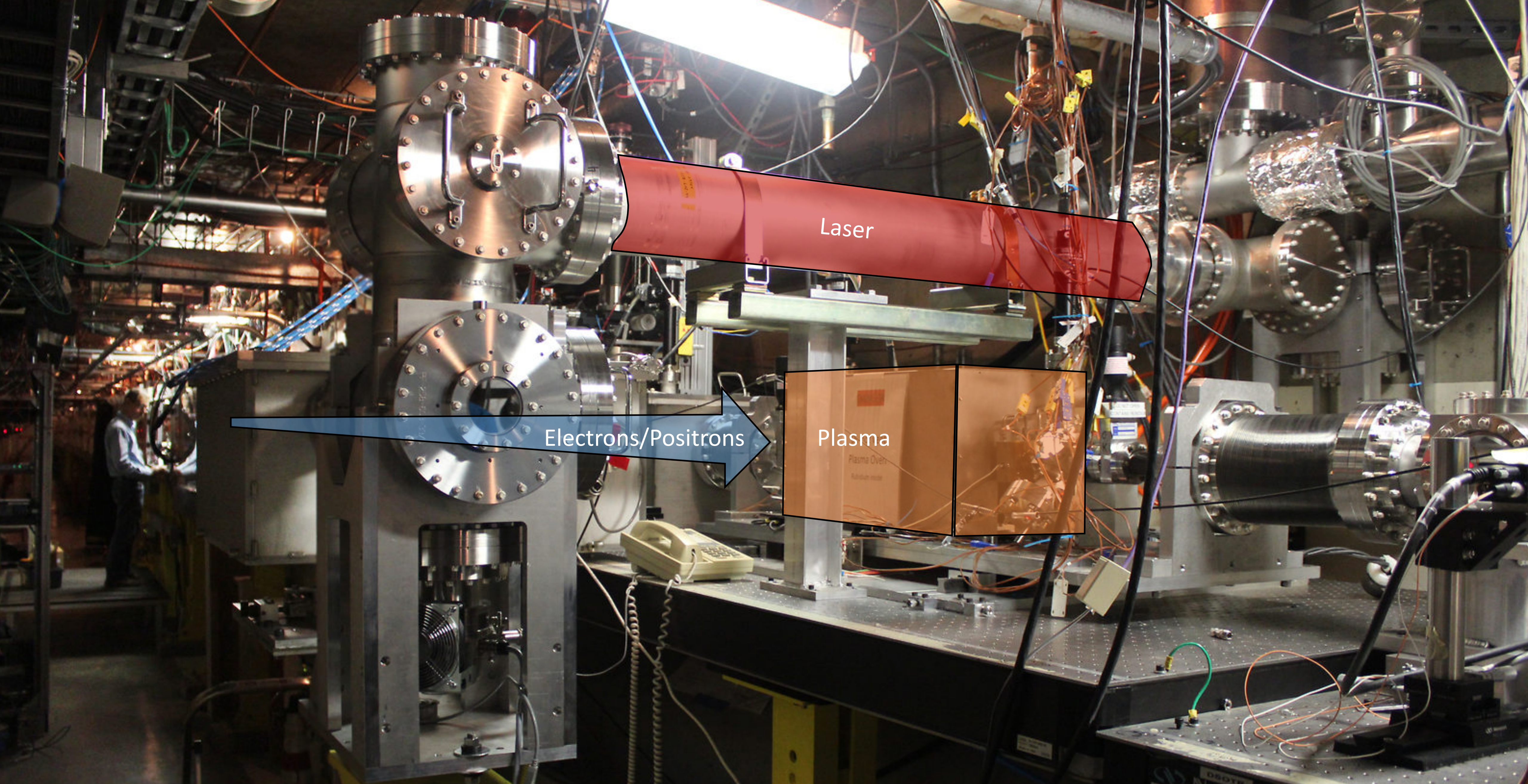
✓ High efficiency e^- acceleration (***Nature*** 515, Nov. 2014)

✓ First high-gradient e^+ PWFA (***Nature*** 524, Aug. 2015)

✓ Demonstrate required emittance, energy spread (***Nature Physics***, Aug. 2019)

Premier R&D facility for PWFA: Only facility capable of e+ acceleration
Highest energy beams uniquely enable gradient > 1 GV/m

Results from FACET



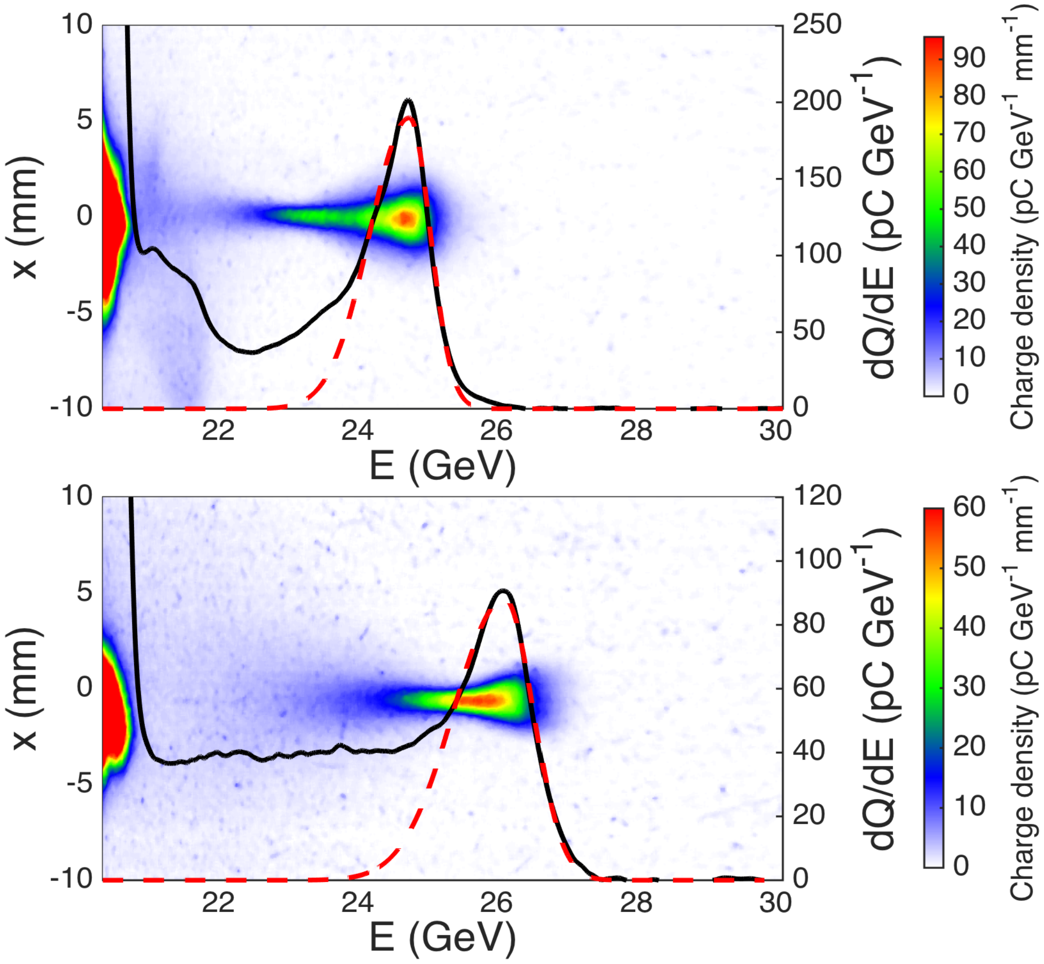
Positron Beam-Driven PWFA at FACET

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 exciting and unexpected result!

Experimental results in 1.3 m plasma

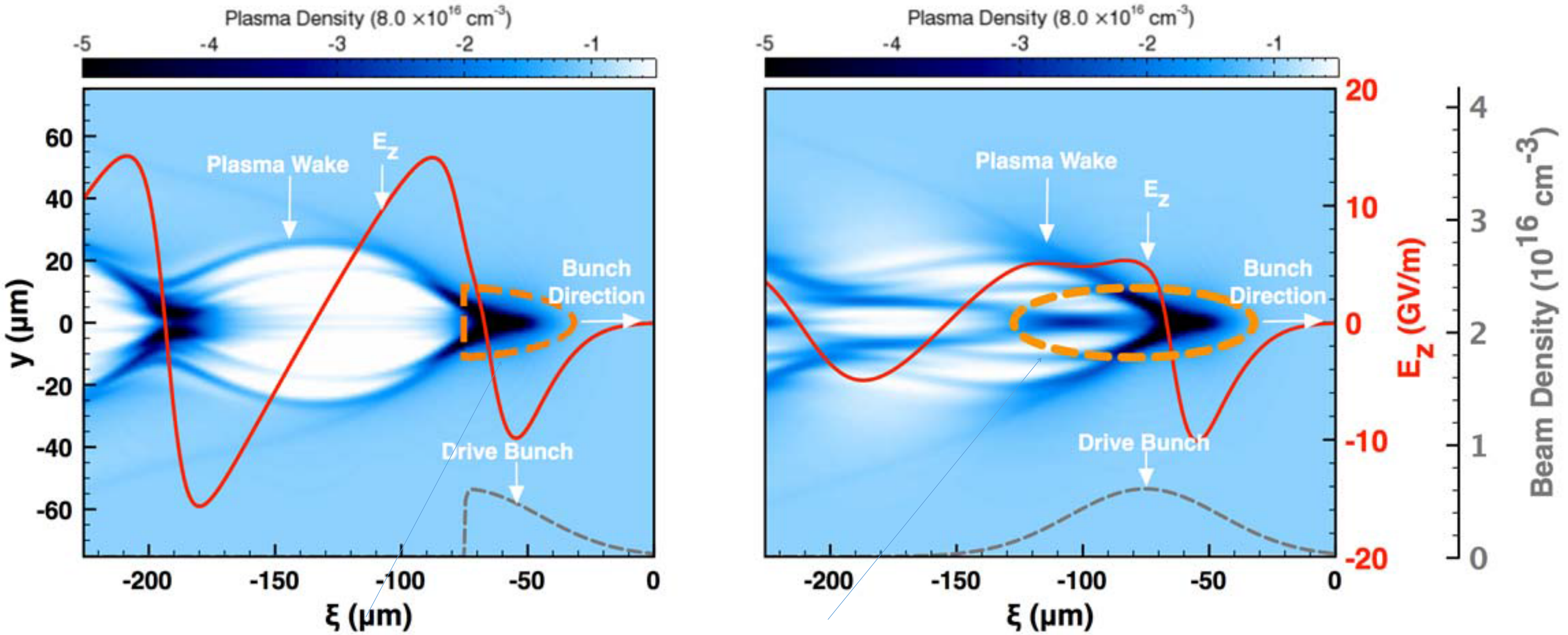


S. Corde *et al.*, Nature 524, 442 (2015)

Positron Beam-Driven PWFA

QuickPIC simulations: loaded vs unloaded wake (truncated bunch)

Unloaded | Loaded

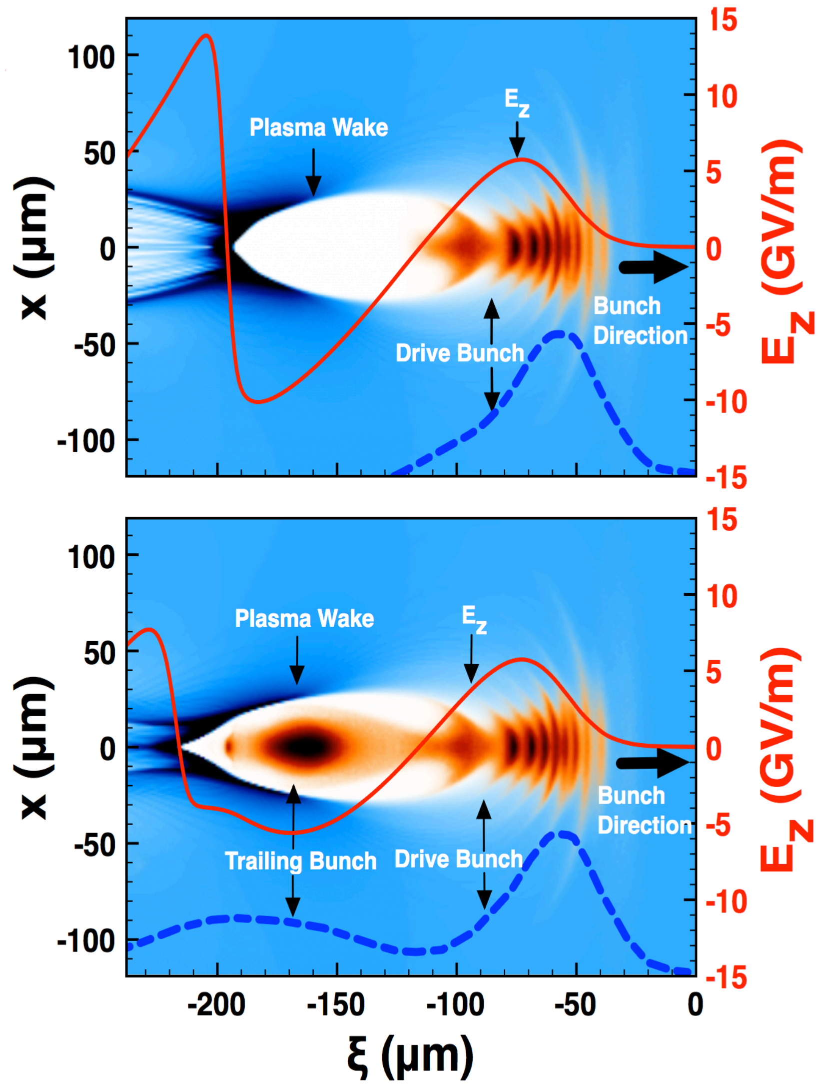


defocusing | focusing

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

Beam loading also affects transverse fields for positron driven wakes!

Beam Loading with Electron Bunches



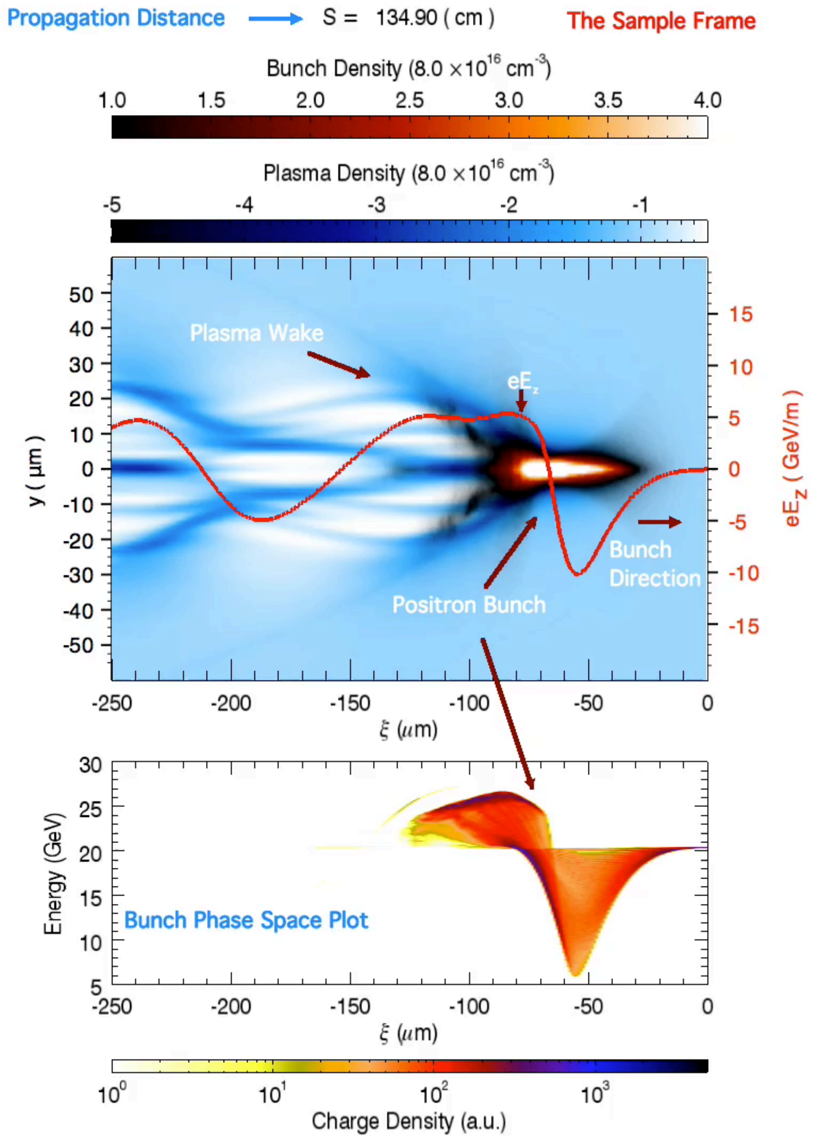
M. Litos *et al.* Nature 515, 92-95 (2014)

- This simulation shows the electron beam-driven wake in the blow out regime
- When the wake is loaded, the bubble regime is still free of plasma electrons and the transverse force is un-modified
- The presence of the trailing electron beam "flattens" the Ez field
- This leads to high efficiency and low energy spread
- However, there is no modification of the transverse fields inside the bubble due to the addition of the trailing electron bunch

Positron Beam-Driven PWFA

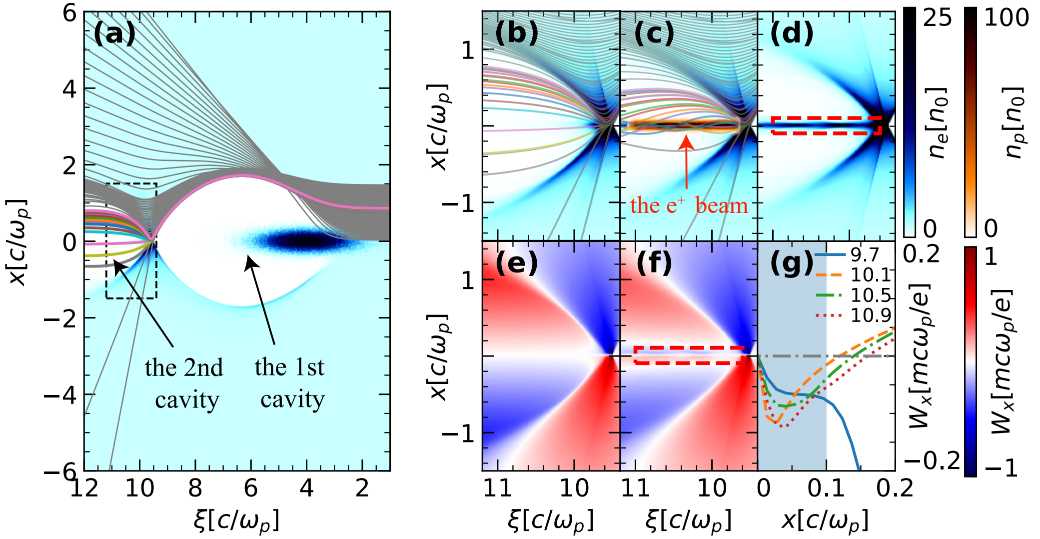
Key question:

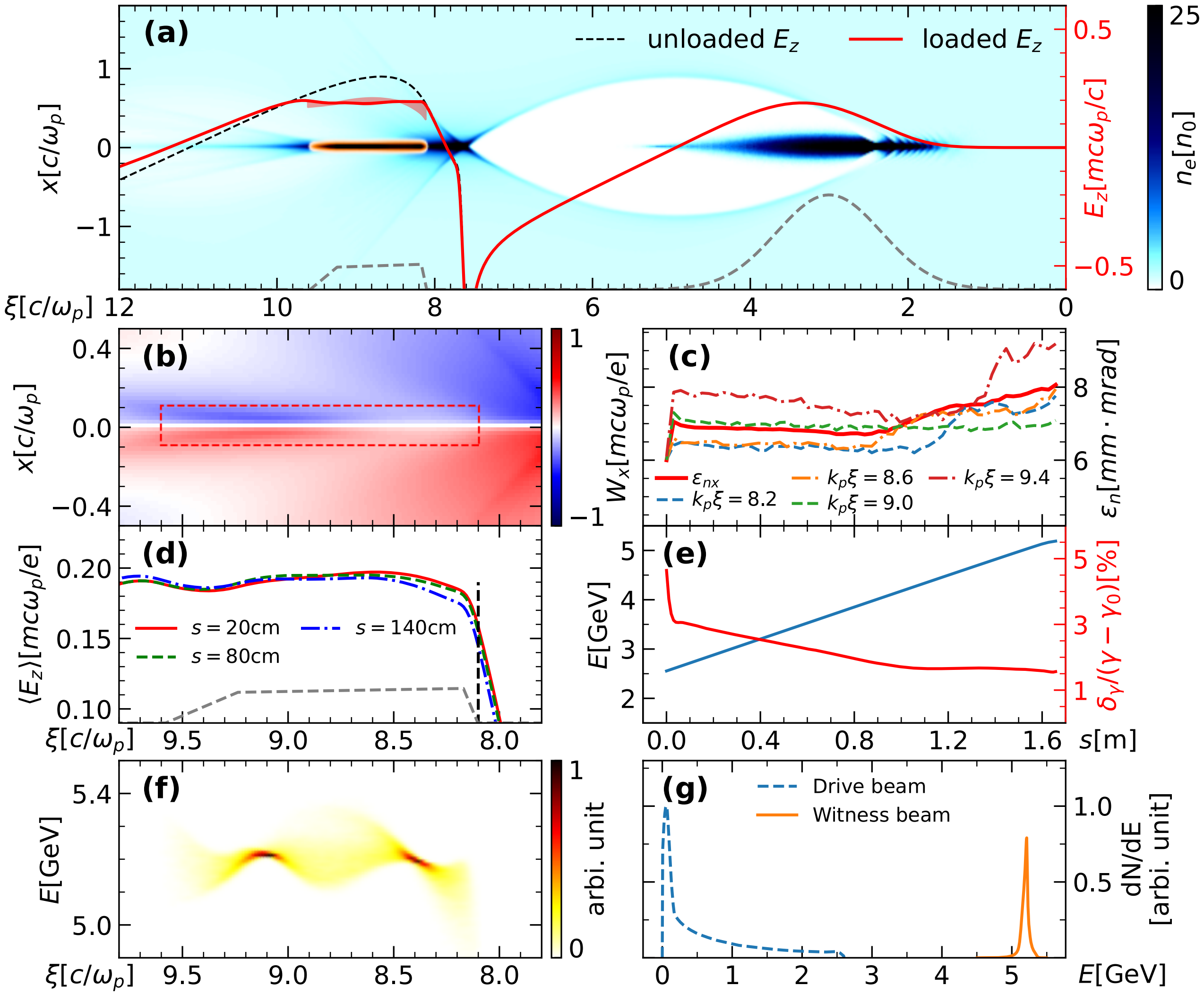
Is there an equilibrium emittance, or is the emittance growth continuous?



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

Positron Beam Loading and Acceleration in the Blowout Regime of Plasma Wakefield Accelerator





- ~100pC e+ charge
- 5GeV energy gain
- 2.4% energy spread
- 7 mm-mrad norm. Emittance
- Wake to beam efficiency 26%

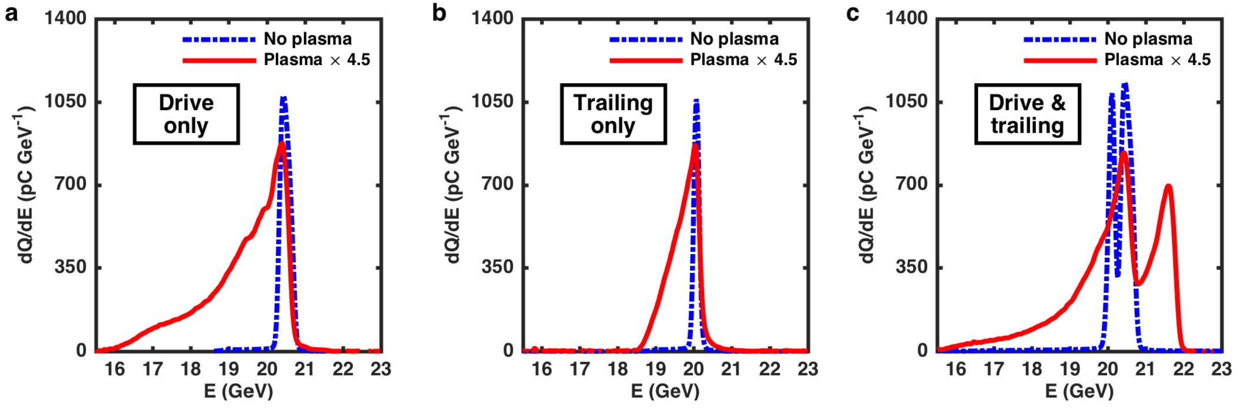
Zhou et al., arXiv:2211.07962v1 (2022)

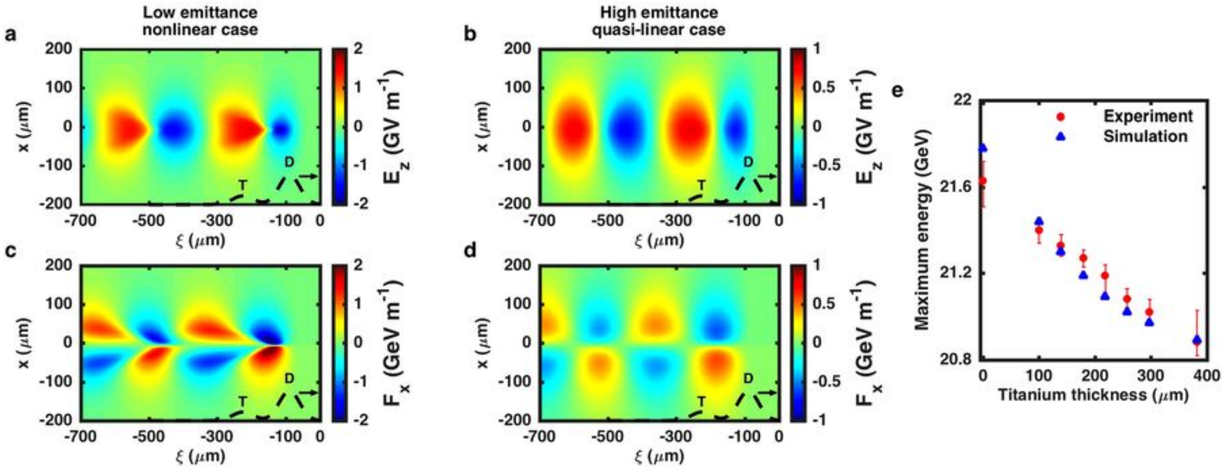
Two-Bunch Positron Beam-Driven PWFA

The results of the single positron bunch experiment naturally beg the question:

Can we repeat these results in the drive-witness scenario?

- This led to the first demonstration of controlled beam loading in the positron beam-driven wake
- We tested this scenario in both the quasi-linear and non-linear regimes

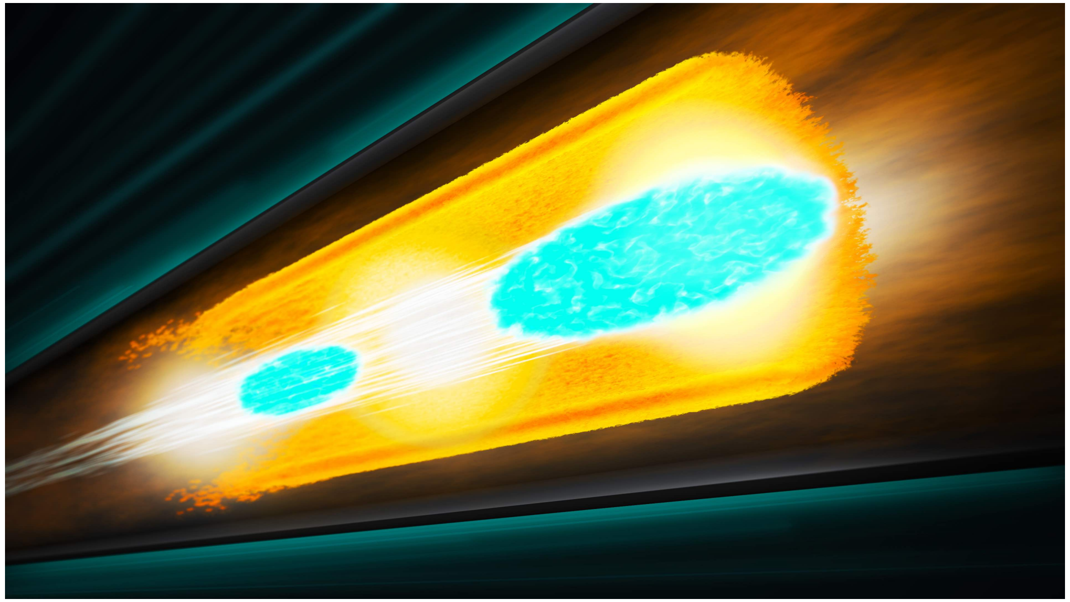


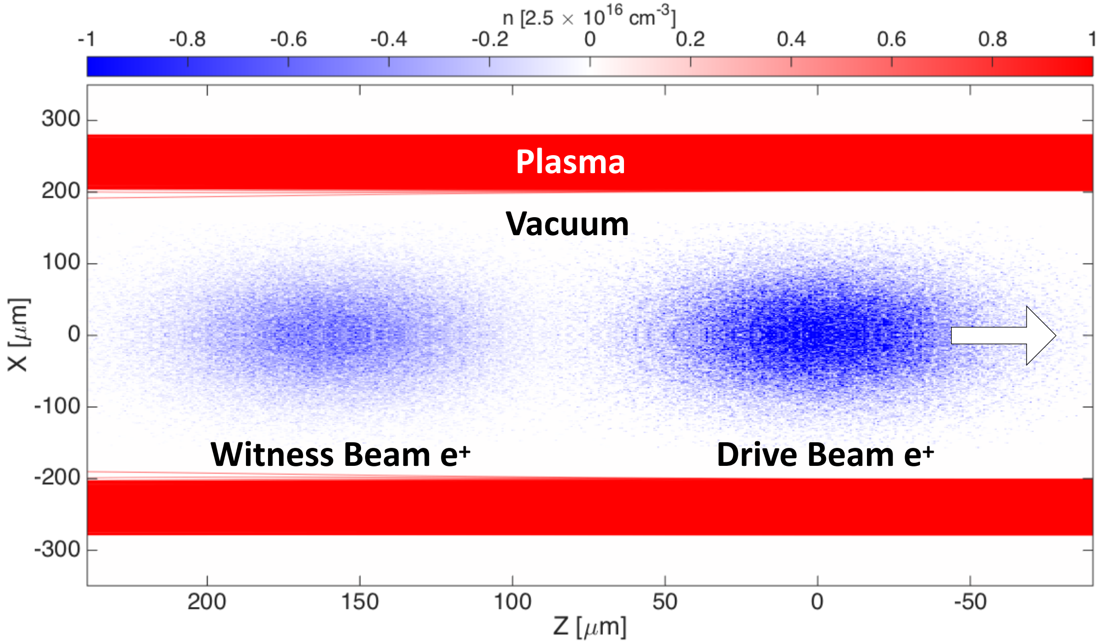


A. Doche *et al.*, Nat. Sci. Rep. 7, 14180 (2017)

SLAC

The Hollow Channel Plasma Accelerator



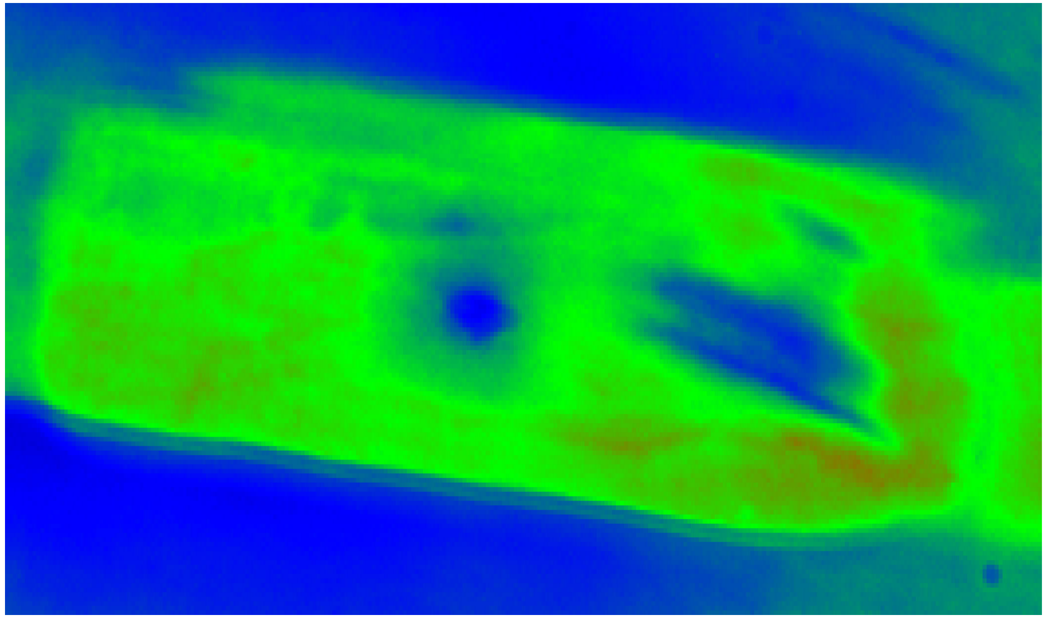


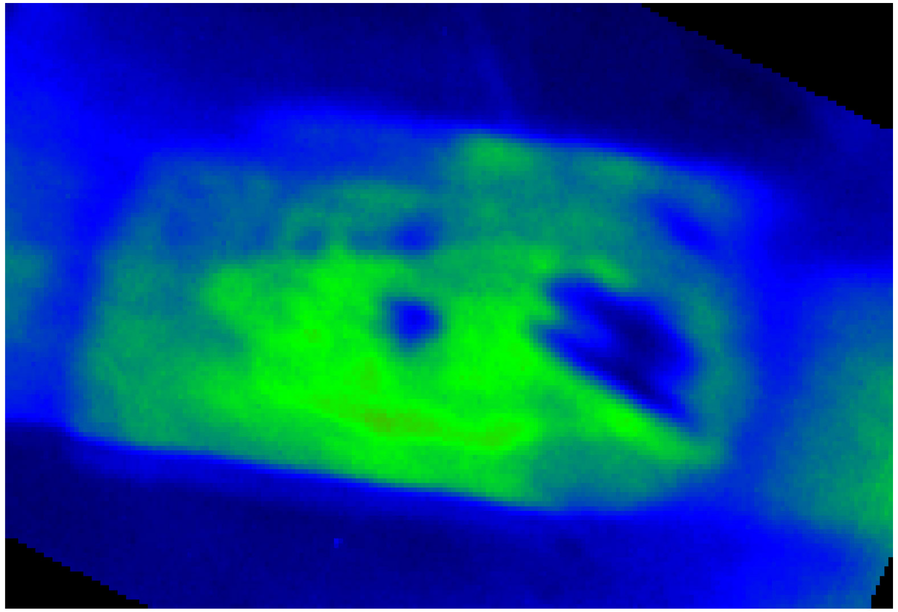
- The Hollow Channel Plasma is a structure that symmetrizes the response of the plasma to electron and positron beams
- There is no plasma on-axis, and therefore no focusing/defocusing force from plasma ions

If at First You Don't Succeed, Try and Try Again

The accelerating wake for a positron beam driven plasma wave can be optimized by using a hollow channel plasma, but can we make such a channel? - Yes

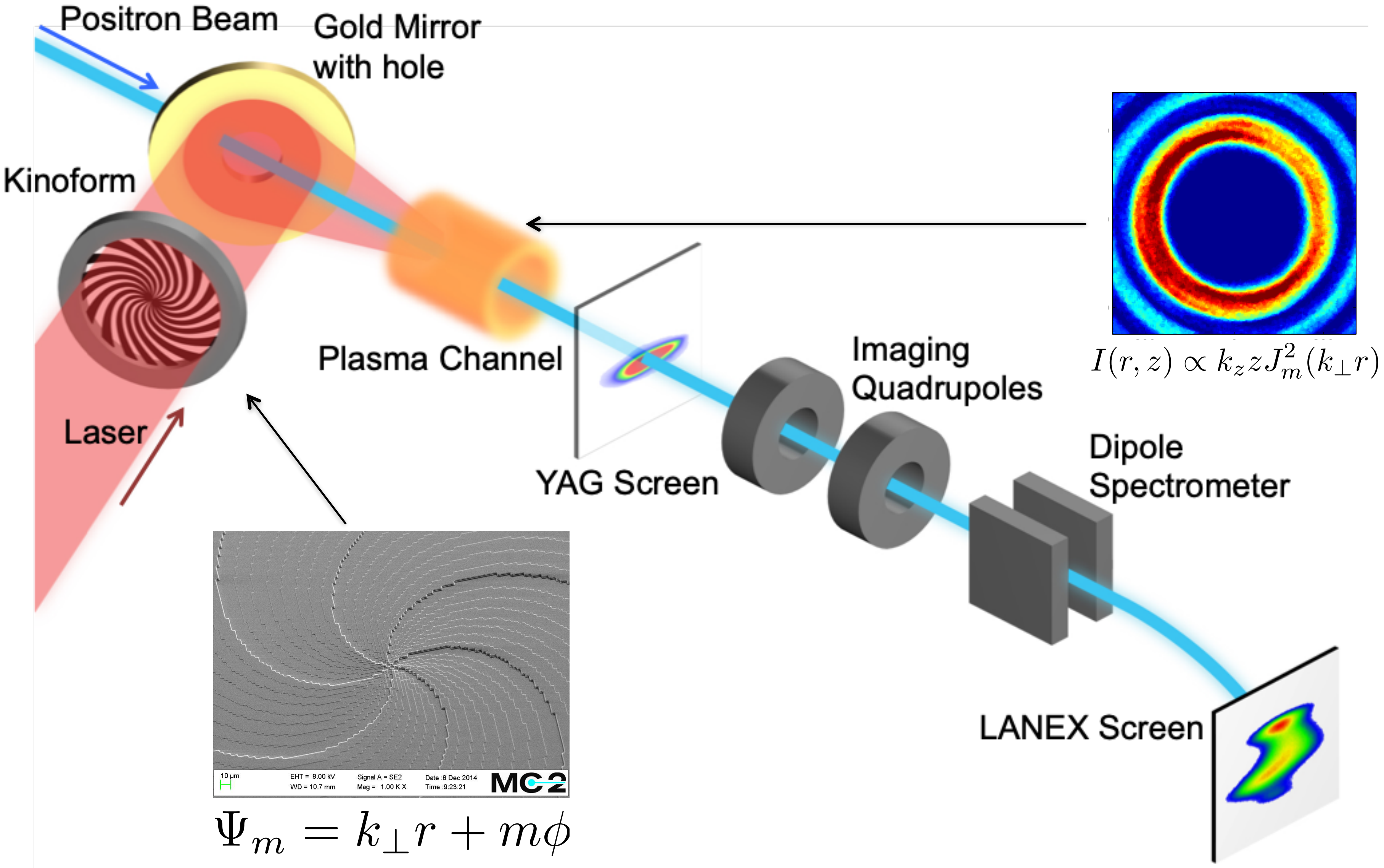
Hollow channel in ionization laser profile is preserved over 1.4m





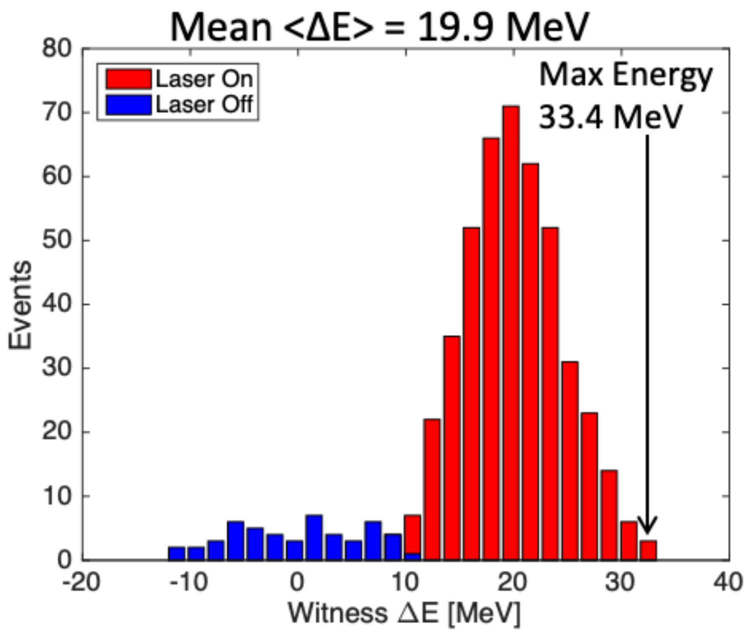
UV profiles 0.3 m (a) and 1.3 m (b) from a damaged UV optic with ~ 500 μm hole in reflective coating (center of images) as well as other forms of damage. The structure of the resultant mask in UV fluence is preserved over the required length to photo-ionize a hollow channel plasma.

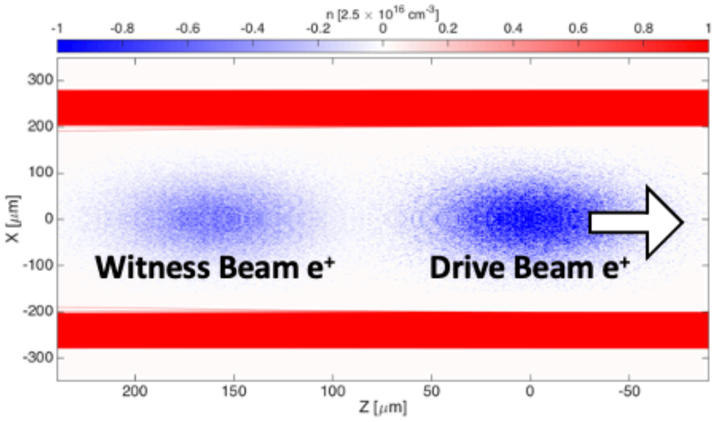
Creating a Hollow Channel Plasma

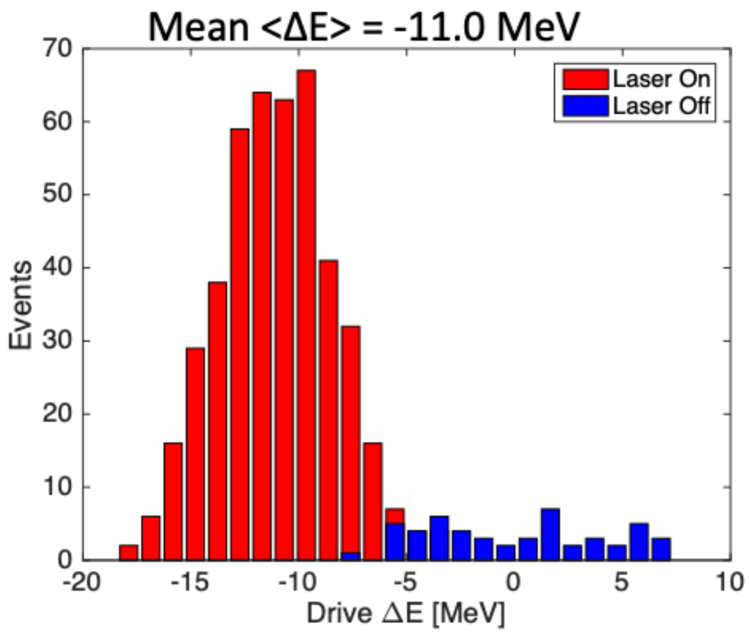


S. Gessner et. al. *Nat. Comm.* 7, 11785 (2016)

Positron Acceleration





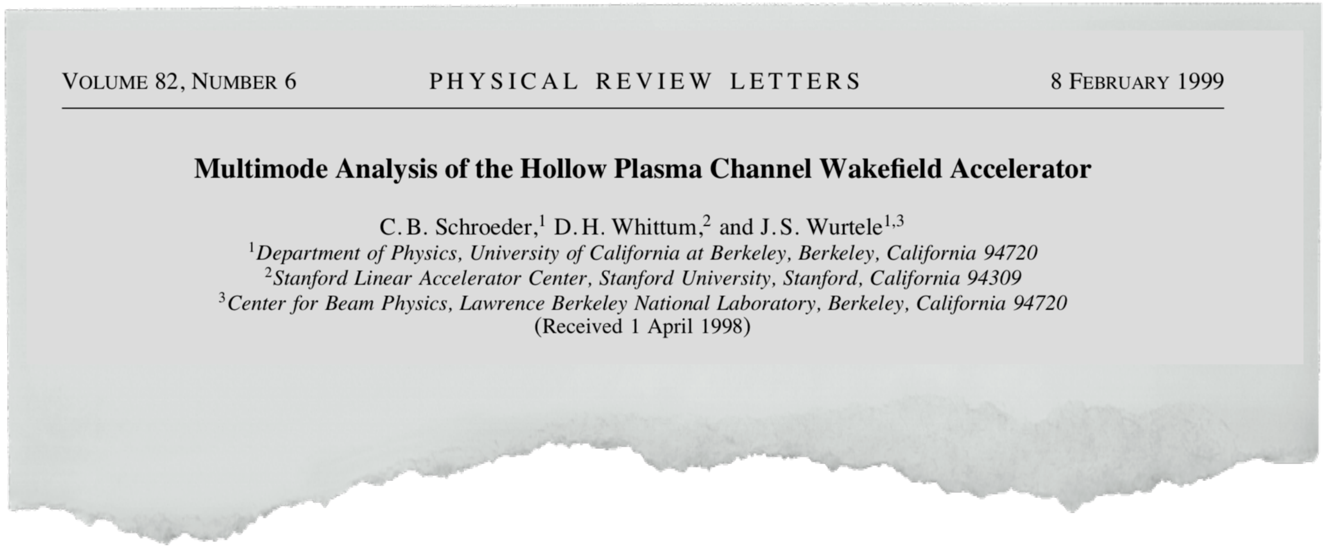


Witness beam gains energy from the wake

Drive beam transfers energy to witness beam

Transverse Wakefields

- 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

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(Received 1 April 1998)

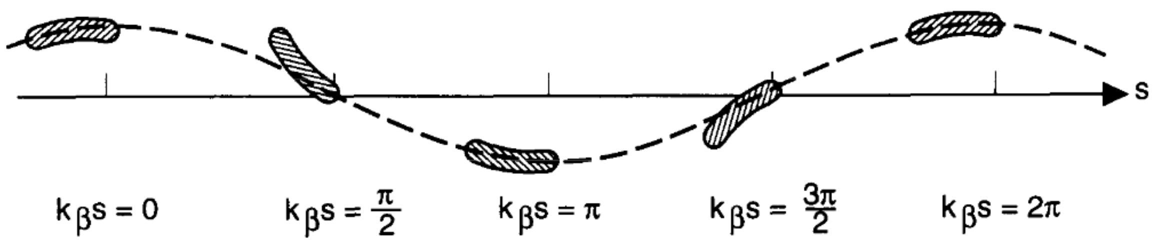
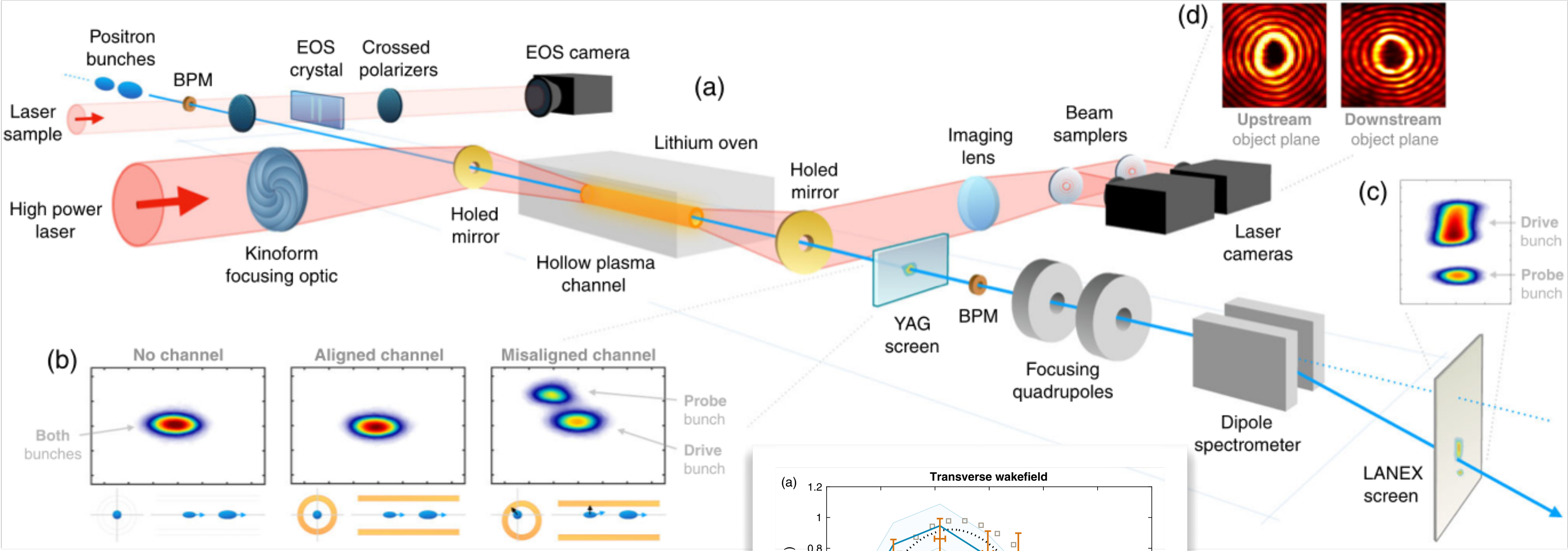
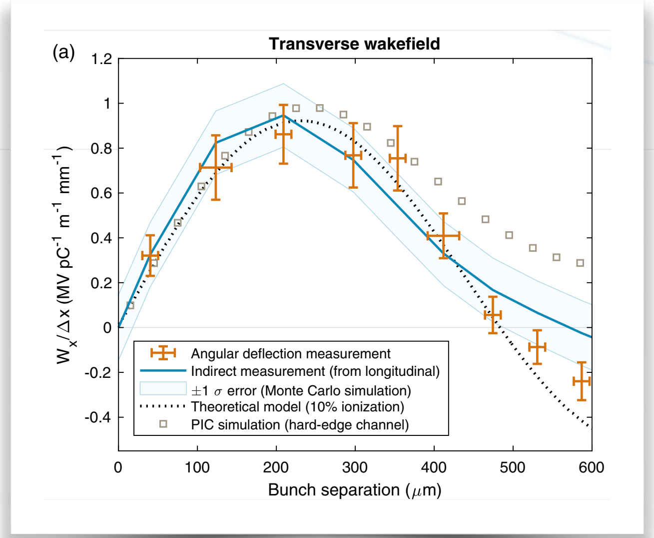


Figure 3.3. Sequence of snapshots of a beam undergoing dipole beam breakup instability in a linac. Values of $k_\beta s$ indicated are modulo 2π. The dashed curves indicate the trajectory of the bunch head.

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

Fields in the Hollow Channel



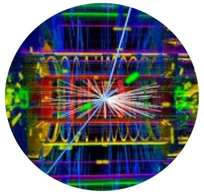


Transverse Wake Amplitude CLIC: 100 V/pC/m/mm

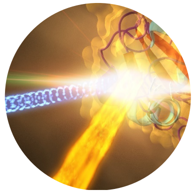
Transverse Wake Amplitude E225: 1M V/pC/m/mm

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

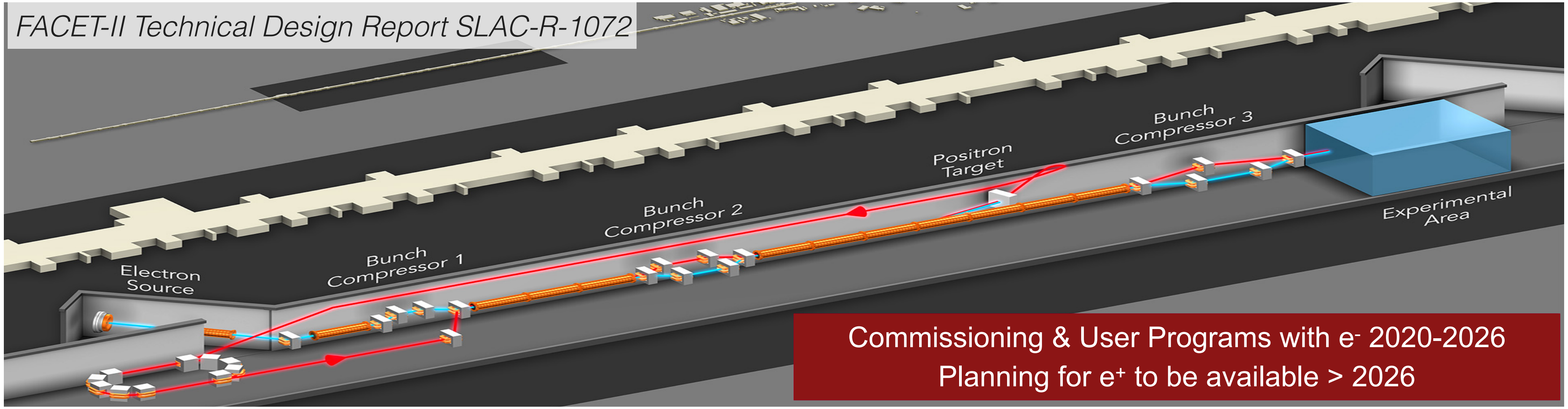
FACET-II: A National User Facility
Based on High-energy Beams and Their Interaction with Plasmas and Lasers



Advance the energy frontier for future colliders



Develop brighter X-rays for photon science



Positron Generation and Trapping without External Source

- Use a pair of electron beams to generate positrons in a tungsten foil at plasma entrance
- Some positrons will get trapped and accelerated in the electron-driven wake
- E-303 experiment: P.I. K. Marsh, UCLA

'Simple' way to probe volume of the region that is accelerating and focussing but cannot access collider level parameters

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22**, 091301 (2019)

Positron beam extraction from an electron-beam-driven plasma wakefield accelerator

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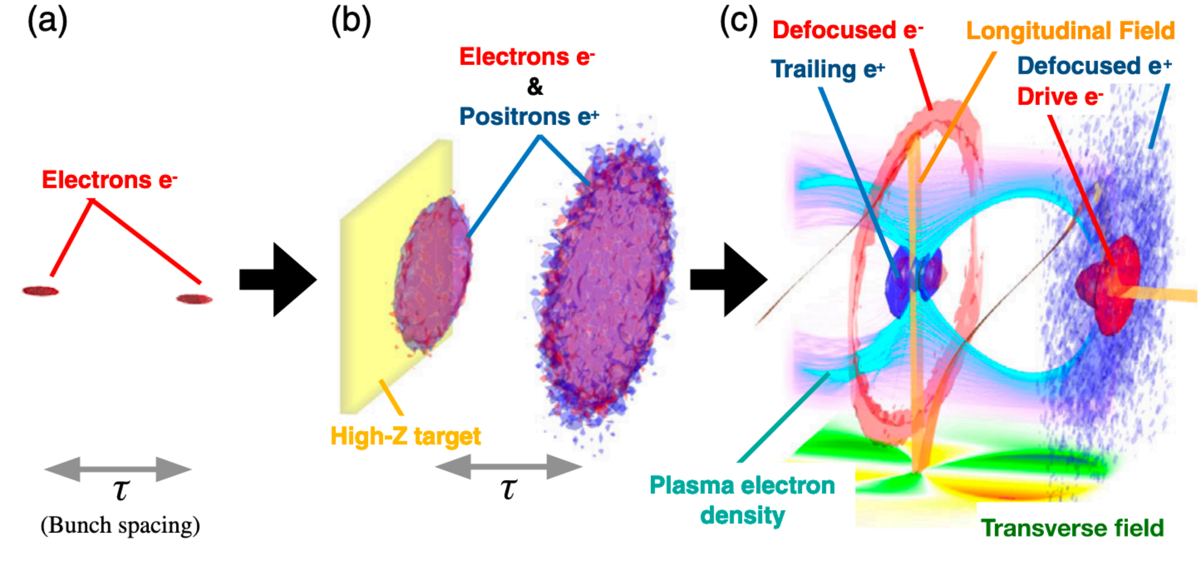
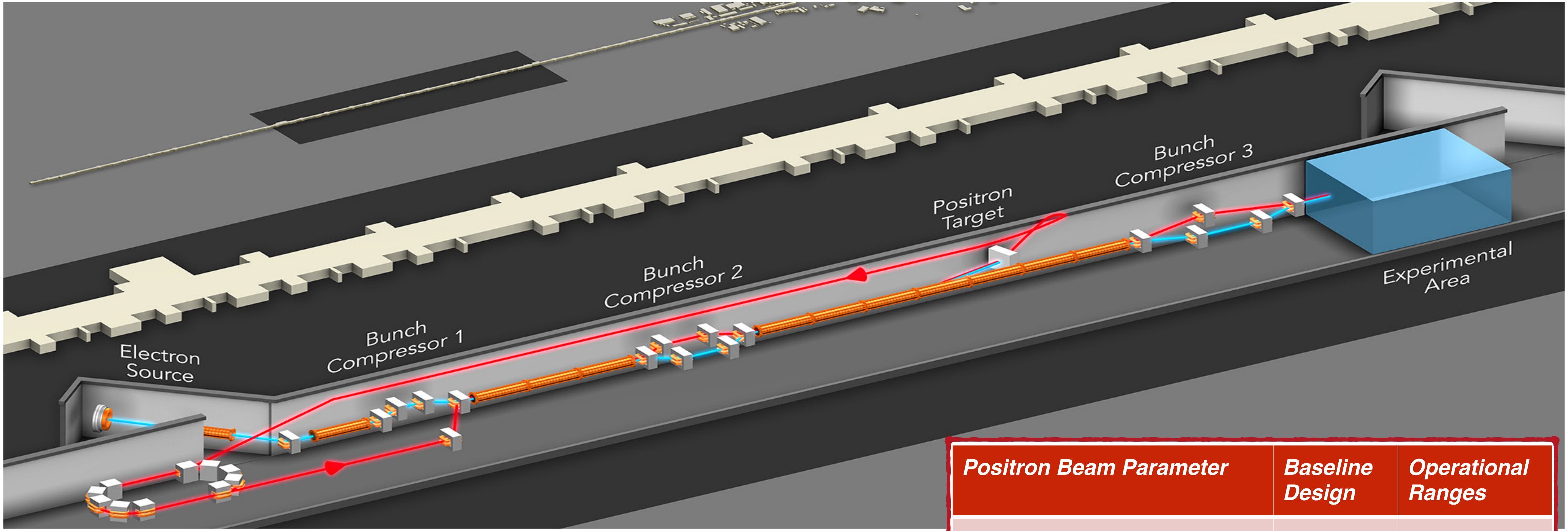


FIG. 1. Schematic diagram of the positron acceleration.

FACET-II Technical Design Report SLAC-R-1072

FACET-II Layout and Beams
A plan is being developed to restore positron capability

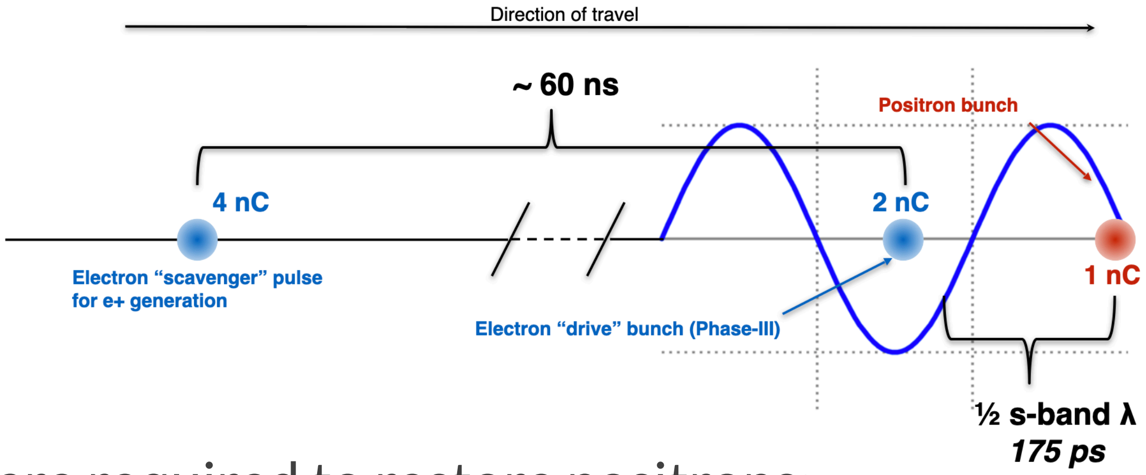


- Simultaneous delivery of up to 1nC e+ & 2nC e- to S20 IP region
- Expected performance modeled with particle tracking, including dynamic errors
- More details in TDR Ch. 8

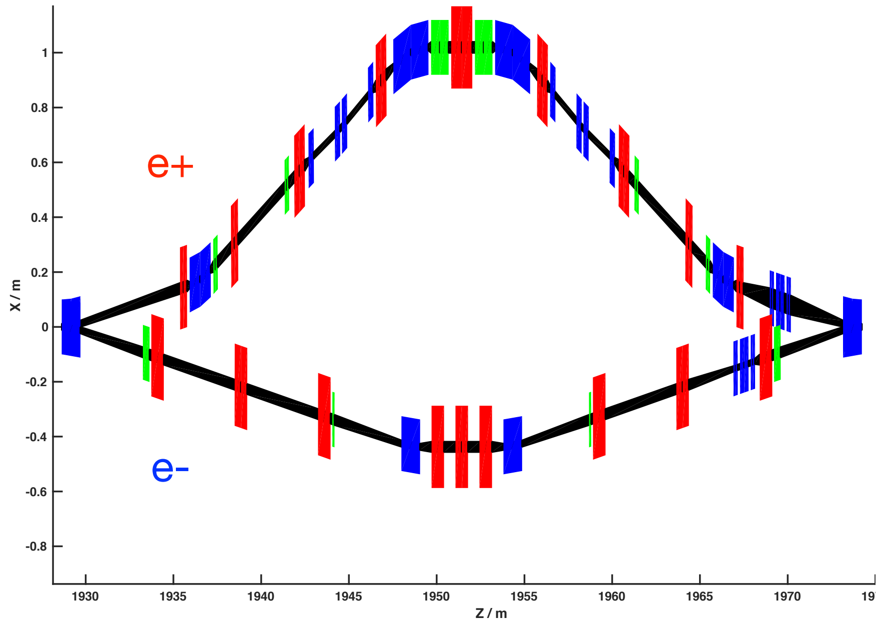
Positron Beam Parameter	*Baseline Design*	*Operational Ranges*
Final Energy [GeV]	*10*	*4.0-13.5*
Charge per pulse [nC]	*1*	*0.7-2*
Repetition Rate [Hz]	*5*	*1-5*
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19	*10, 10*	*6-20*
Spot Size at IP $\sigma_{x,y}$ [μm]	*16, 16*	*5-20*
Min. Bunch Length σ_z (rms)	*16*	*8*
Max. Peak current I_{pk} [kA]	*6*	*12*

Will be Possible to Study Positron PWFA in Electron Wakes

Positrons can be restored to Sector 20 by utilizing existing S19 positron source with a ~4 nC electron driver pulse



Simultaneous e- e+ delivery (dz +/- 600 μm) made possible by adding **BC20P beamline**

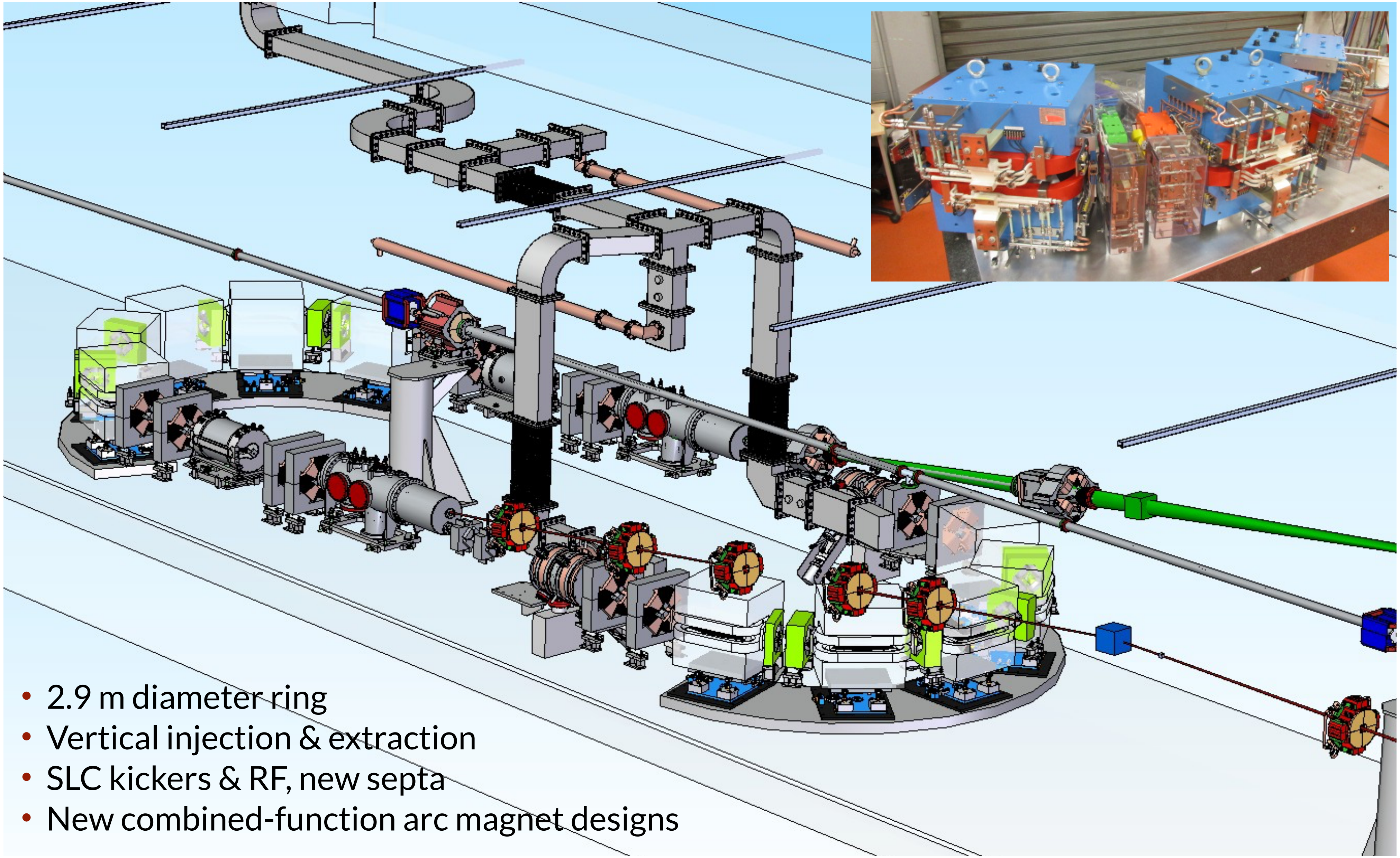


Hardware required to restore positrons:

- New BC14 chicane section
- 335 MeV booster Linac in return line
- New compact DR in Sector 10
- New beamlines to extract beam from return line into DR, extract beam from DR and extract, compress & inject into BC11

SLAC

335 MeV Positron Damping Ring in Sector 10



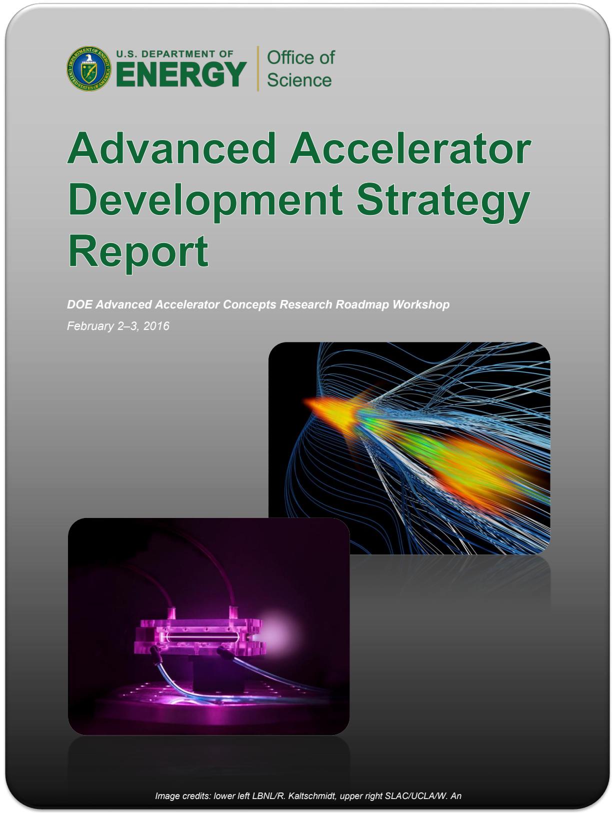
- 2.9 m diameter ring
- Vertical injection & extraction
- SLC kickers & RF, new septa
- New combined-function arc magnet designs

Collider Designs Require New Ideas for Positron PWFA

Beam Driven Plasma R&D 10 Year Roadmap					
2016	2018	2020	2022	2024	2026
PWFA-LC Concept Development and Parameter Studies					
Beam Dynamics and Tolerance Studies					
Positron Acceleration					
FACET			FACET-II Phase 2: Positrons		
Simulate, Test and Identify the Optimal Configuration for Positron PWFA					

Present ('New Regime' only)		Goals
4GeV		100pC, >1GeV @ >1GeV/m, dE/E < 5%, Emittance Preserved in at least one regime:
Q ~ 100 pC		
3 GeV/m		'New Regime' seeded with two bunches
ΔE/E ~ 2%		Hollow Channel Plamsas
ε not measured		Quasi non-linear

Plasma Source Development
Goals
Tailored density ramps for beam matching and emittance preservation
Uniform, hollow and near-hollow transverse density profiles
Accelerating region density adjustable from 10^{15} - 10^{17} e^{-}/cm^{3}
Accelerating length > 1m
Scalable to high repetition rate and high power dissipation



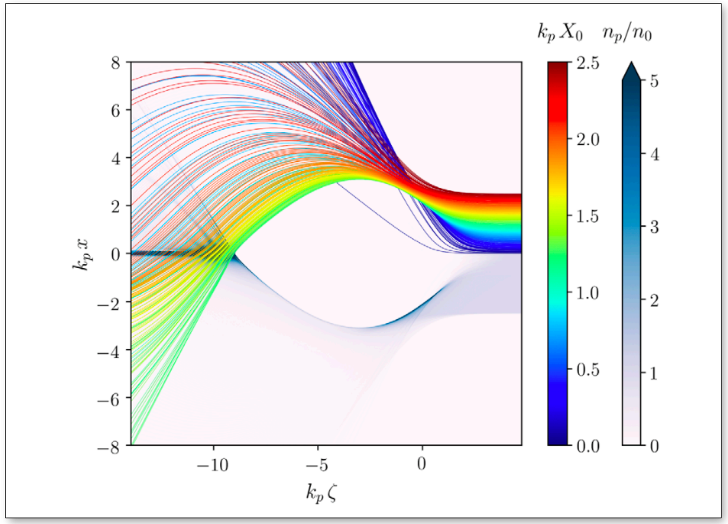
- Transversely tailored plasmas
- Transversely tailored drivers
- Long term evolution of beams/ plasmas into exotic equilibrium

SLAC

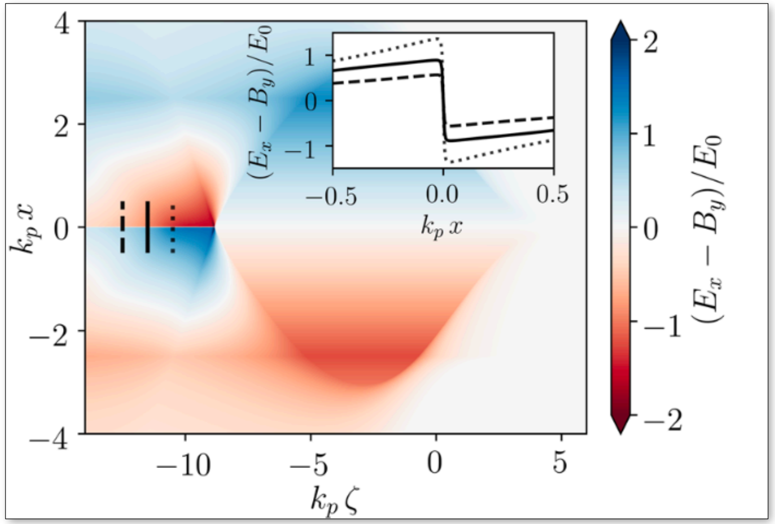
Transversely Tailored Plasmas

- Changing the shape of the ionized plasma region modifies the trajectories of plasma electrons in the wake.
- This leads to an elongated region in the back of the wake where positron bunches are focused and accelerated.
- E-333 experiment: DESY/LBNL/SLAC collaboration

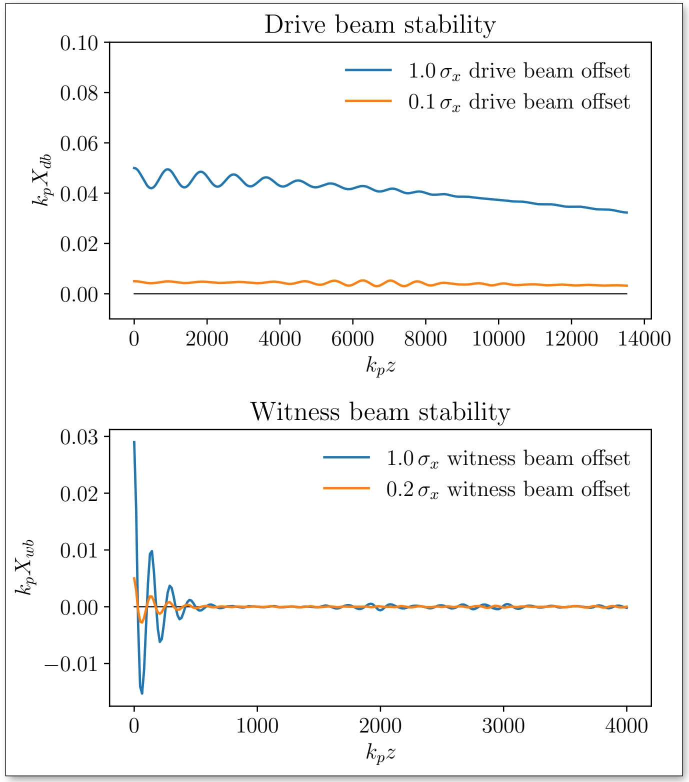
[S. Diederichs et. al. Phys. Rev. Accel. Beams 25, 091304 (2022)]



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

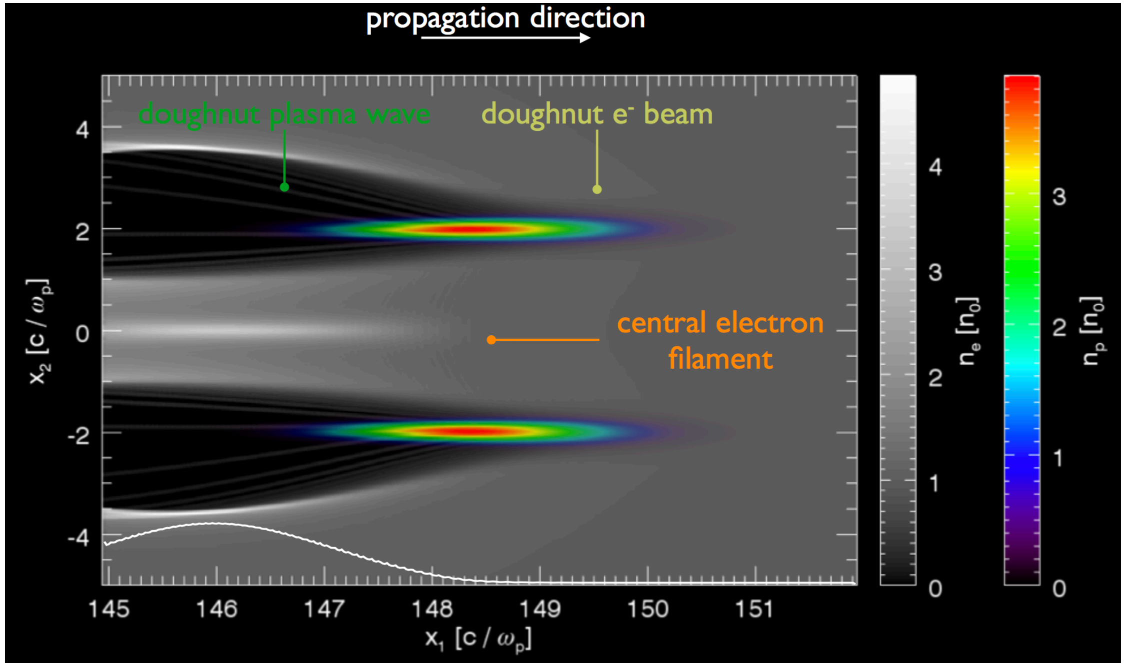


[S. Diederichs et. al. Phys. Rev. Accel. Beams 23 121301 (2020)]



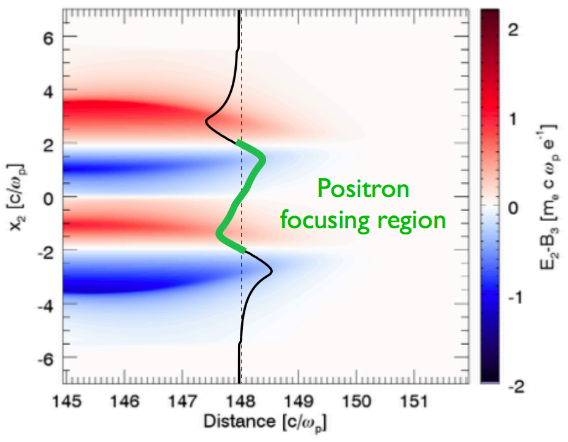
Transversely Tailored Drivers a.k.a. Wake Inversion

- Certainly a challenge for the accelerator physicists
- Optimizations are possible trading efficiency, energy spread and emittance



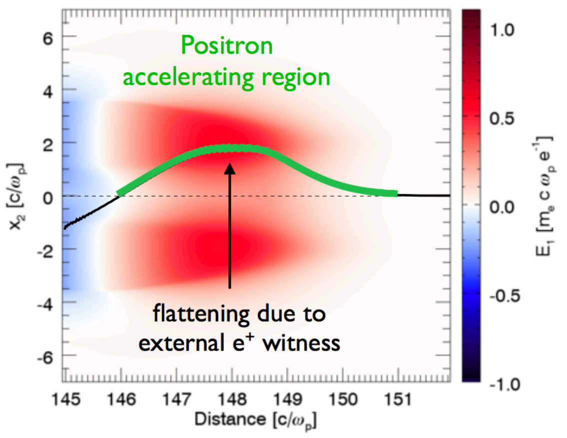
J. Vieira, et al. PRL 112 215001 (2014)
N. Jain et al. PRL 115 195001(2015)

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**

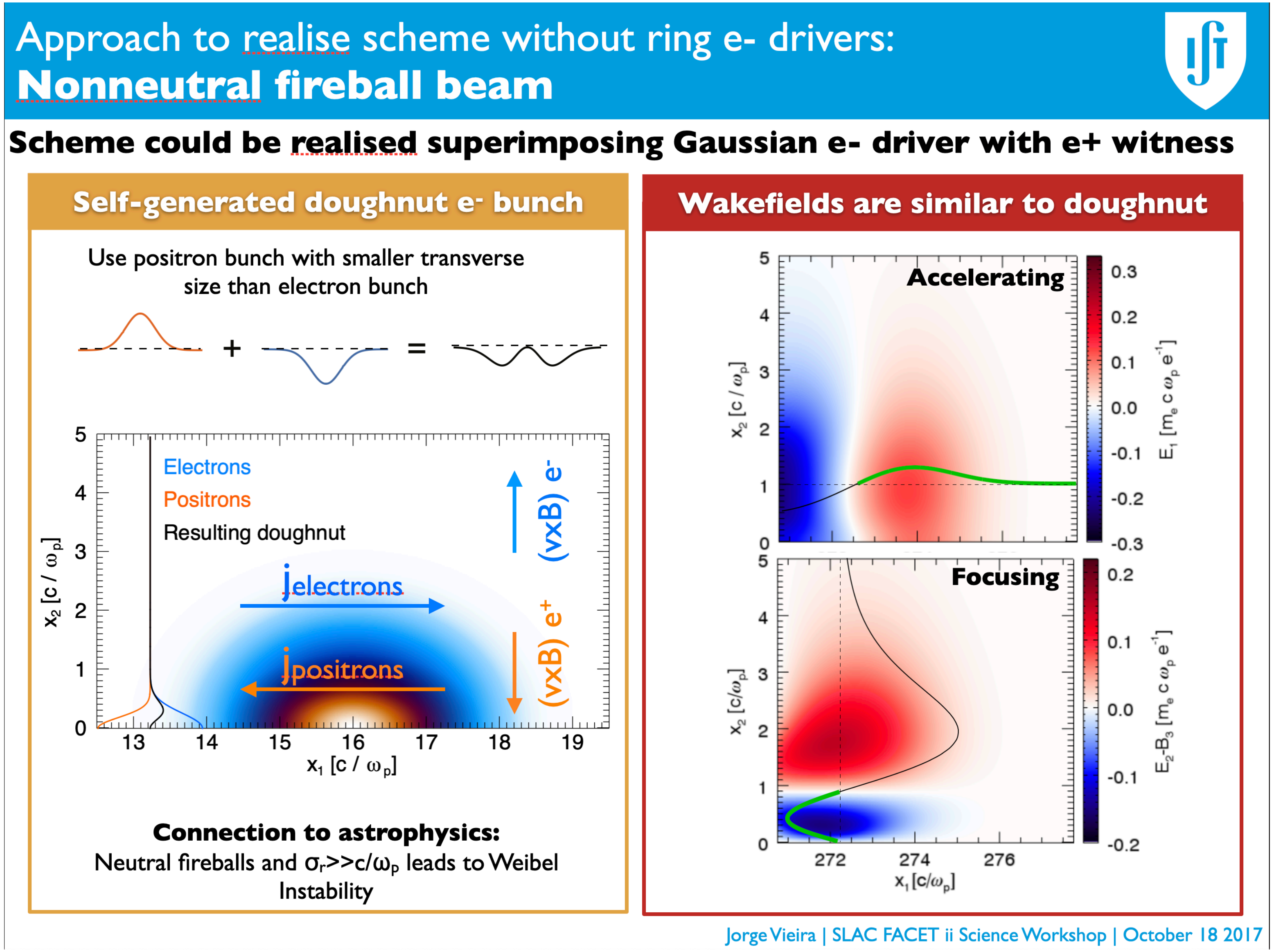
Accelerating force

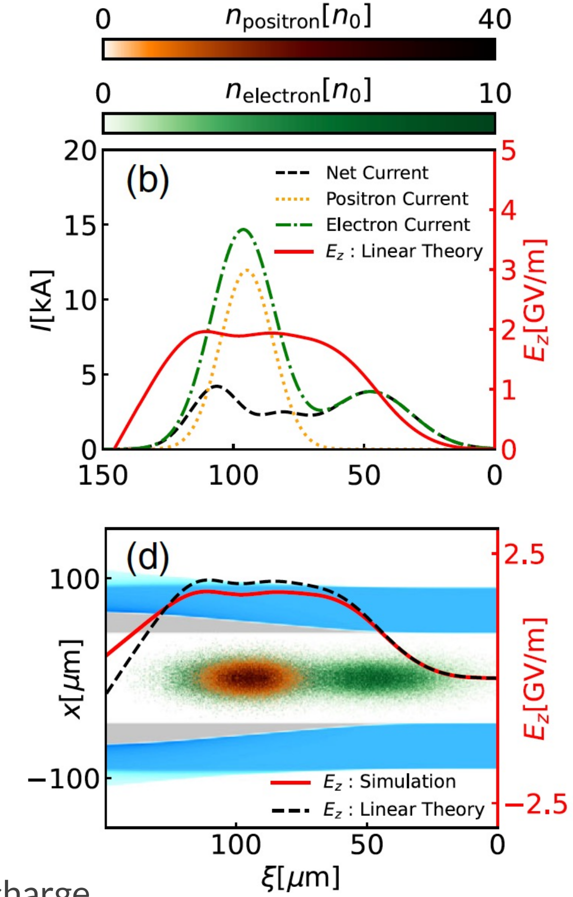


- e+ can **accelerate at the front**
- **Beam loading** is possible
- **Energy spread** growth can be **controlled**

Fireball Beams!

Zhou et al. (PRAB 25, 091303 2022)



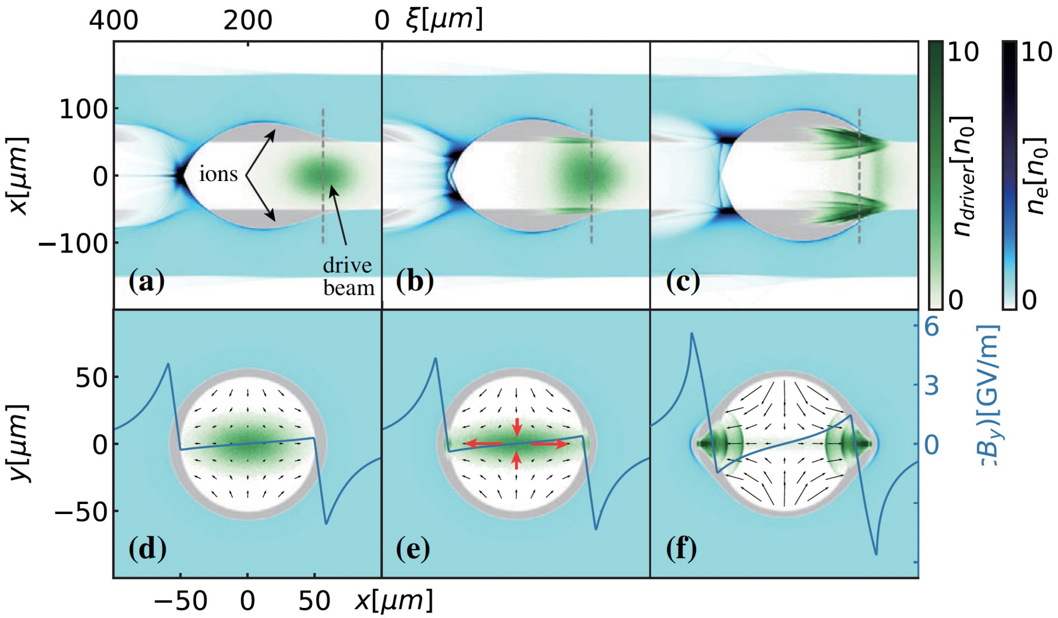


- ~ nC charge
- ~ GV/m gradient
- ≲ 0.5% induced energy spread
- ~ 50% energy transfer efficiency

Stability? External focusing needs to be demonstrated

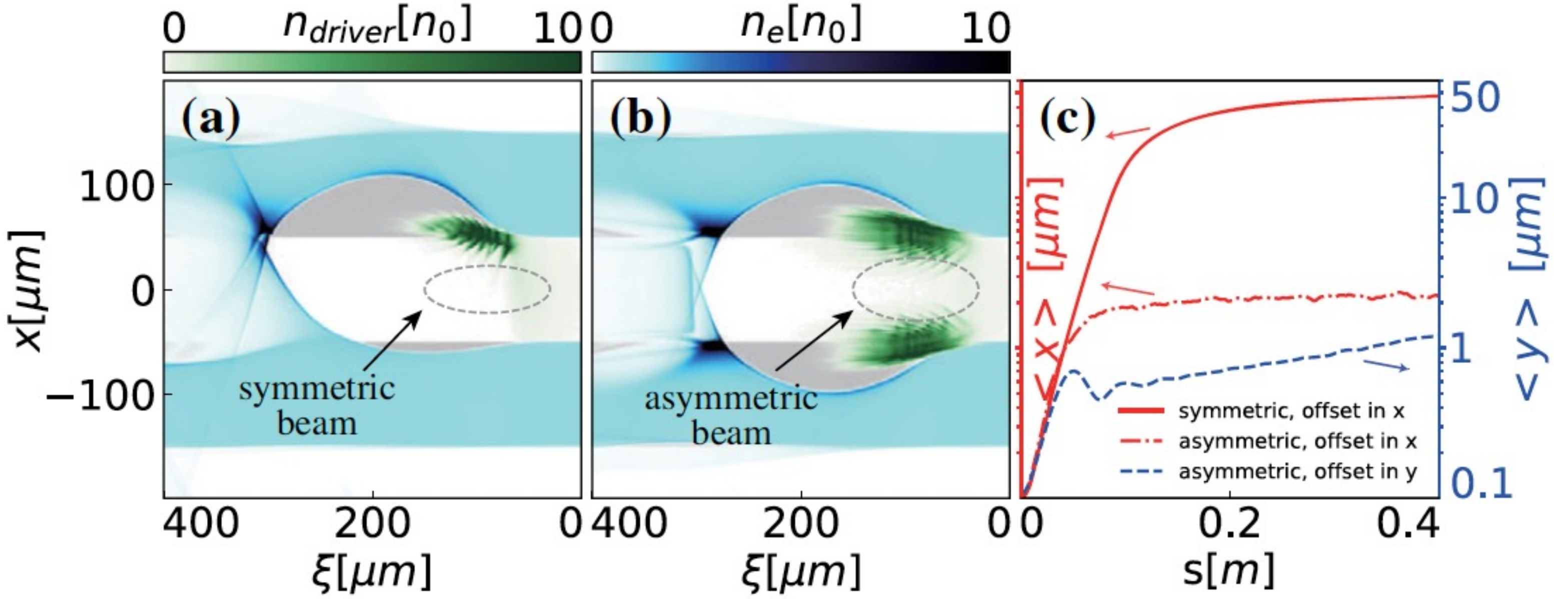
High Efficiency Uniform Wakefield Acceleration of a Positron Beam Using Stable Asymmetric Mode in a Hollow Channel Plasma

Recent Proposals with New Equilibrium Conditions

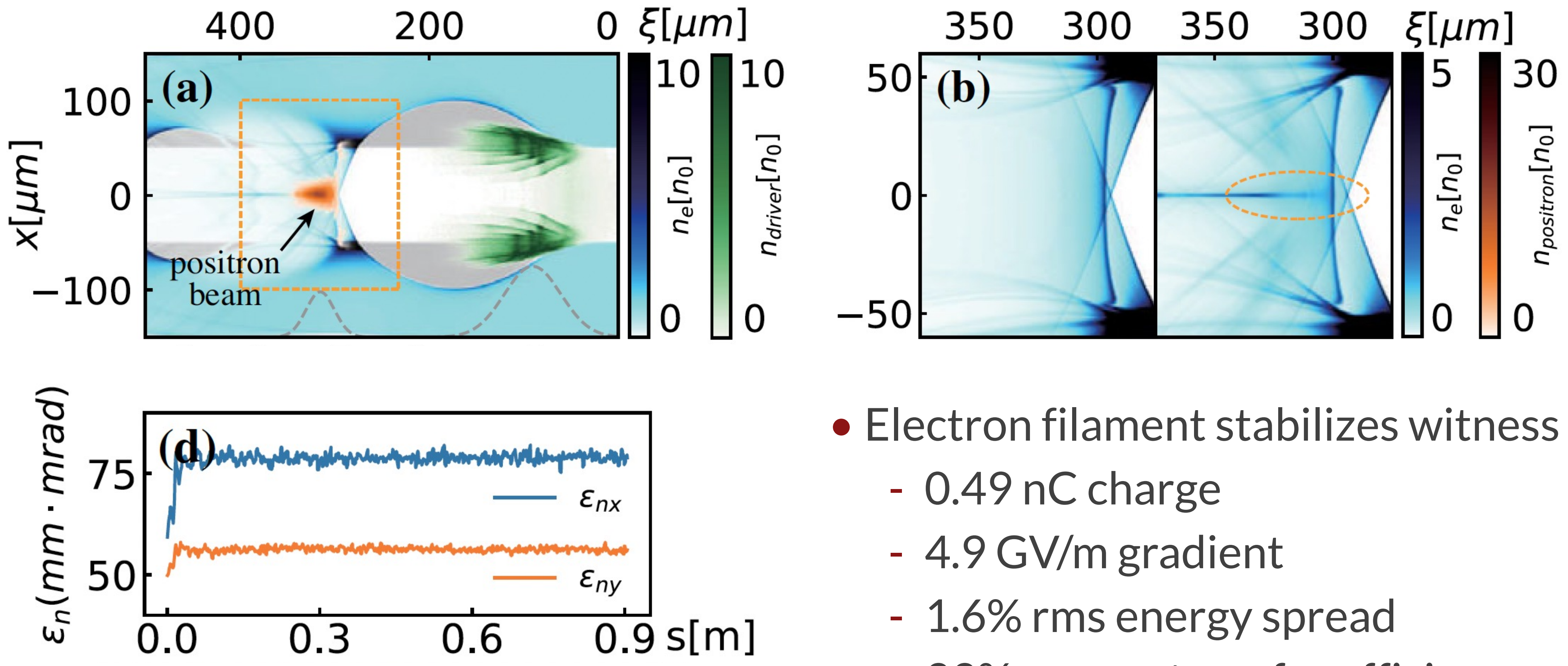


Zhou et al., PRL 127, 174801 (2021)

- Drive beam hits channel wall
- Creates a quadrupole moment
- Stabilizes the drive beam in hollow plasma channel



High Efficiency Uniform Wakefield Acceleration of a Positron Beam Using Stable Asymmetric Mode in a Hollow Channel Plasma



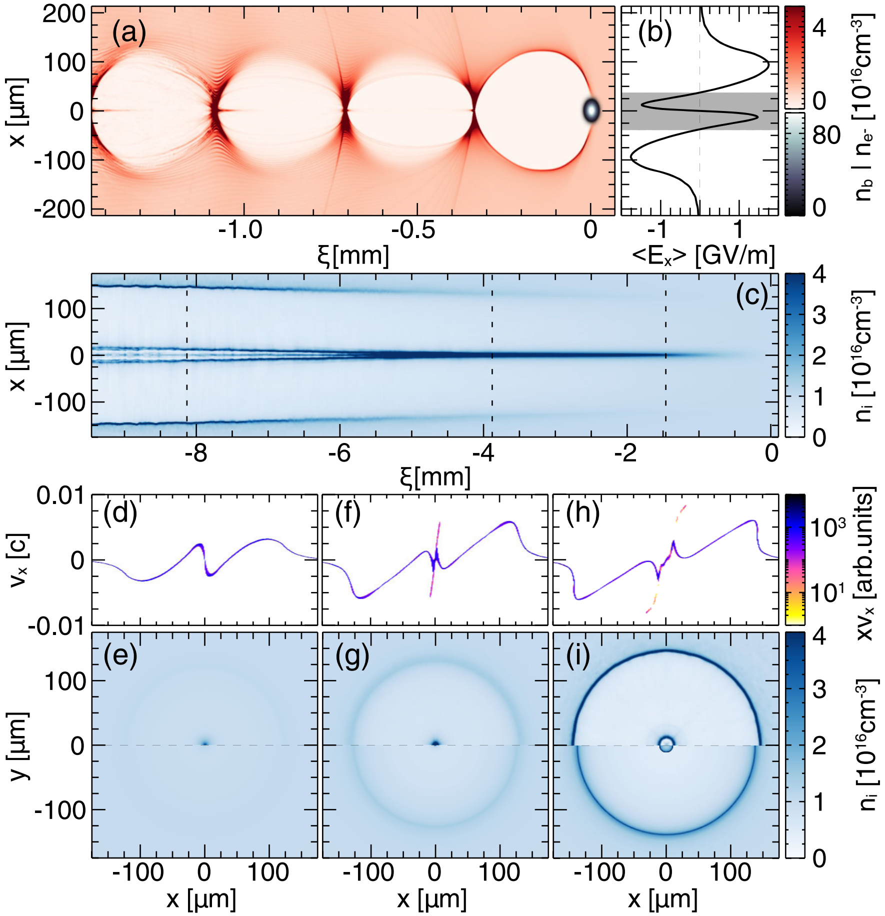
Zhou et al., PRL 127, 174801 (2021)

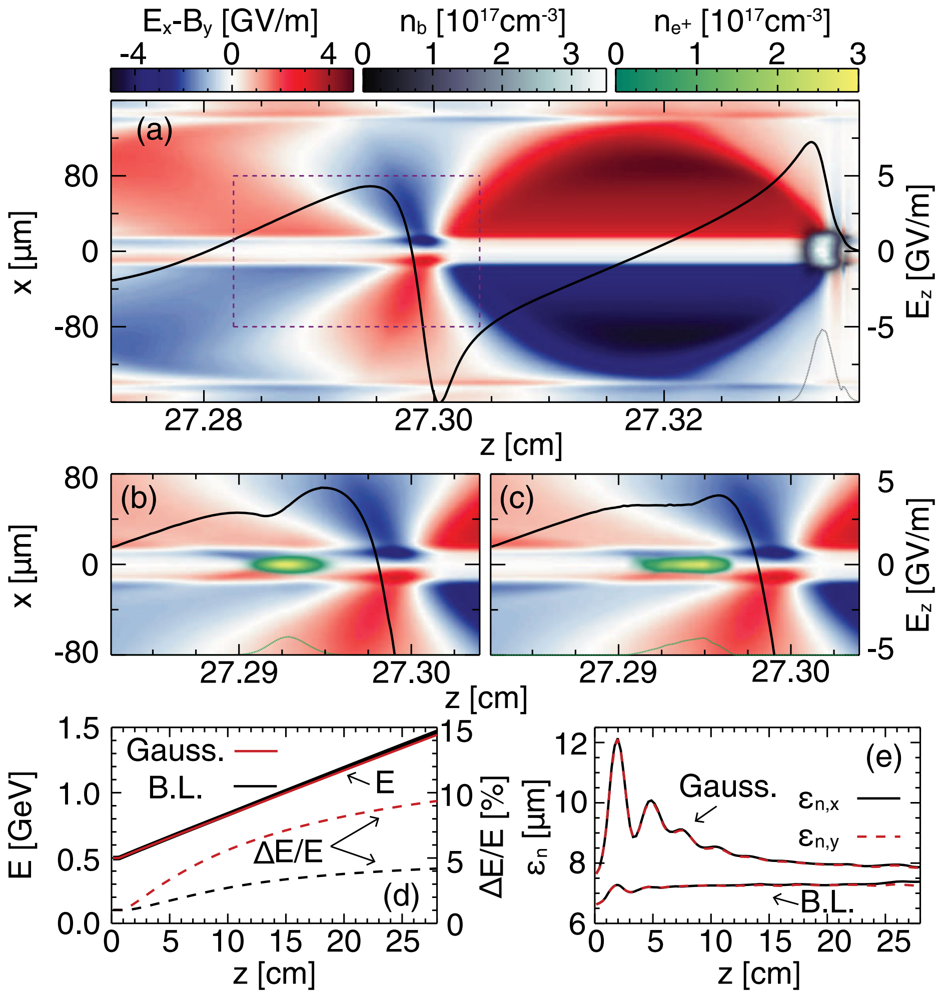
Diederichs et al. (in preparation)

- Electron filament stabilizes witness
  - 0.49 nC charge
  - 4.9 GV/m gradient
  - 1.6% rms energy spread
  - 33% energy transfer efficiency
  - > 50 μm central slice emittance
- Finite temperature in plasma electrons further mitigates emittance growth

Recent Proposals with New Equilibrium Conditions

"Electron and positron acceleration in self-generated, thin, warm hollow plasma channels." E-337





T. Silva et al. (IST)

[Phys. Rev. Lett. 127, 104801 (2021)](https://doi.org/10.1103/PhysRevLett.127.104801)

Conclusions & Outlook

- **Positron PWFA Experiments** by the Numbers:
  - 1 Laboratory: SLAC
  - 2 Facilities: FFTB and FACET
  - 3 Experiments: E162, E200, E225
  - 7 Publications (see previous slides)
- Positron acceleration is 50% of a PLC but only a small fraction of PWFA research
- The non-linear blowout regime is great for electrons but does not work for positrons
- High-gradient acceleration of positrons in plasma has been demonstrated
- Need alternative approaches engineering the plasma and/or beams to get all of the properties we want – gradient, efficiency, emittance…
- Research progress correlates with having the ability to test concepts experimentally
- A plan has been developed to restore (and improve) our capabilities to test concepts for positron PWFA at FACET-II
- With positron upgrade FACET-II will be first facility capable of studying electron-driven, positron witness PWFA

Help maintain the momentum and submit new ideas at:
https://facet.slac.stanford.edu/proposals

Questions?