Positrons at FACET-II: Status and Potential

FACET-II

Facility for Advanced Accelerator Experimental Tests

ALEGRO2024

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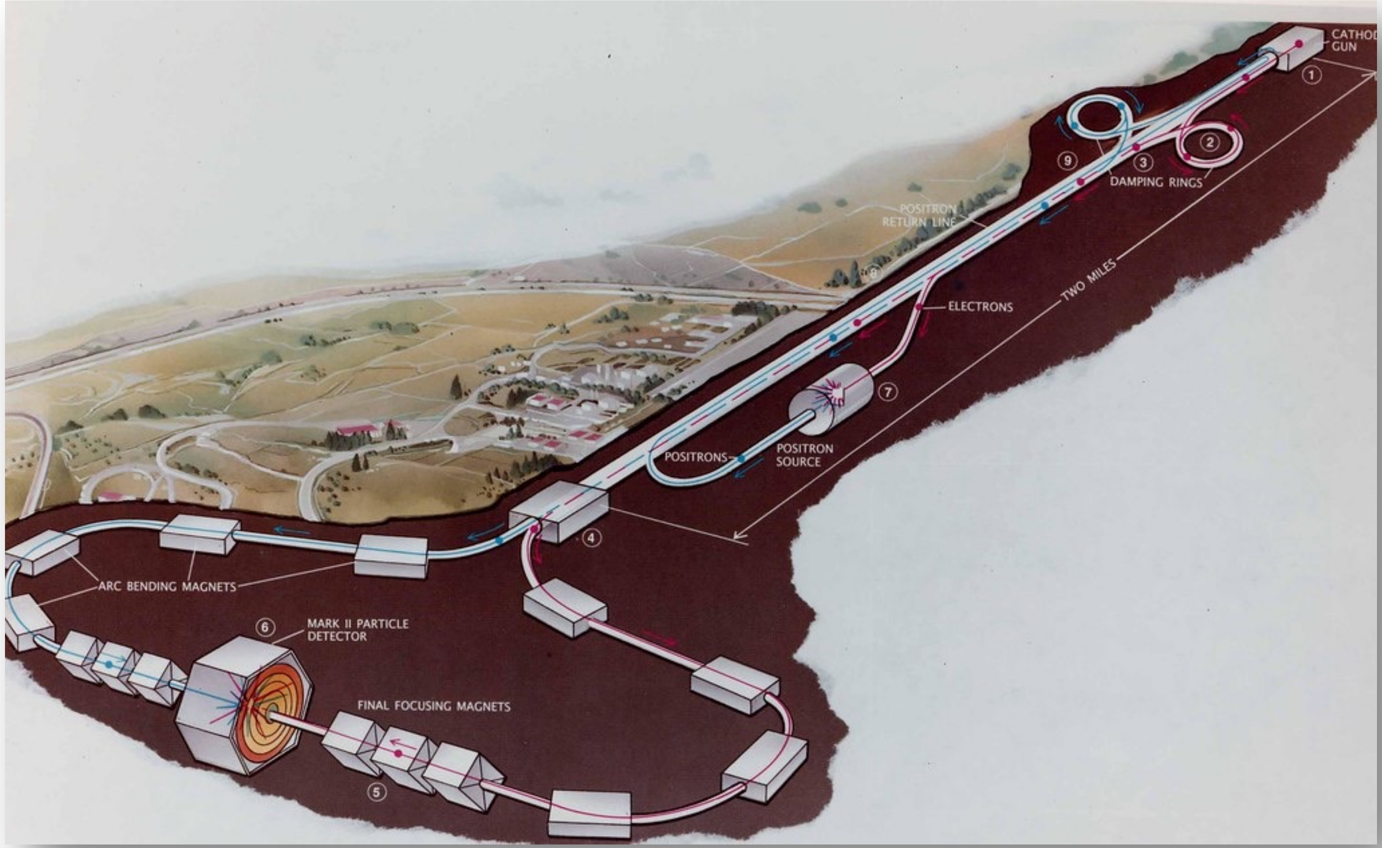
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Linear Colliders

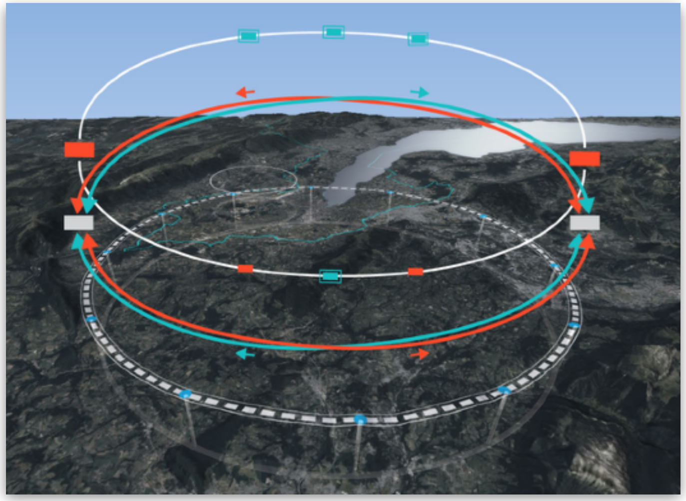
- Linear Colliders collide electron and **positron** beams
- They are used for precision particle physics studies
- To date, there has only been one linear collider ever built: The SLAC Linear Collider (SLC) which operated from 1986-1998
- 100GeV pCM in 3km
- Technology does not scale well to today's energy frontier

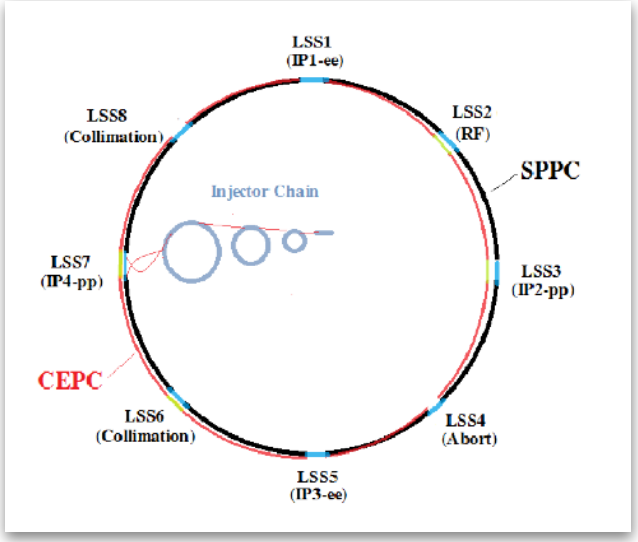


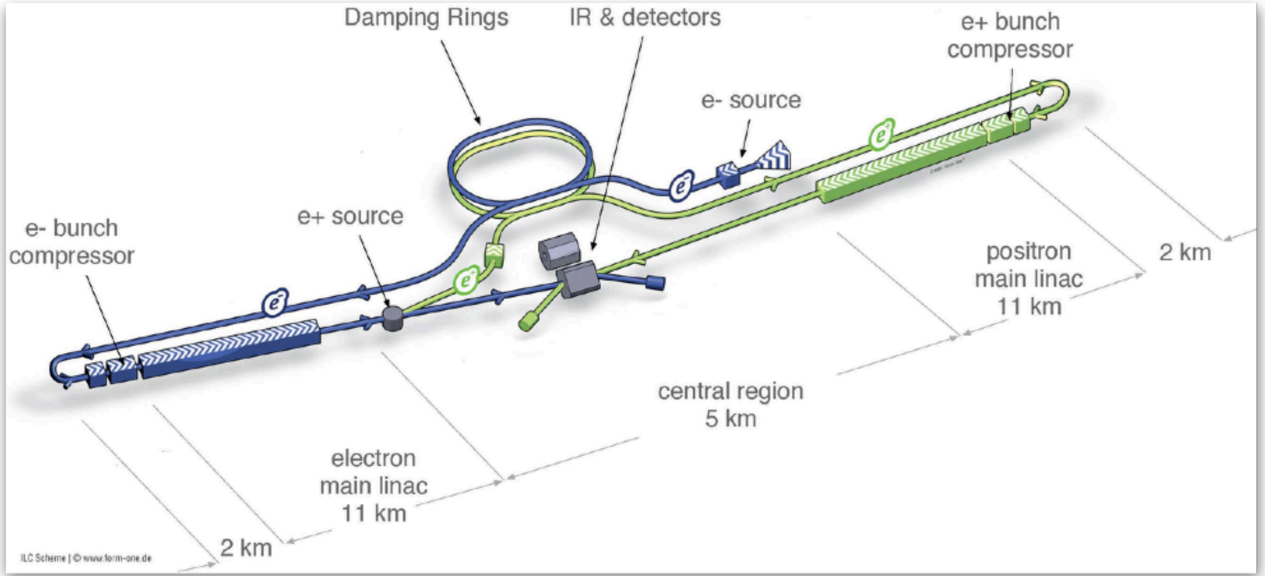
The ALEGRO (Advanced LinEar collider study GROup) Workshop will concentrate on addressing the recent progress and necessary steps towards realizing a linear collider for particle physics based on novel-accelerator technology

Linear Colliders and The Future of Particle Physics

- US Snowmass and European Strategy visions seem aligned – maximize HL-LHC and plan for a Higgs factory as a next step
- Current vision of US P5 (Particle Physics Project Prioritization Panel) aligns with Michael Peskin's original ALEGRO provocation:
  - We know how to build a Higgs factory with relatively mature technology (FCCee or ILC)
  - AAC should focus on the energy frontier: 10TeV
- European situation is less binary with emergence and momentum of HALHF







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

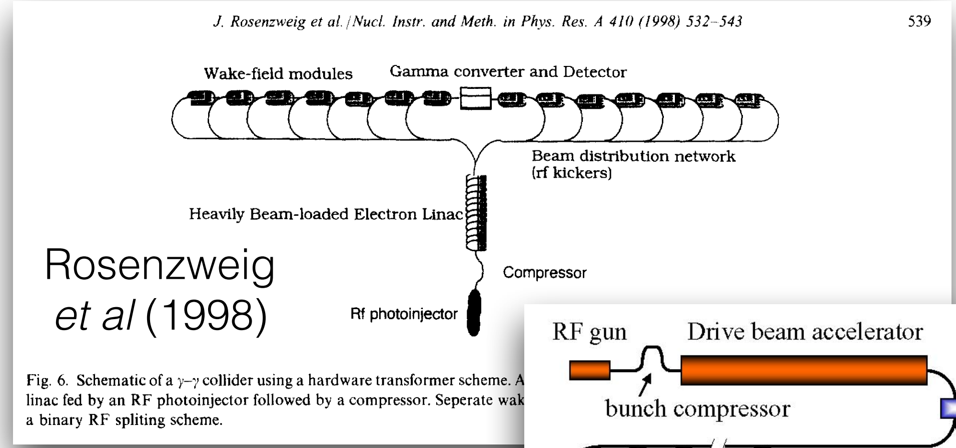
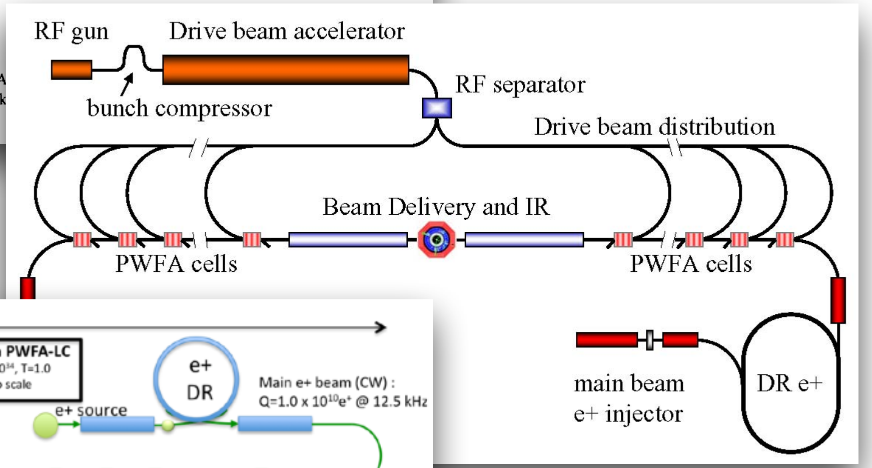
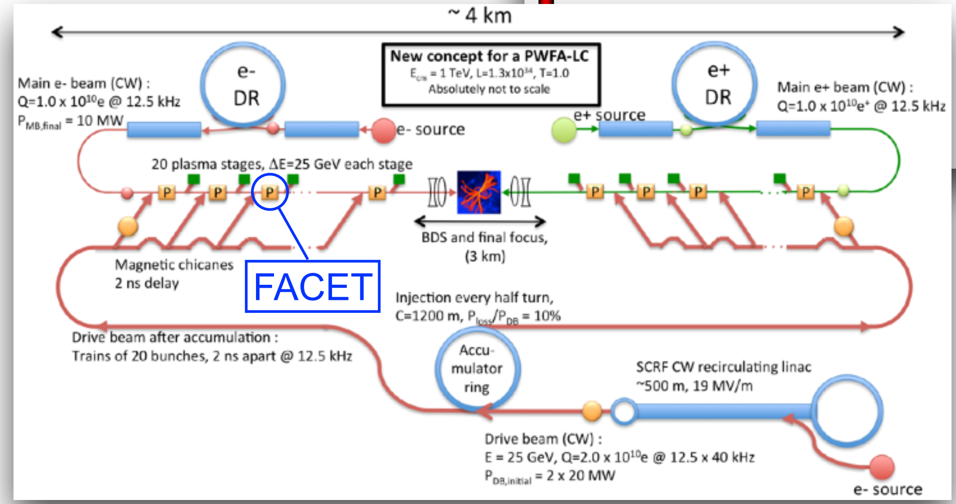


Fig. 6. Schematic of a γ–γ collider using a hardware transformer scheme. A linac fed by an RF photoinjector followed by a compressor. Seperate wak a binary RF spliting scheme.

Rosenzweig *et al* (1998)

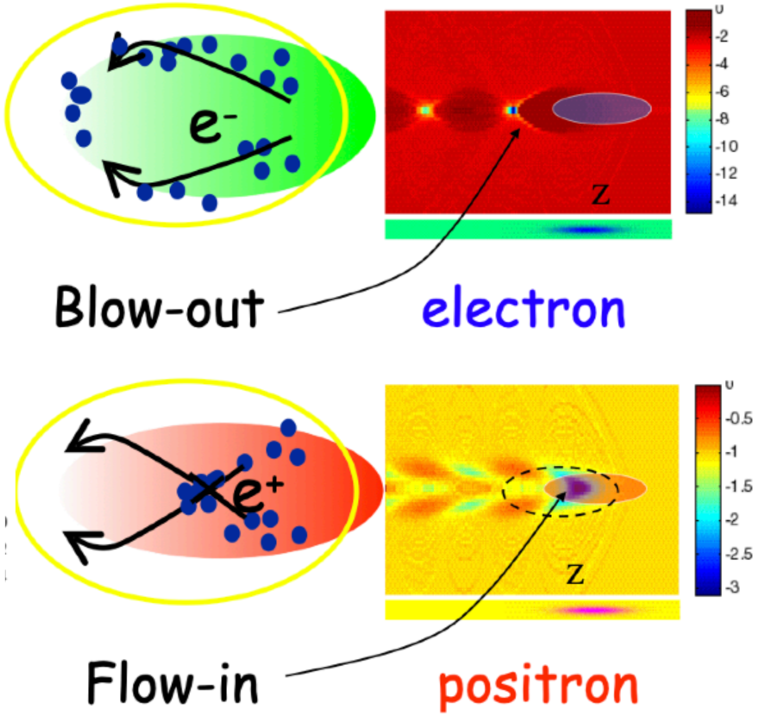
Seryi *et al* (2008)
SLAC-PUB-13766





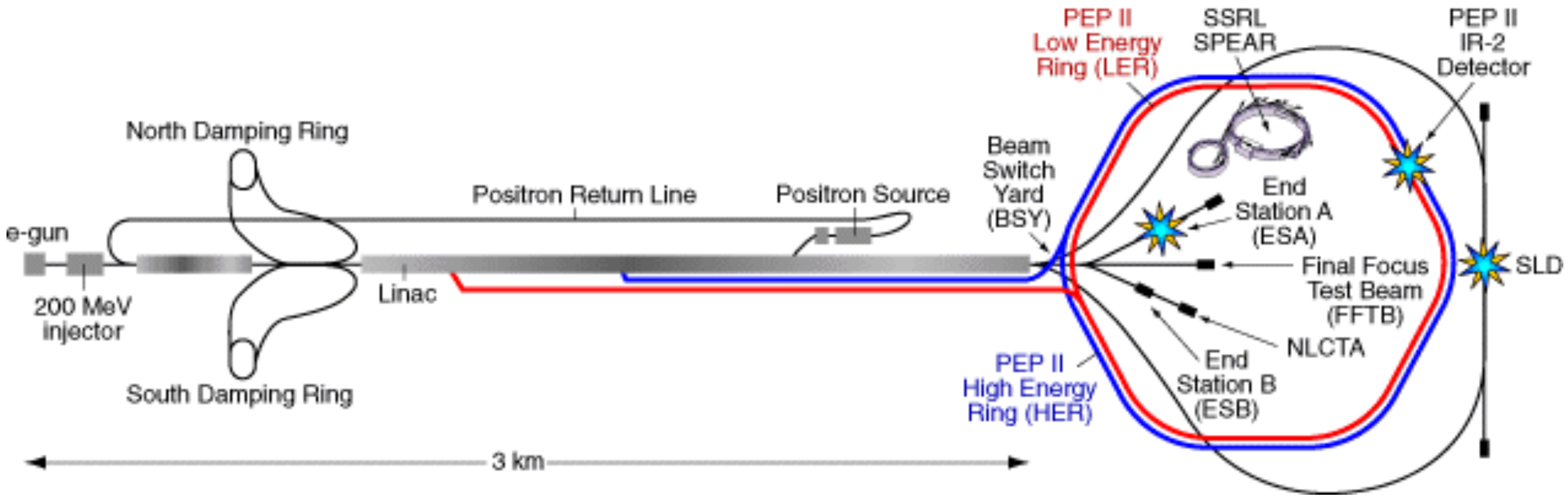
Adli *et al* (2013)
SLAC-PUB-15426

- Collider concepts assume high degree of symmetry between electron and positrons
- **This is not a good assumption with plasma!**

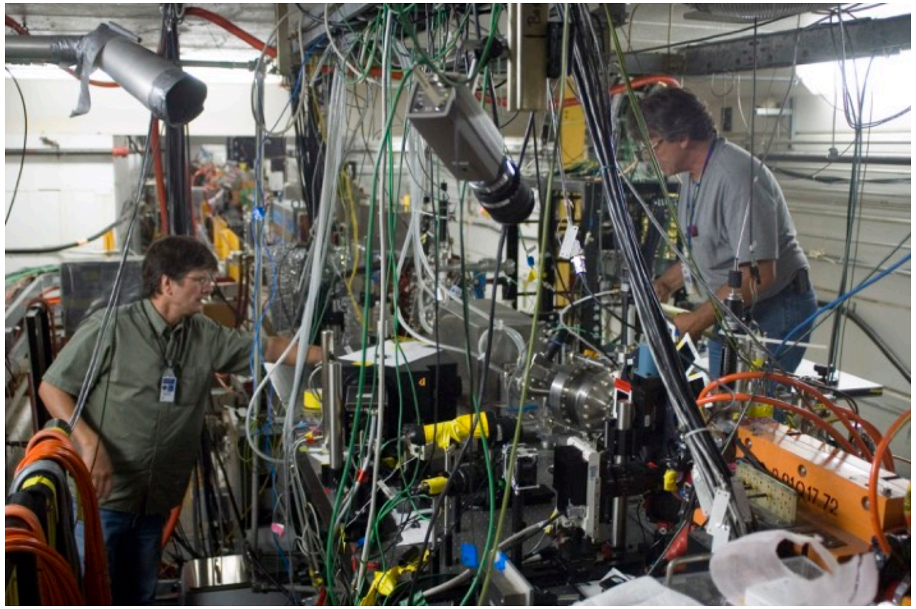


Planning for FACET-II to offer ability to test concepts in collider relevant regimes

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



- Q = 3.2nC/bunch
- 1-10Hz
- 28.5GeV
- $\sigma_z \sim 700\mu m$ (for e^+)
- $N_p \sim 10^{12}$ - $10^{14}/cm^3$



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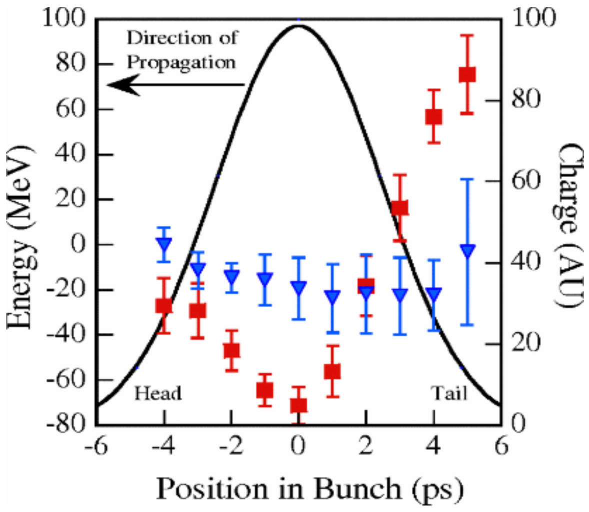
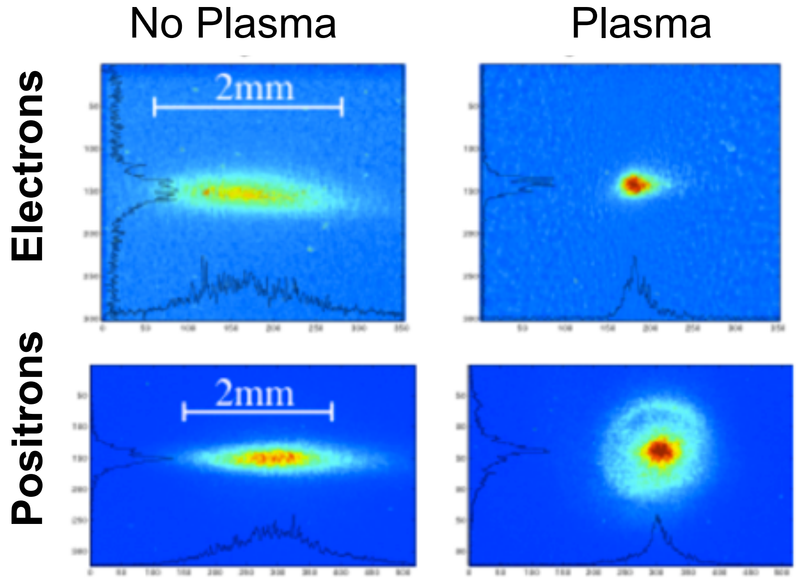
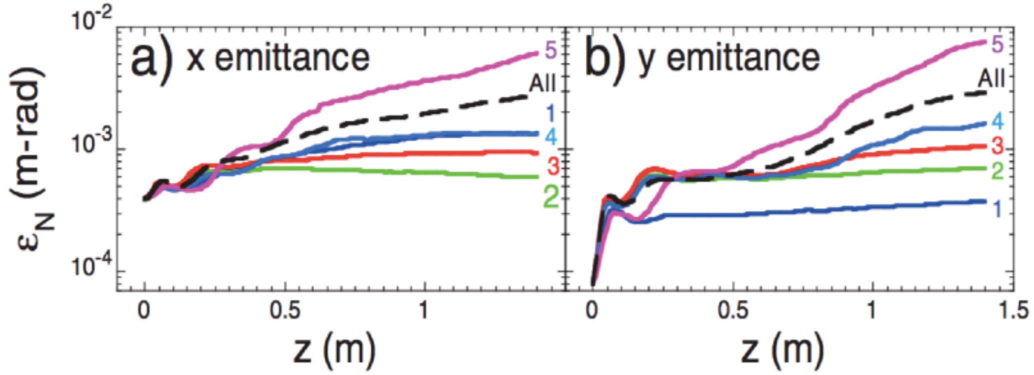
First Measurements of Acceleration and Focusing in e^+ PWFA

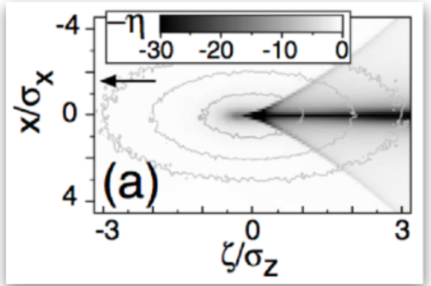






Positron beam transport in plasma
M. J. Hogan et. al. *Phys. Rev. Lett*. 90 205002 (2003)
Halo formation due to non-linear fields
P. Muggli et. al. *Phys. Rev. Lett*. 101 055001 (2008)

First acceleration of positron beams in plasma
B. Blue et. al. *Phys. Rev. Lett.* 90 214801 (2003)



- Acceleration was observed at low beam/plasma densities with linear wakes
- Beam evolution in meter long plasmas generates non-linearities
- 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

Positron beam evolution in the plasma is important for understanding the final beam parameters

FACET: A National User Facility (2012-2016)
Preserved SLC Positron Infrastructure and Added New Compressor Chicane

- FFTB decommissioned in 2006 for LCLS construction
- FACET enabled compressed positron bunches for higher-densities and higher gradients

Q = 3.2nC/bunch, 1-10Hz, 20GeV

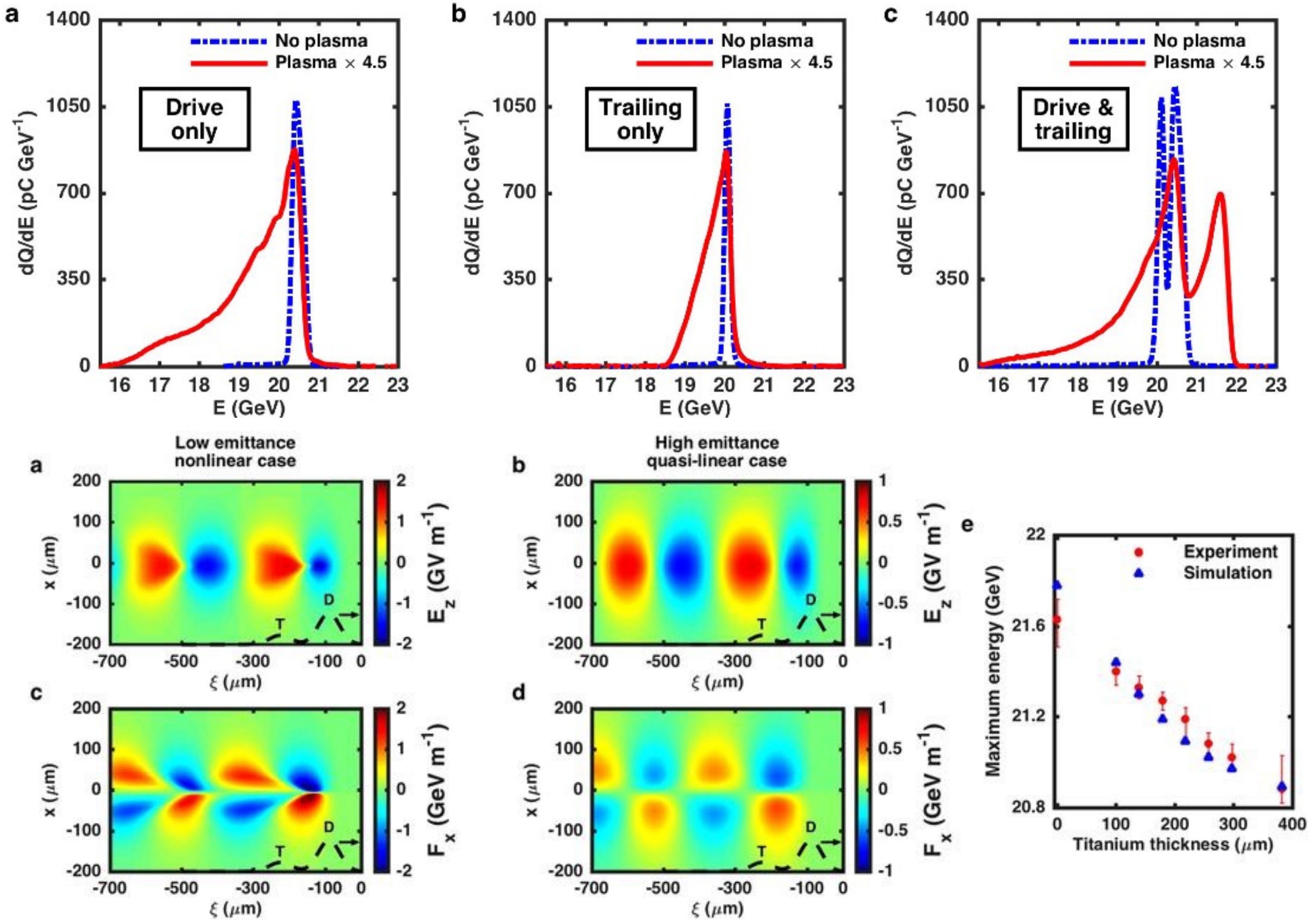
$\boldsymbol{\sigma_z \sim 20\mu m}$ **(for** $\boldsymbol{e^+}$**),** $\boldsymbol{n_p \sim 10^{15} - 10^{17}/cm^3}$

- Collimation techniques used to create two tightly spaced electron bunches could be used equally well for positrons
- A concept was developed for creating electron-driver positron-witness configuration but this was not realized before FACET was decommissioned to make way for LCLS-II

Two-Bunch Positron Beam-Driven PWFA

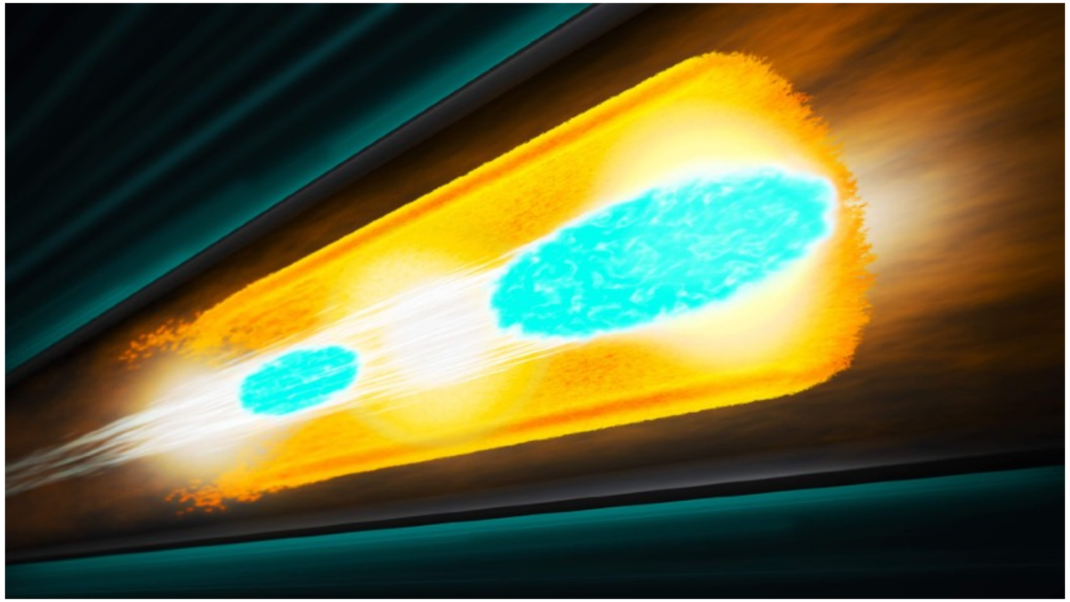
The results of the two-bunch electron experiments naturally beg the question: Can we repeat these results for positrons?

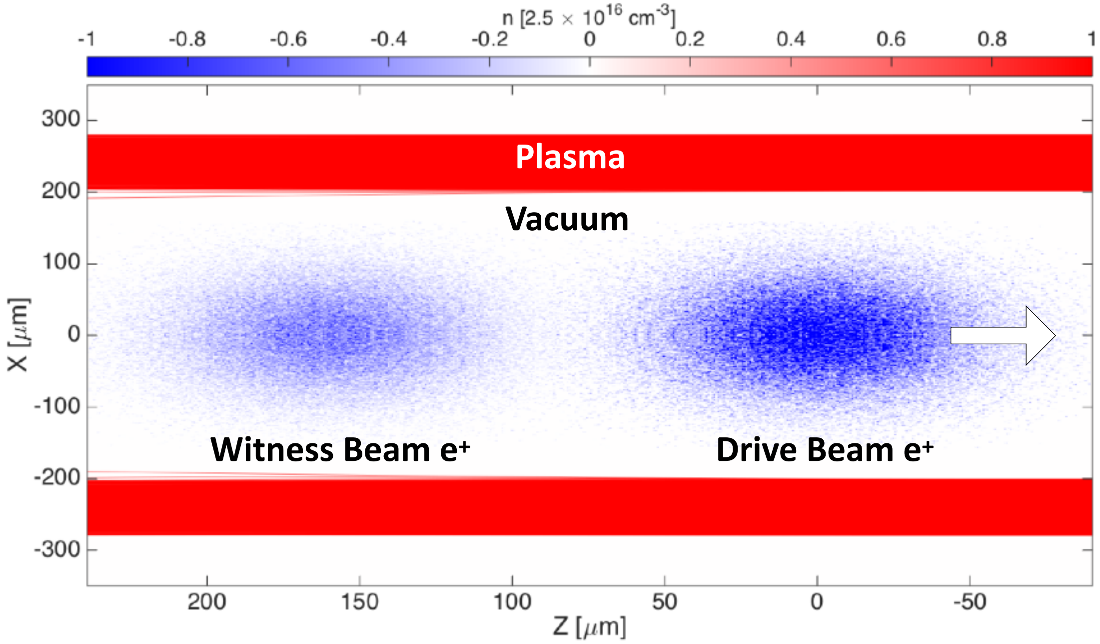
- This led to the first demonstration of controlled beam loading in the positron beam-driven wake
- We tested this scenario in both the quasi-linear and non-linear regimes



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

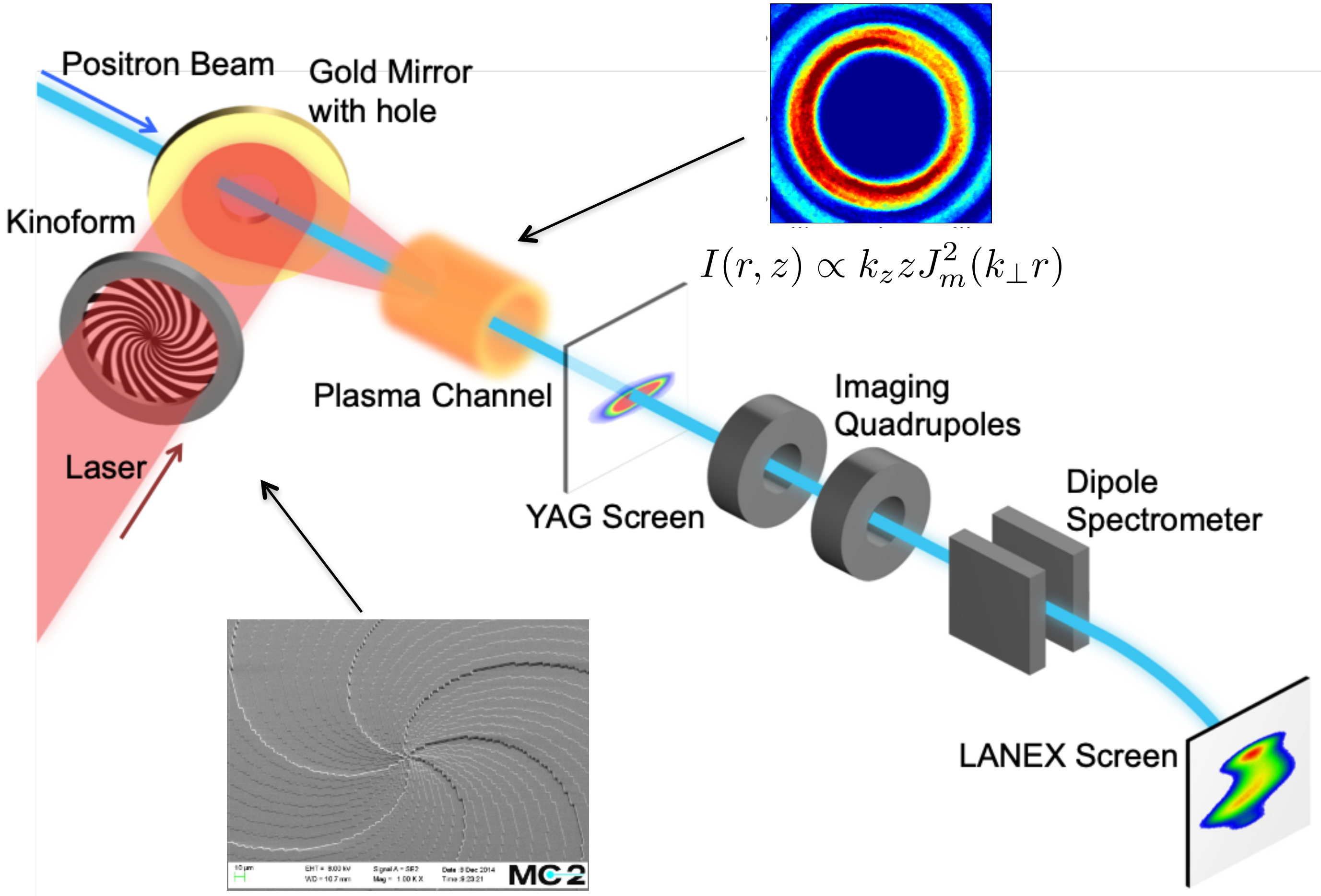
The Hollow Channel Plasma Accelerator





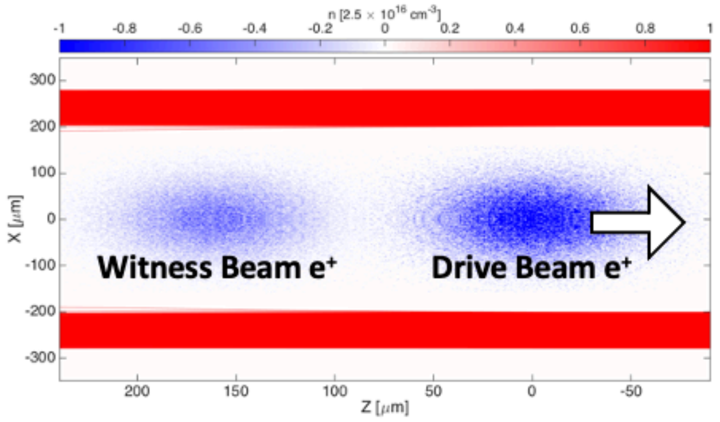
- The Hollow Channel Plasma is a structure that symmetrizes the response of the plasma to electron and positron beams
- There is no plasma on-axis, and therefore no focusing/defocusing force from plasma ions

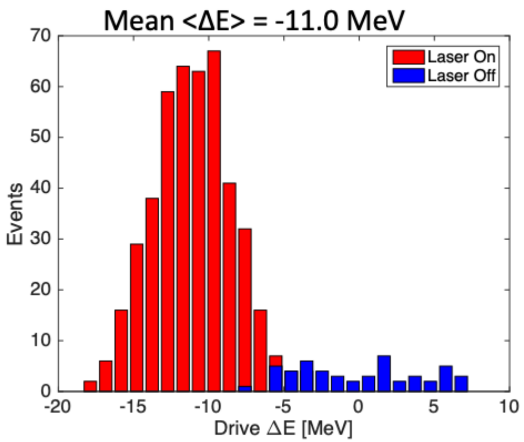
Positron Acceleration in a Hollow Channel Plasma



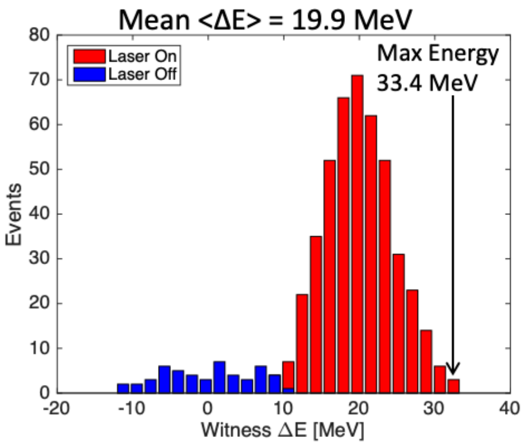
$$I(r,z) \propto k_z z J_m^2(k_\perp r)$$

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





Drive beam transfers energy to the wake



Witness beam gains energy from the wake

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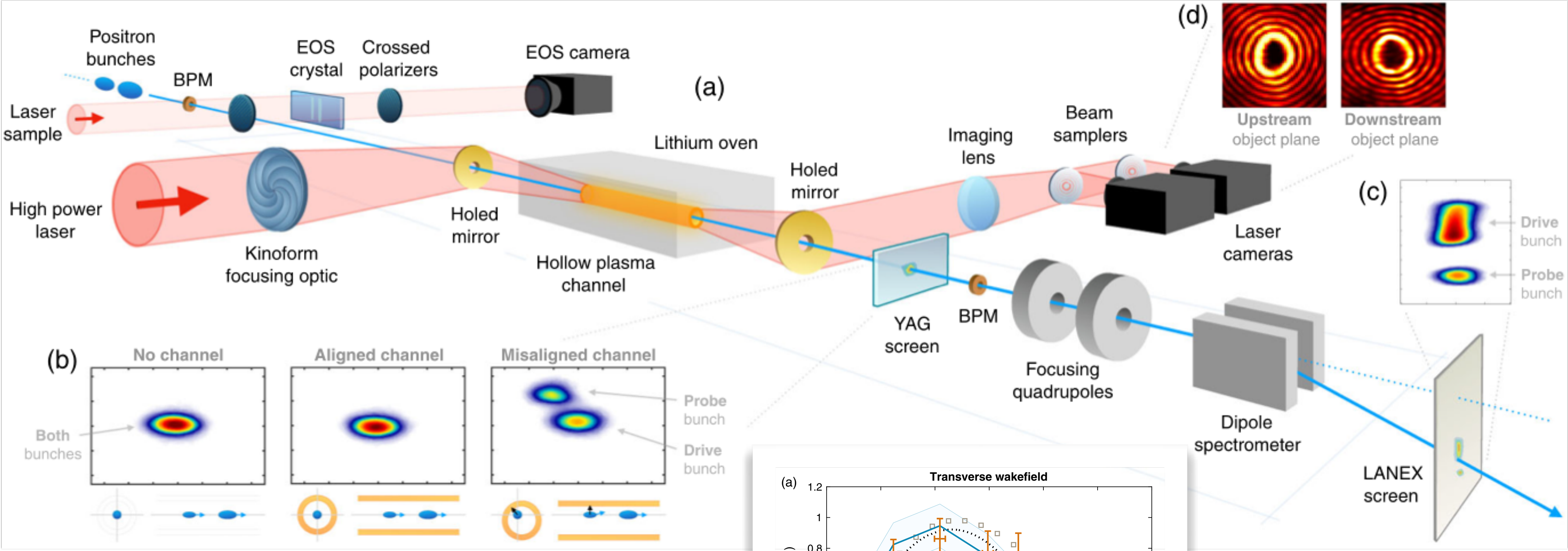
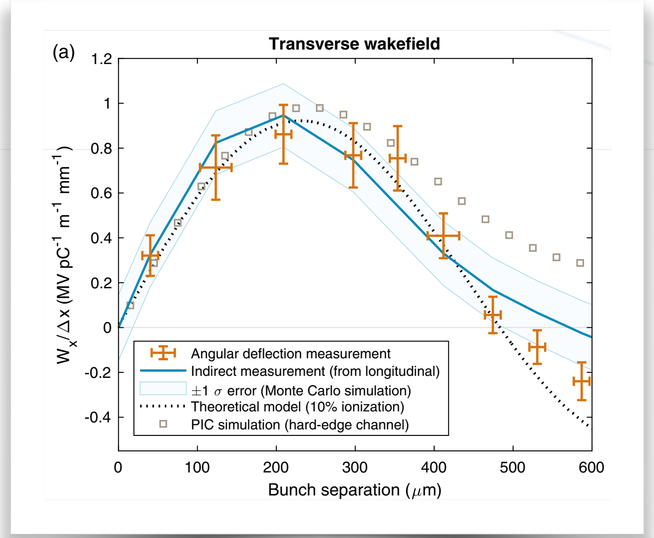
S. Gessner et. al. *Nat. Comm.* 7, 11785 (2016)

Transverse 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).

Positron Beam-Driven PWFA at FACET

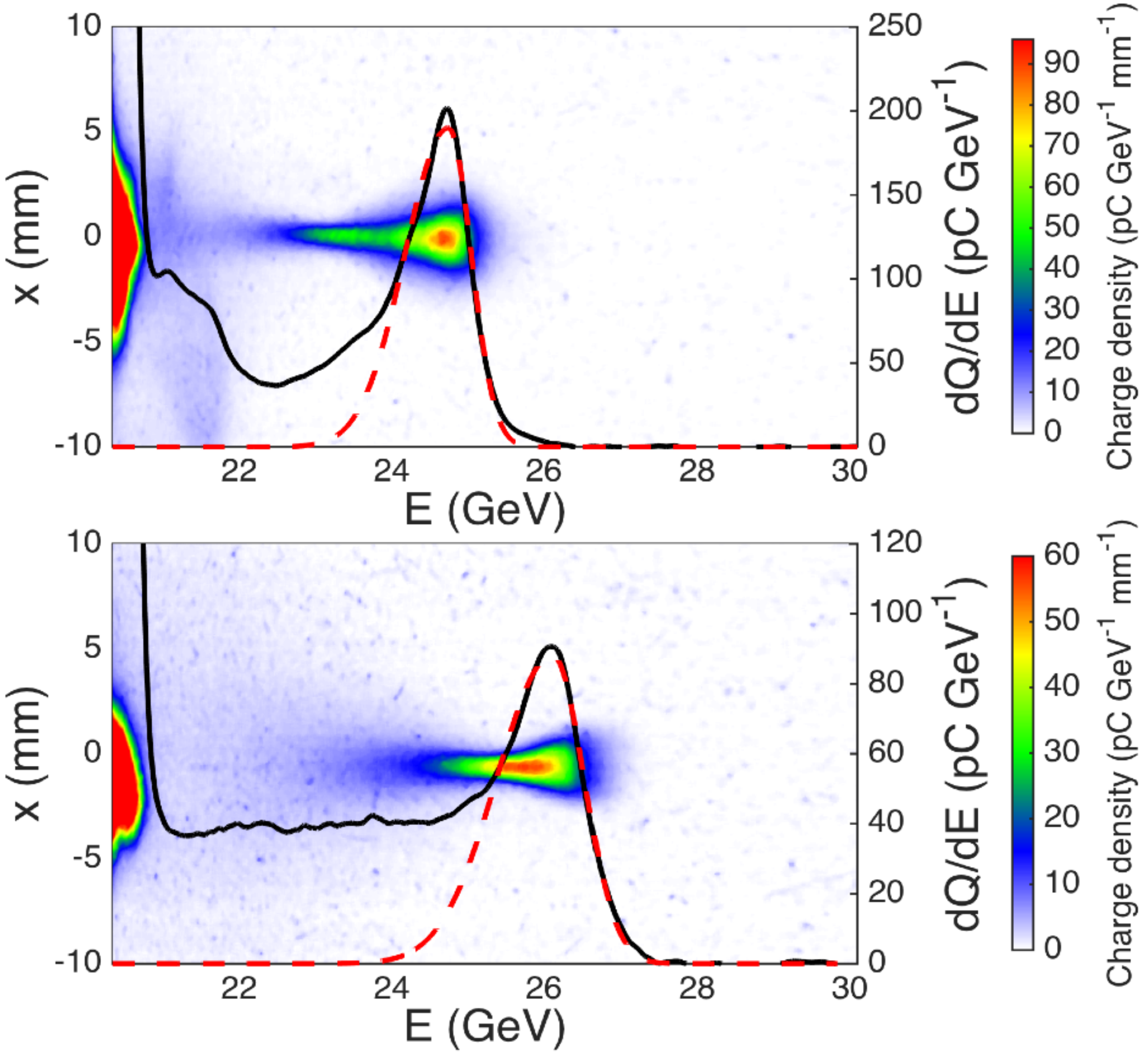
FACET was able to provide high-density, compressed positron beams for non-linear PWFA experiments

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!

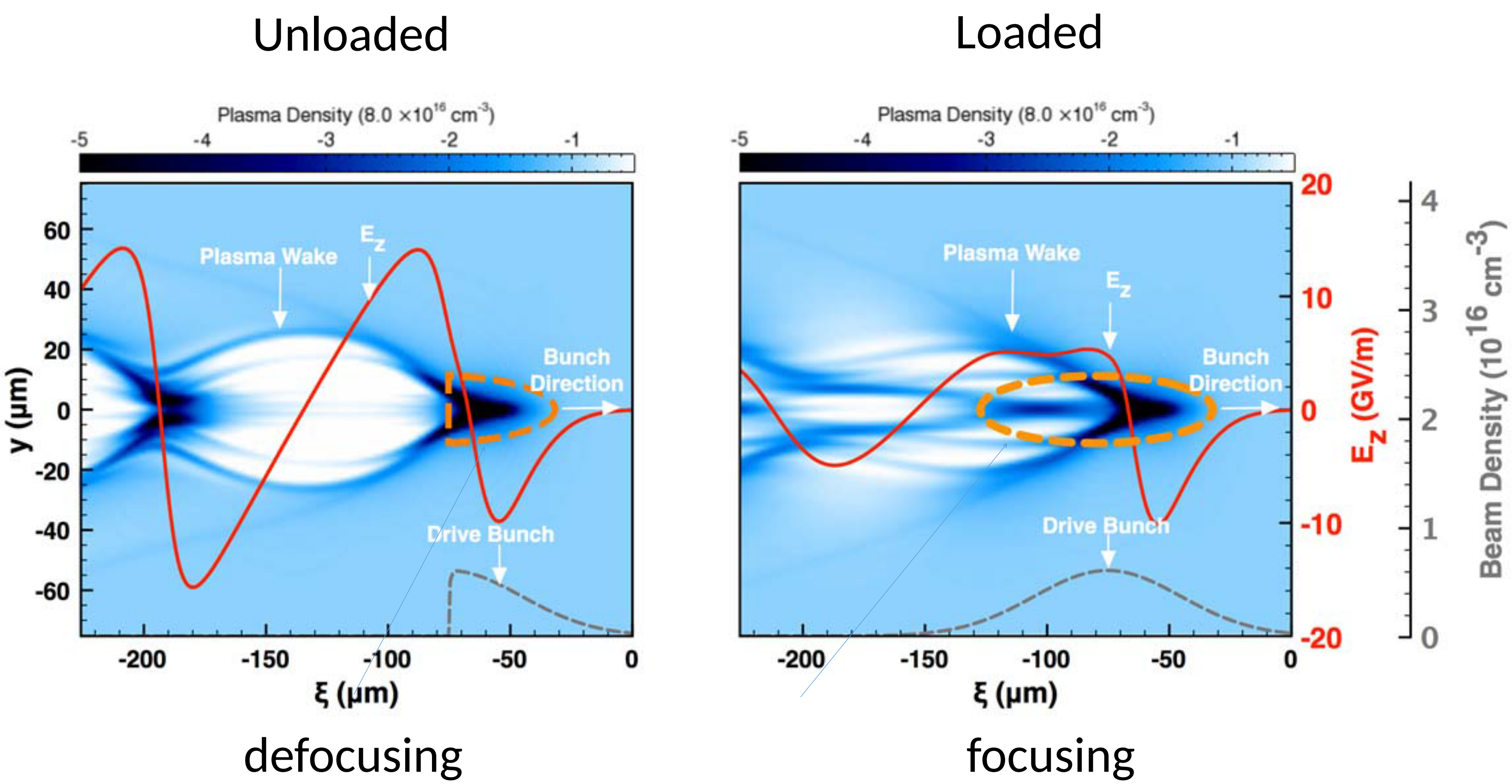
S. Corde *et al.*, Nature 524, 442 (2015)

Experimental results in 1.3 m plasma



Positron Beam-Driven PWFA

QuickPIC simulations: loaded vs unloaded wake (truncated bunch)



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

Beam loading also affects transverse fields for positron driven wakes!

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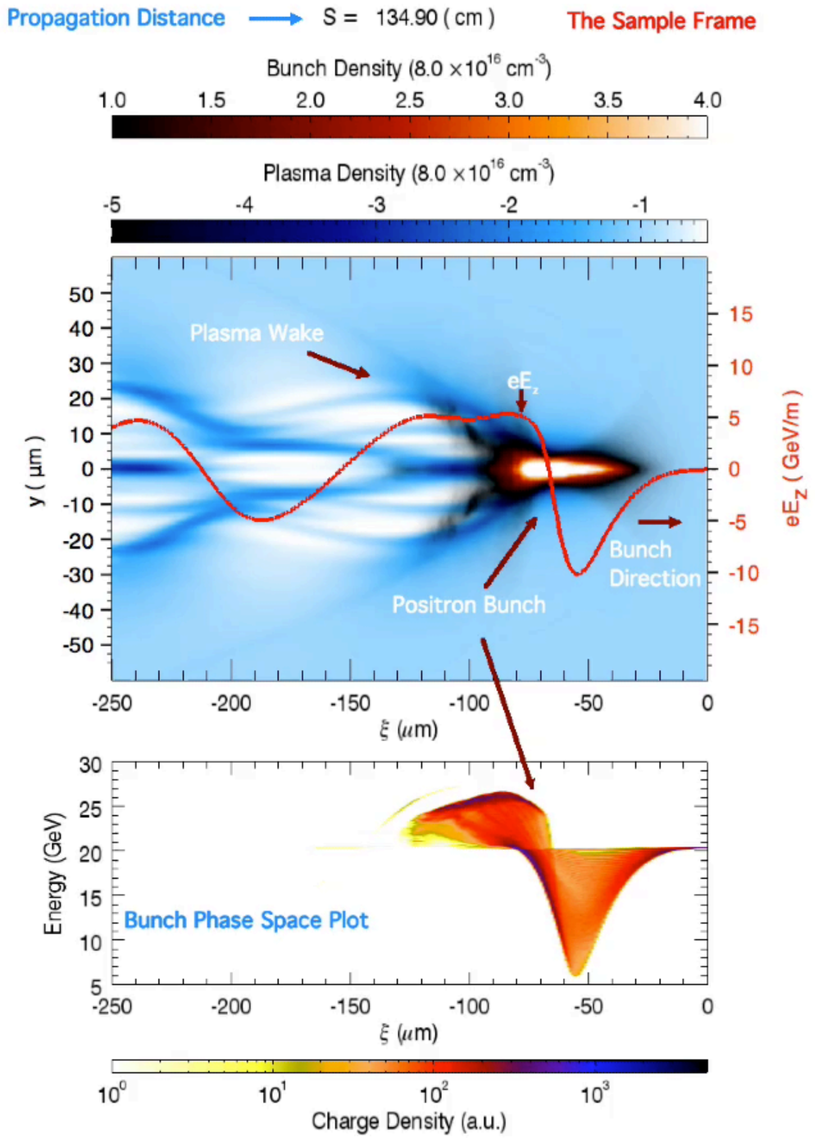
Positron Beam-Driven PWFA

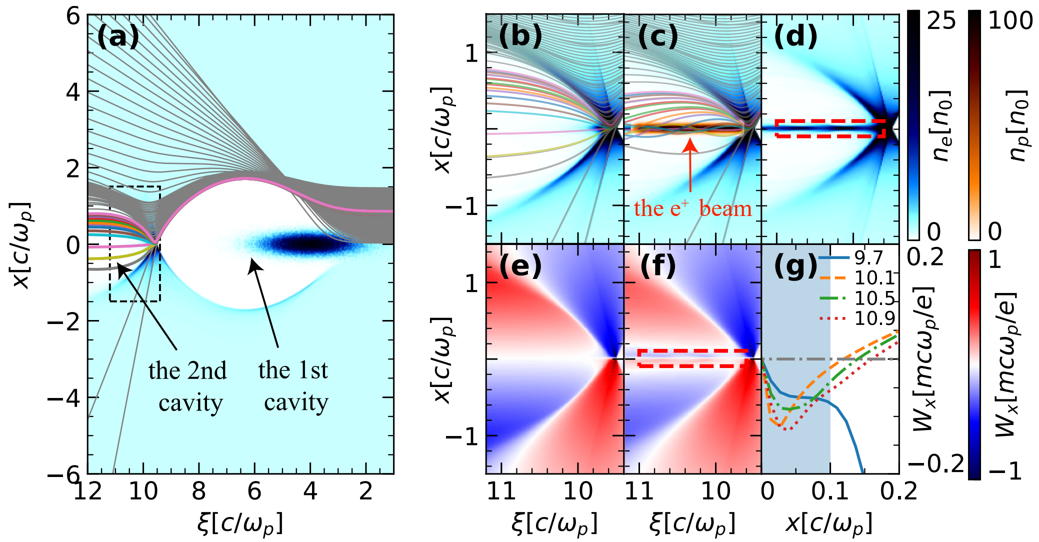
Key questions:

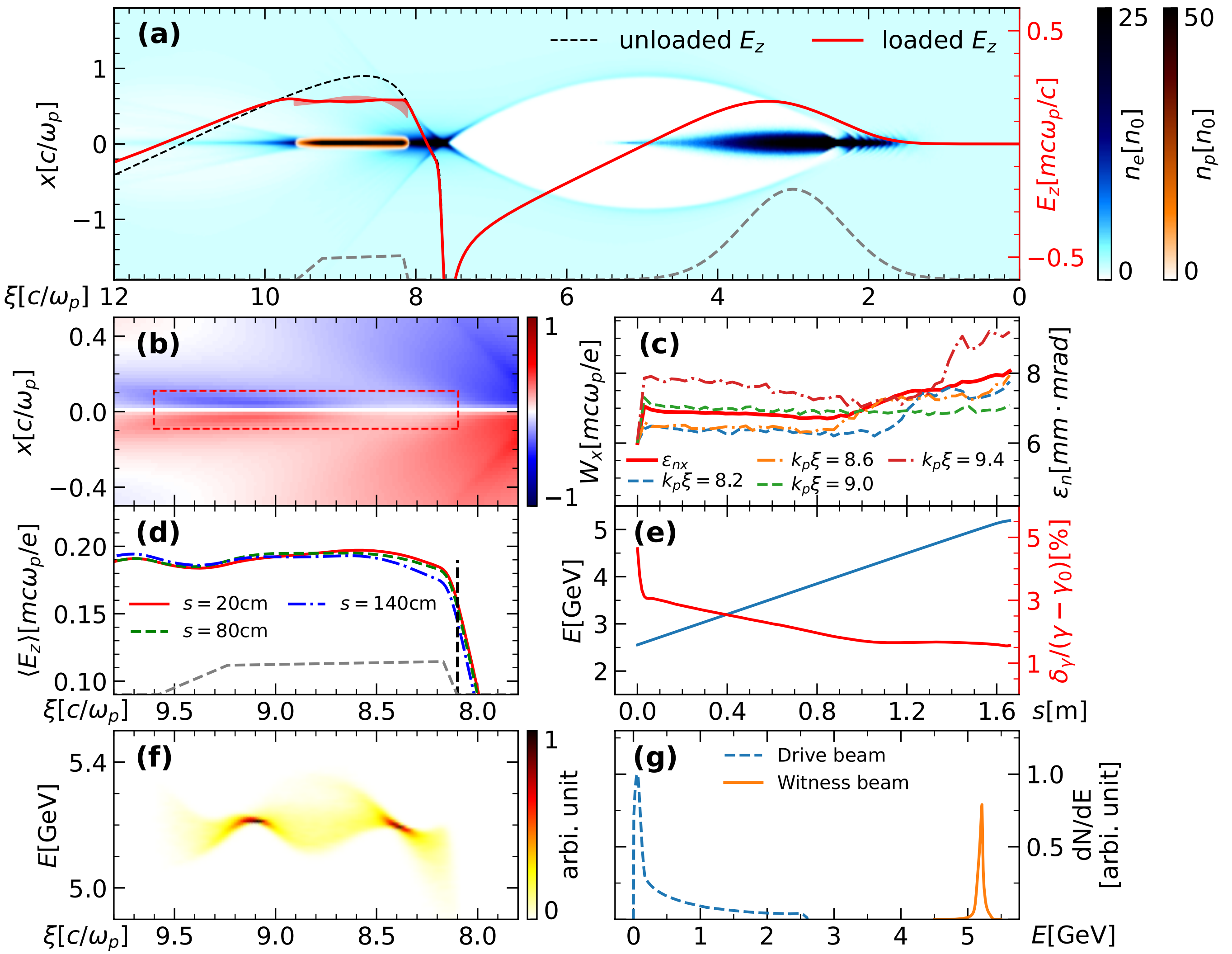
1. Is there an equilibrium emittance, or is the emittance growth continuous?
2. Is there a way to start from this state directly without the lengthy evolution?



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)

The AAC Community Needs New Facilities with Beams Suitable to Test New Concepts for Positron Acceleration in Plasma

OPEN ACCESS
IOP Publishing
Plasma Physics and Controlled Fusion
Plasma Phys. Control. Fusion **64** (2022) 044001 (8pp)
https://doi.org/10.1088/1361-6587/ac4e6a

Plasma-based positron sources at EuPRAXIA

Gianluca Sarri*, Luke Calvin and Matthew Streeter

Laser-driven high-quality positron sources as possible injectors for plasma-based accelerators

Aaron Alejo, Roman Walczak & Gianluca Sarri

Scientific Reports **9**, Article number: 5279 (2019) | Cite this article

PHYSICAL REVIEW ACCELERATORS AND BEAMS **26**, 123402 (2023)

Compact source of positron beams with small thermal emittance

Rafi Hessami*
Applied Physics Department, Stanford University, Stanford, California 94305, USA and SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
Spencer Gessner†
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

	Units	FACET-I	FACET-II	LWFA
E	GeV	21	10	1
P	W	7.4	9.6	3
Q_e	pC	350	500	2
σ_x	µm	30	4	16
σ_y	µm	30	4	16
σ_z	µm	50	6.4	0.6
$\bar{\varepsilon}_{xx}$	mm mrad	200	7	500
$\bar{\varepsilon}_y$	mm mrad	50	3	500
ΔE	%	1.5	1	5
f	Hz	1	1	$10–10^3$
ℓ	$cm^{-2}\,s^{-1}$	5×10^{23}	6×10^{25}	$10^{22–24}$

See 'Laser-driven production of ultra-short high quality positron beams' by Gianluca Sarri in morning session

TABLE II. Beam parameters at the end of the simulation.

Beam parameter	Value
Beam energy	17.6 MeV
Beam charge	15.43 pC
Bunch length (rms)	190 µm
Energy spread (rms)	0.76%
Transverse emittance	0.60 µm rad

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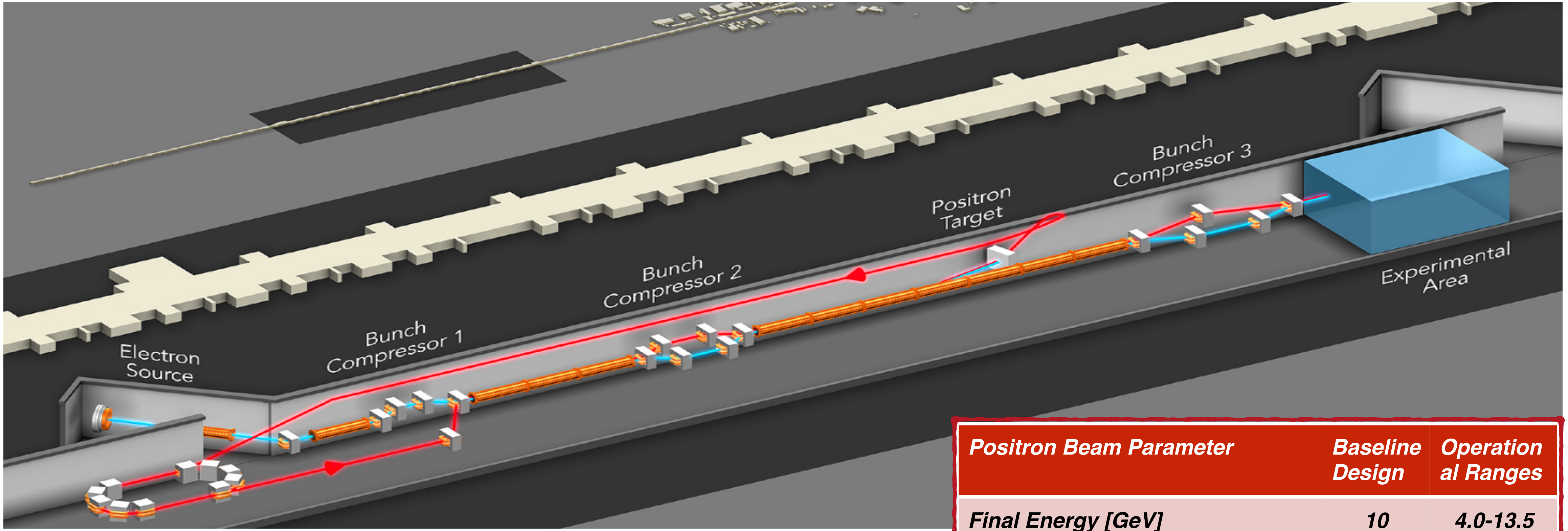
FACET-II Layout and Beams
A plan is being developed to restore positron capability

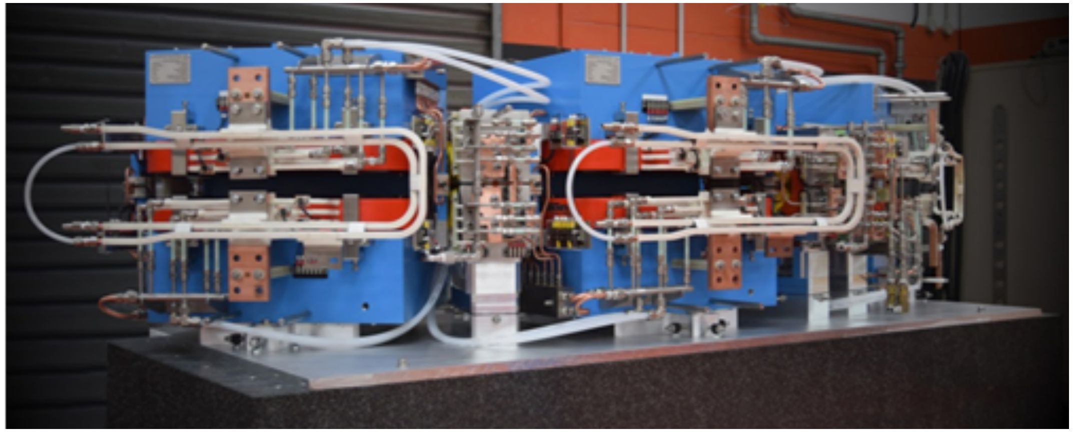


- Simultaneous delivery of up to 1nC e+ & 2nC e- to S20 IP region
- Expected performance modeled with particle tracking, including dynamic errors
- More details in TDR Ch. 8

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 [μm]	*10, 10*	*6-20*
Spot Size at IP $\sigma_{x,y}$ [μm]	*16, 16*	*5-20*
Min. Bunch Length σ_z (rms) [μm]	*16*	*8*
Max. Peak current I_{pk} [kA]	*6*	*12*

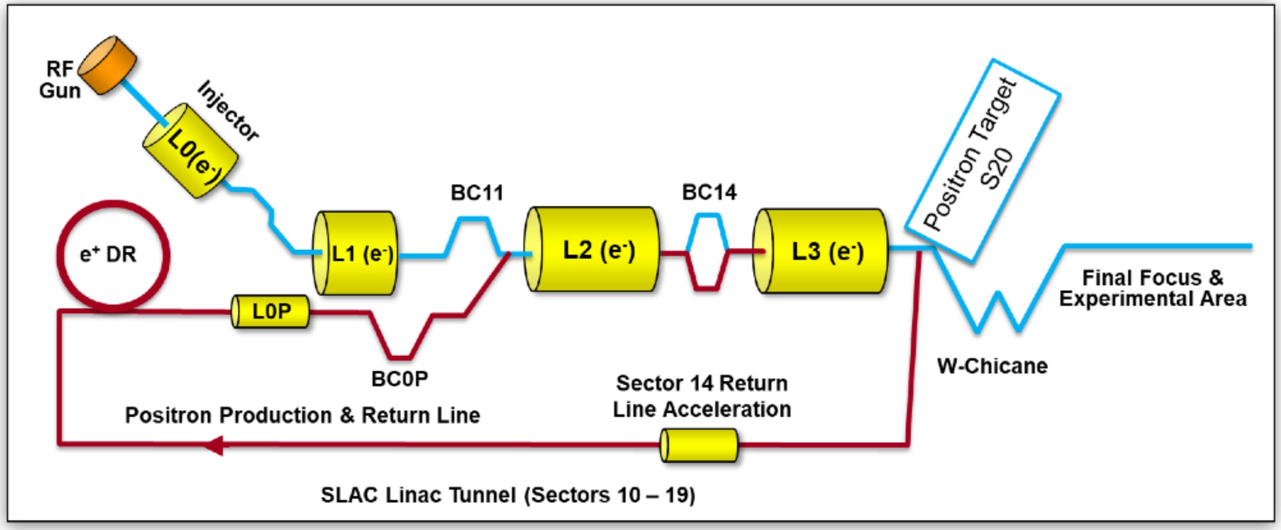
Restoring Positrons to FACET-II – We Can Do This!

- Damping Ring magnet design was completed, and prototypes were procured as part of the FACET-II Project
- Positrons were descoped from FACET-II Project (2016-2018)
- User interest in positrons did not fade away
- New initiatives on hold pending Snowmass and P5
- DOE HEP response to P5 report will be unveiled at May 2024 HEPAP meeting
- LCLS-II HE installation is fast approaching (2025-2026)

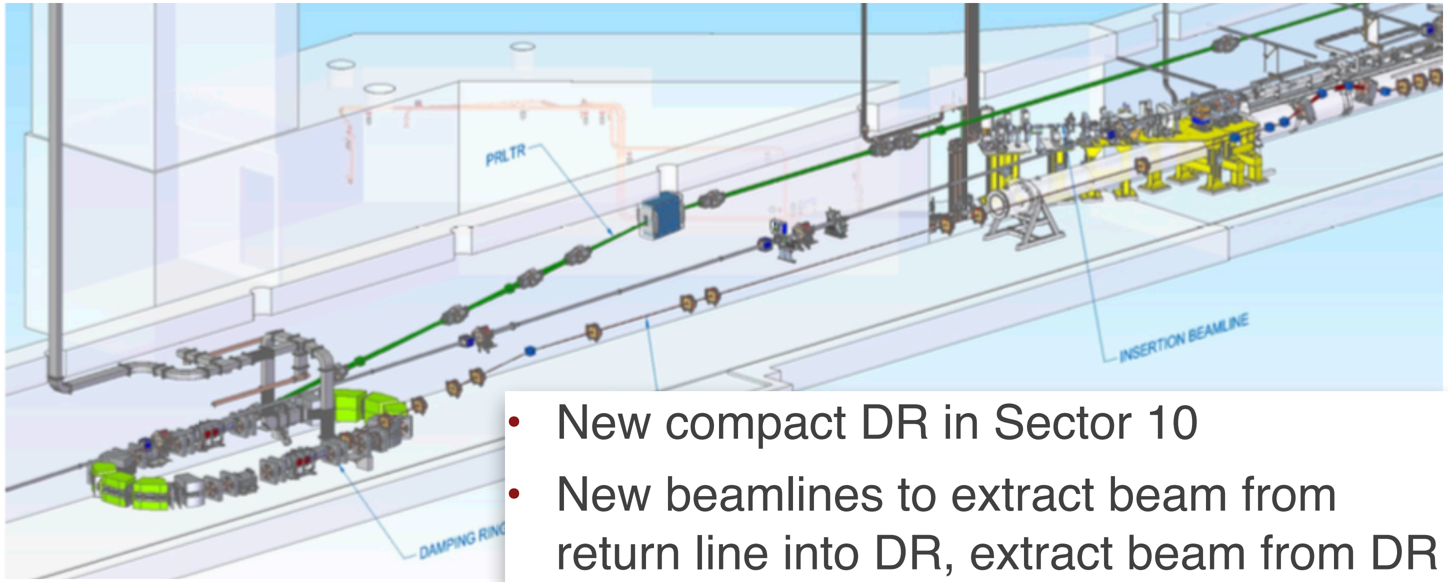


See 'US perspective on plasma based accelerators and future colliders' by Cameron Geddes Tuesday session

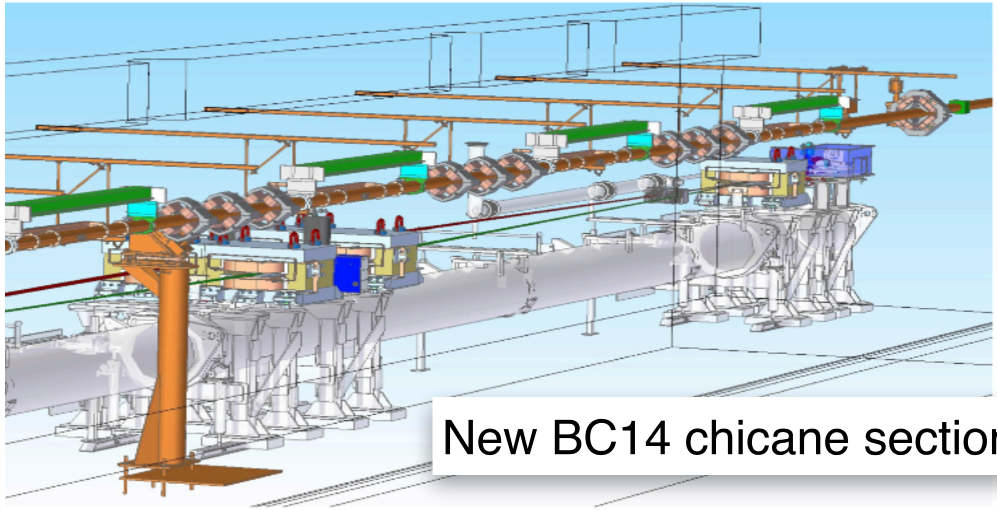
P5 report recognizes the importance of test facilities and in Area Recommendation 8 "…An upgrade for FACET-II e+ is uniquely positioned to enable study of positron acceleration in high gradient plasmas…"



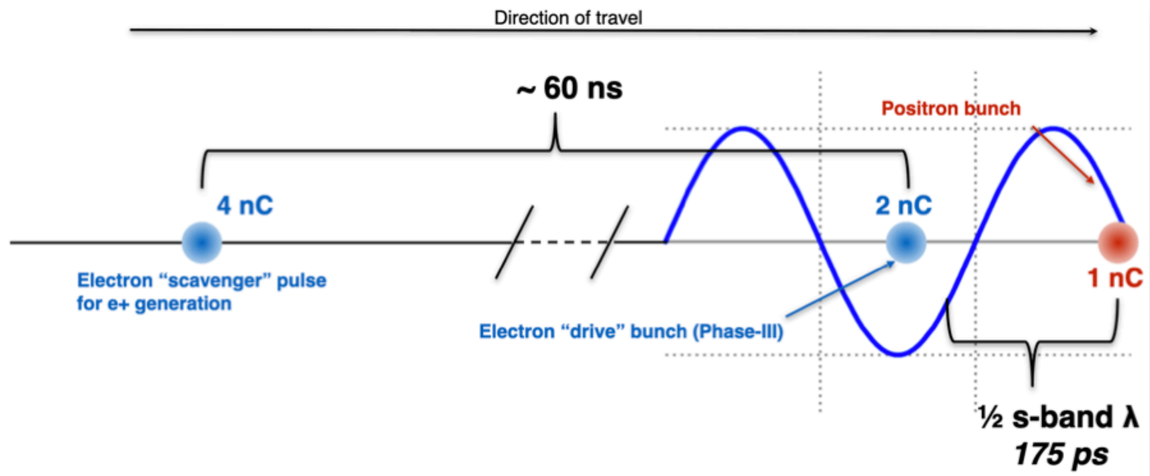
FACET-II Proposal Will Enable Studying Positron PWFA in Electron Wakes

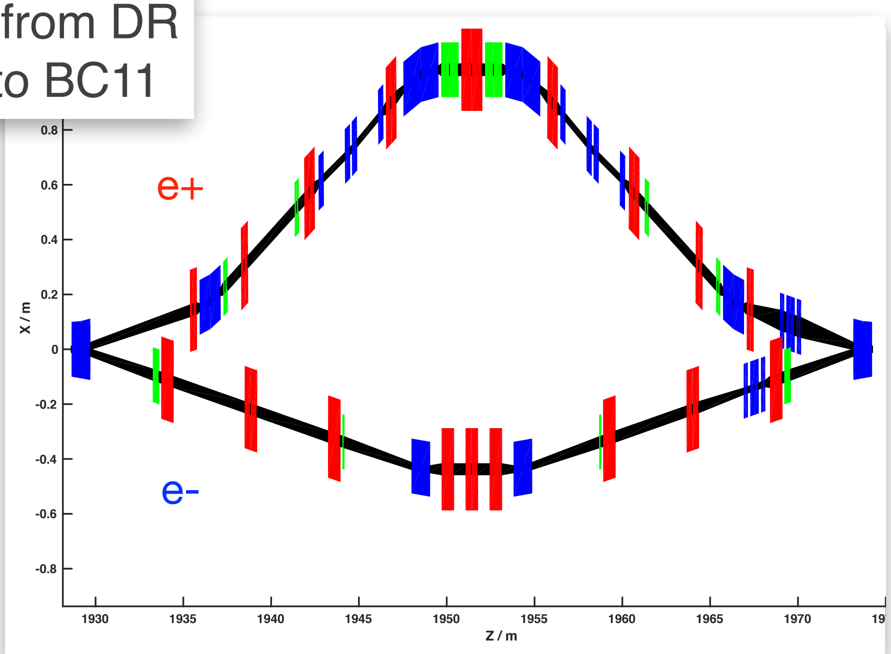


- New compact DR in Sector 10
- New beamlines to extract beam from return line into DR, extract beam from DR and extract, compress & inject into BC11



New BC14 chicane section





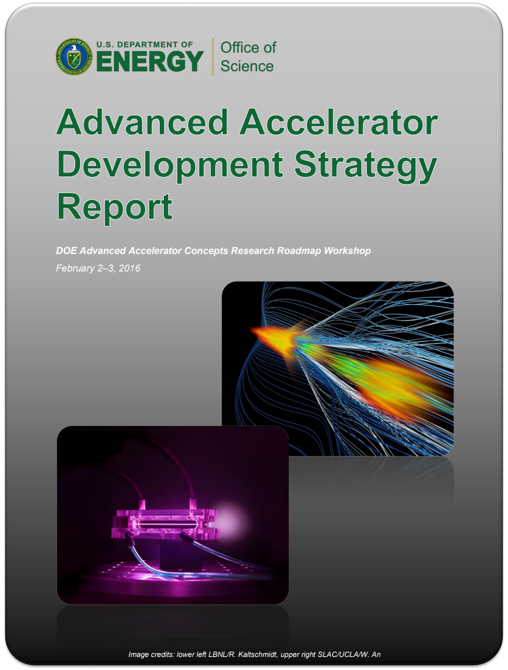
Simultaneous e- e+ delivery (dz +/- 600 μm) made possible by adding **BC20P beamline**

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



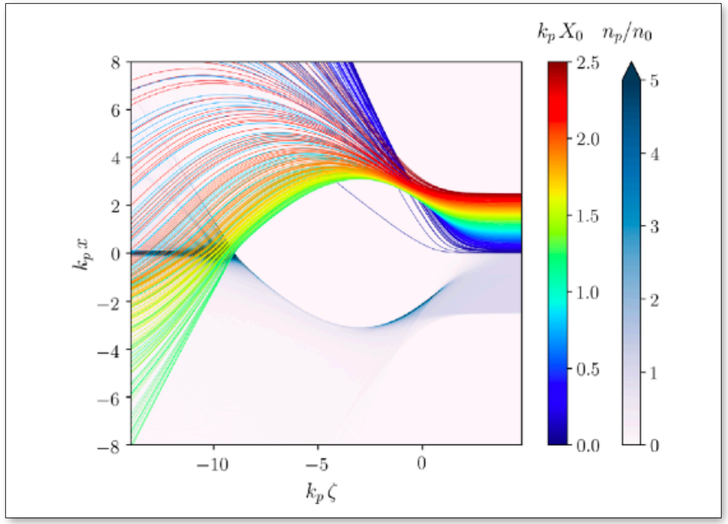
- Transversely tailored plasmas
- Transversely tailored drivers
- Long term evolution of beams/ plasmas into exotic equilibrium

Excellent overview 'Positron acceleration: a systematic overview' by Severin Diederichs @ ALEGRO2023

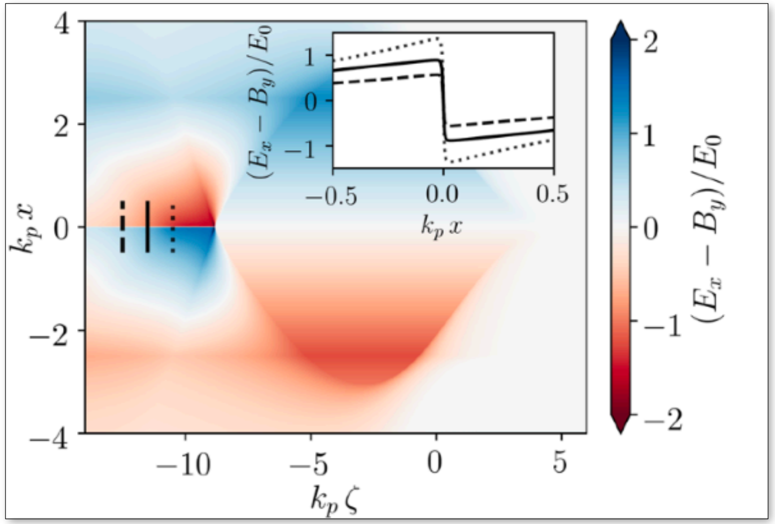
Transversely Tailored Plasmas

- 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

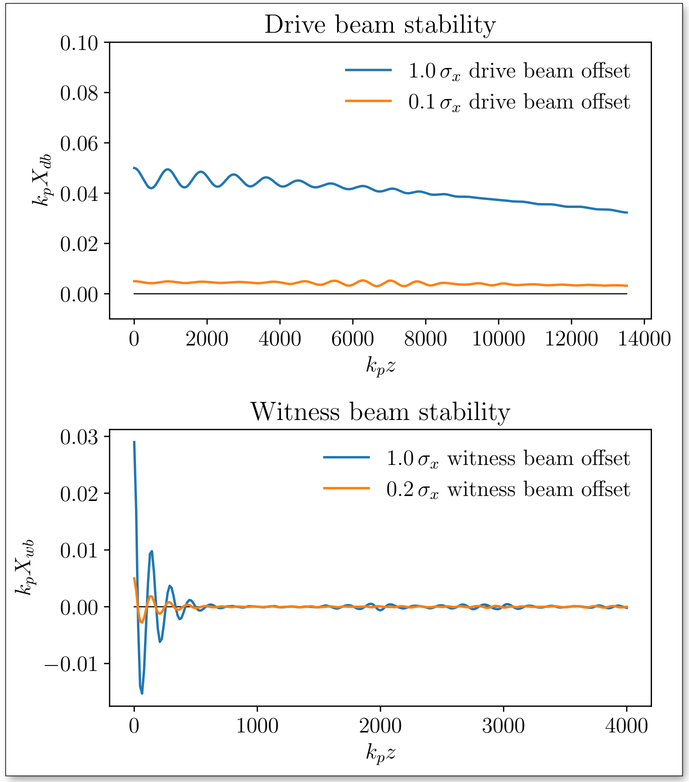
S. Diederichs et. al. Phys. Rev. Accel. Beams 25, 091304 (2022)



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

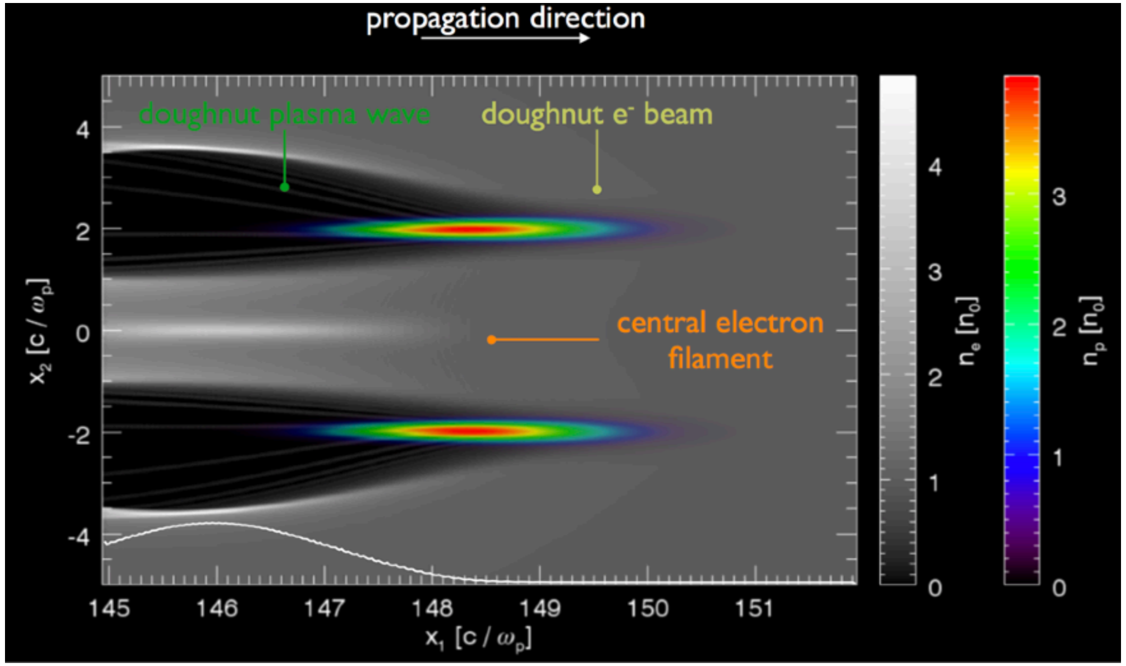


S. Diederichs et. al. Phys. Rev. Accel. Beams 23 121301 (2020)

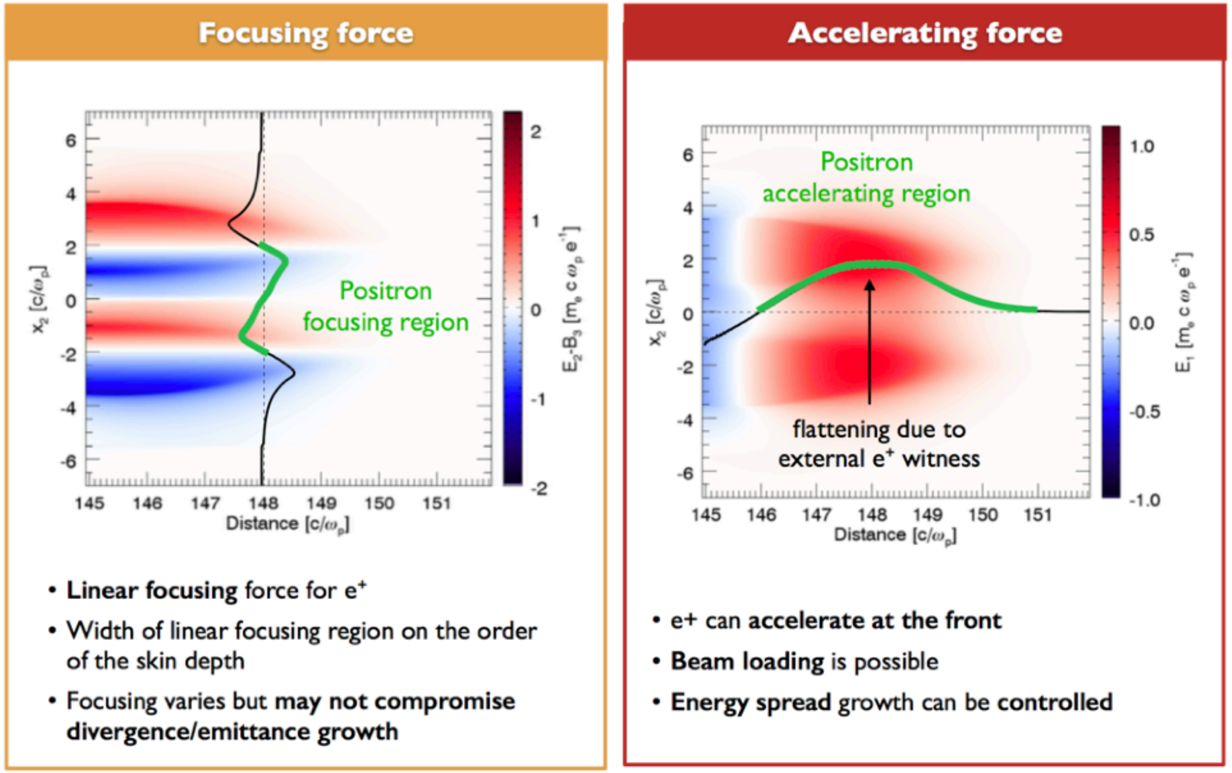


Transversely Tailored Drivers a.k.a. Wake Inversion

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

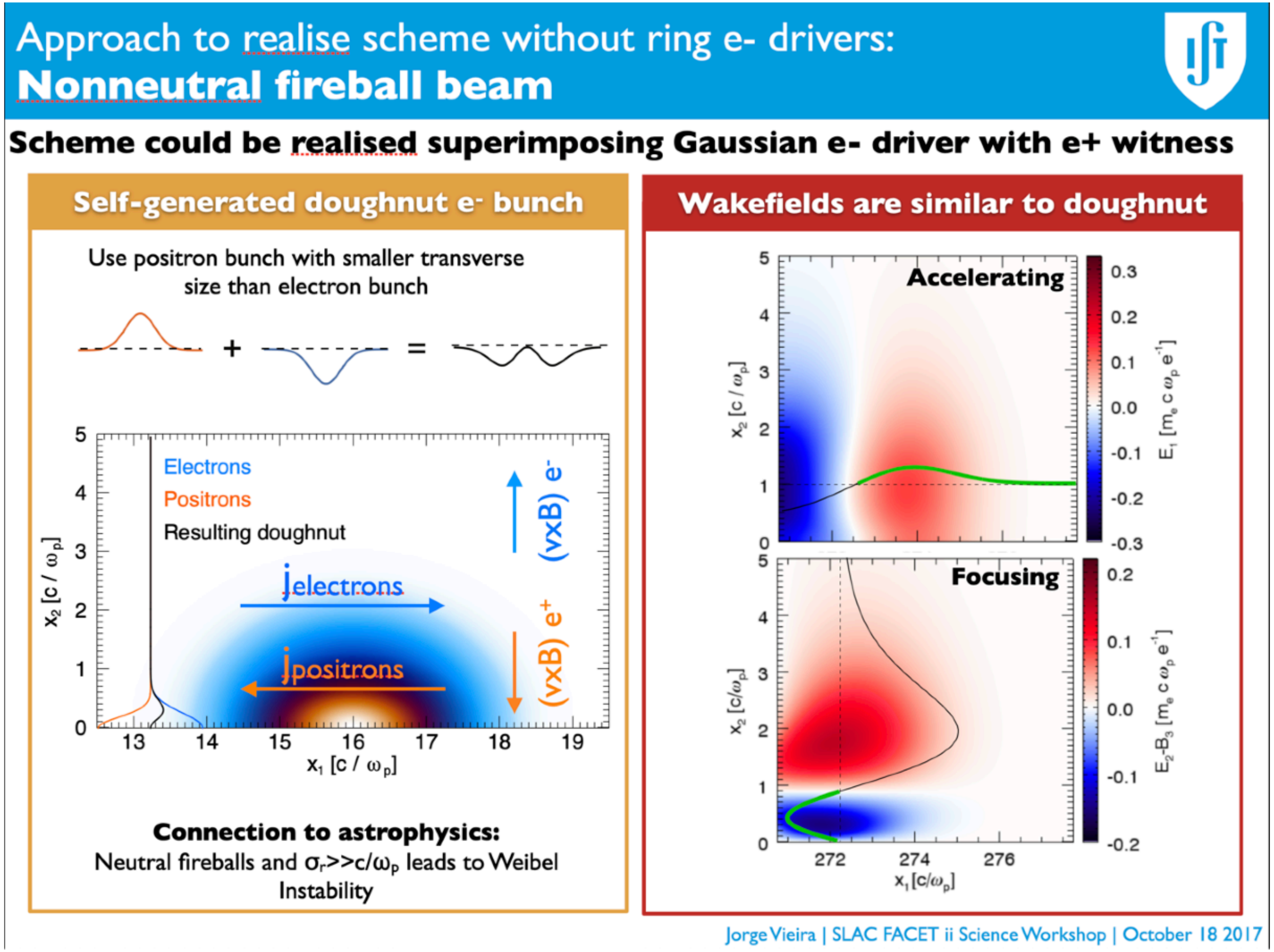


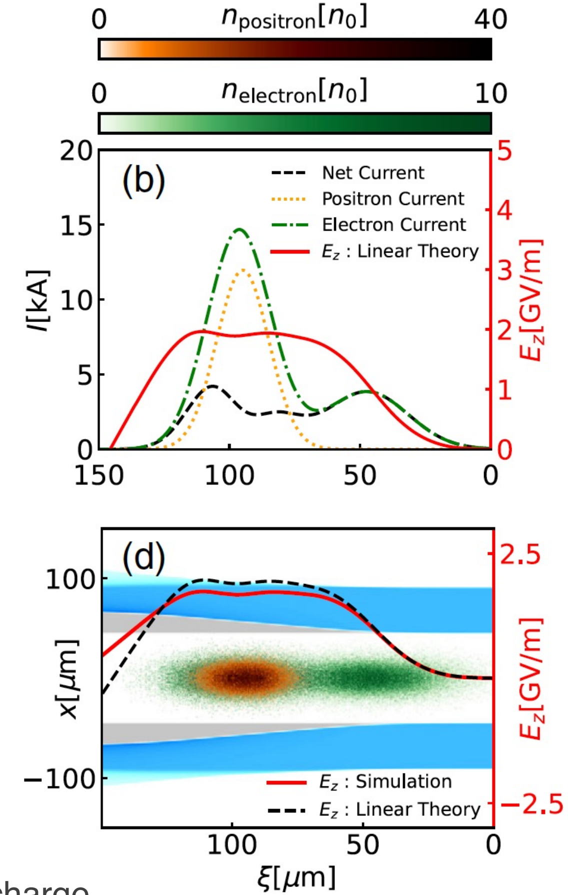
J. Vieira, et al. PRL 112 215001 (2014)
N. Jain et al. PRL 115 195001(2015)



Fireball Beams!

Zhou et al. (PRAB 25, 091303 2022)





~ nC charge

~ GV/m gradient

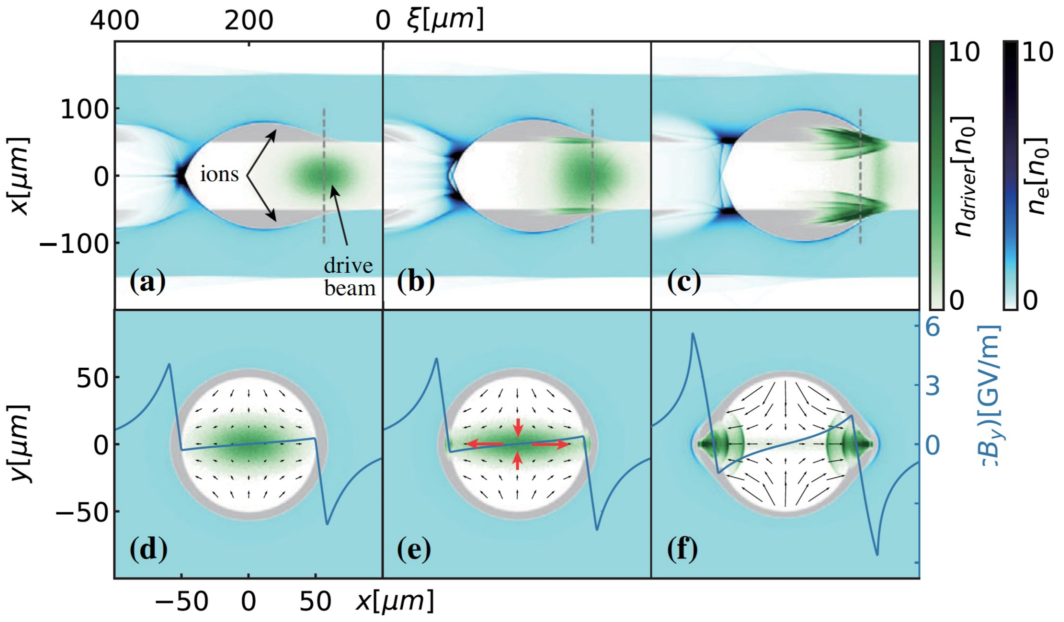
≲ 0.5% induced energy spread

~ 50% energy transfer efficiency

Stability? External focusing needs to be demonstrated

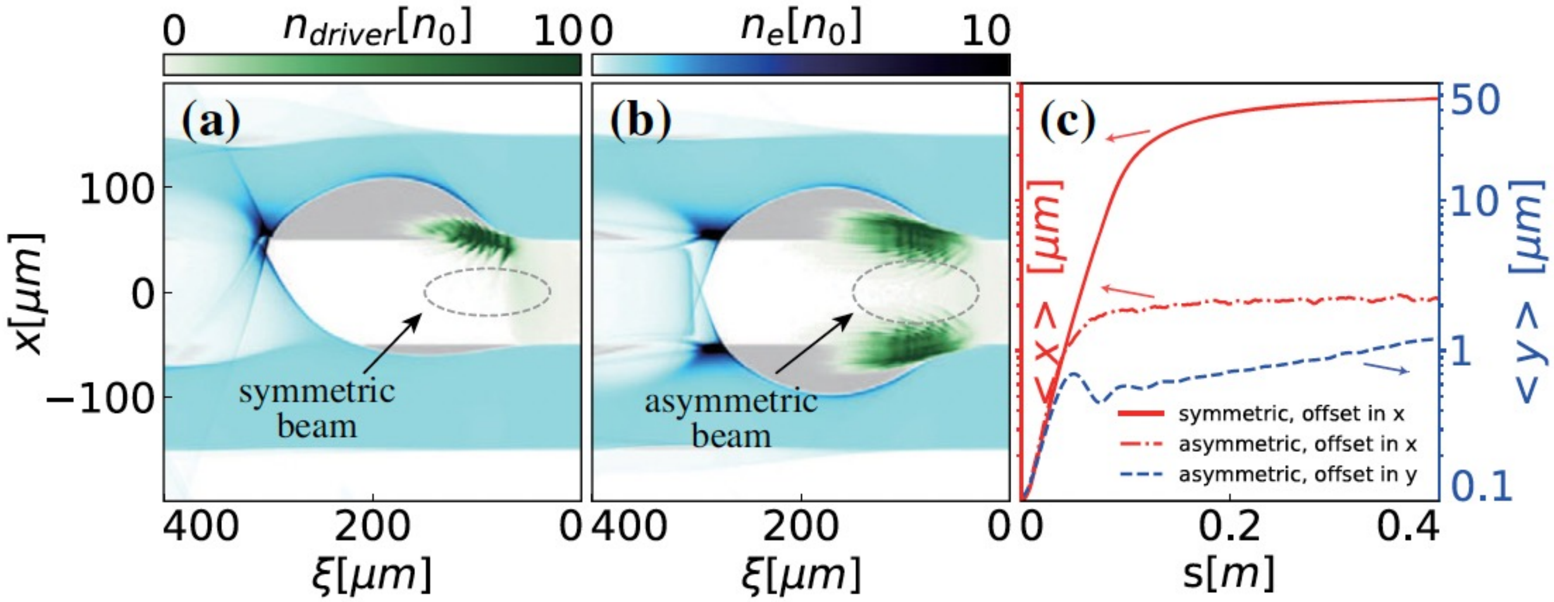
High Efficiency Uniform Wakefield Acceleration of a Positron Beam Using Stable Asymmetric Mode in a Hollow Channel Plasma

Recent Proposals with New Equilibrium Conditions



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

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



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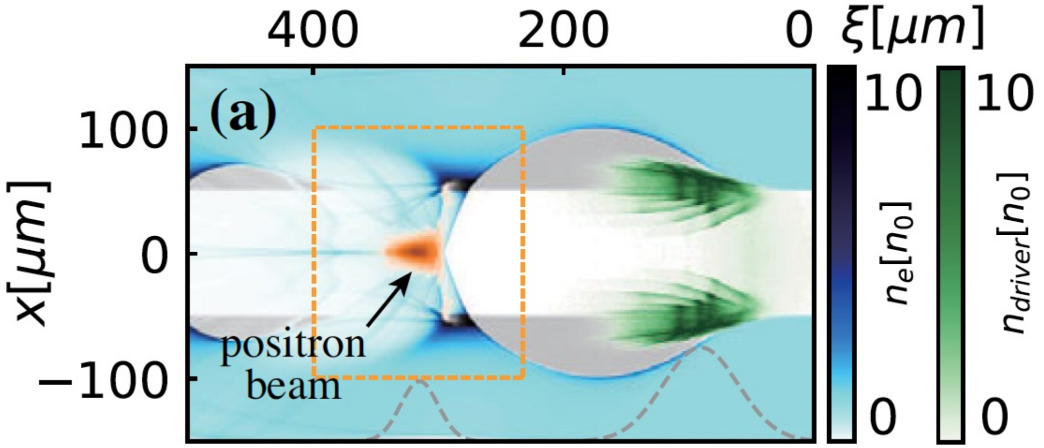
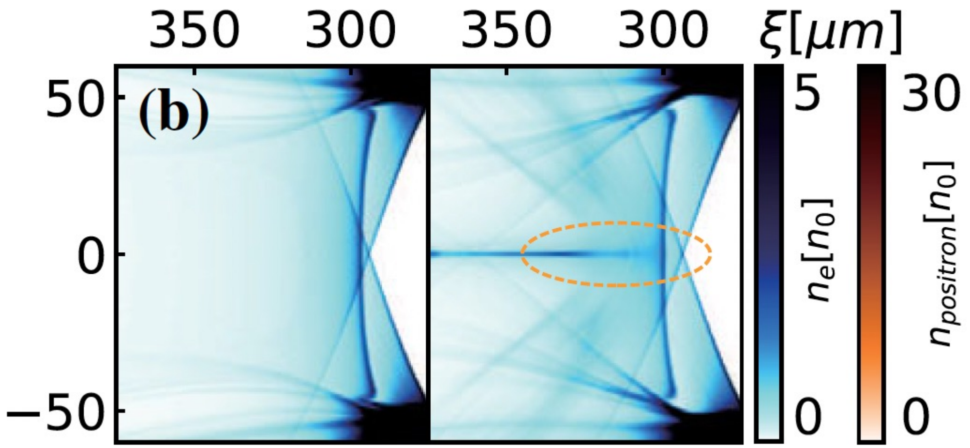
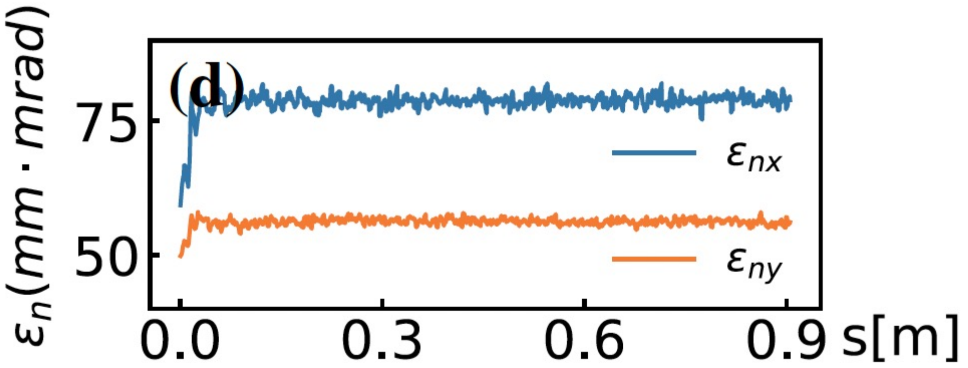






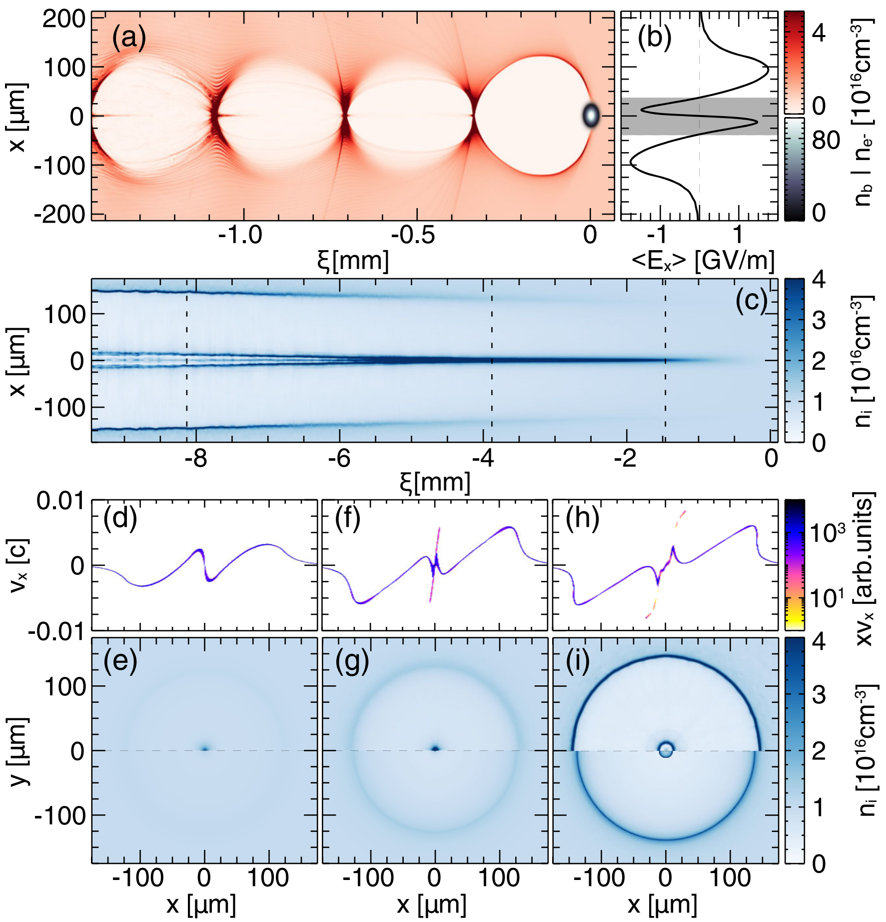
- Electron filament stabilizes witness
  - 0.49 nC charge
  - 4.9 GV/m gradient
  - 1.6% rms energy spread
  - 33% energy transfer efficiency
  - > 50 μm central slice emittance
- Finite temperature in plasma electrons further mitigates emittance growth

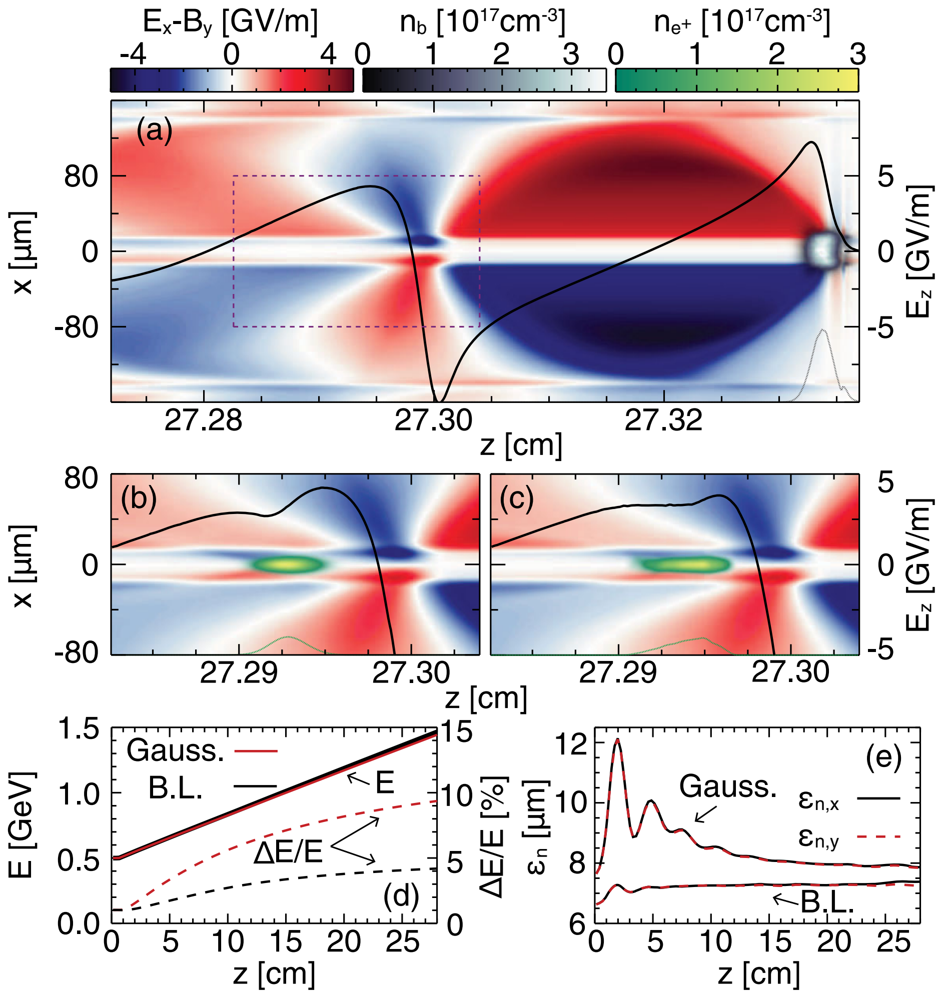
Zhou et al., PRL 127, 174801 (2021)

Diederichs et al. Phys. Plasmas 30, 073104 (2023)

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)](#)

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New Ideas Keep Coming: ‘laser-augmented blowout scheme’

PHYSICAL REVIEW E **105**, 055207 (2022)

Positron acceleration via laser-augmented blowouts in two-column plasma structures

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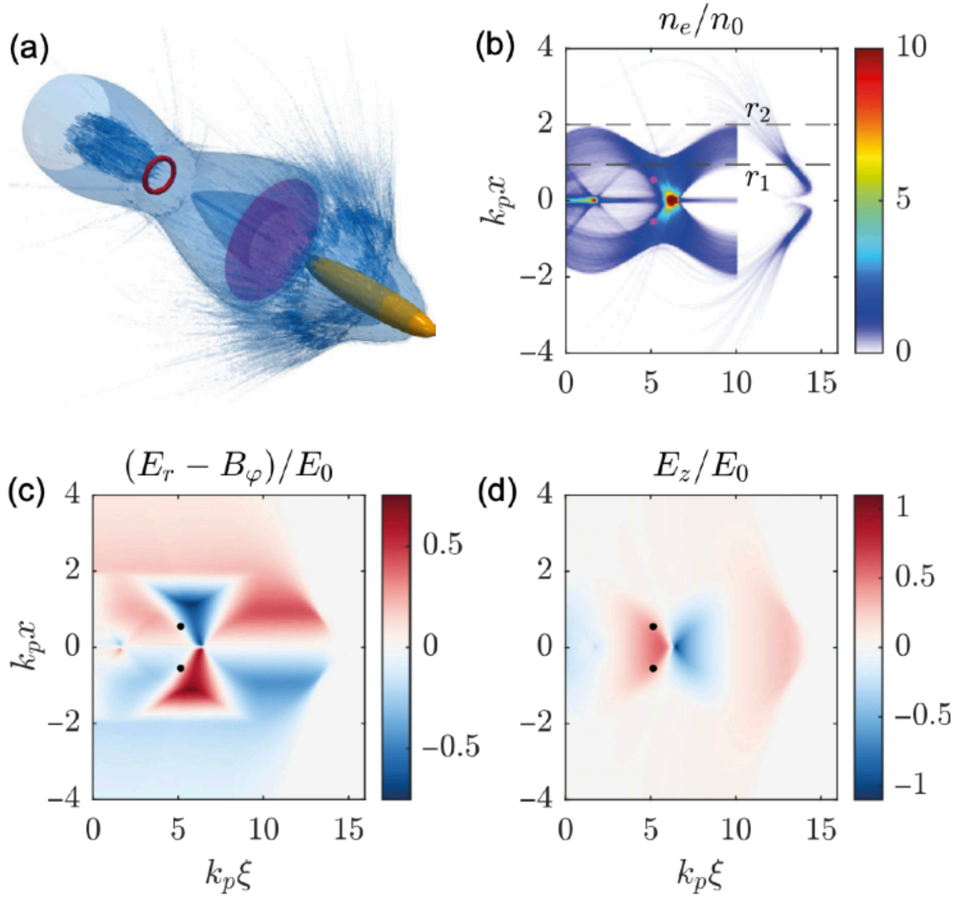
- Two plasma columns: a Gaussian electron bunch (yellow) beam ionizes a thin column and a trailing laser pulse (purple) ionizes a wider column
- The trailing positron bunch (red) is donut or ring-shaped such that the entire bunch is inside the blowout sheath at the beginning of the second bubble, also shown in (b)
- Both the (c) focusing force and (d) accelerating field are shown, indicating the location of the positron bunch (black dots)



Power Efficiency is Critical –
Accelerating Gradient (even with good emittance) Is Not Sufficient

PHYSICAL REVIEW ACCELERATORS AND BEAMS **27,** 034801 (2024)

Positron acceleration in plasma wakefields

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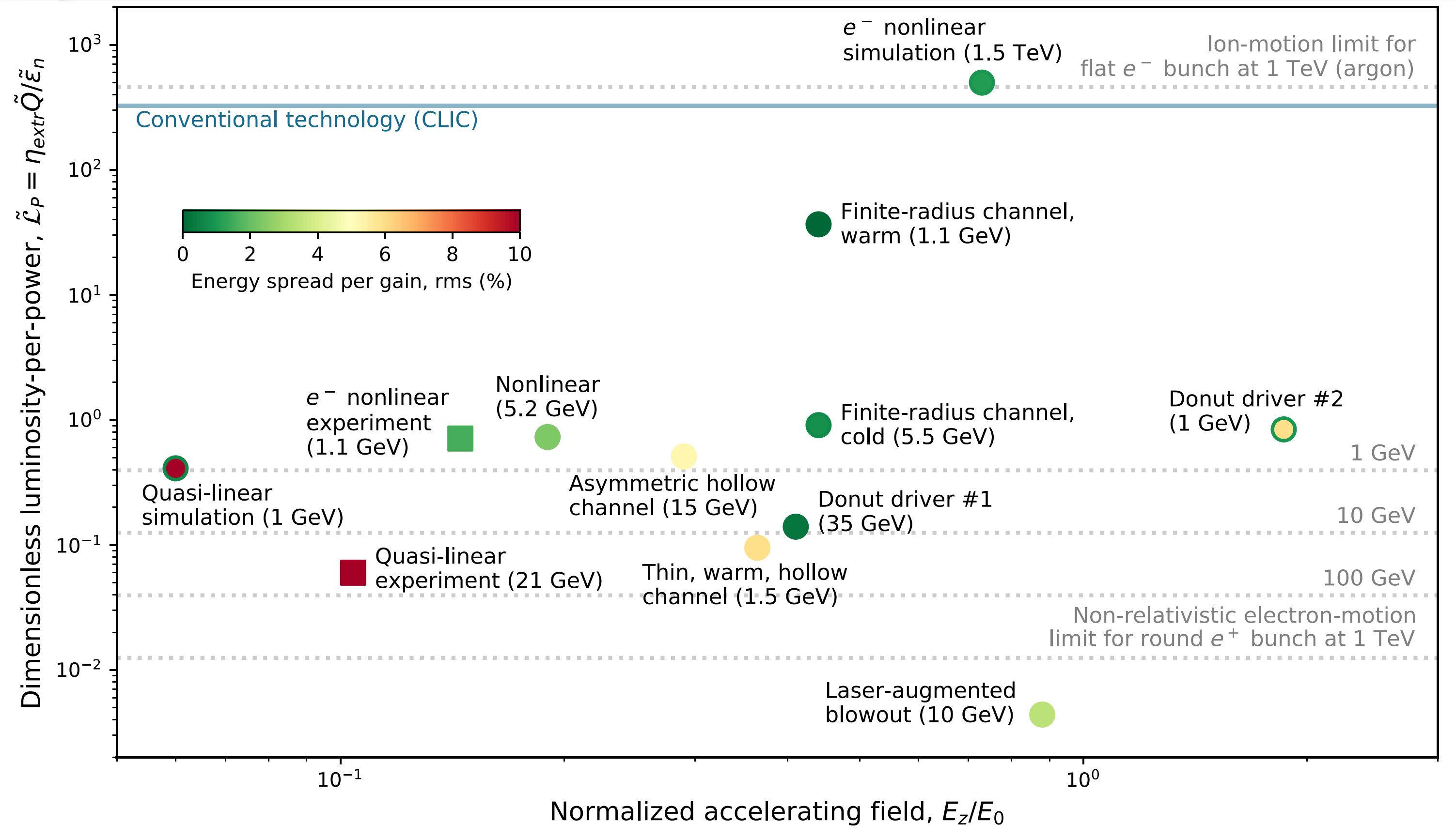

See 'Positron acceleration in plasma wakefields for linear colliders: a review of progress and challenges' by Sebastien Corde tomorrow morning

Positron Summary and Outlook

- 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

FACET-II will re-examine options with DOE HEP when response to P5 report is available. With a commitment and strong support from SLAC the plan could be executed on 5 year time scale without interruption of existing user program.