ALEGRO Workshop 2019

Positron bunch acceleration in Plasma

Sébastien Corde and Spencer Gessner

March 29, 2019

Outline

- Scientific context of positron acceleration in plasma

- Experimental progress achieved in plasma-based positron acceleration

    - ➢ High-field positron acceleration in nonlinear regime
    - ➢ Acceleration of a distinct positron bunch (in uniform and hollow plasmas)
    - ➢ Transverse wakefields in hollow plasma channels

- Challenges and path forward

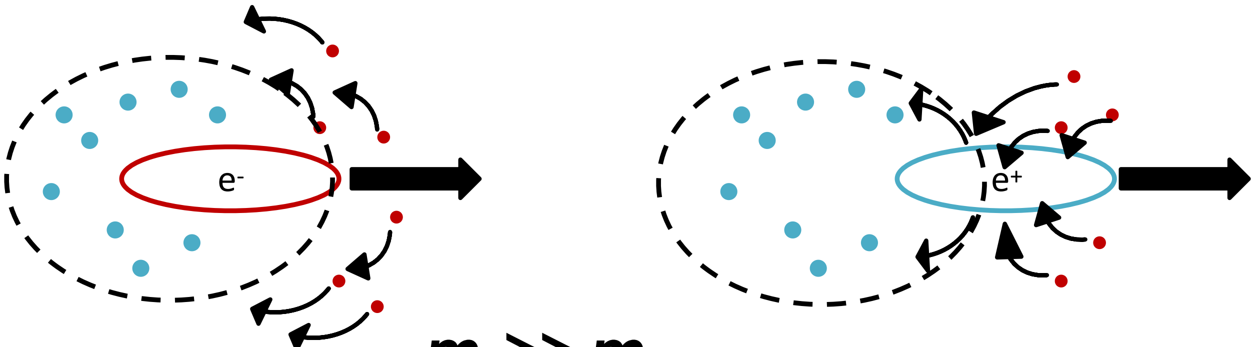
Scientific context

Plasmas in nonlinear regime are asymmetric accelerators

Plasma acceleration is being considered for an advanced linear collider, where positrons are strongly desired. But:

« The most outstanding problem is the acceleration of positrons with bunch brightness, required for a linear collider » [Lebedev *et al.*, World Sci. (2016)].

Nonlinear plasma wakefields are asymmetric accelerators: there are profound difference between electron and positron acceleration in nonlinear plasma wakefields.



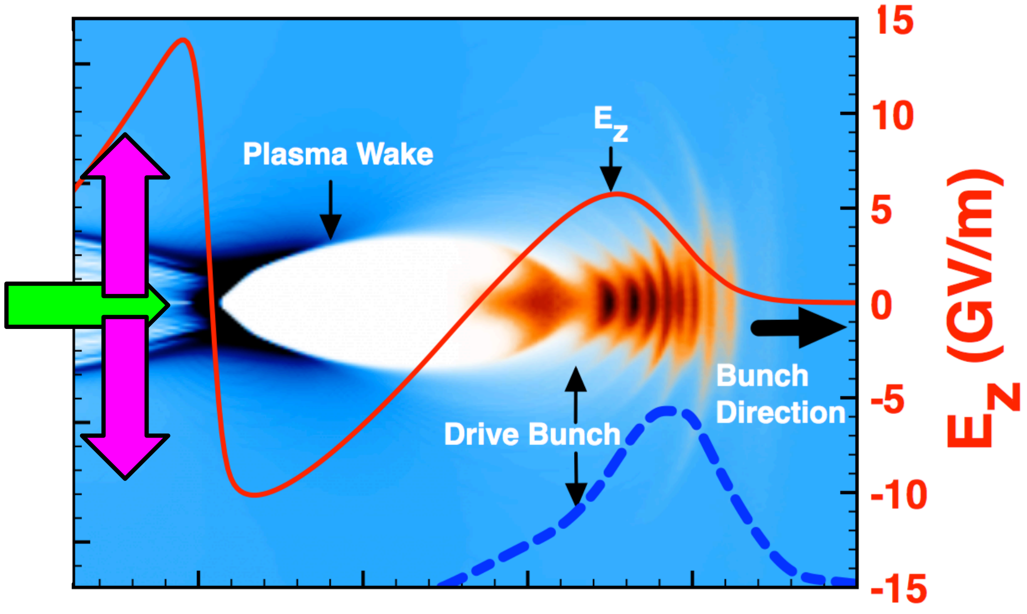
$m_i >> m_e$

The plasma electrons are mobile but the ions are not.

The symmetry of the accelerating mechanism is broken in the nonlinear regime.

Plasmas in nonlinear regime are asymmetric accelerators

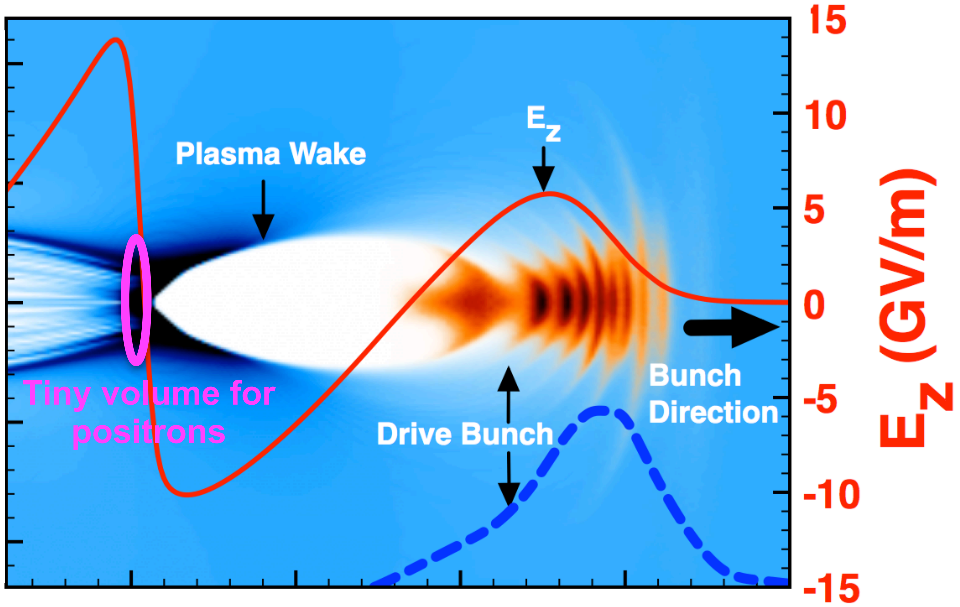
Electron-driven or laser-driven nonlinear blowout wakes:



But the field is defocusing in this region.

Plasmas in nonlinear regime are asymmetric accelerators

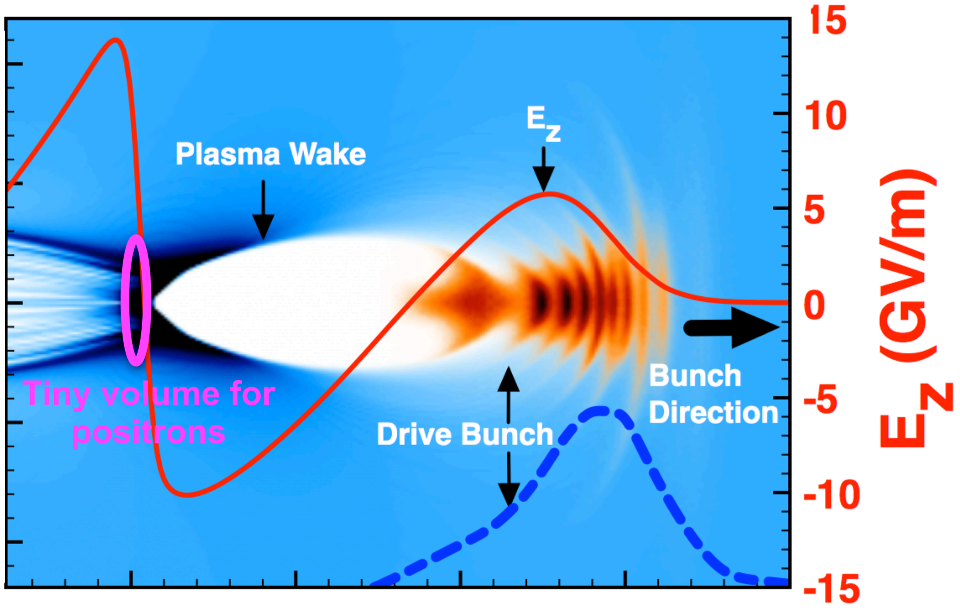
Electron-driven or laser-driven nonlinear blowout wakes:



Tiny volume where it's simultaneously accelerating and focusing. But E_z varies rapidly in this volume, both transversely and longitudinally.

Plasmas in nonlinear regime are asymmetric accelerators

Electron-driven or laser-driven nonlinear blowout wakes:

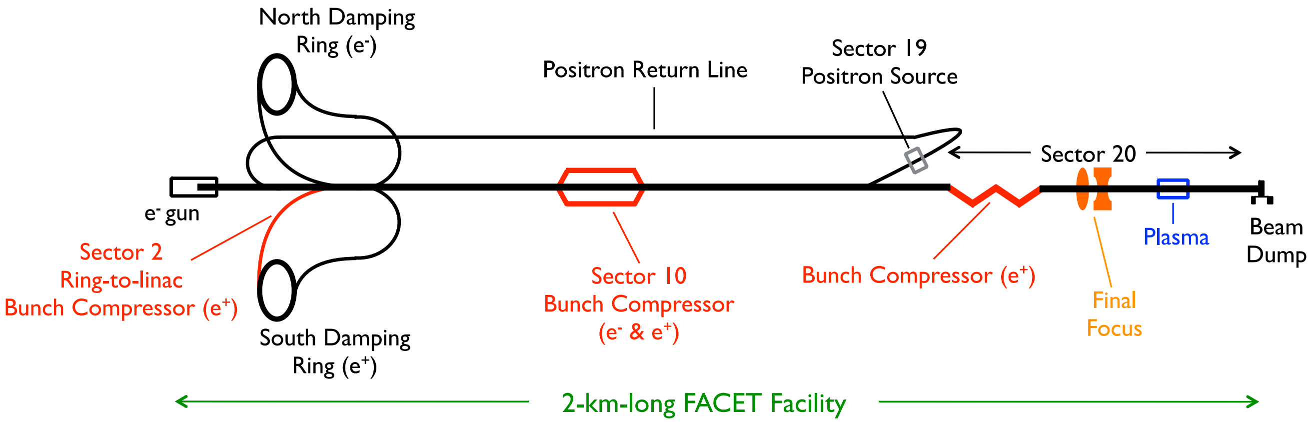


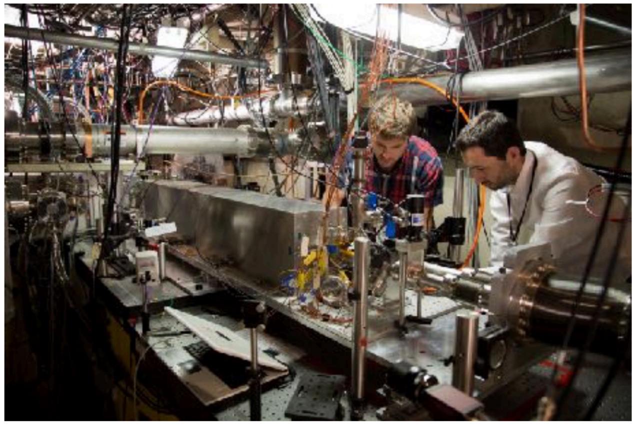
Transverse force is highly nonlinear in r

→ emittance growth

Experimental progress in plasma-based positron acceleration

Positron acceleration in PWFA



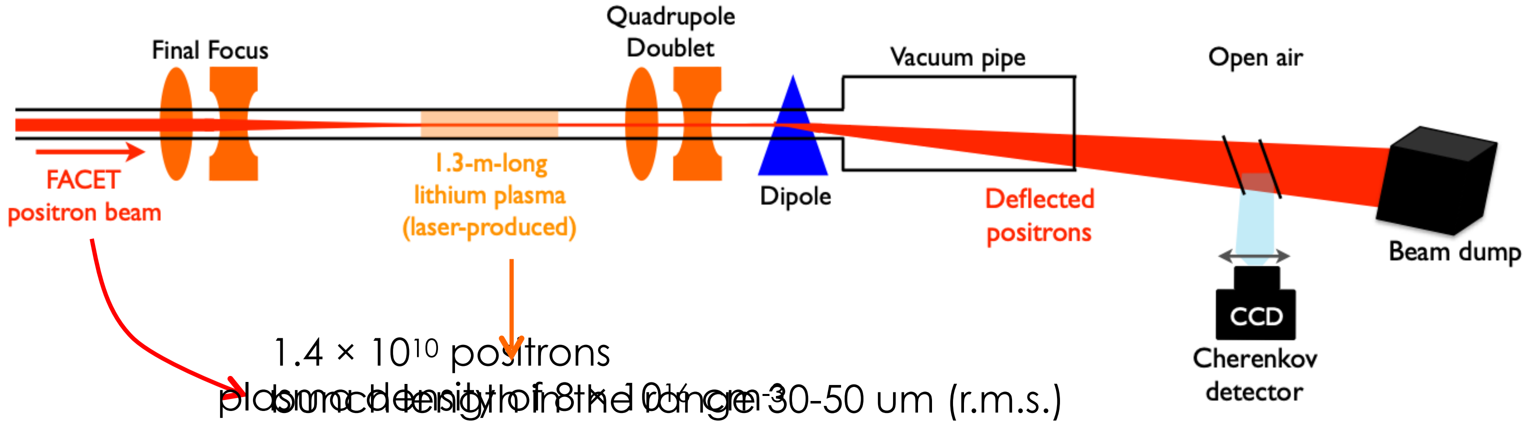


Spencer Gessner (left) and Sebastien Corde (right) at FACET tunnel, SLAC.
Image source: SLAC National Accelerator Laboratory

- A short and intense positron beam is needed for the experiment.
- Positrons originate from the electromagnetic shower produced when a 20.35 GeV electron beam passes through a thick tungsten alloy target.
- Separate bunch compressor in Sector 10 to compress the positron bunch.
- First experiment to use compressed and short positron beam suited for PWFA.

Positron acceleration in uniform plasma

Experimental set-up:



1.4 × 10^{10} positrons

bunch length in the range 30-50 um (r.m.s.)

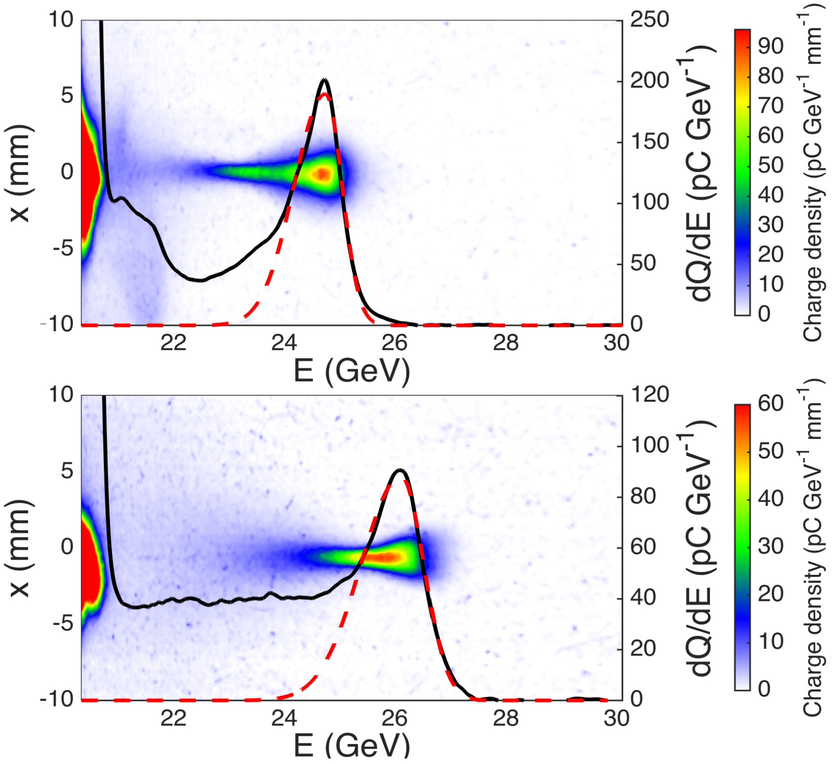
20.35 GeV energy

plasma density of 8 × 10^{16} cm^{-3}

Positron acceleration in uniform plasma

- Unexpected result: a large number of positrons are accelerated.
- 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.).

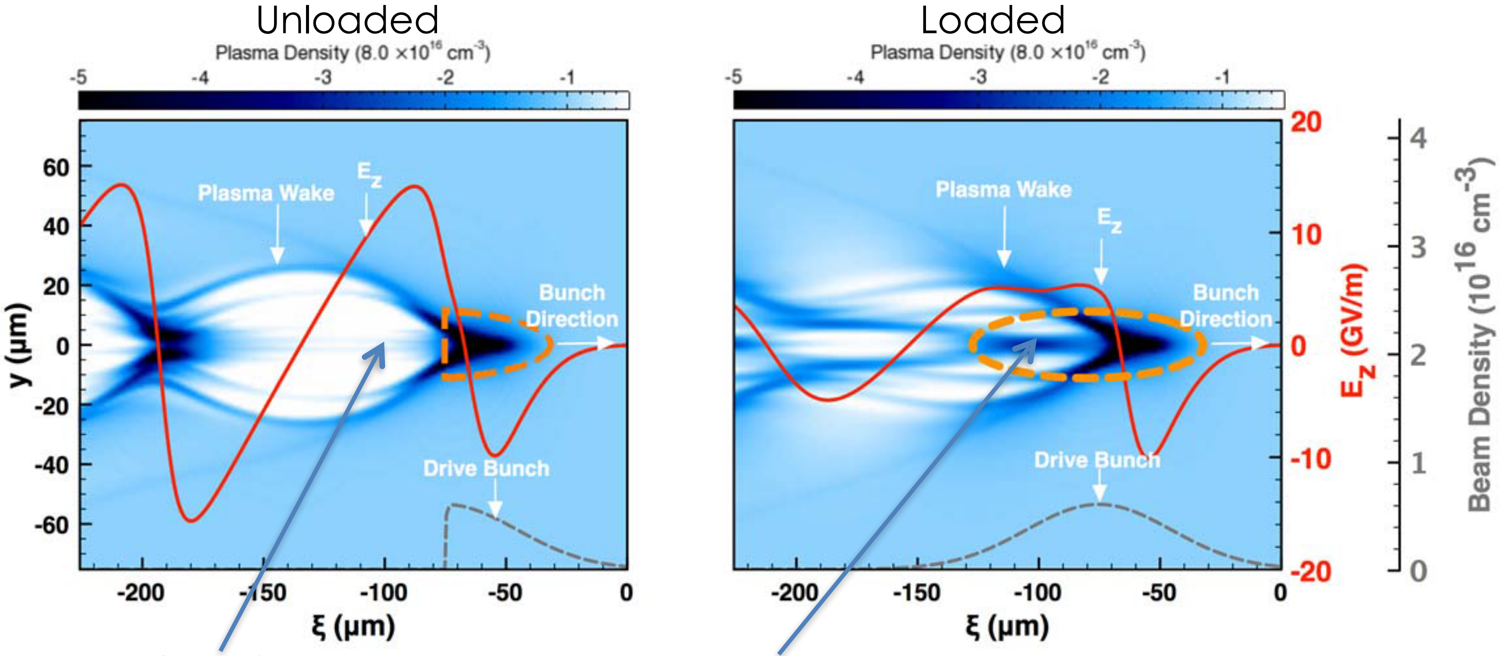
Experimental results in 1.3 m plasma



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

Positron acceleration in uniform plasma

QuickPIC simulations: loaded vs unloaded wake (truncated bunch)



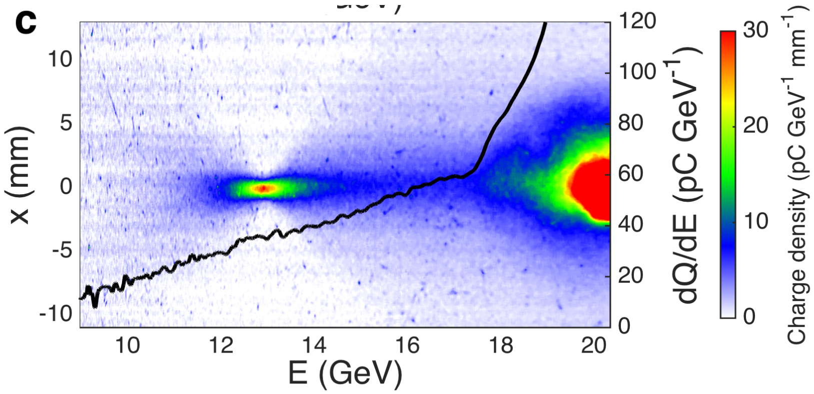
Beam loading also affects transverse fields for positron driven wakes!

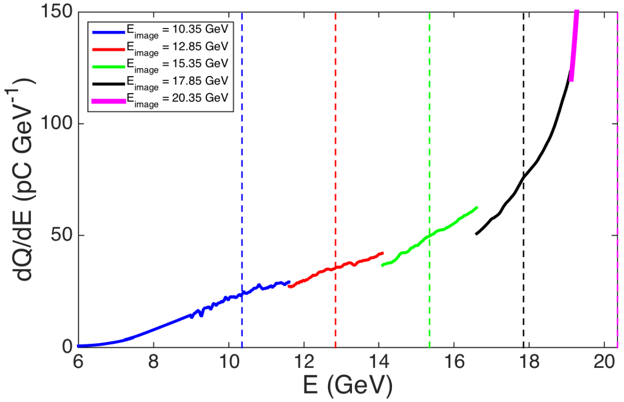
S. Corde *et al.*, Nature **524**, 442 (2015)

Positron acceleration in uniform plasma

Particle deceleration – wake excitation:

- Positrons decelerated by up to 10 GeV or greater.
- Can be used to quantify the energy transferred to the plasma wave, and then the fraction of this energy being extracted by the accelerated peak.
- Energy extraction efficiency of about 30% is deduced.

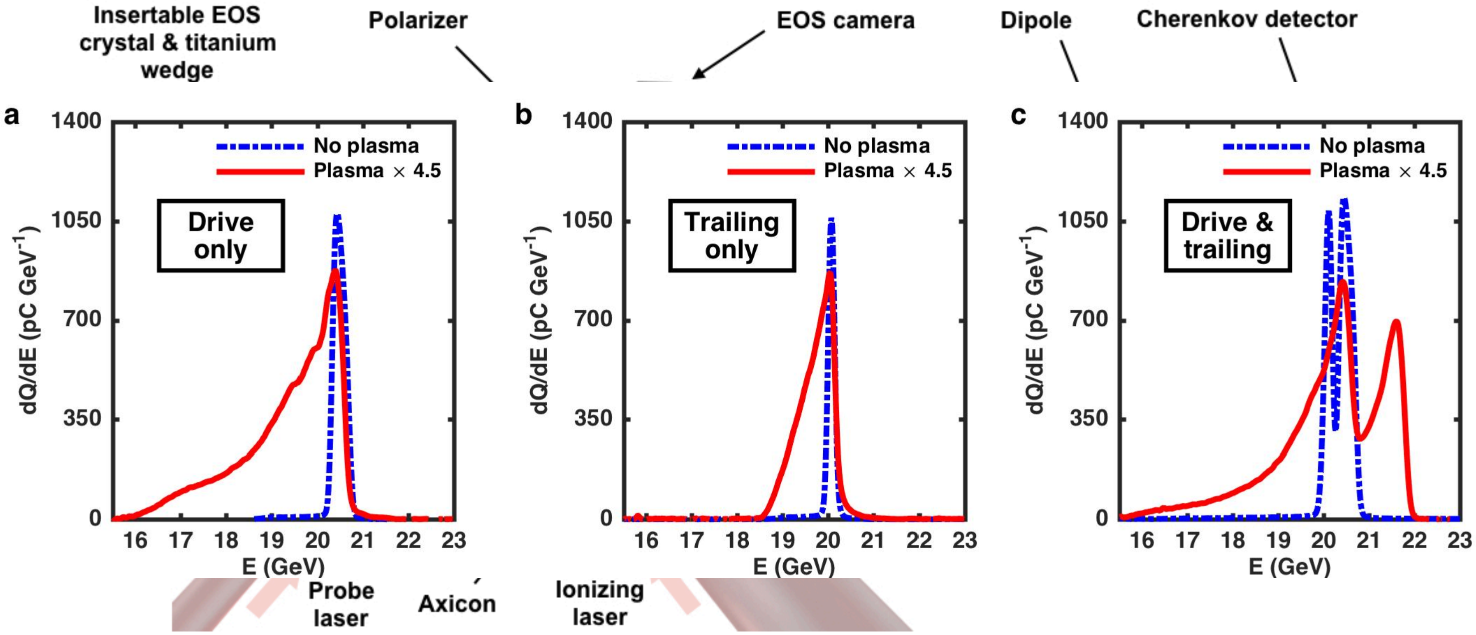




Positron acceleration in uniform plasma

For multi-stage plasma-based positron acceleration:

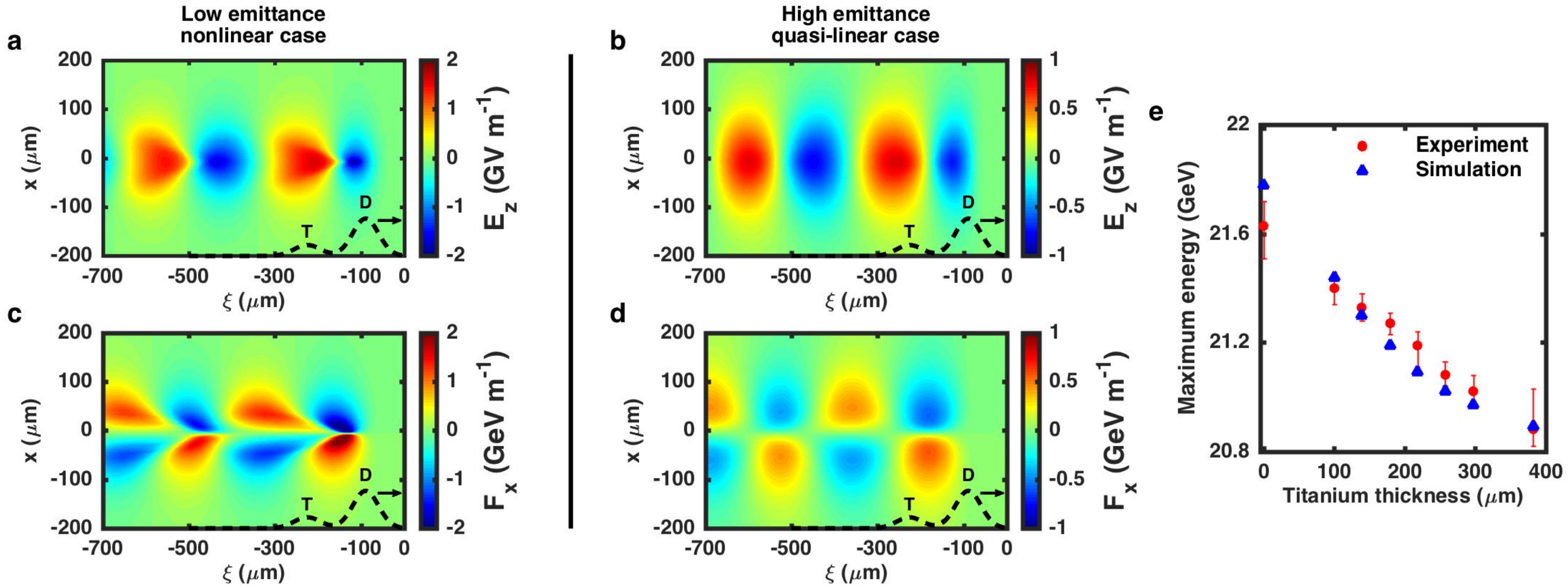
- need to demonstrate the acceleration of a distinct bunch of positrons (trailing)
- need a two-bunch experimental setup (drive + trailing)



A. Doche *et al.*, Scientific Reports **7**, 14180 (2017)

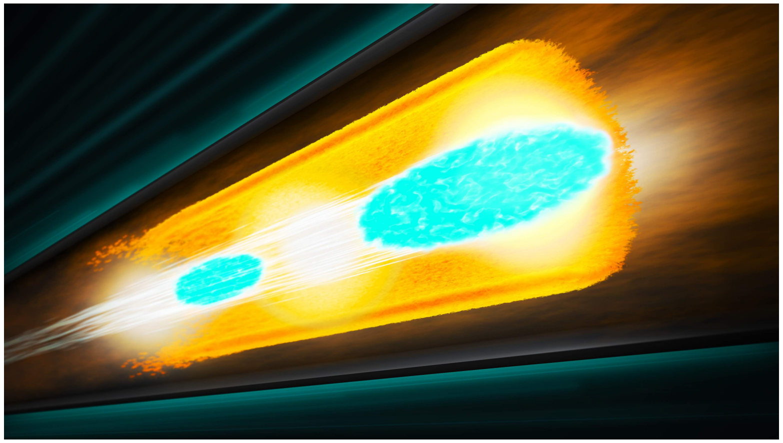
Positron acceleration in uniform plasma

By varying incoming emittance, experiment spans nonlinear to quasi-linear regime



A. Doche *et al.*, Scientific Reports **7**, 14180 (2017)

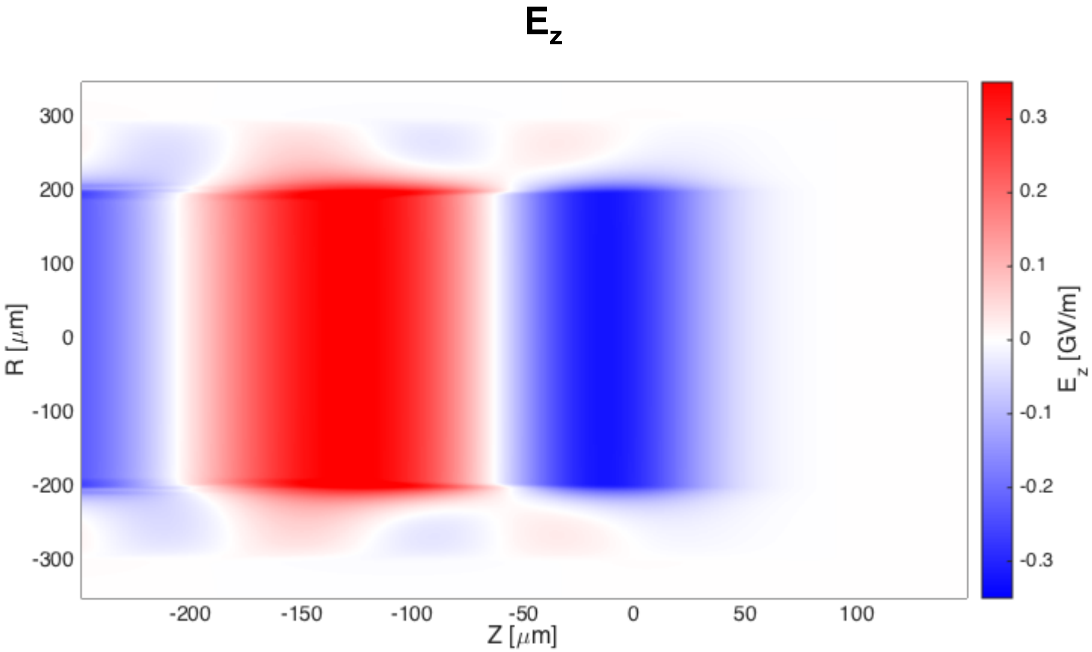
Positron acceleration in hollow plasma channels



An alternative idea: the hollow plasma channel, a tube of plasma

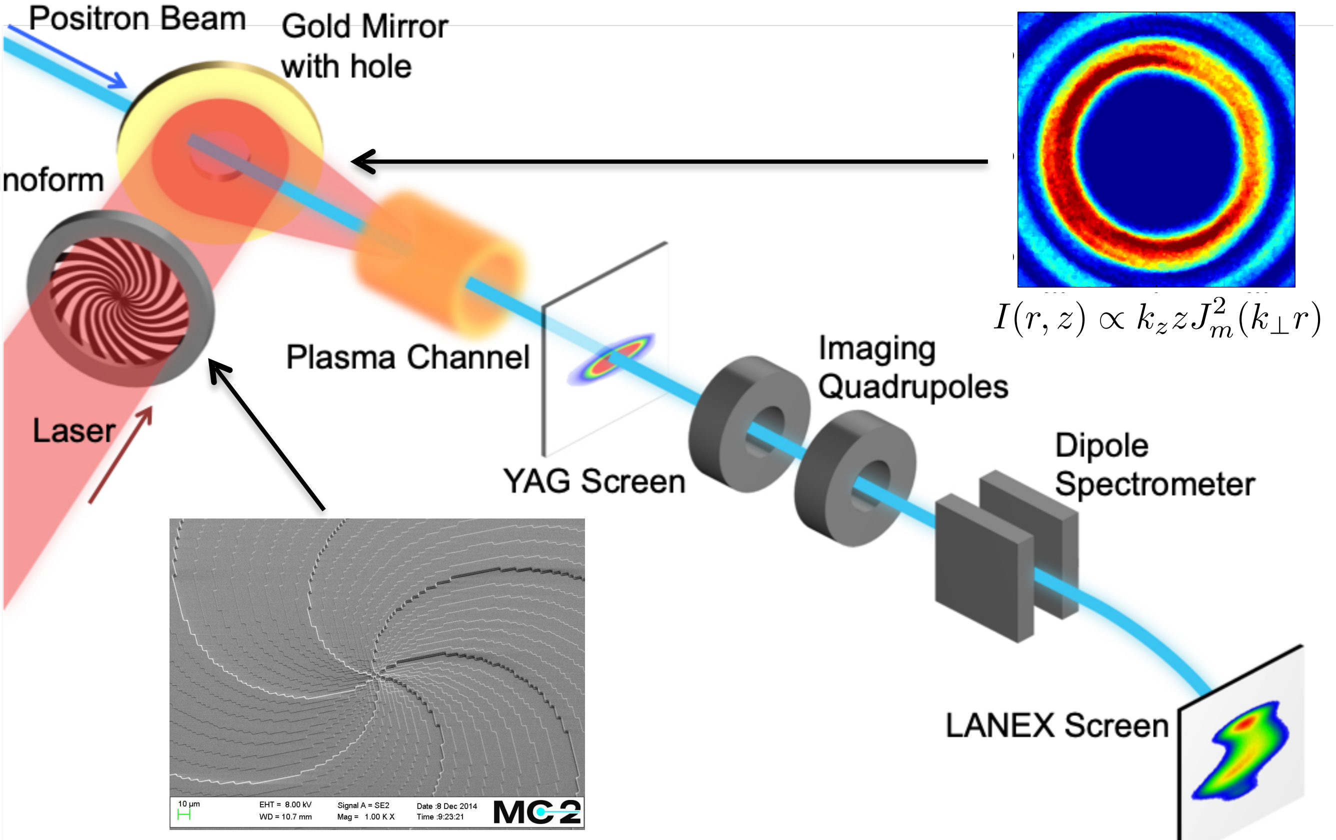
- Beams propagate in the center, where there is no plasma
- As a consequence, no transverse force in the channel

Positron acceleration in hollow plasma channels



Hollow channels provide large accelerating fields *without* focusing fields.

Positron acceleration in hollow plasma channels



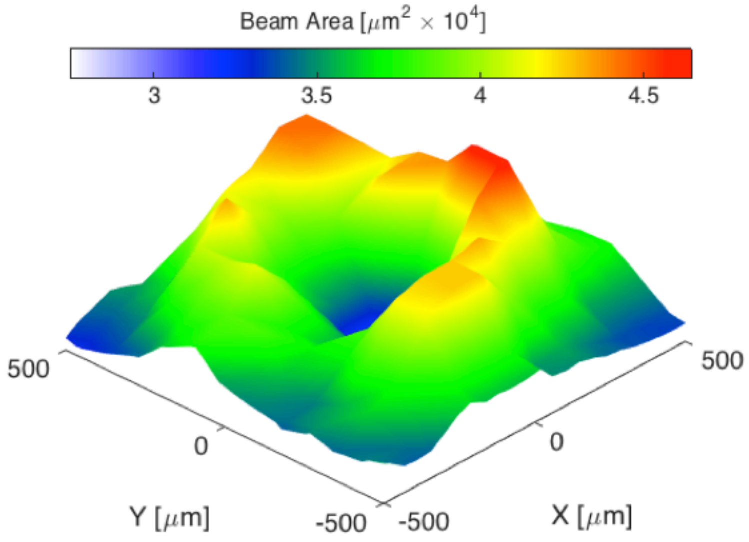
$$I(r,z) \propto k_z z J_m^2(k_\perp r)$$

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

Positron acceleration in hollow plasma channels

We measure changes to the beam as the beam is translated in the transverse directions x and y. The beam size increases when the beam interacts with the plasma channel.

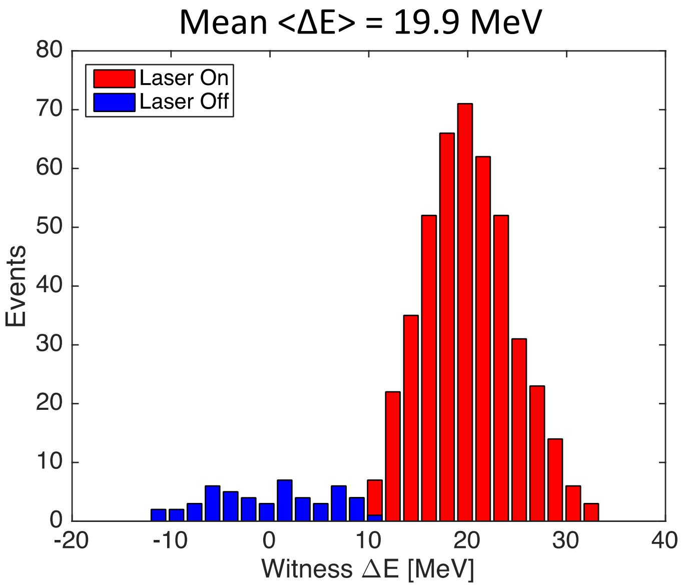
Both the Kick Map and Beam Area Measurement (Volcano Plot) are consistent with an annular plasma channel.



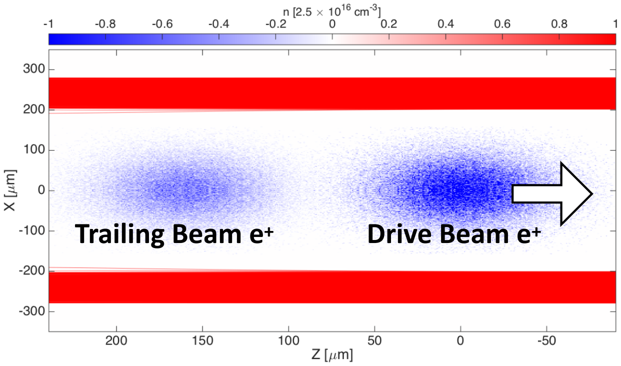
S. Gessner *et al.*, Nat. Commun. **7**, 11785 (2016)

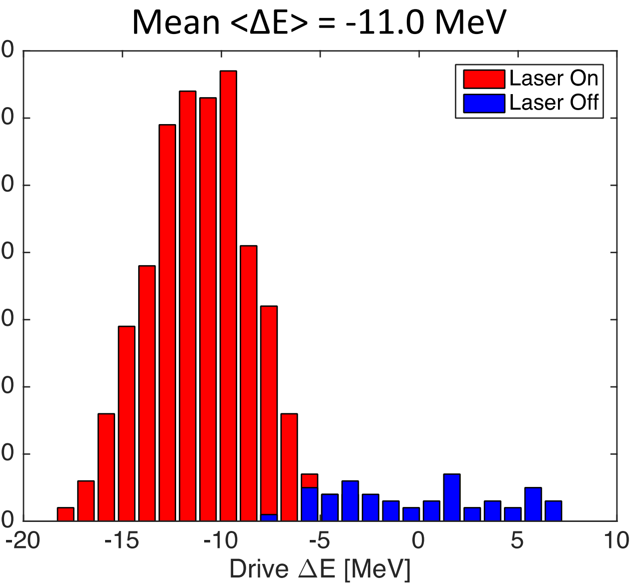
Positron acceleration in hollow plasma channels

Hollow plasma channel with two beams:



Trailing beam gains
energy from the wake





Drive beam transfers
energy to wake

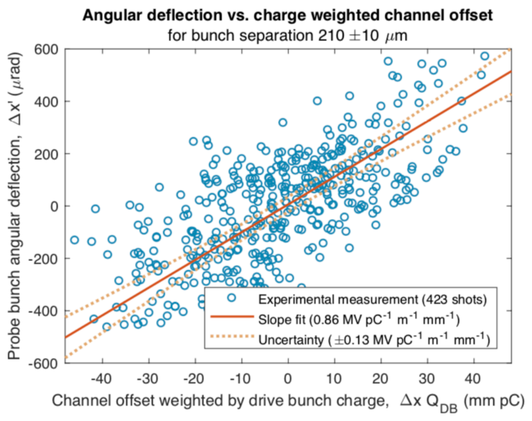
At a bunch separation of 400 microns, the trailing bunch gains about 20 MeV on average, while the drive beam loses about 11 MeV.

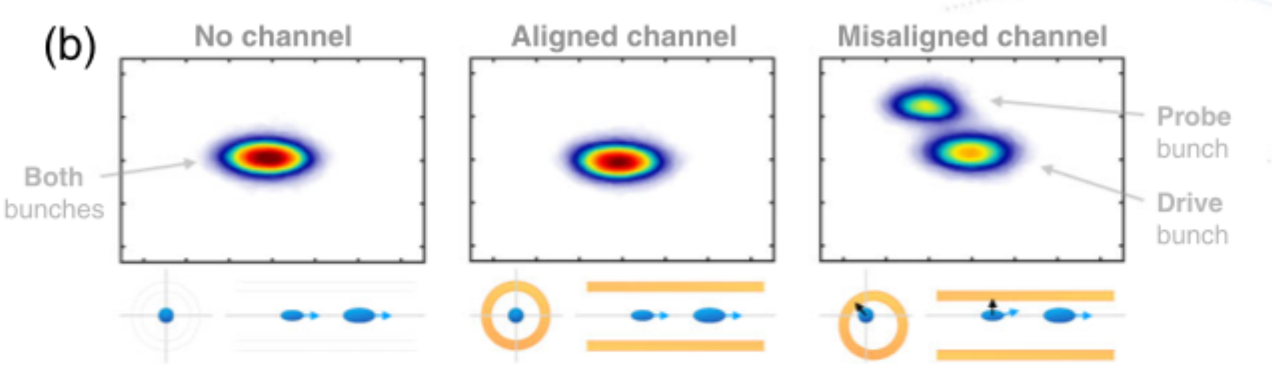
Hollow plasma channels

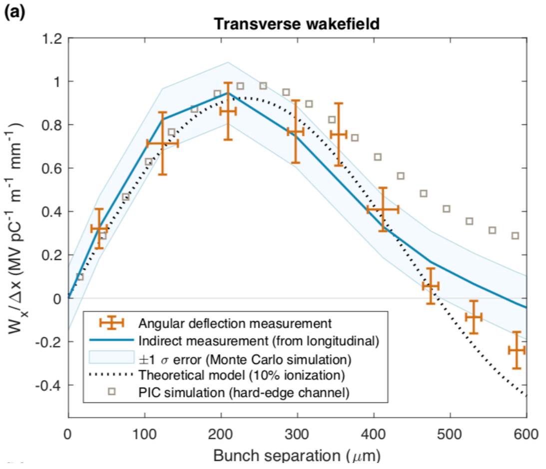
We measured the transverse wakefields in the hollow channel and the result agrees with our theoretical calculation:

$$10^6 \text{ V/(pC m mm)}$$

Or about 10,000 times stronger than the wakefields in CLIC!







→ Need mitigation mechanisms for transverse instability

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

Challenges and path forward

Challenges for quasi-linear plasma wakefield

- ➢ Plasma density perturbation from a drive particle beam in the linear regime:

$$\delta n(\xi, r) = -\frac{q}{e}\int_{\xi}^{\infty} n_{\mathrm{drive}}(\xi', r)\sin[k_p(\xi - \xi')]\, k_p d\xi'$$

- ➢ How to accelerate trailing positron bunch in quasi-linear plasma wakefield?

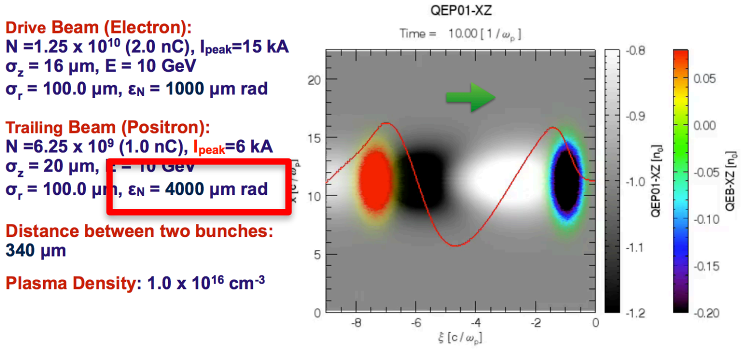
$$\frac{d^2\sigma_r}{dz^2} = -K\sigma_r + \frac{\epsilon^2}{\sigma_r^3} \quad \text{(envelope equation)}$$

- ➢ Need matched trailing positron bunch = stable propagation for trailing positron bunch, otherwise the bunch collapses.

Possible solution: high emittance or low charge

→ High emittance not acceptable solution, low charge may be acceptable with bunch train and energy recovery.

Other solution: nonlinear beam loading: $n_t > n_0$



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

Trailing Beam (Positron):
N =6.25 x 10^9 (1.0 nC), I_{peak}=6 kA
σ_z = 20 μm, E = 10 GeV
σ_r = 100.0 μm, ε_N = 4000 μm rad

Distance between two bunches:
340 μm

Plasma Density: 1.0 x 10^{16} cm^{-3}

Weiming An | ALEGRO Positron Acceleration in Plasma Mini-Workshop, CERN | February 9 2018

⟶ Strong self wakefield, electron motion, longitudinal and transverse beam loading

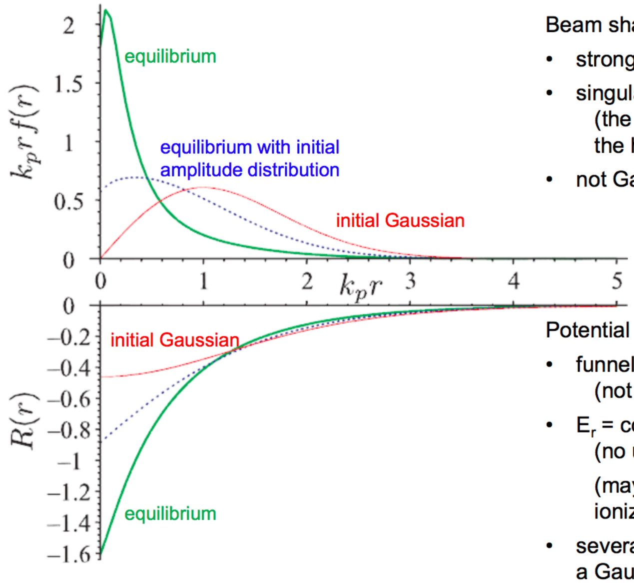
Linear plasma wakefield

When the transverse force is no longer linear in *r*, the concept of matching needs to be upgraded to transverse equilibrium distribution

Radial equilibrium distribution for single bunch in linear wakefield:

- Equilibrium is not Gaussian, strongly peaked on axis, has long radial tails, is slice-dependent.
- If bunch is initially Gaussian, it evolves with emittance growth until equilibrium (quasi-steady state) is reached, after which emittance could be preserved.

$$n(\xi, r) = n_{\text{peak}} f(r) g(\xi)$$



Beam shape:

- strongly peaked near the axis
- singular behaviour (1/r)
  (the smaller the initial emittance, the higher on-axis density)
- not Gaussian

Potential well:

- funnel-shaped
  (not usual parabolic)
- E_r = const up to the axis
  (no usual linear decrease)
  (may be important for ionization by the beam field)
- several times deeper than for a Gaussian beam

K. Lotov, Phys. Plasmas 24, 023119 (2017)

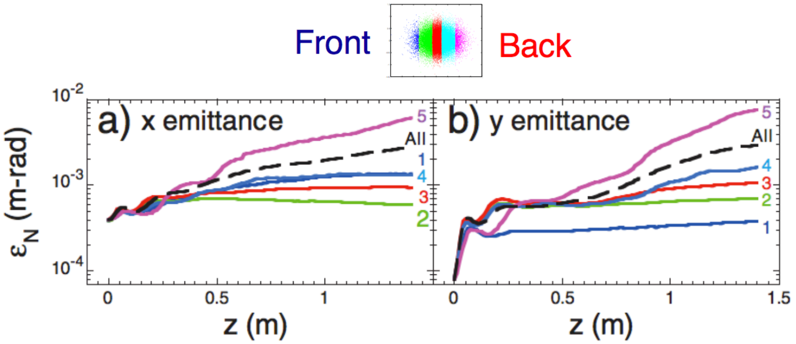
Challenges for nonlinear plasma wakefield

Conventional wisdom: transverse force must be linear in to allow for emittance preservation.

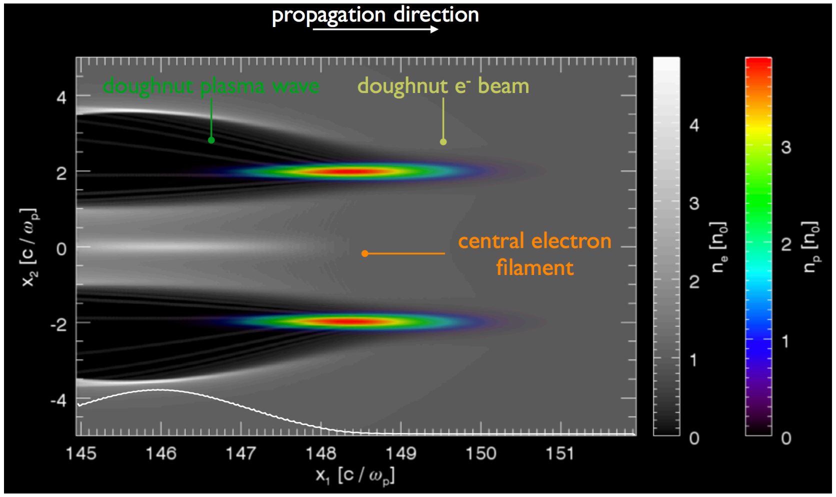
For positrons in the nonlinear regime, the focusing force is generally nonlinear in , and is slice dependent.
→ emittance growth

Plasma wake shaping using e.g. doughnut-shaped drivers
→ linear focusing force

Potential for preserved emittance in nonlinear plasma wakefield



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



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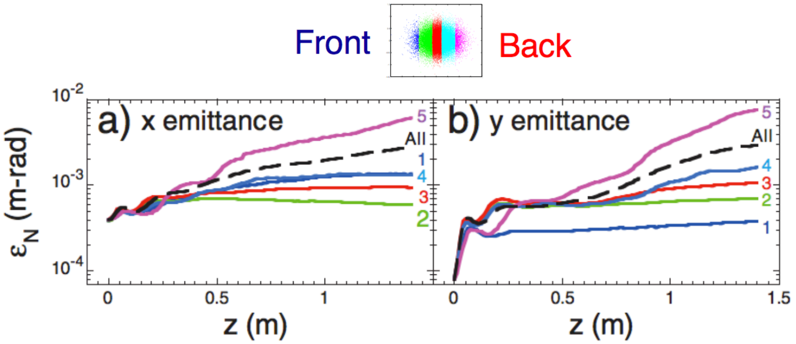
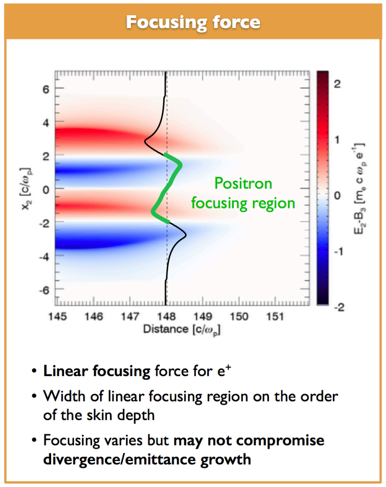
Potential for preserved emittance in nonlinear plasma wakefield

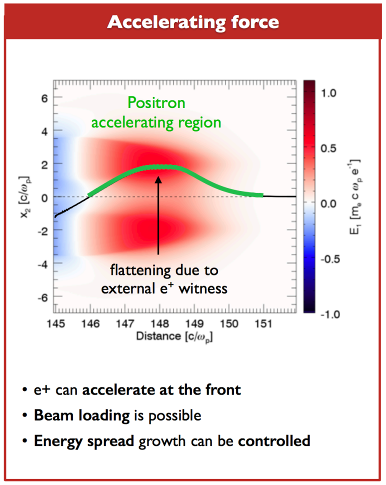
Betatron cooling?



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



- **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**



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

Nonlinear plasma wakefield

For high positron charge, and to reach good efficiency, same problem as quasi-linear regime (but relaxed because of higher fields) :

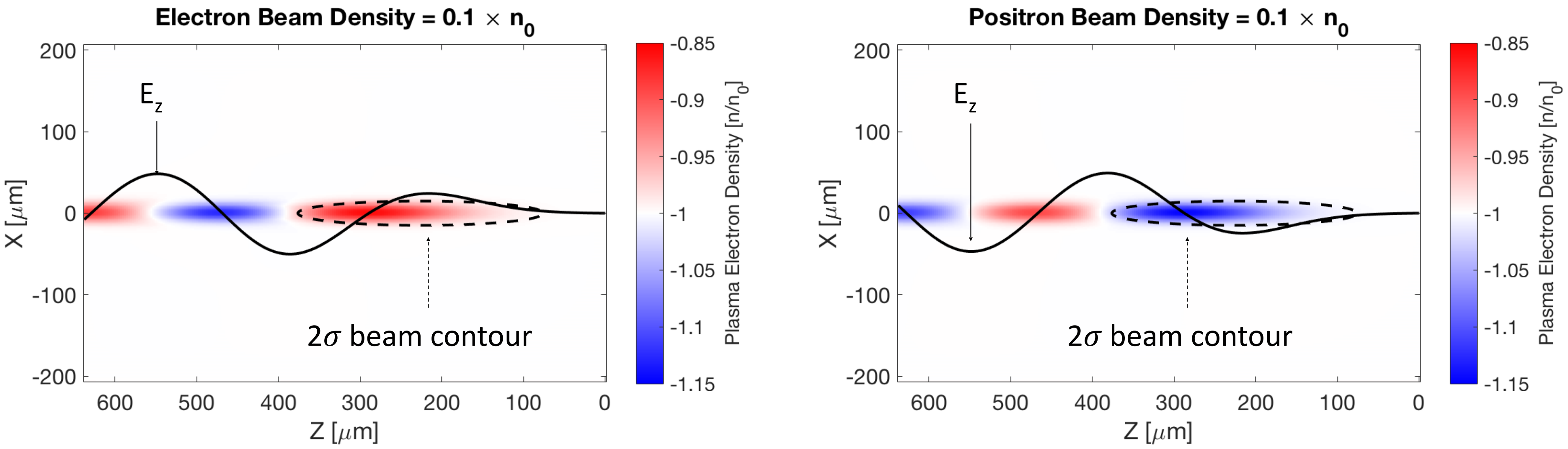
strong self wakefield

electron motion

non-Gaussian radial equilibrium

Challenges for uniform plasmas

General problematic of electron motion:

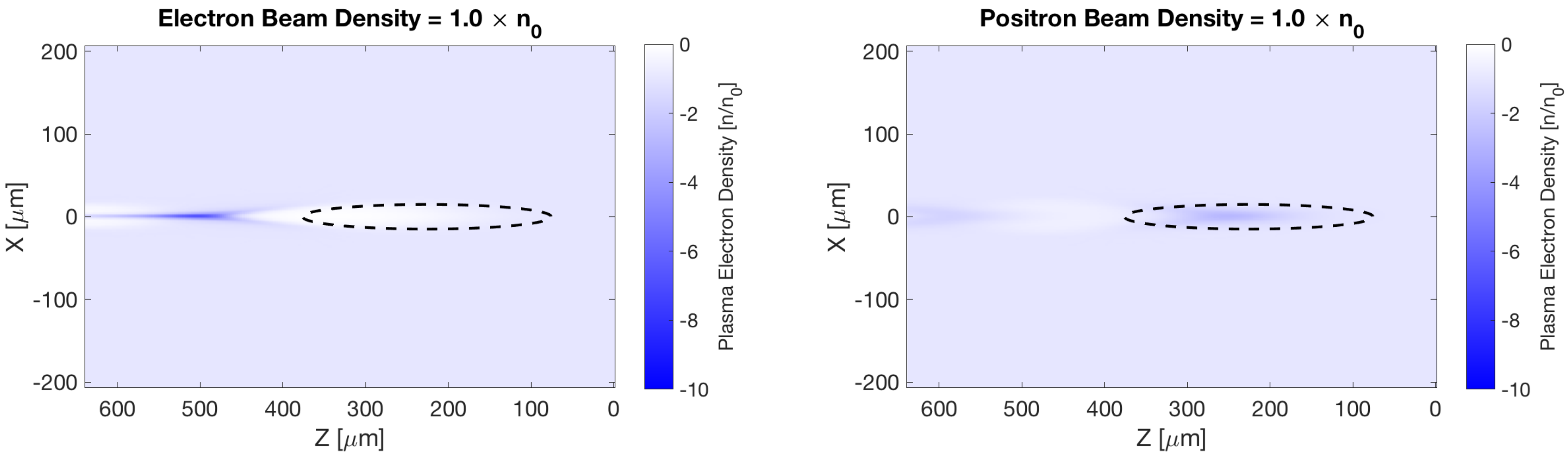


In the linear regime, the response is symmetric.

QuickPIC Simulation run on Hoffman2 at UCLA

Challenges for uniform plasmas

General problematic of electron motion:



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

QuickPIC Simulation run on Hoffman2 at UCLA

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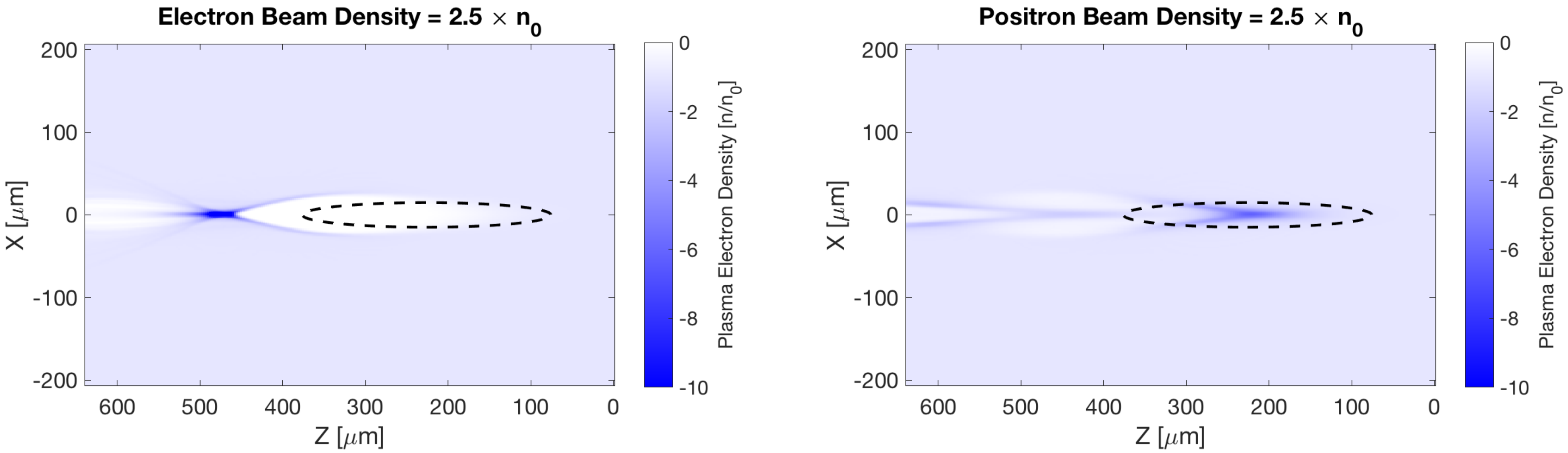

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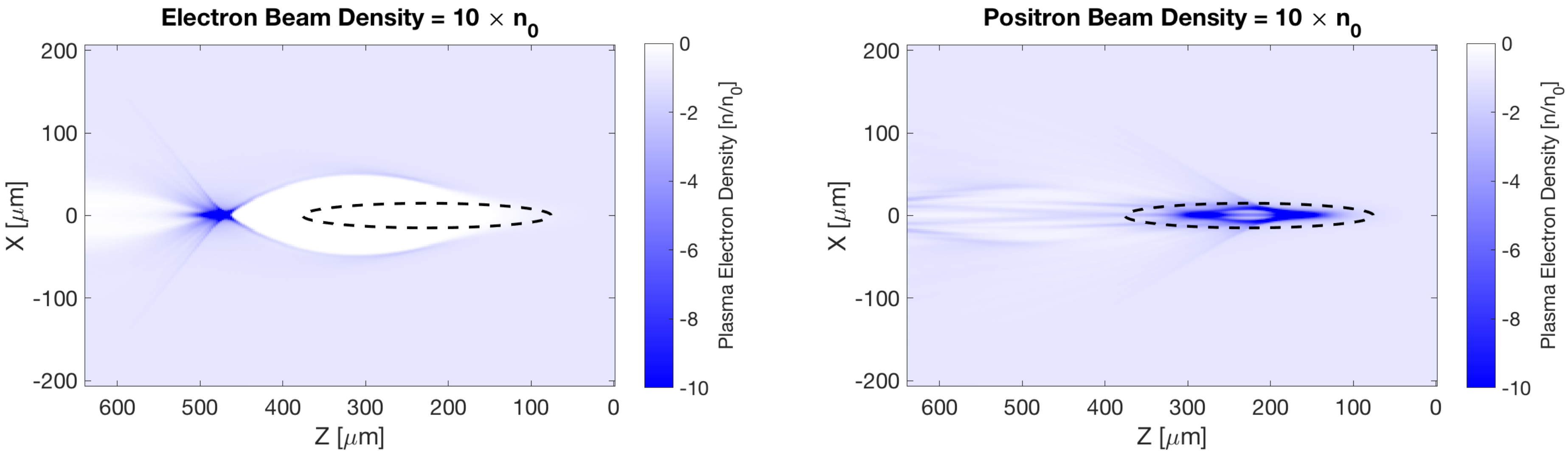

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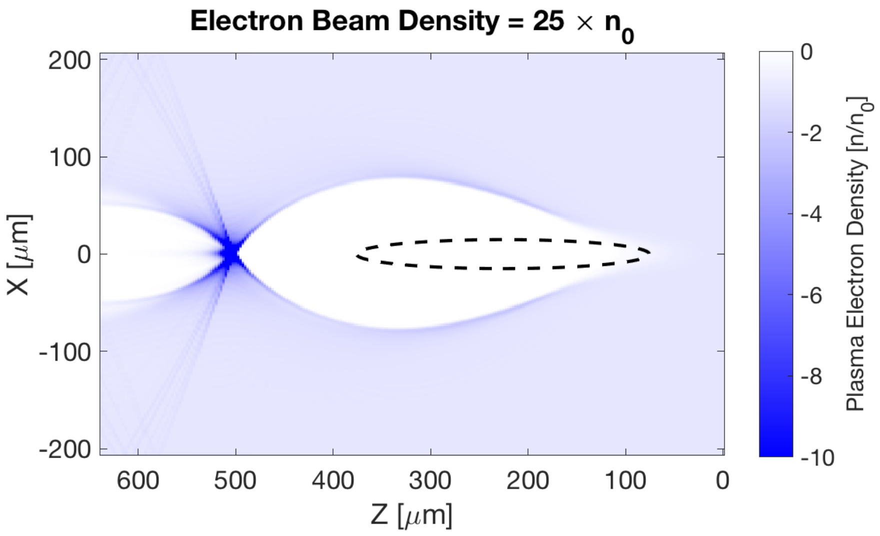
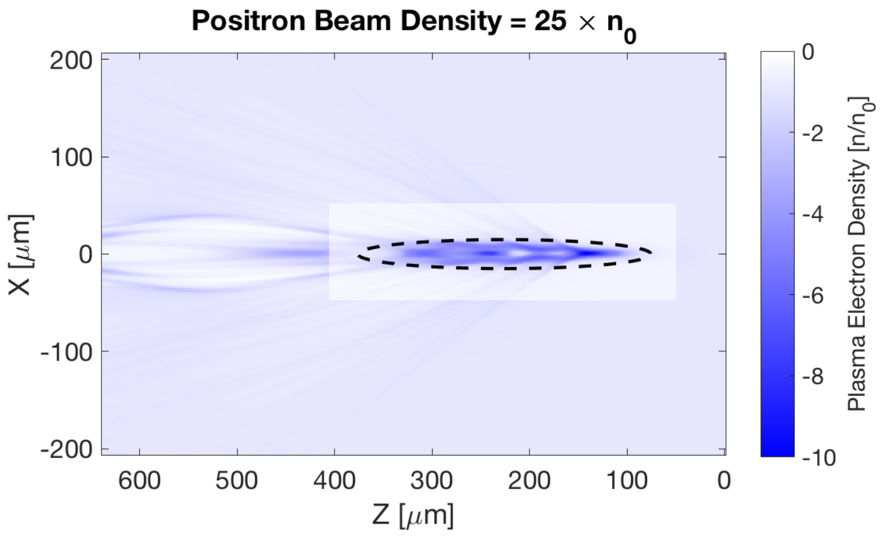

Electron Beam Density = 25 × n_0


Positron Beam Density = 25 × n_0

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

And more complicated.

QuickPIC Simulation run on Hoffman2 at UCLA

Hollow plasma channels

➢ Need mitigation mechanisms for transverse instability in hollow plasma channels.

➢ Interbunch: effect of drive transverse wakefield on trailing positron bunch must be cancelled by placing the trailing bunch at the zero crossing of the transverse wakefield.

➢ Intrabunch: transverse wakefield from the trailing e^+ bunch on itself, requires instability mitigation:

- Standard method: external focusing and energy chirp (BNS damping).

  → need research for higher focusing gradient optics

  Lensing with high-energy counter propagating electrons?
  (C. Lindstrøm, PhD thesis, 2019)

  → final dechirper to allow for higher chirp in the main plasma linac

- Investigate flat geometries (flat beams, flat channels)
- C. Lindstrøm's optimization with 1% energy spread and 1 T pole field: reaching 1 GeV/m requires large drive charge (~10 nC), don't go to small channel diameters (~500 um ok), requires 10-100 nm alignment tolerances.

Future research towards plasma-based e$^-$/e$^+$ collider

Goal: to achieve simultaneously stability, low emittance, high efficiency

Challenges for electron acceleration in blowout regime

ion motion

hosing instability

Challenges for positron acceleration in plasma

electron motion

beam breakup instability

(uniform plasma)

(hollow plasma)

To be discussed: table of beam parameters for a plasma-based e^-/e^+ collider

electron beam parameters

(assumes 4x times better interstage wrt Lindstrøm apochromatic design: 10 m instead of 40 m at 500 GeV)

Drive beam		Main beam	
Energy	100 GeV	Final energy	10 TeV
Charge	2 nC	Charge	1 nC
Normalized Emittance	<10 mm.mrad	Normalized emittance	<0.1 mm.mrad
Energy spread	<1%	Energy spread	<1%

Accelerator parameters	
Accelerating field	10 GV/m
Wall plug efficiency	1-10 %
Repetition rate	10-1000 kHz
Plasma stage length	10 m
Number of stages	100
Total interstage length	3 km
Total plasma linac length	4 km
Tolerances	<10-100 nm, <0.1-1 urad

positron beam parameters

(assumes hollow channel with 1T pole external focusing)

Drive beam		Main beam	
Energy	100 GeV	Final energy	10 TeV
Charge	10 nC	Charge	5 nC
Normalized Emittance	<10 mm.mrad	Normalized emittance	<0.1 mm.mrad
Energy spread	<1%	Energy spread	<1%

Accelerator parameters	
Accelerating field	1 GV/m
Wall plug efficiency	1-10 %
Repetition rate	10-1000 kHz
Plasma stage length	100 m
Number of stages	100
Total interstage length	3 km
Total plasma linac length	13 km
Tolerances	<10-100 nm, <0.1-1 urad

S. Corde, M. Hogan, S. Gessner, C. Lindstrøm

Conclusion

Quasi-linear plasma wakefield

How to accelerate low emittance beams with high efficiency?

Multi-pulse, energy recovery, nonlinear beamloading.

Hollow plasma channels

How to mitigate transverse instabilities?

Position trailing bunch at zero-crossing of transverse wakefield, look for damping mechanisms, flat channels, electron lensing.

Nonlinear plasma wakefield

How to preserve emittance?

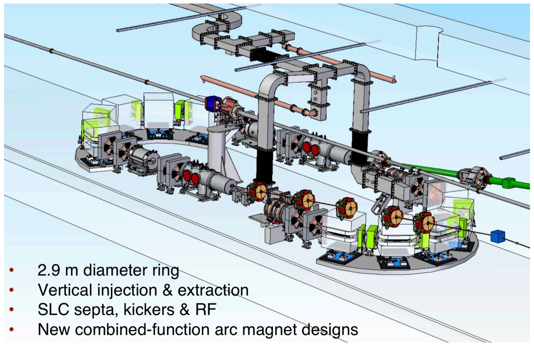
Doughnut-shaped wakes, weird trailing bunch shaping, single-stage accelerator, betatron cooling.

Futures experiments:

- ➢ In-situ (in plasma) generation of positrons in FACET-II 1st phase
- ➢ Use of electrons to study linear regime and hollow plasma channels
- ➢ 2nd phase of FACET-II: delivery of positron beams to IP

Thank you for your attention

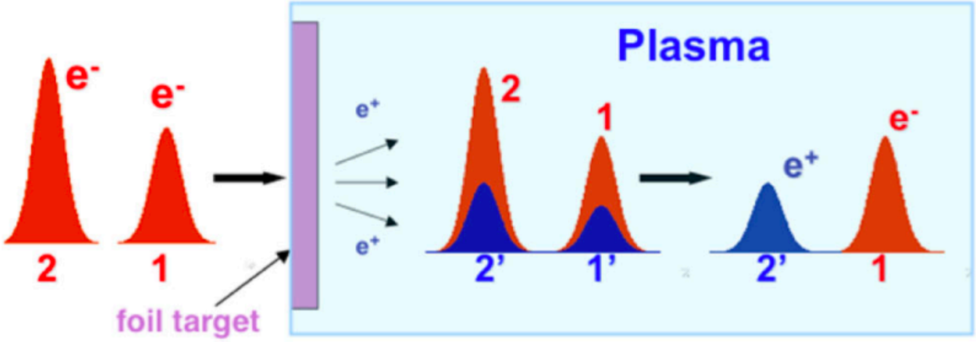
Positron sources?



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

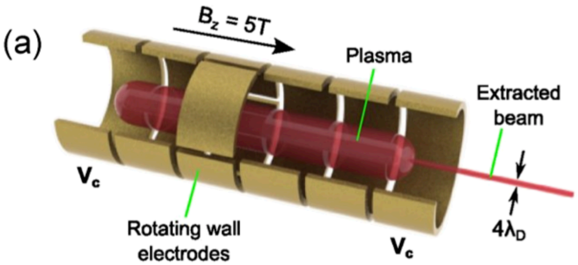
Compact Damping Rings

V. Yakimenko, FACET-II TDR, SLAC-R-1072



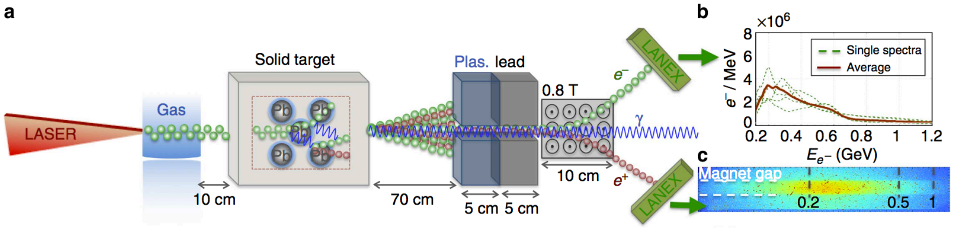
In-Situ Positron Generation

X. Wang, PRL 101, 124801 (2008)



Positron Beams from Electro-static Traps

J. Danielson, Rev. Mod. Phys., Vol. 87, 2015

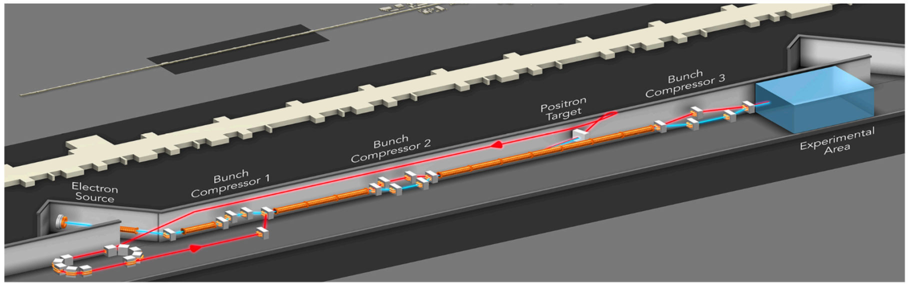


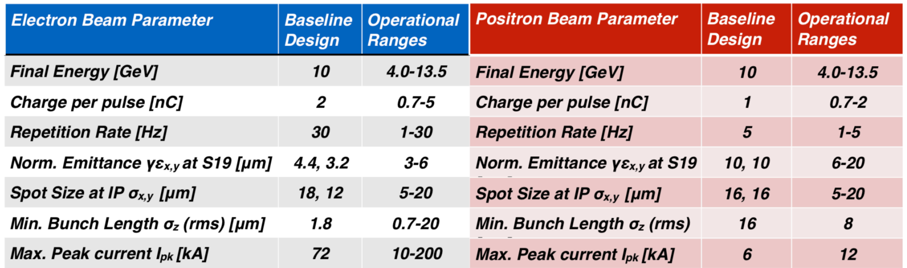
Laser Generated Positron Beams

G. Sarri, Nat. Comm., 6747, 2015

Positron facilities?

FACET-II @ SLAC

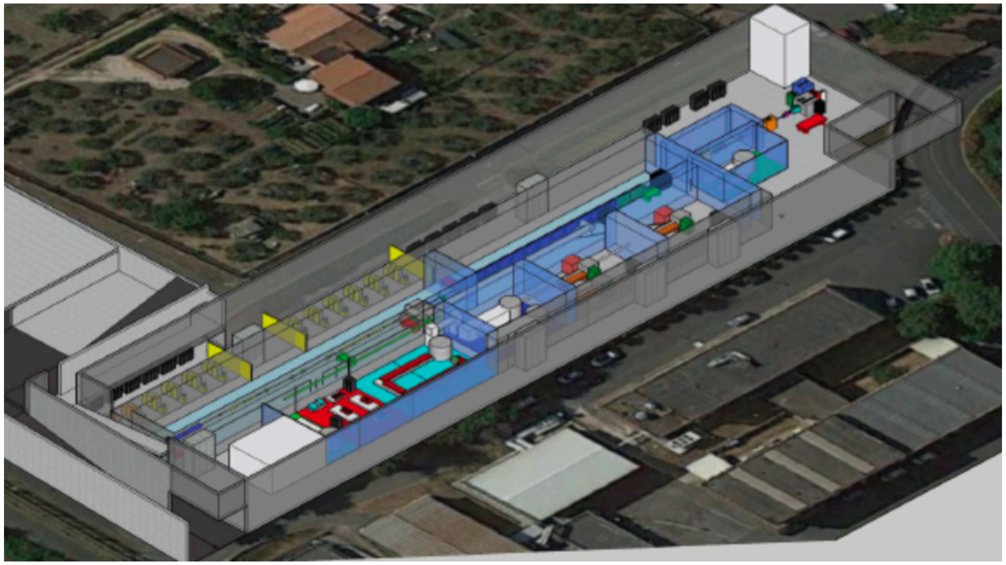




Electron Beam Parameter	*Baseline Design*	*Operational Ranges*	*Positron Beam Parameter*	*Baseline Design*	*Operational Ranges*
Final Energy [GeV]	*10*	*4.0-13.5*	*Final Energy [GeV]*	*10*	*4.0-13.5*
Charge per pulse [nC]	*2*	*0.7-5*	*Charge per pulse [nC]*	*1*	*0.7-2*
Repetition Rate [Hz]	*30*	*1-30*	*Repetition Rate [Hz]*	*5*	*1-5*
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19 [μm]	*4.4, 3.2*	*3-6*	*Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19*	*10, 10*	*6-20*
Spot Size at IP $\sigma_{x,y}$ [μm]	*18, 12*	*5-20*	*Spot Size at IP $\sigma_{x,y}$ [μm]*	*16, 16*	*5-20*
Min. Bunch Length σ_z (rms) [μm]	*1.8*	*0.7-20*	*Min. Bunch Length σ_z (rms)*	*16*	*8*
Max. Peak current I_{pk} [kA]	*72*	*10-200*	*Max. Peak current I_{pk} [kA]*	*6*	*12*

FACET-II is the only facility that plans to provide positron beams for PWFA experiments. Contact M. Hogan for more information: hogan@slac.stanford.edu

EUPRAXIA @ LNF



The design for EUPRAXIA includes a user facility for positron beams. An exciting development! Contact R. Walczak for details: roman.walczak@physics.ox.ac.uk

Linear plasma wakefield

Alternative: multi bunch and energy recovery

But: luminosity decreases when charge per bunch decreases

Main figure of merit!

$$\mathcal{L} = \frac{N^2 f}{4\pi\sigma_x\sigma_y} \qquad \Longrightarrow \qquad \frac{\mathcal{L}}{P_{\text{wall}}} \sim \boxed{\frac{N\eta_{\text{driver}}\eta_{\text{wake}}}{\epsilon_r}}$$