CLIC Workshop 2019

Status of Positron Acceleration in PWFA

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January 23, 2019

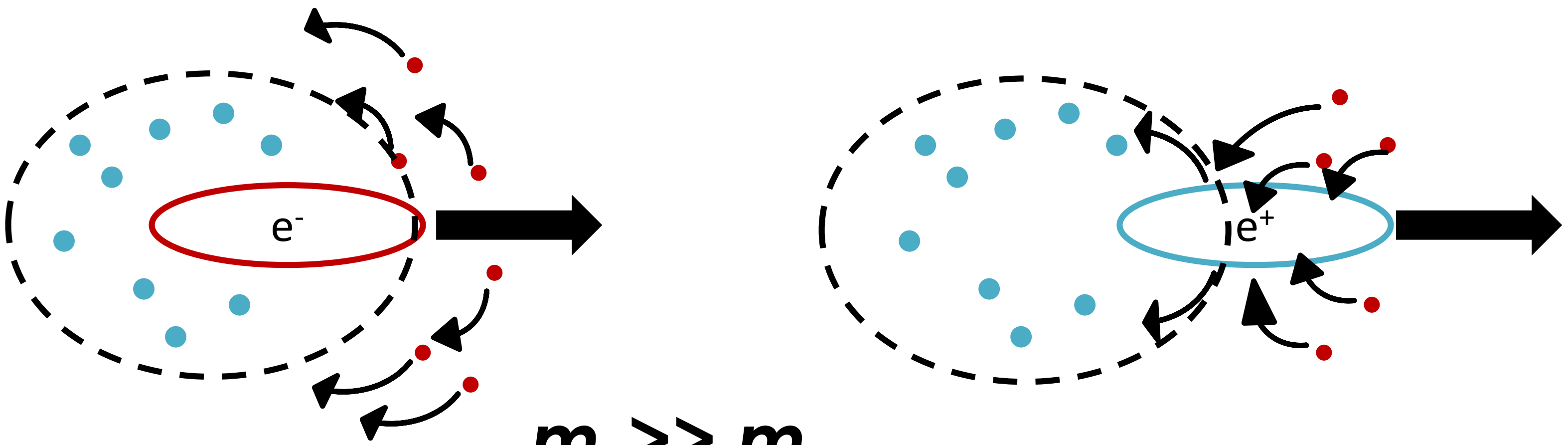
Outline

- 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 schemes (both laser-driven and particle-beam-driven) are promising candidates for an advanced linear collider. But plasmas are asymmetric accelerators: there are profound difference between electron and positron acceleration in plasmas.



$m_i >> m_e$

The plasma electrons are mobile but the ions are not.

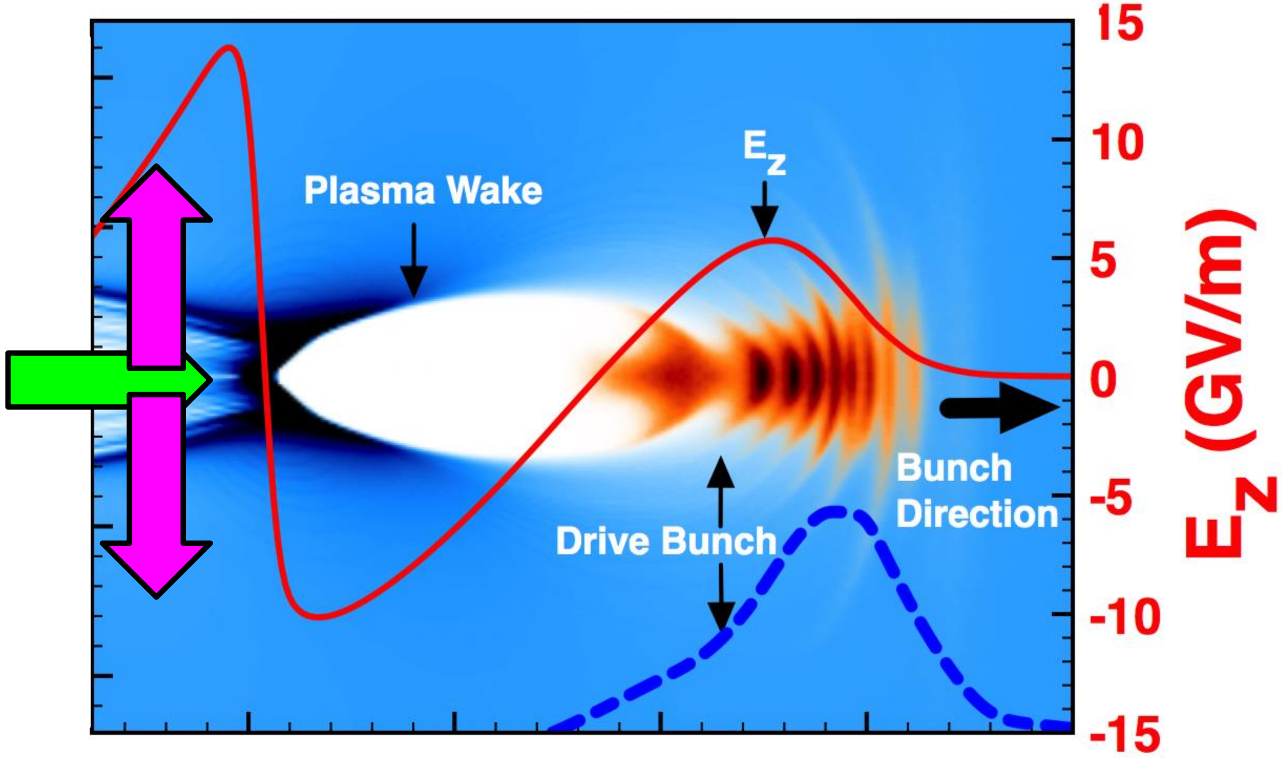
The symmetry of the accelerating mechanism is broken.

Exception

Linear plasma waves are symmetrical.

Plasmas in nonlinear regime are asymmetric accelerators

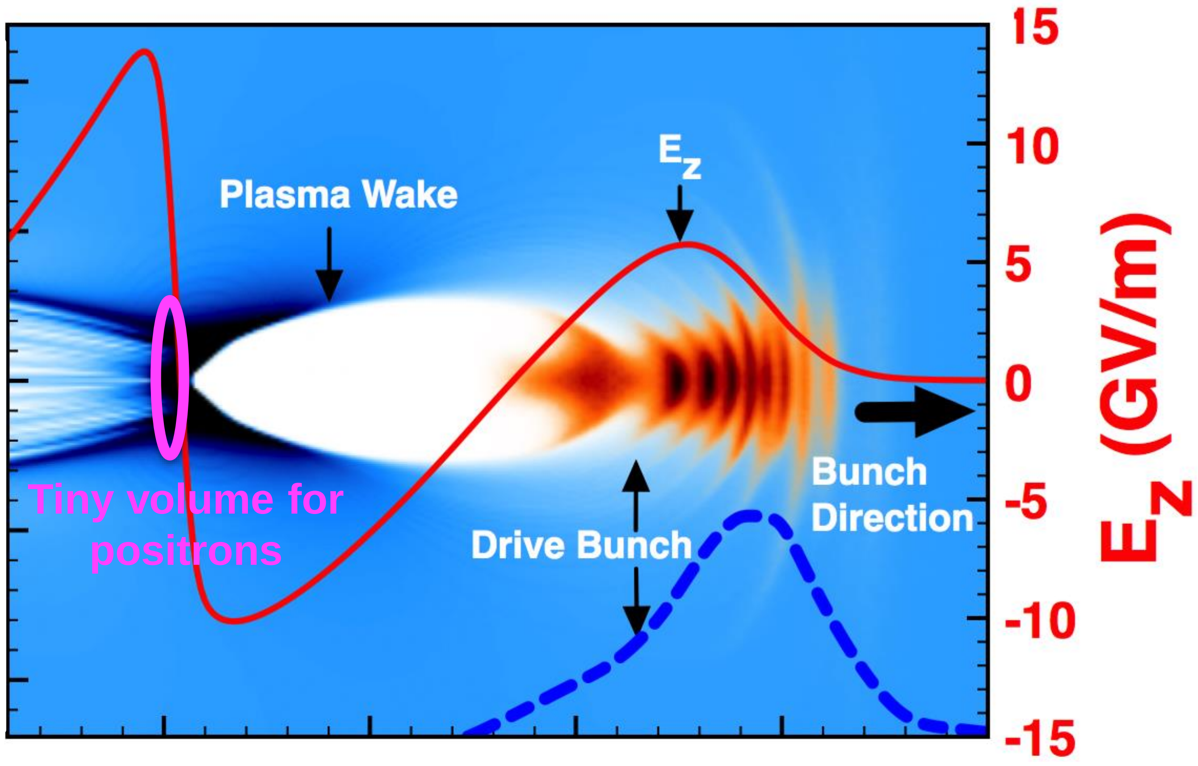
Electron-driven or laser-driven nonlinear blowout wakes:



But the field is defocusing in this region.

Plasmas in nonlinear regime are asymmetric accelerators

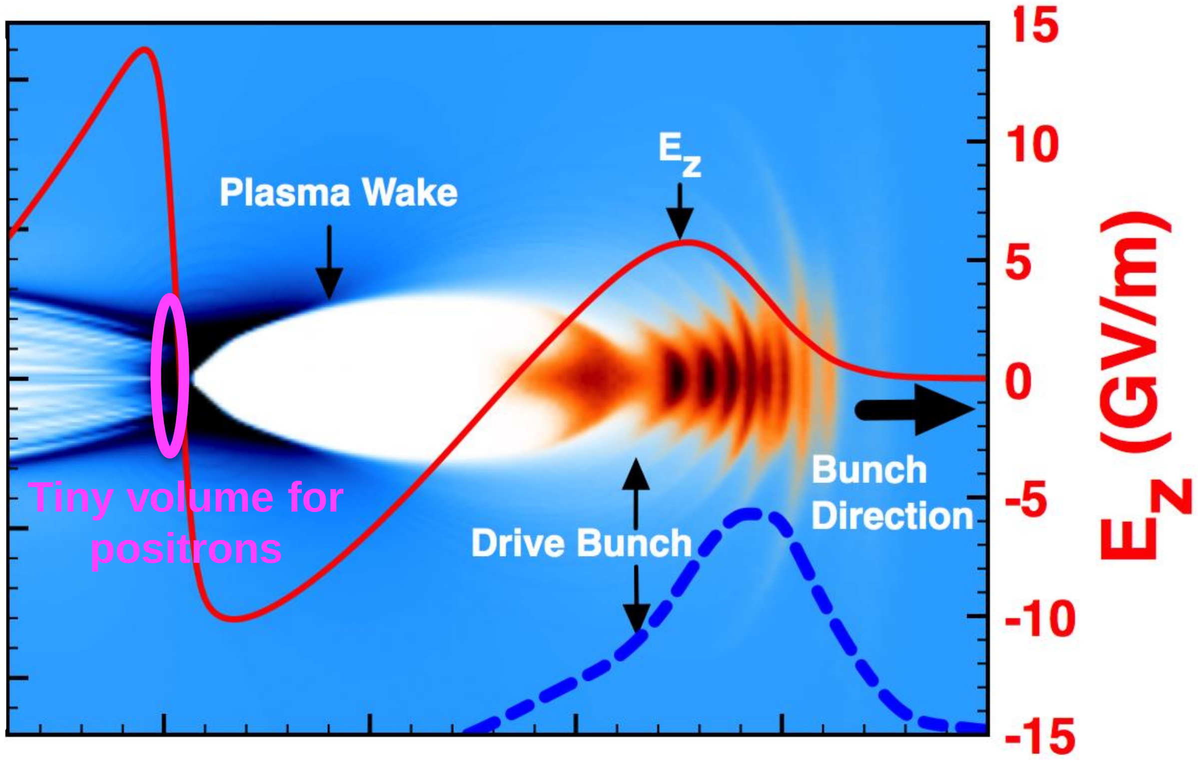
Electron-driven or laser-driven nonlinear blowout wakes:



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:



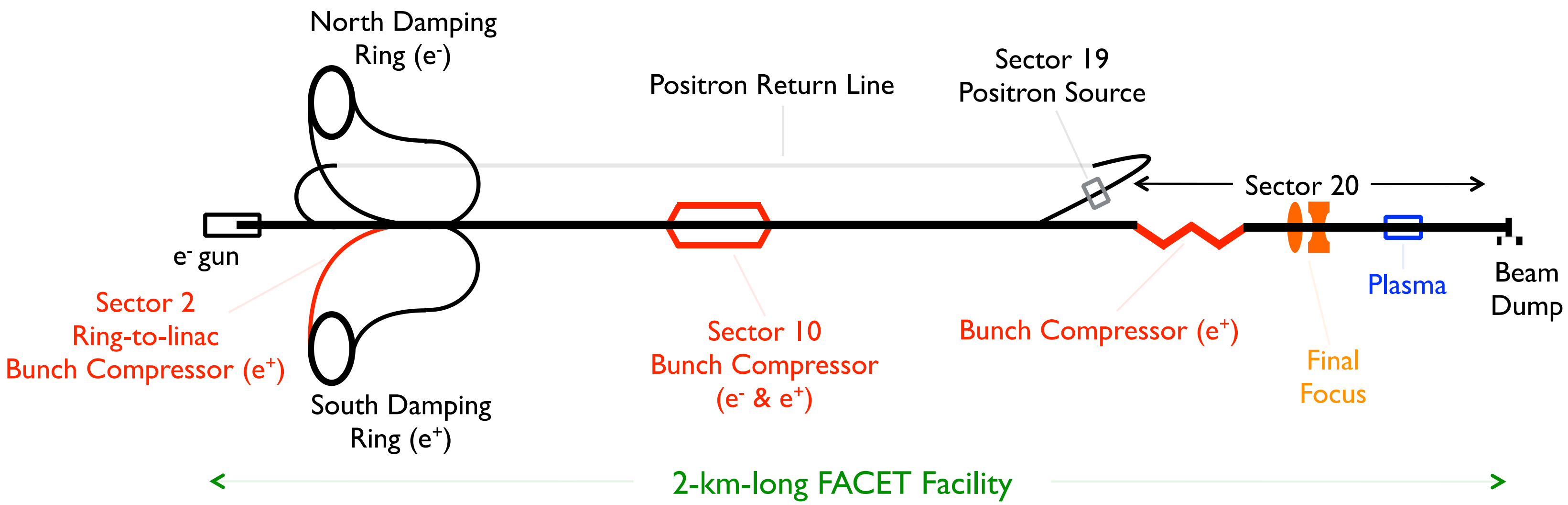
Transverse force is highly nonlinear in r

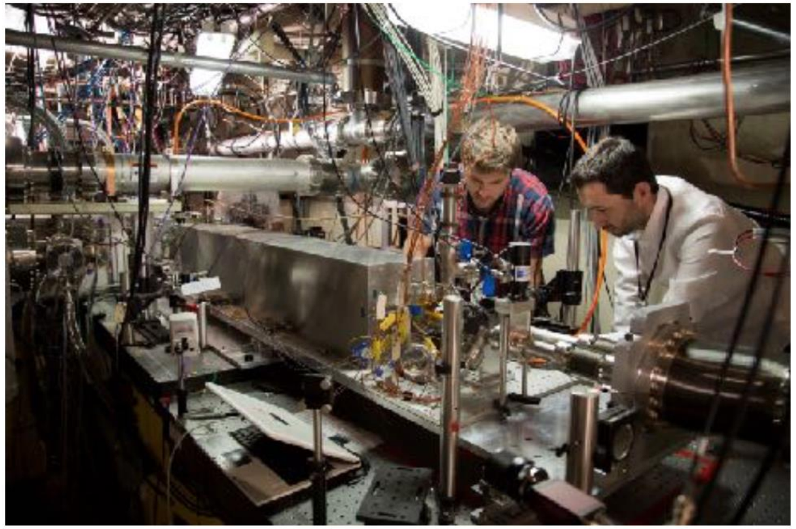
→ emittance growth

Experimental progress in plasma-based positron acceleration

Positron acceleration in PWFA

FACET SLAC NATIONAL ACCELERATOR LABORATORY



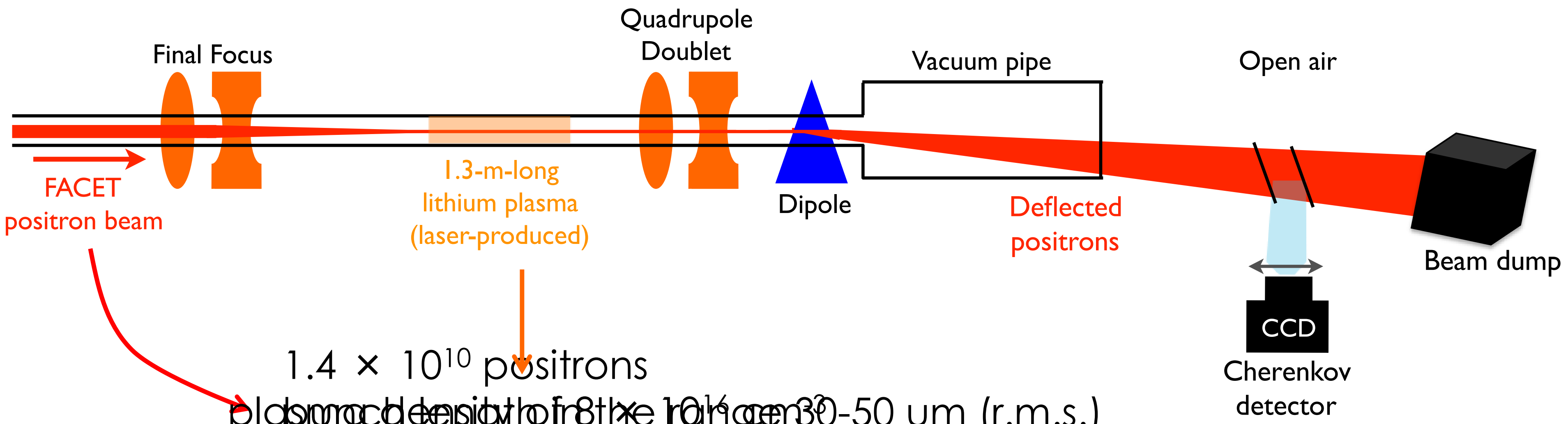


Spencer Gessner (left) and Sebastien Corde (right) at FACET tunnel, SLAC.
Image source: SLAC National Accelerator Laboratory

- 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

plasma density of 8×10^{16} cm^{-3}

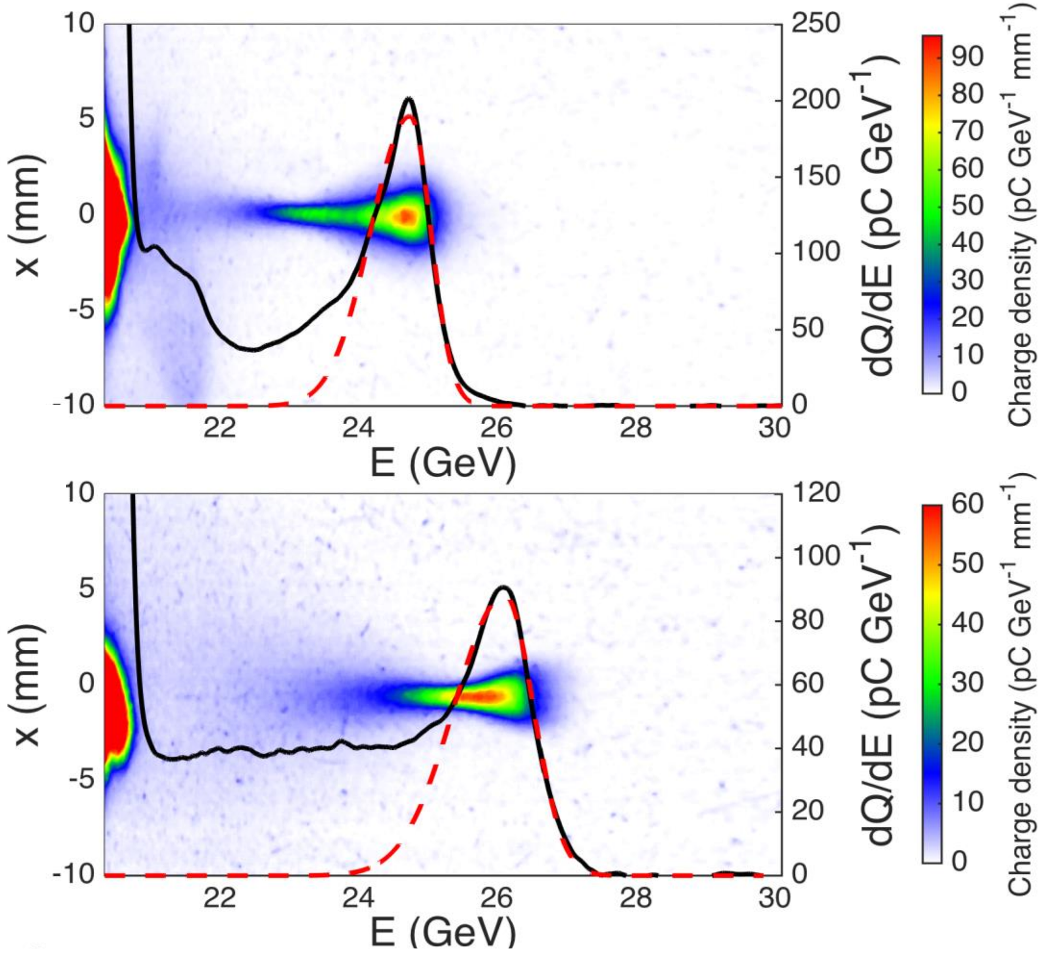
bunch length in the range 30-50 um (r.m.s.)

20.35 GeV energy

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

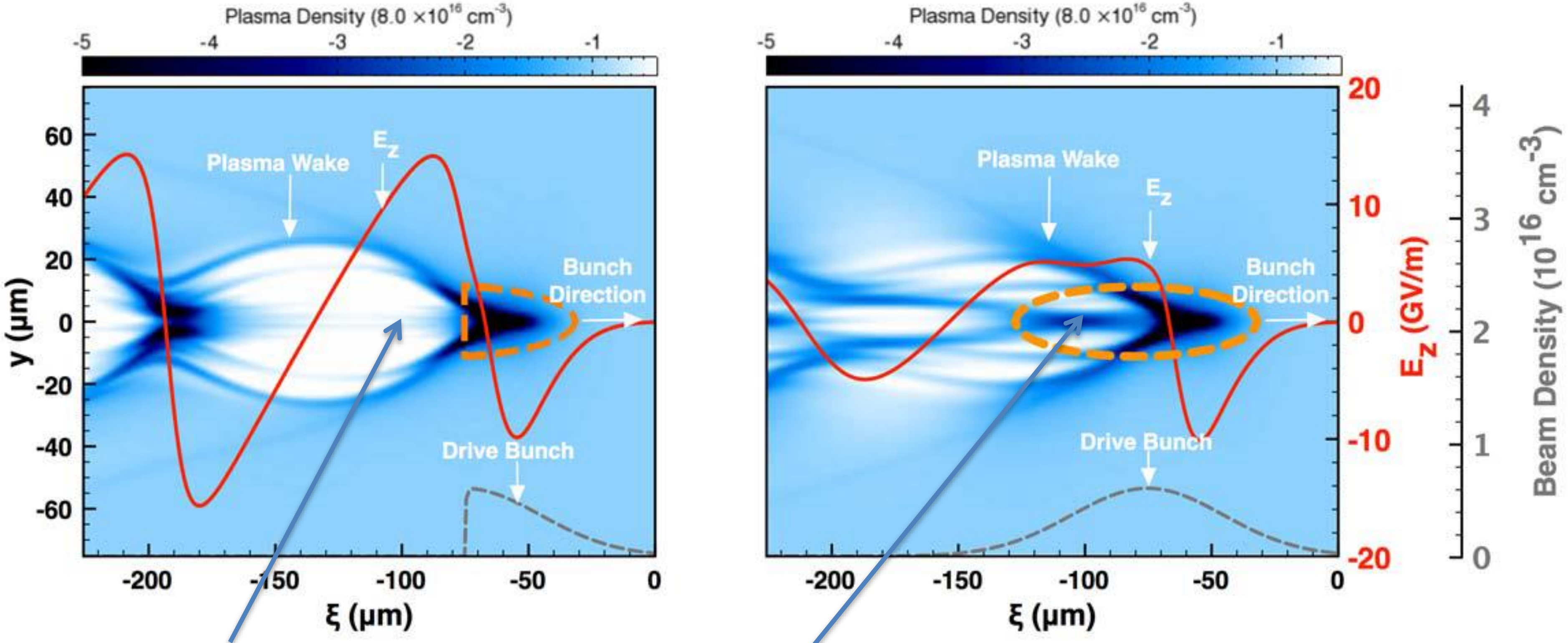


S. Corde *et al.*, Nature **524**, 442 (2015)

Positron acceleration in uniform plasma

QuickPIC simulations: loaded vs unloaded wake (truncated bunch)

Unloaded Loaded



defocusing focusing

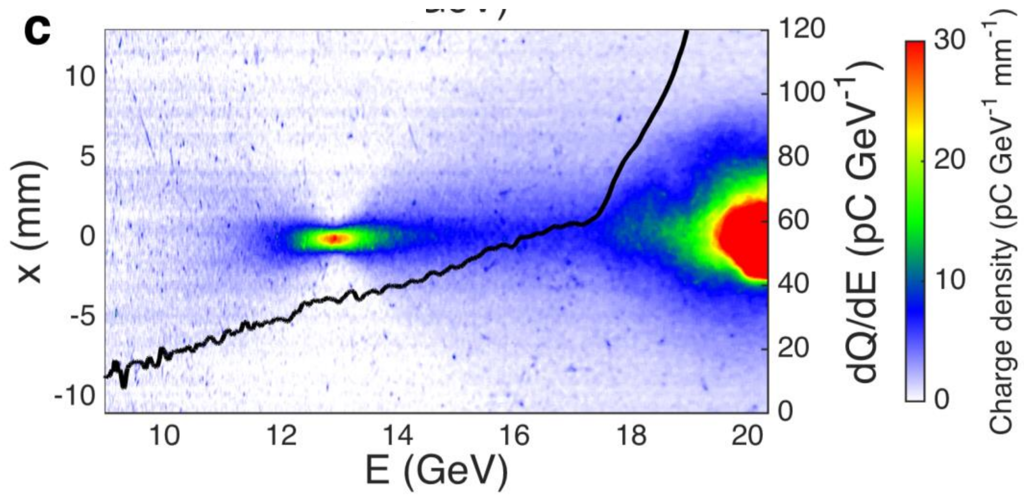
Beam loading also affects transverse fields for positron driven wakes!

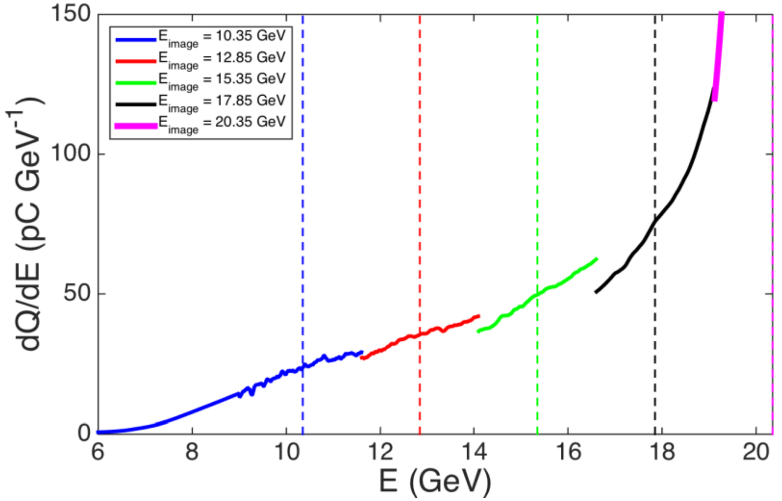
S. Corde *et al.*, Nature **524**, 442 (2015)

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.

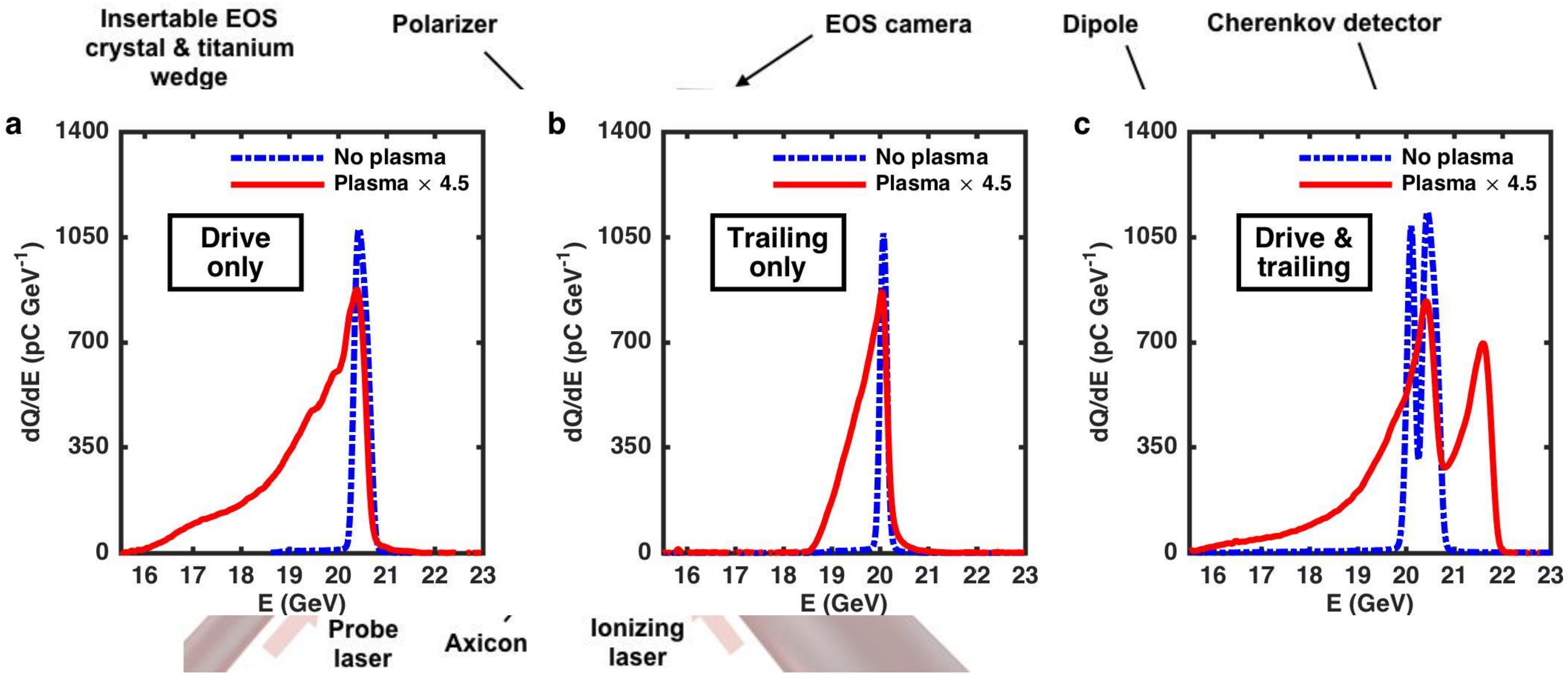




Positron acceleration in uniform plasma

For multi-stage plasma-based positron acceleration:

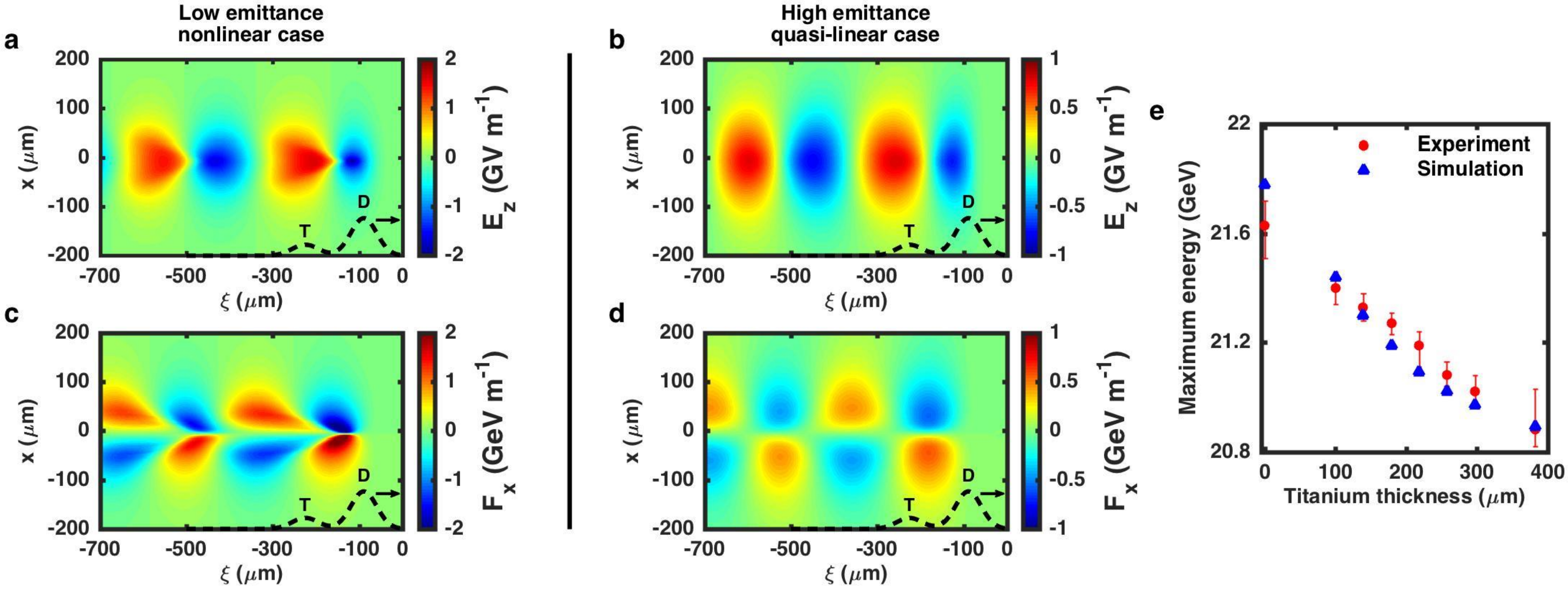
- need to demonstrate the acceleration of a distinct bunch of positrons (trailing)
- need a two-bunch experimental setup (drive + trailing)



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



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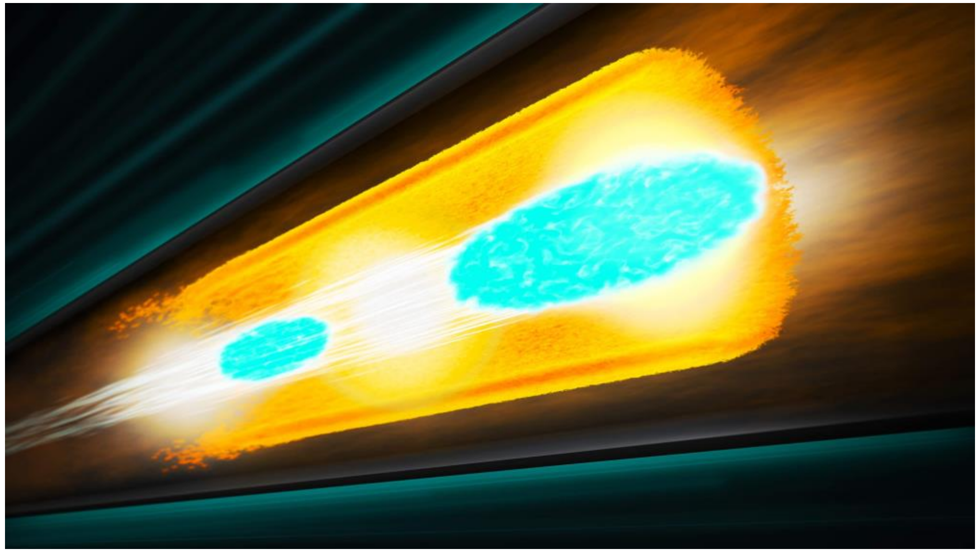
Positron acceleration in hollow plasma channels

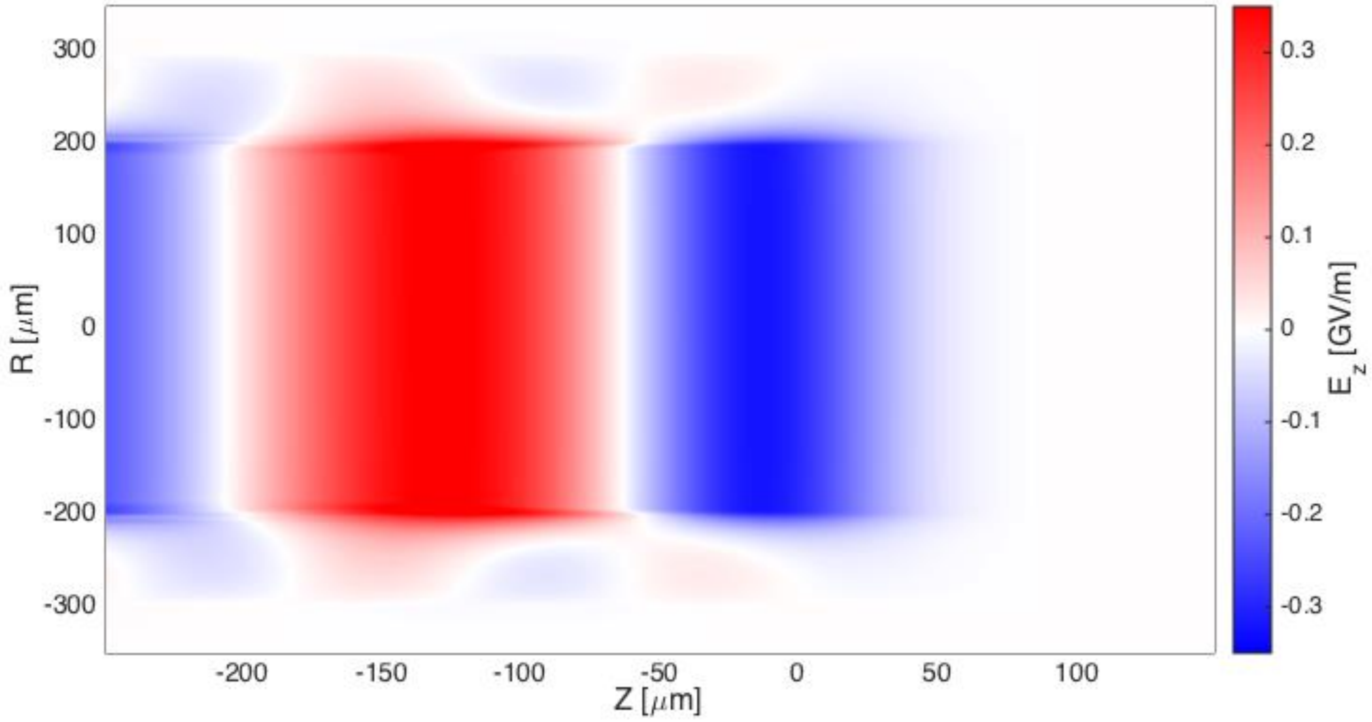


An alternative idea: the hollow plasma channel, a tube of plasma

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

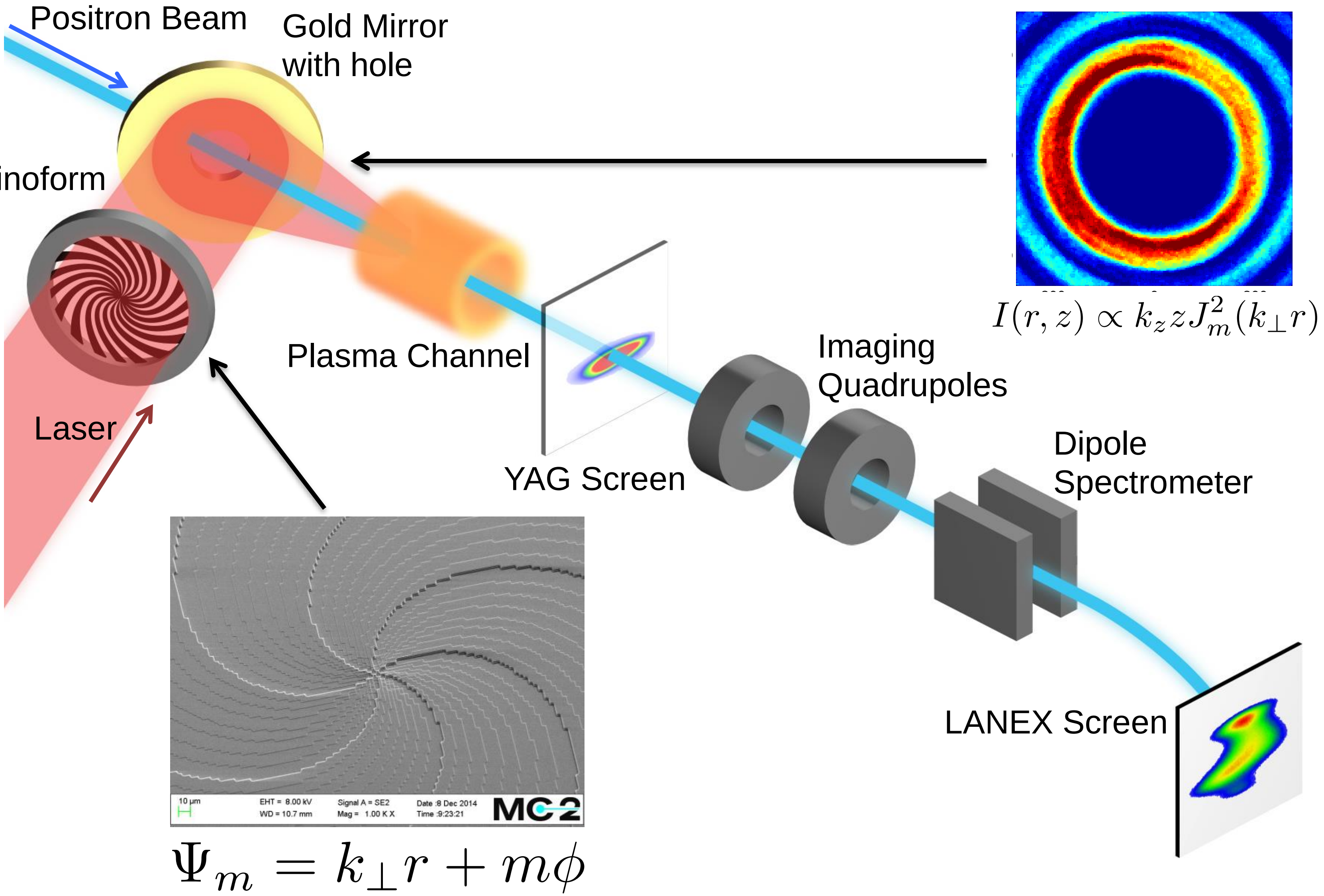
Positron acceleration in hollow plasma channels

E_z



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

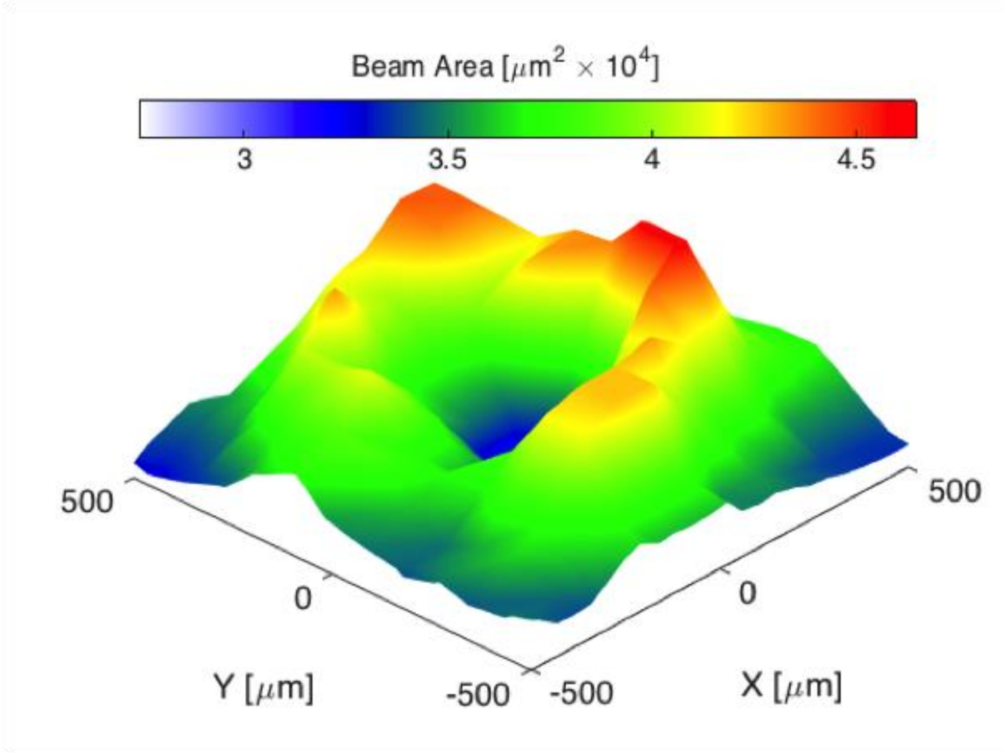
Positron acceleration in hollow plasma channels



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.

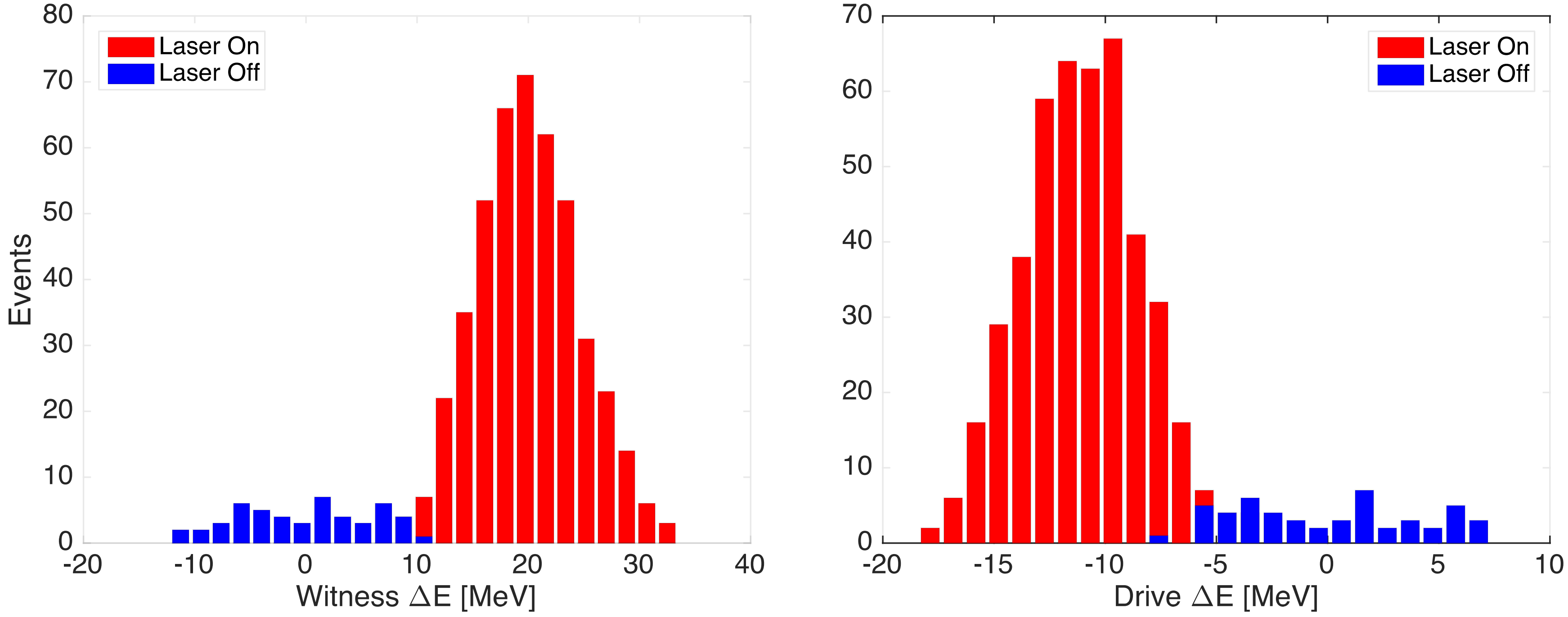
Both the Kick Map and Beam Area Measurement (Volcano Plot) are consistent with an annular plasma channel.



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

Positron acceleration in hollow plasma channels

Hollow plasma channel with two beams:



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

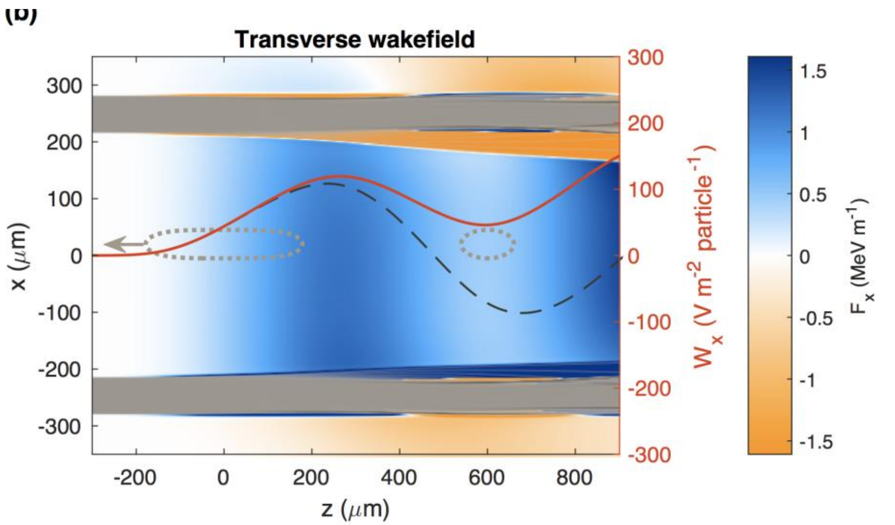
Positron acceleration in hollow plasma channels

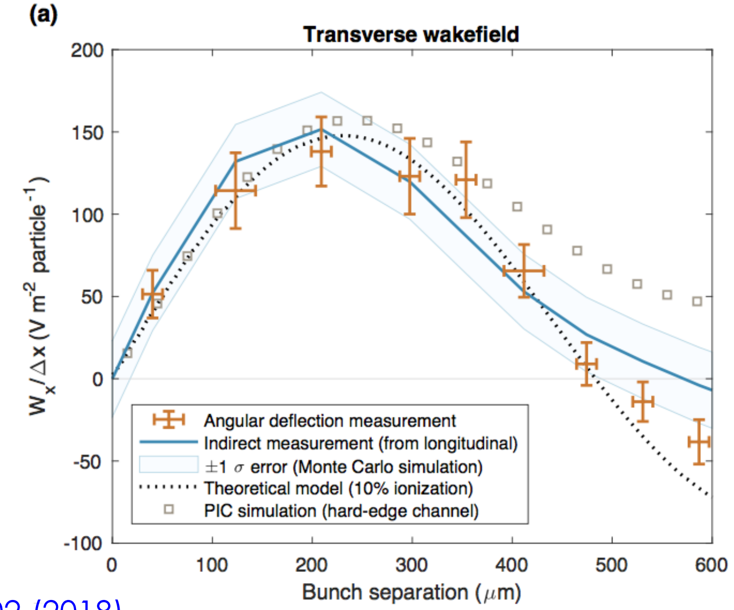
- Typical CLIC transverse wakefields per offset in structures:
  ~1-100 V/pC/m/mm

- Hollow channel (500 μm diameter at 3 x 10^{15} cm^{-3}):
  ~150 V/m^2/particle = ~1 000 000 V/pC/m/mm

  - Experimental measurement [C. Lindstrøm *et al.*, 2018] of transverse wakefield in hollow plasma channel largely agrees with theoretical model [C. Schroeder *et al.*, Phys. Rev. Lett. 82, 1177 (1999)].

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





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:

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

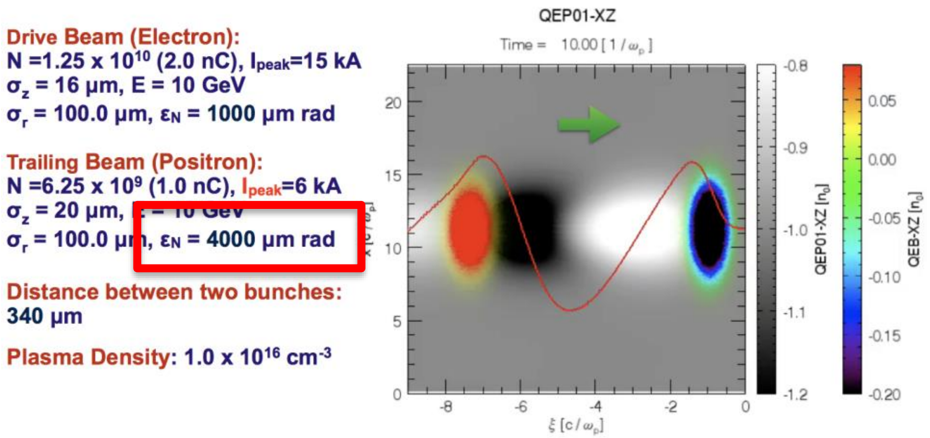
- How to accelerate trailing positron bunch in quasi-linear plasma wakefield?

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

- 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.



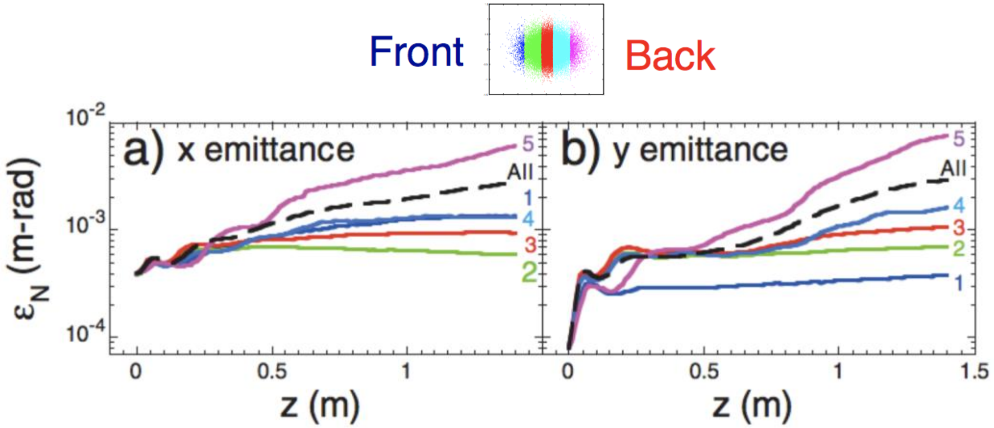
Challenges for nonlinear plasma wakefield

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

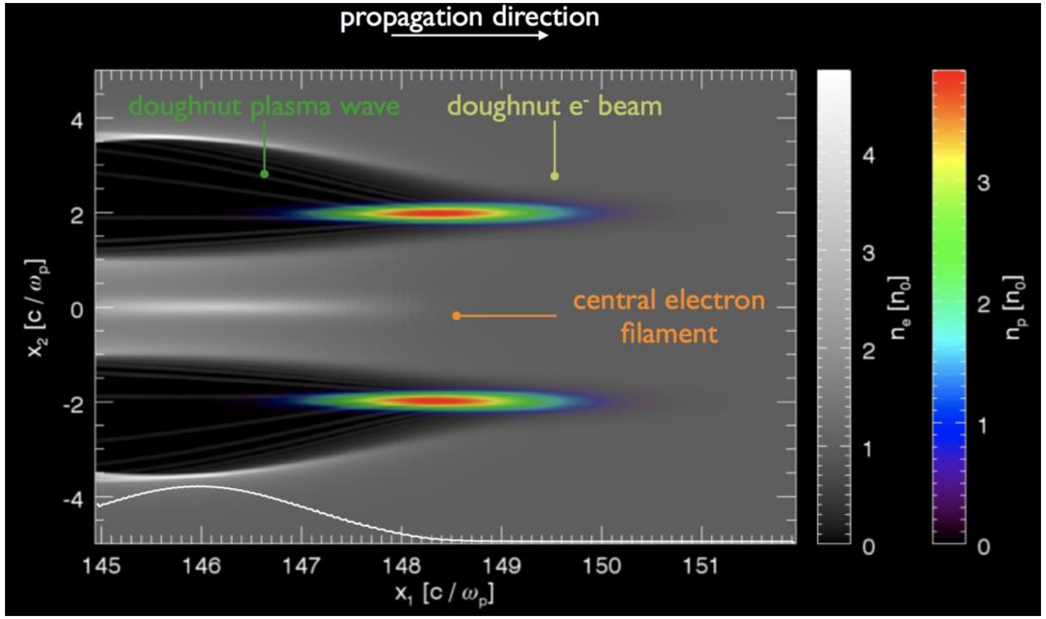
For positrons in the nonlinear regime, the focusing force is generally nonlinear in r, and is slice dependent.
→ emittance growth

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

Potential for high efficiency and preserved emittance in nonlinear plasma wakefield



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



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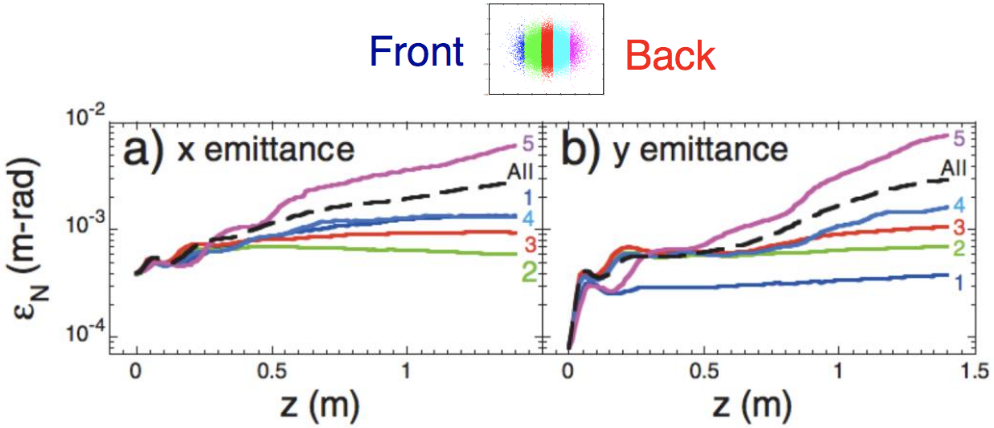
Betatron cooling?



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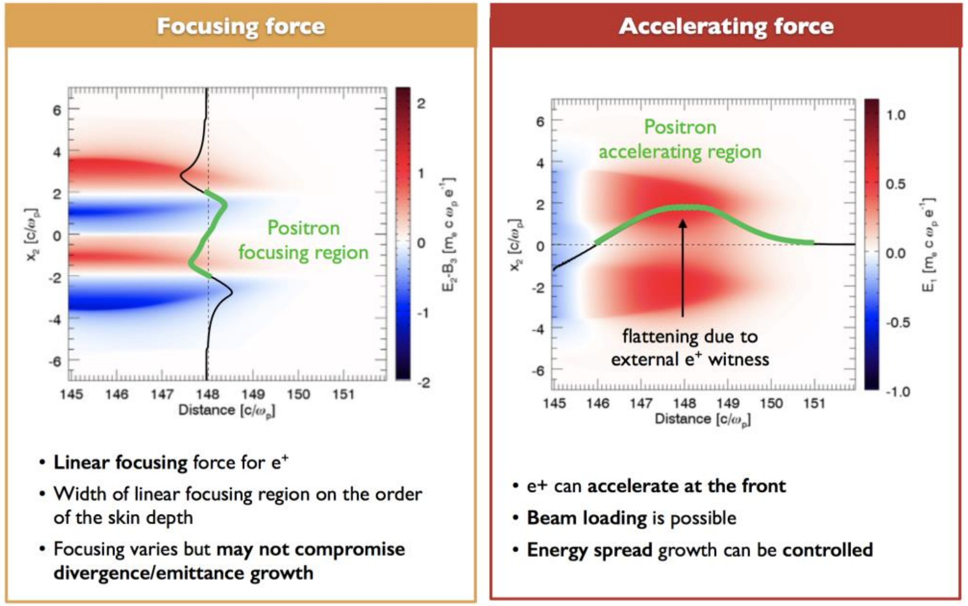

Challenges for hollow plasma channels

- **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 on itself, requires instability mitigation:
  - Standard method: external focusing and energy chirp (BNS damping).
    - → need research for higher focusing gradient optics
    - → final dechirper to allow for higher chirp in the main plasma linac
  - 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.
  - Study the use of flat geometries (flat beam and flat channel).
  - Coaxial geometries:
    - → still requires external focusing
    - → detuning achieved by nonlinear phase mixing, is there a compromise to reach between nonlinear emittance growth and instability mitigation?

Conclusion

Quasi-linear plasma wakefield

How to accelerate low emittance beams with high efficiency?

Multi-pulse, energy recovery.

Hollow plasma channels

How to mitigate transverse instabilities?

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

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