Positron acceleration in plasma-based particle accelerators

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On behalf of the E-200 collaboration

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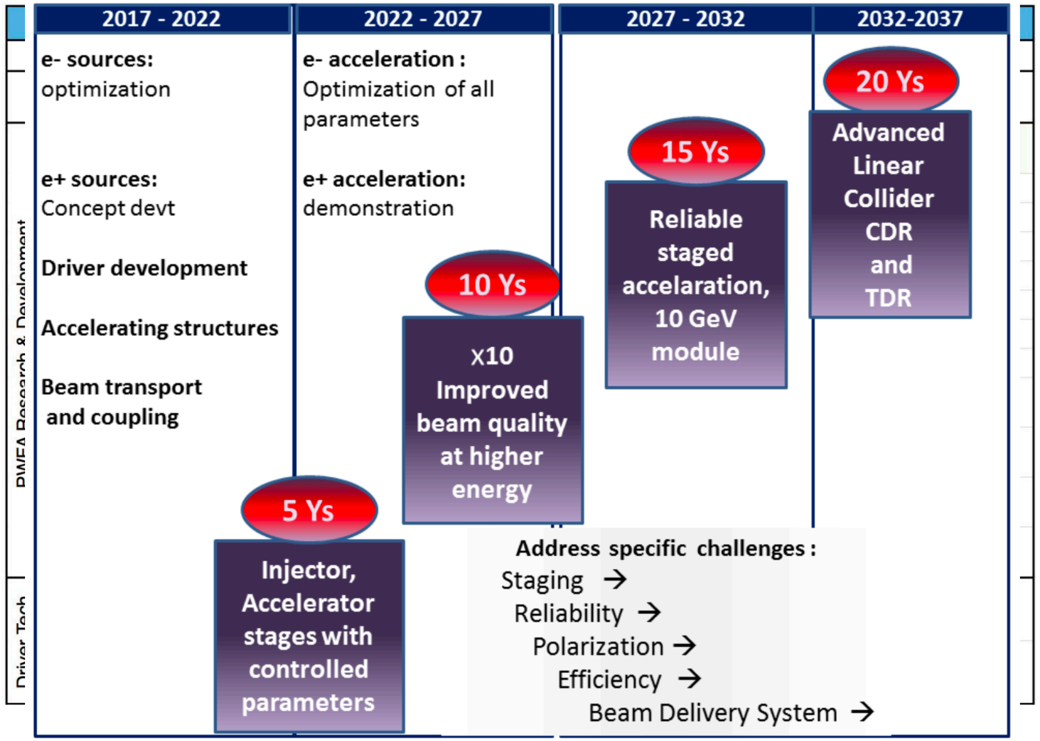
Outline

- Brief recall of the scientific context for positrons
- Single-bunch plasma-based positron acceleration
- Acceleration of a distinct positron bunch in a plasma
- What's next

Towards advanced linear colliders

Plasma acceleration is being considered for application to High Energy Physics experiments, where positrons are strongly desired.

US PWFA roadmap



Towards advanced linear colliders

Plasma acceleration is being considered for application to High Energy Physics experiments, where positrons are strongly desired.

→ **Positron is half the equation we have to deal with!**

Yet very little research on how to accelerate positrons in plasmas.

$$A = \frac{e^{+}\ \mathrm{research}}{e^{-}\ \mathrm{research}} \ll 1$$

Mostly due to the lack of facilities delivering positrons for plasma acceleration research.

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

Towards advanced linear colliders

As of now, no self-consistent scheme for accelerating positrons in plasma.

Plasma-based particle accelerators face a major challenge:

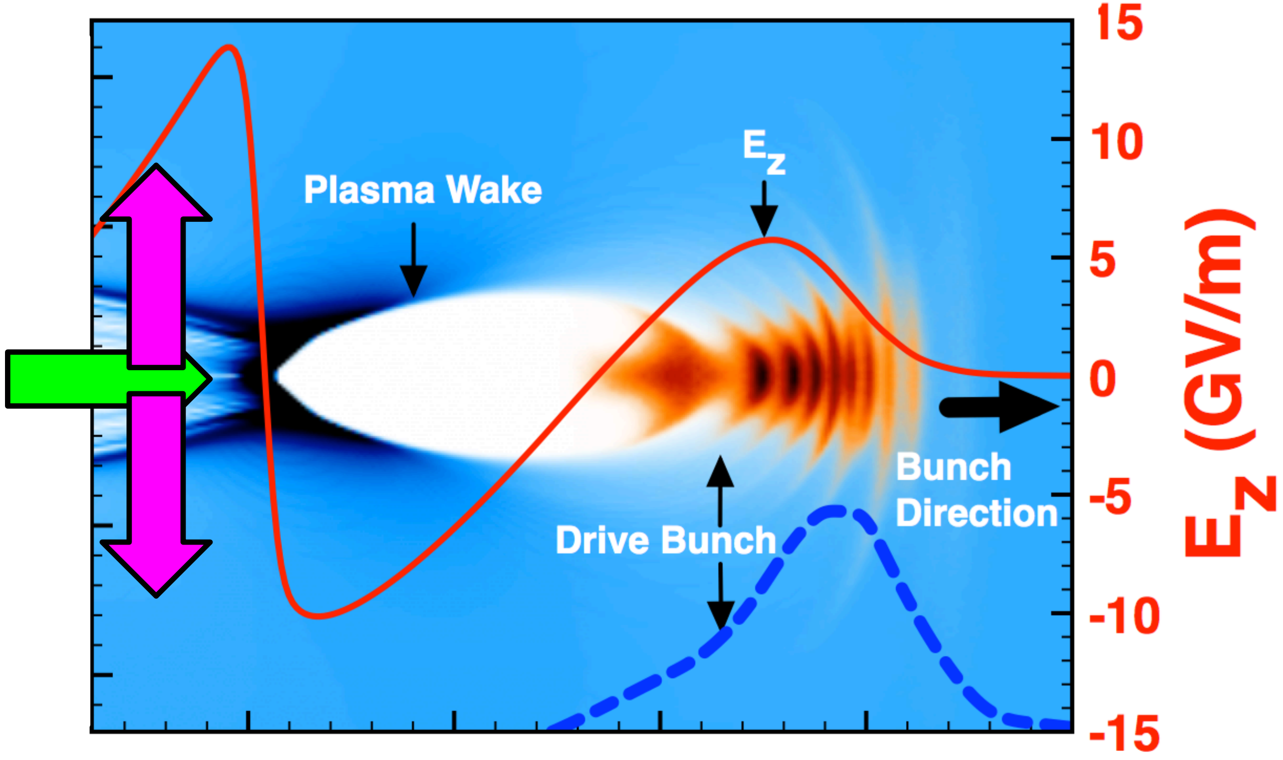
The positron problem

Can’t address all issues all at once, need to go step by step.

Need to raise awareness of this challenge to go “nonlinear” $A \sim 1$.

Plasma-based positron acceleration

Electron-driven blowout wakes:

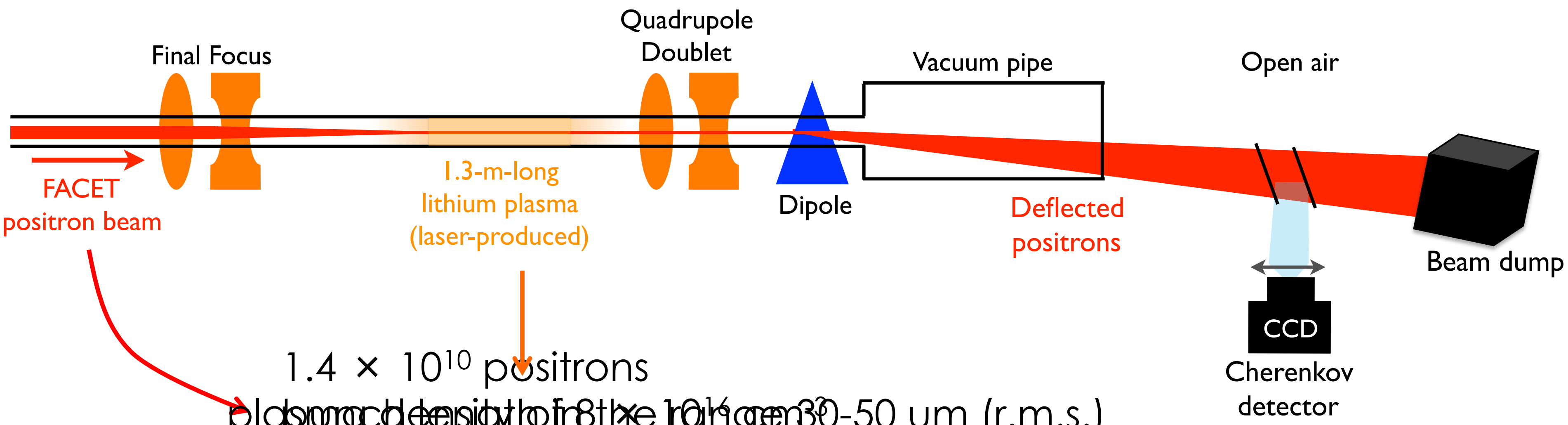


But the field is defocusing in this region.

Positron acceleration in a self-loaded plasma wakefield

Experimental results on e^+ beam-plasma interaction

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.)

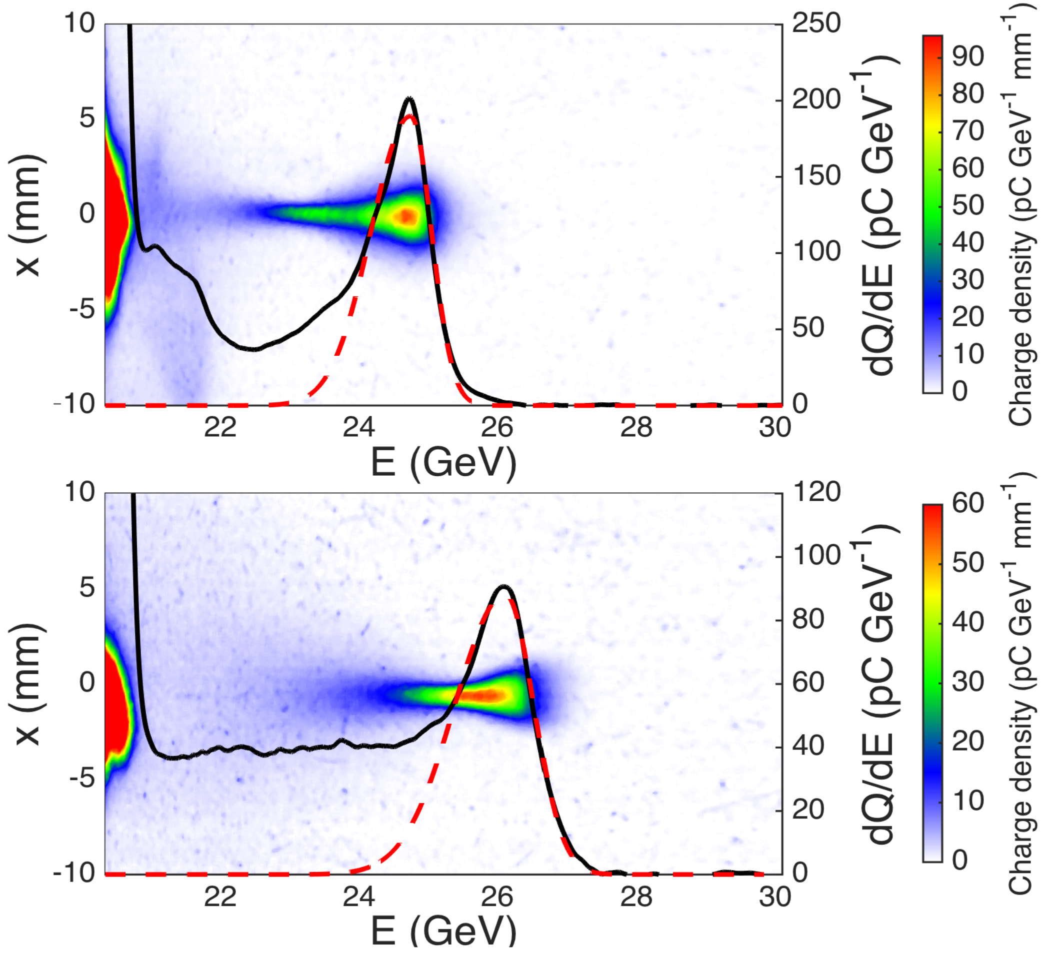
20.35 GeV energy

Experimental results on e+ beam-plasma interaction

Particle acceleration:

- 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.).

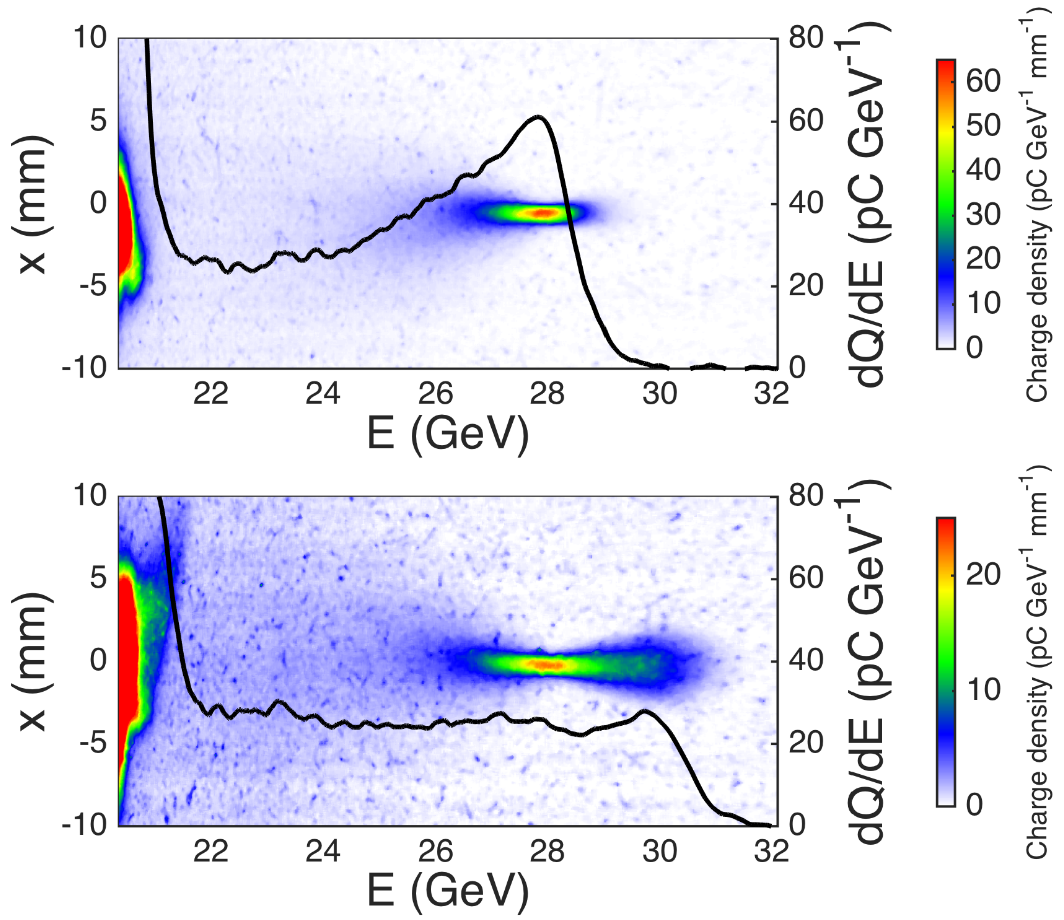
Experimental results in 1.3 m plasma



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

Experimental results on e^+ beam-plasma interaction

Experimental results in 1.3 m plasma



Particle acceleration:

- Positrons accelerated to energies greater than 30 GeV.
- Energy gradients can be as high as 8 GeV/m.

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

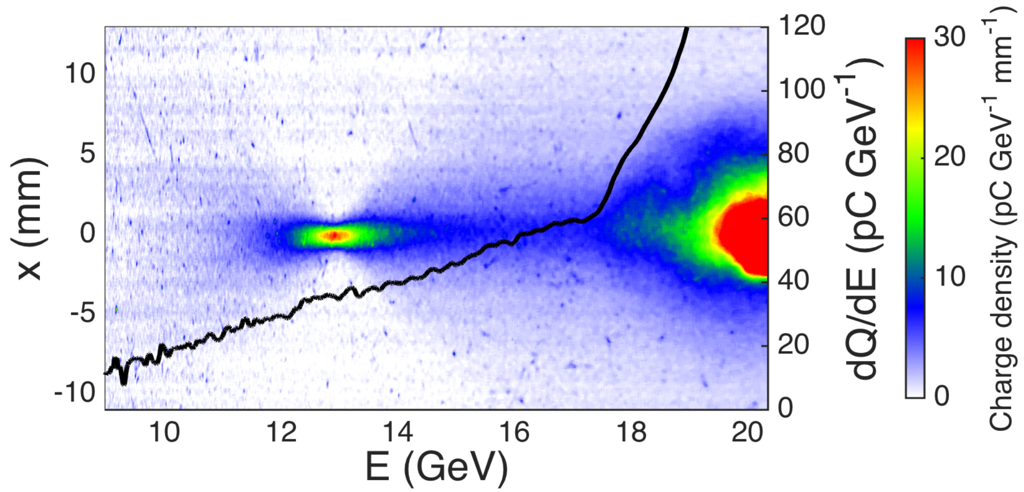
Experimental results on e^+ beam-plasma interaction

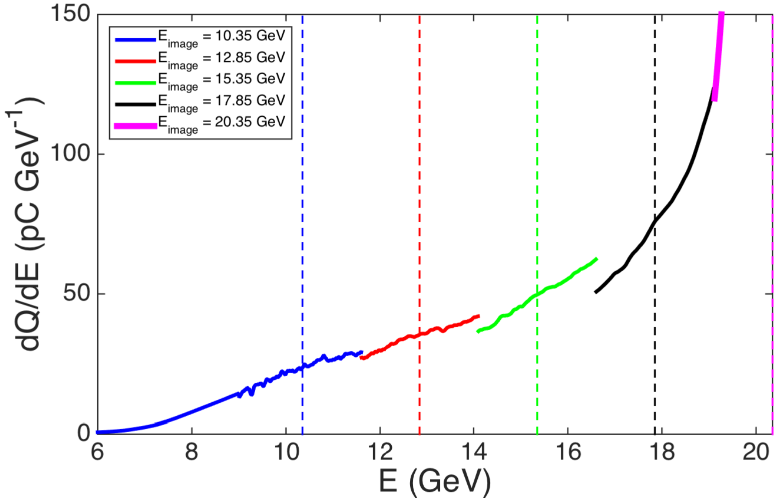
Particle deceleration – wake excitation:

- 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.





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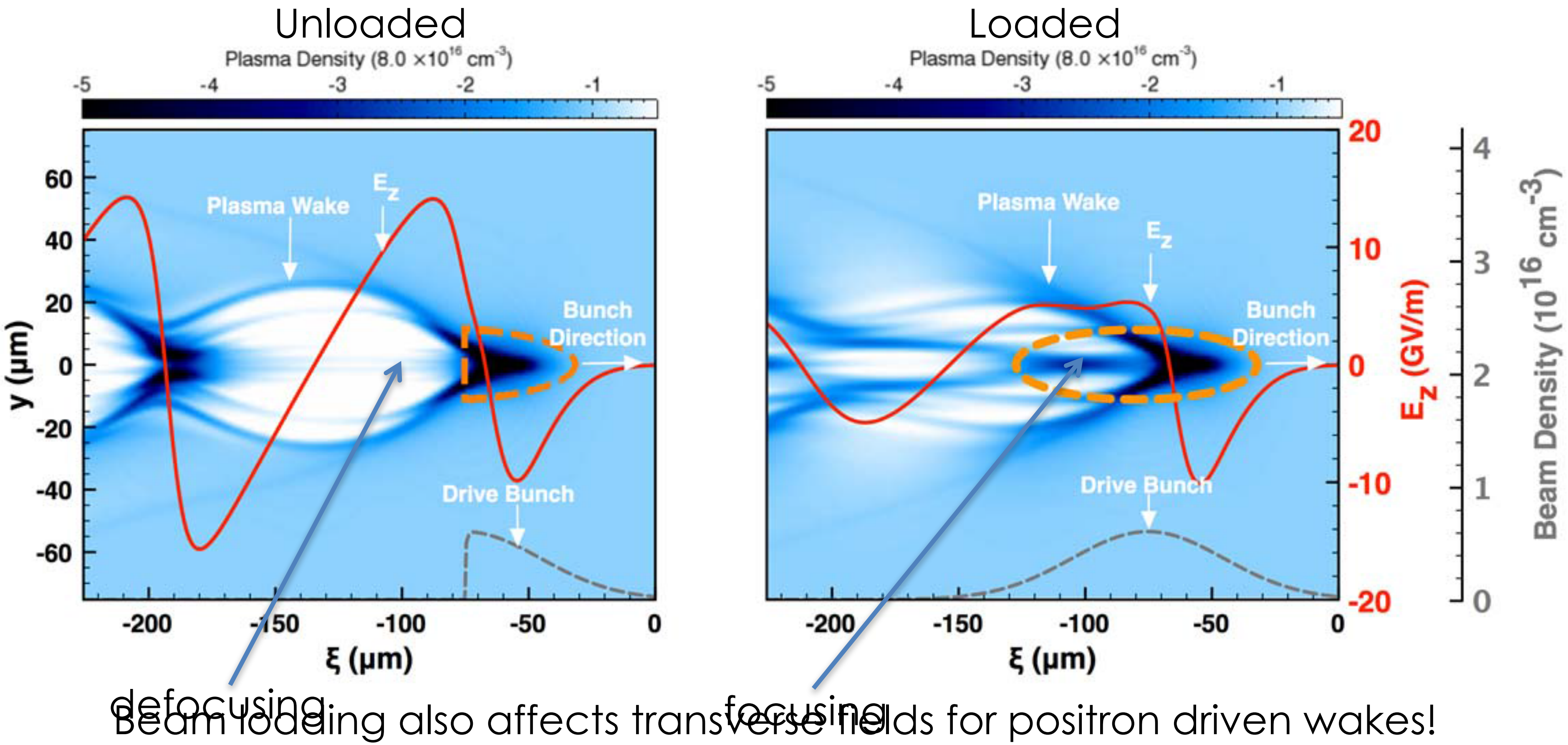
Interpretation with particle-in-cell simulations

QuickPIC simulations: loaded vs unloaded wake (truncated bunch)

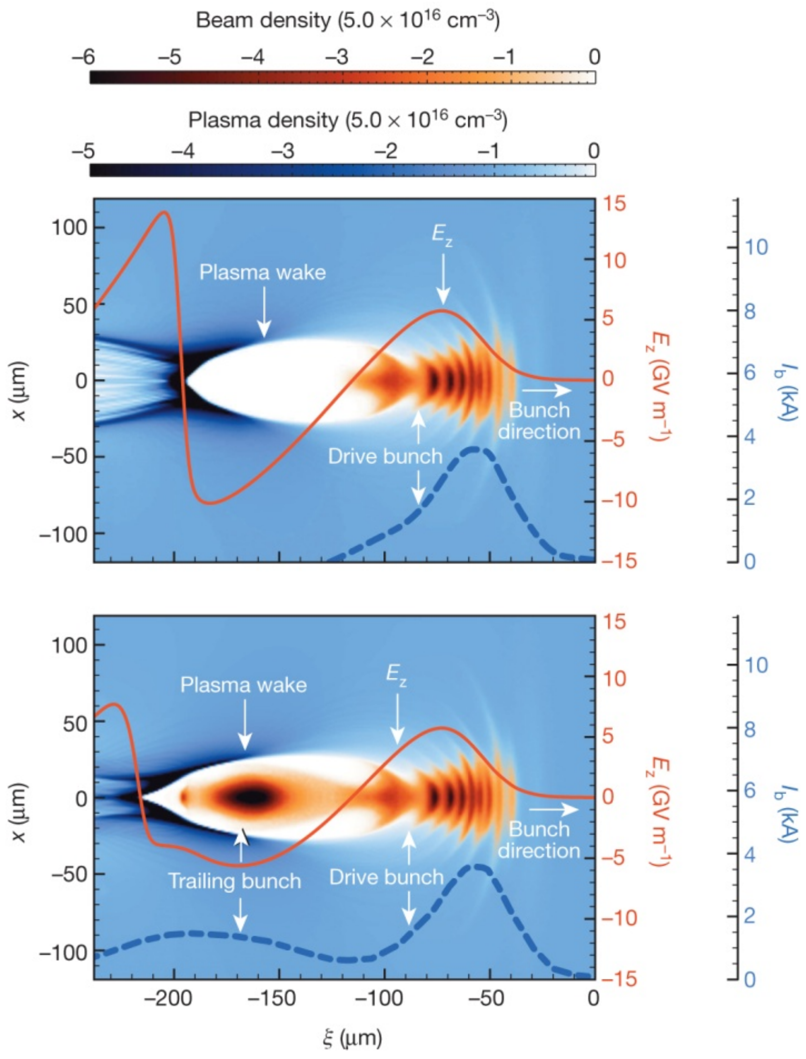


Beam loading also affects transverse fields for positron driven wakes!

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

Interpretation with particle-in-cell simulations

Electron drive and trailing bunches



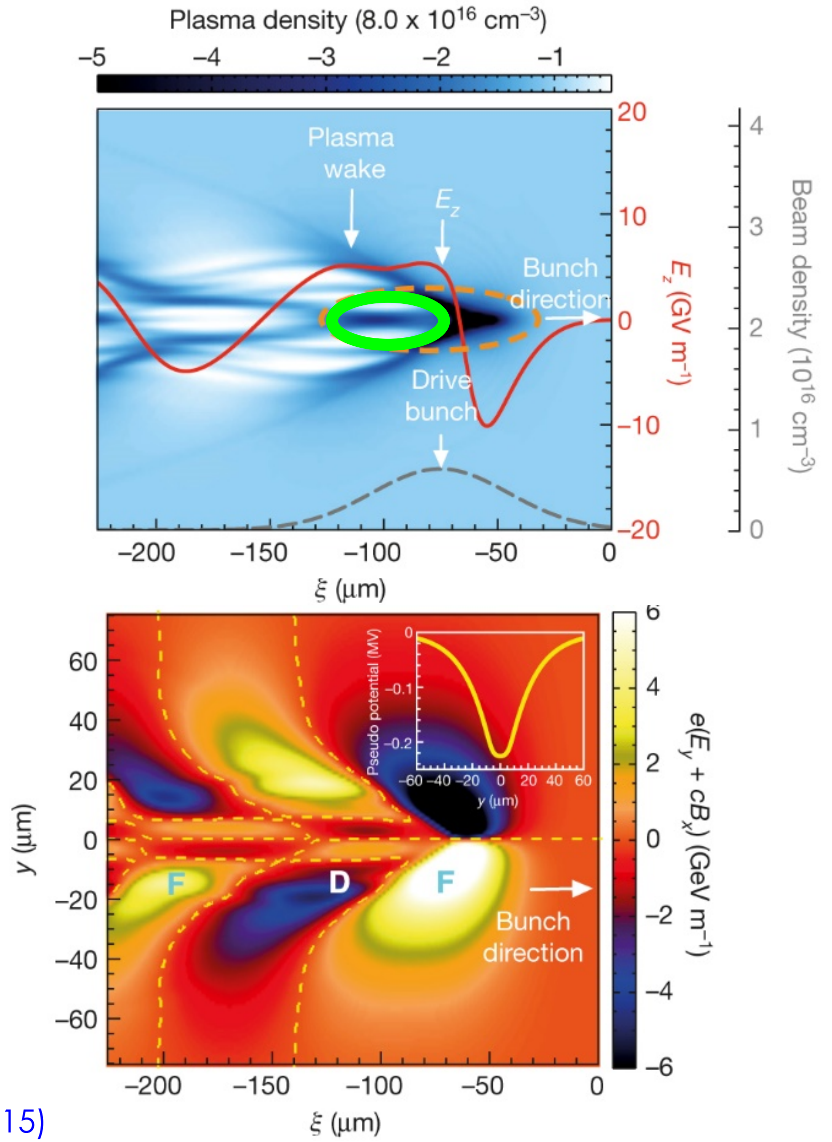
Beam loading with electron bunches:

- The trailing electron bunch inside the bubble flattens the longitudinal field.
- The presence of the trailing bunch causes the sheath trajectory to change. The sheath of electrons cross the axis at a later point in time.
- But it has no effect on the transverse focusing force experienced by electrons in the trailing bunch.

Interpretation with particle-in-cell simulations

Beam loading with positrons:

- The positrons in the tail of the bunch change the trajectories of plasma electrons.
- There is now a region of plasma electrons on axis that provides a focusing force for the positrons.
- Beam loading also affects transverse fields, we call this effect “transverse beam loading”.

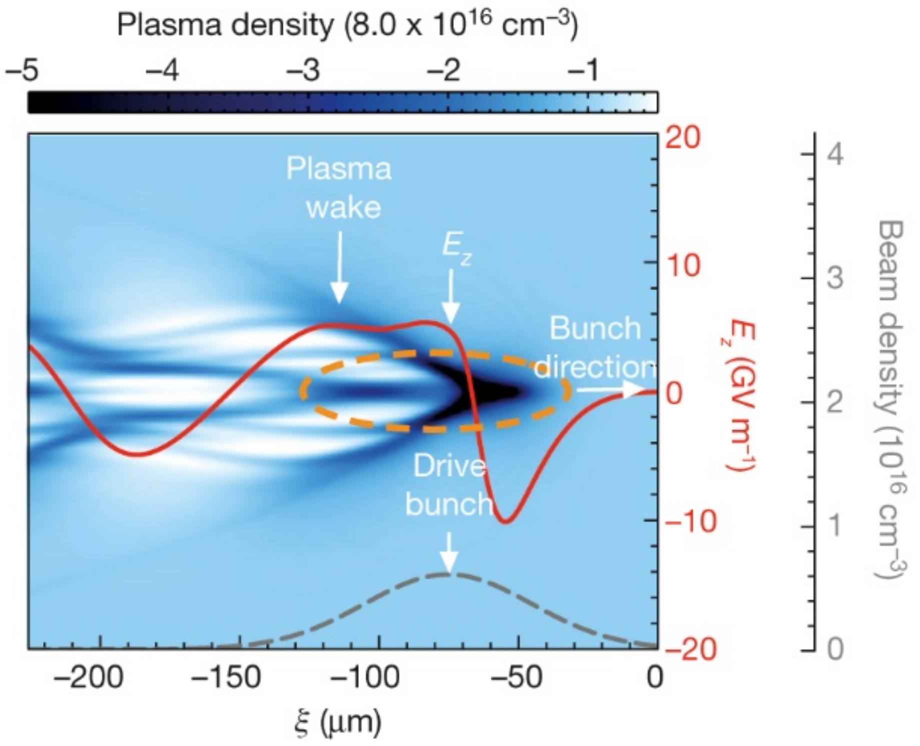


S. Corde *et al.*, Nature **524**, 442 (2015)

Interpretation with particle-in-cell simulations

Self-loading of the wake:

- The experiment involves a single positron bunch, not a two bunch drive-witness configuration.
- The E_z-field abruptly switches sign when most plasma electrons cross the propagation axis.
- A large number of positrons experience an accelerating field and load the wake.
- The front of a single e^+ bunch excites the wake while the rear of the same bunch loads and extracts energy from it. This is referred to as "self-loading".

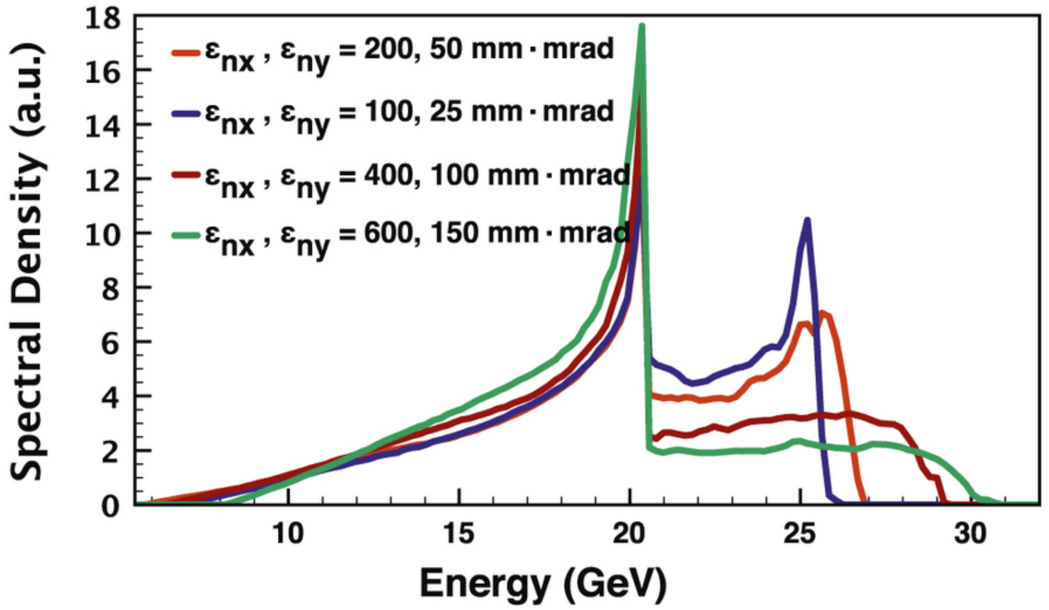


S. Corde *et al.*, Nature **524**, 442 (2015)

Interpretation with particle-in-cell simulations

Dependence with beam emittance:

- Beam loading depends on how many positrons are near the beam axis.
- The emittance determines the beam density.
- In simulations, we observe that low emittance (high density) beams load and flatten the wake. The outgoing energy spectra are peaked.
- High emittance (low density) beams do not load the wake and produce broadband spectra with high energy gains.



Energy spectra for different incoming positron beam emittances. Simulations from QuickPIC.

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

Acceleration of a distinct positron bunch

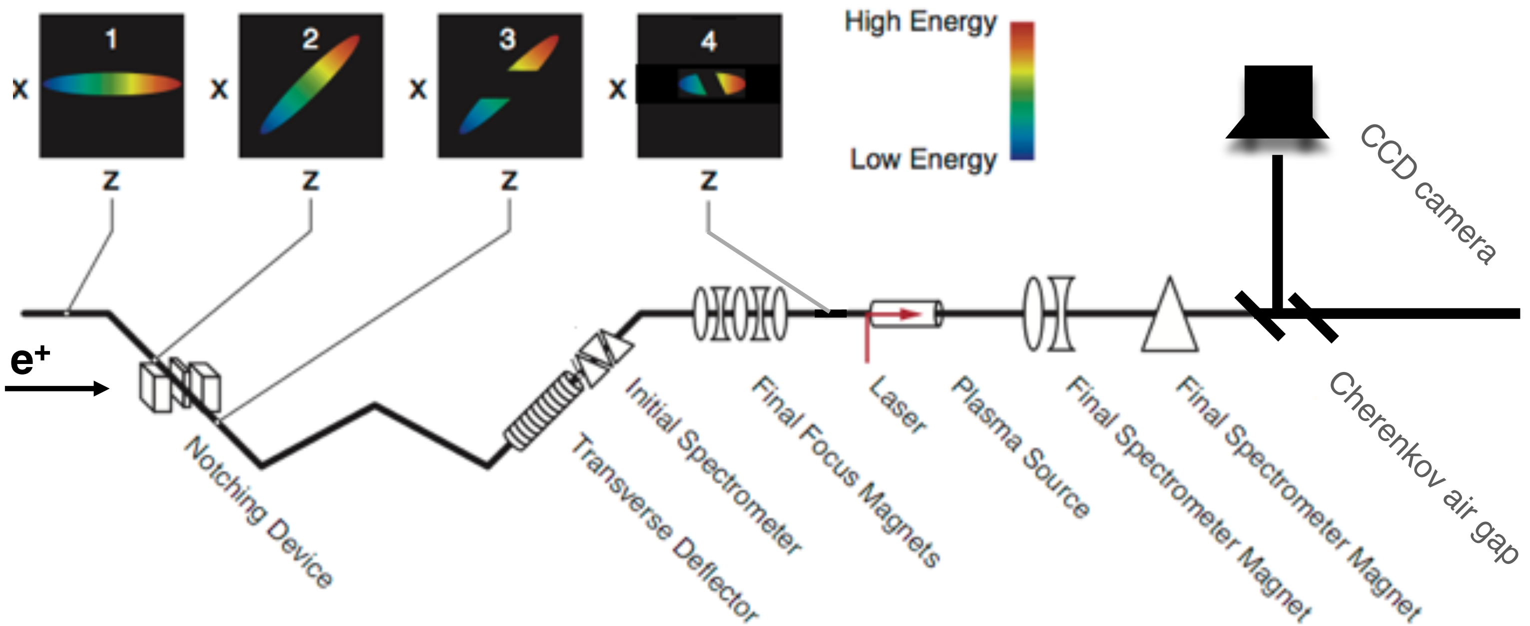
Distinct positron bunch acceleration in PWFA

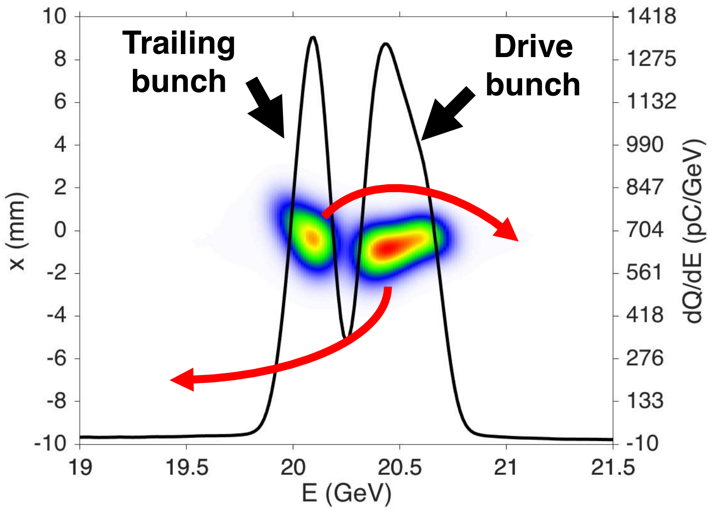
Useful accelerators:

- accelerate beams
- have high efficiency

Demonstration requires two beams:

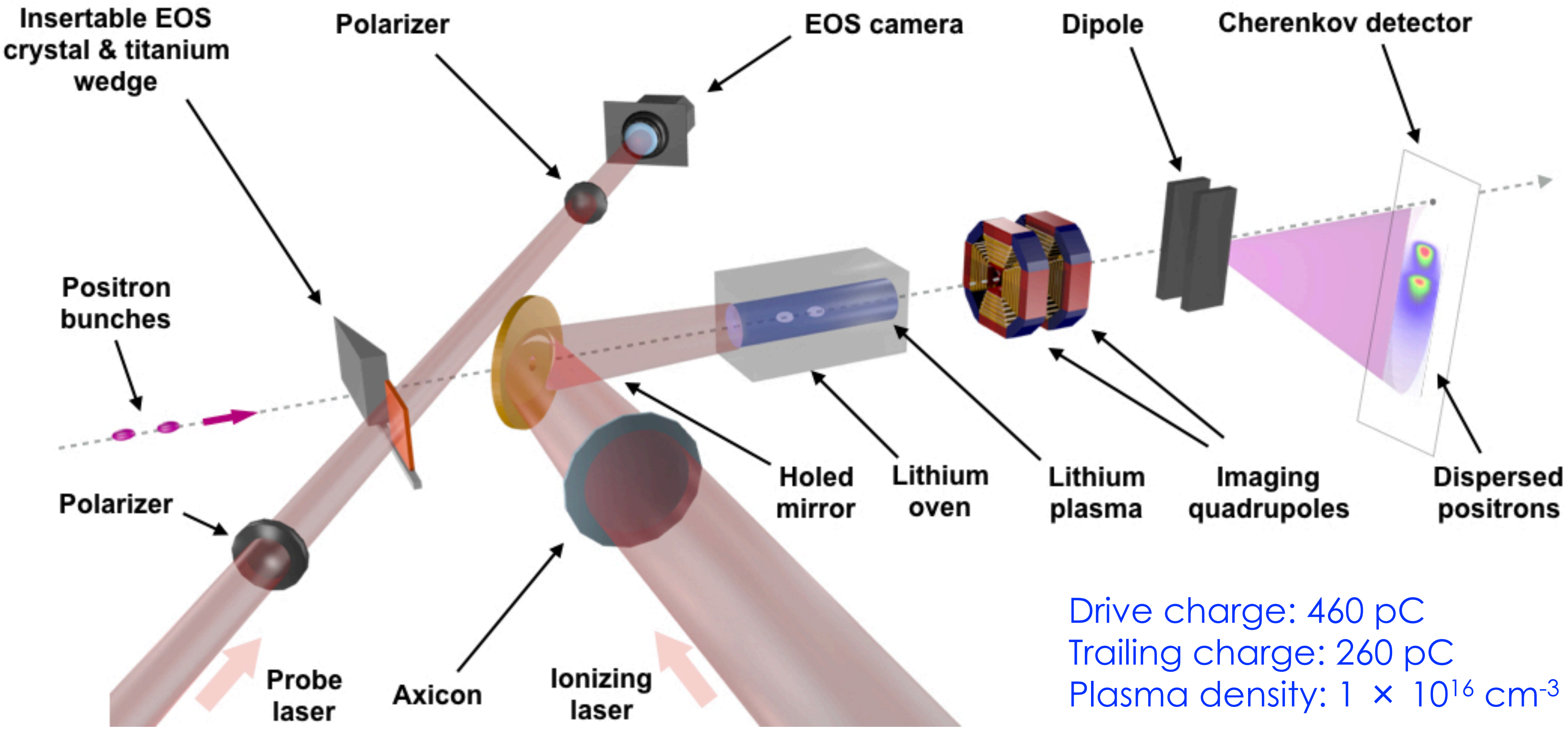
- One for driving the wave
- One for high-efficiency acceleration
- Pre-ionized lithium vapor by laser





- Drive and trailing bunches are separated by 100-135 um longitudinally
- Drive energy centered at 20.55 GeV, witness at 20.05 GeV

Distinct positron bunch acceleration in PWFA

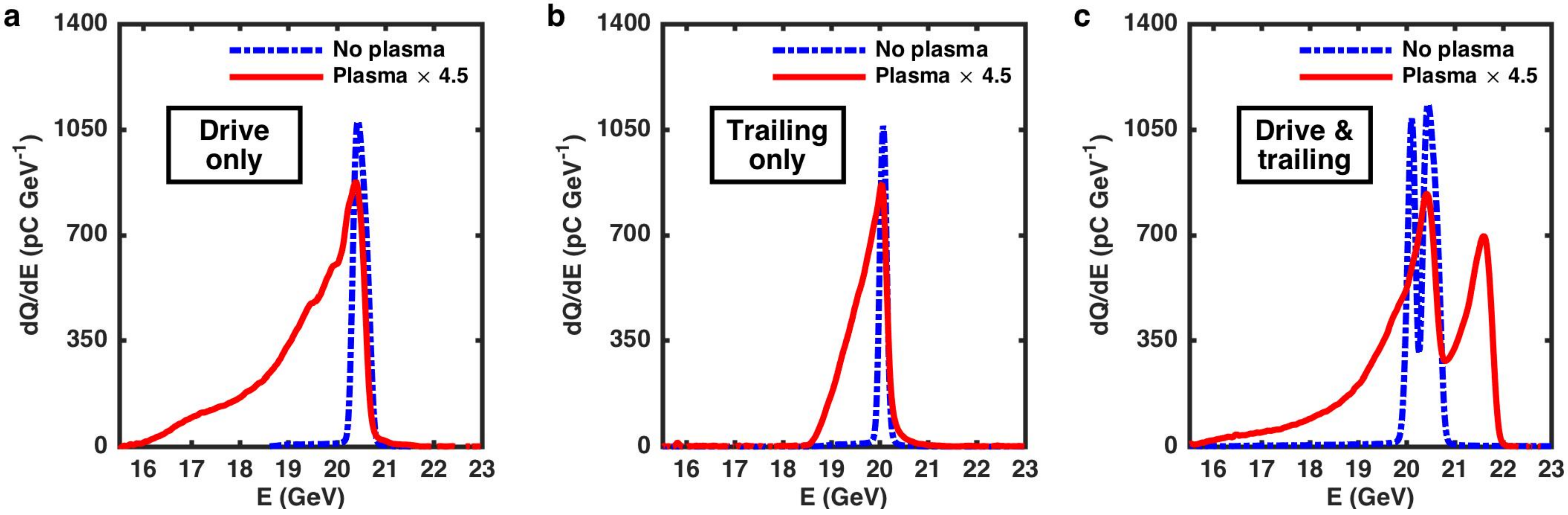


Drive charge: 460 pC
Trailing charge: 260 pC
Plasma density: 1×10^{16} cm^{-3}

A. Doche *et al.*, Scientific Reports (in press)

Distinct positron bunch acceleration in PWFA

First demonstration of high-field plasma-based acceleration of a distinct positron bunch

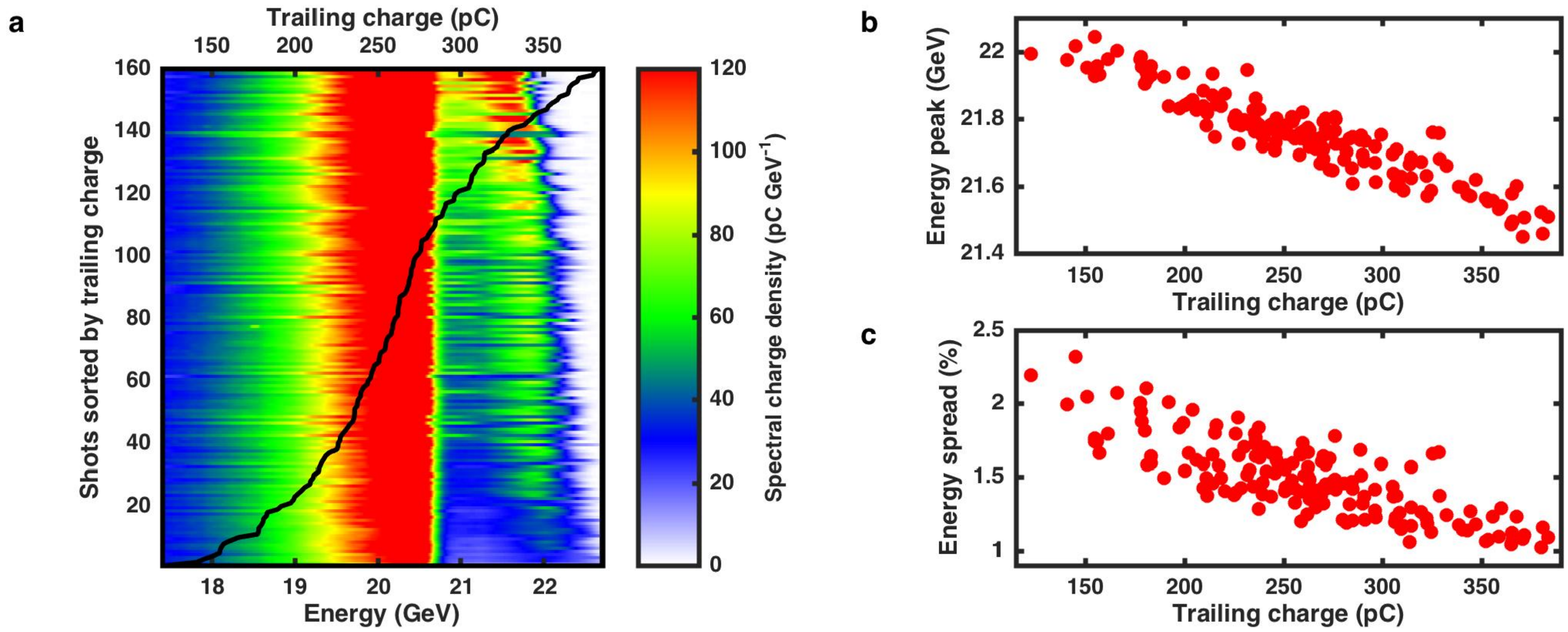


Wake-to-bunch energy extraction efficiency is estimated to be 40%

A. Doche *et al.*, Scientific Reports (in press)

Distinct positron bunch acceleration in PWFA

Sorting our data with incoming trailing charge, a clear evidence of beam loading appears:



A. Doche *et al.*, Scientific Reports (in press)

Influence of driver emittance on plasma wake excitation

With a linear transverse force, $F_r \propto r$, we have:

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

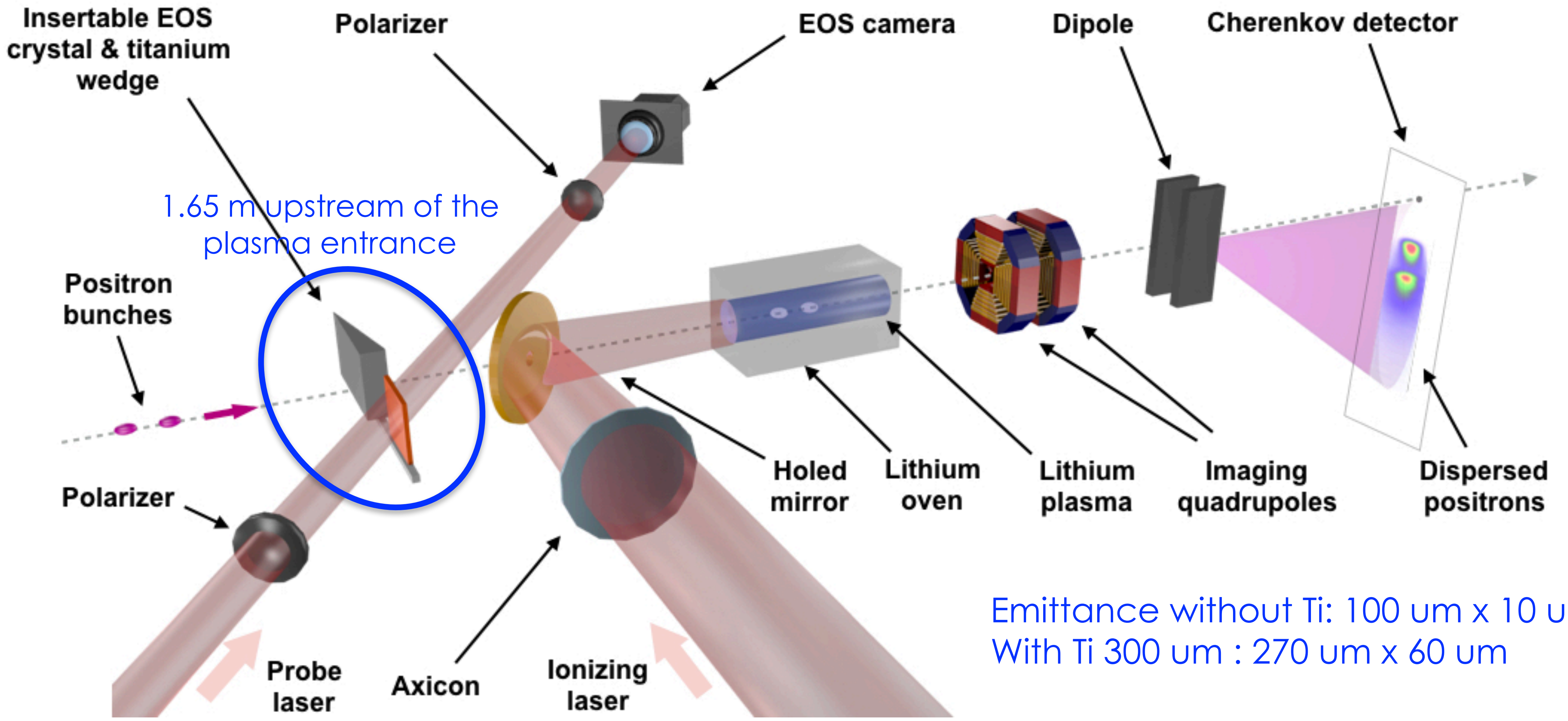
For example in the blow-out regime: $K = {k_\beta}^2$ and matching $\left(\frac{d\sigma_r}{dz} = 0\right)$ occurs for $\beta = 1/k_\beta$ and $\alpha = 0$.

For a positron beam, the focusing force increases (K is not constant) when the beam size decreases, leading to a self-focusing of the positron beam.

After the evolution due to self-focusing, a quasi-steady state and an equilibrium beam size is reached when the focusing force is balanced by the emittance term.

Bottom line: higher emittance → higher equilibrium beam size → smaller bunch density.

Influence of driver emittance on plasma wake excitation

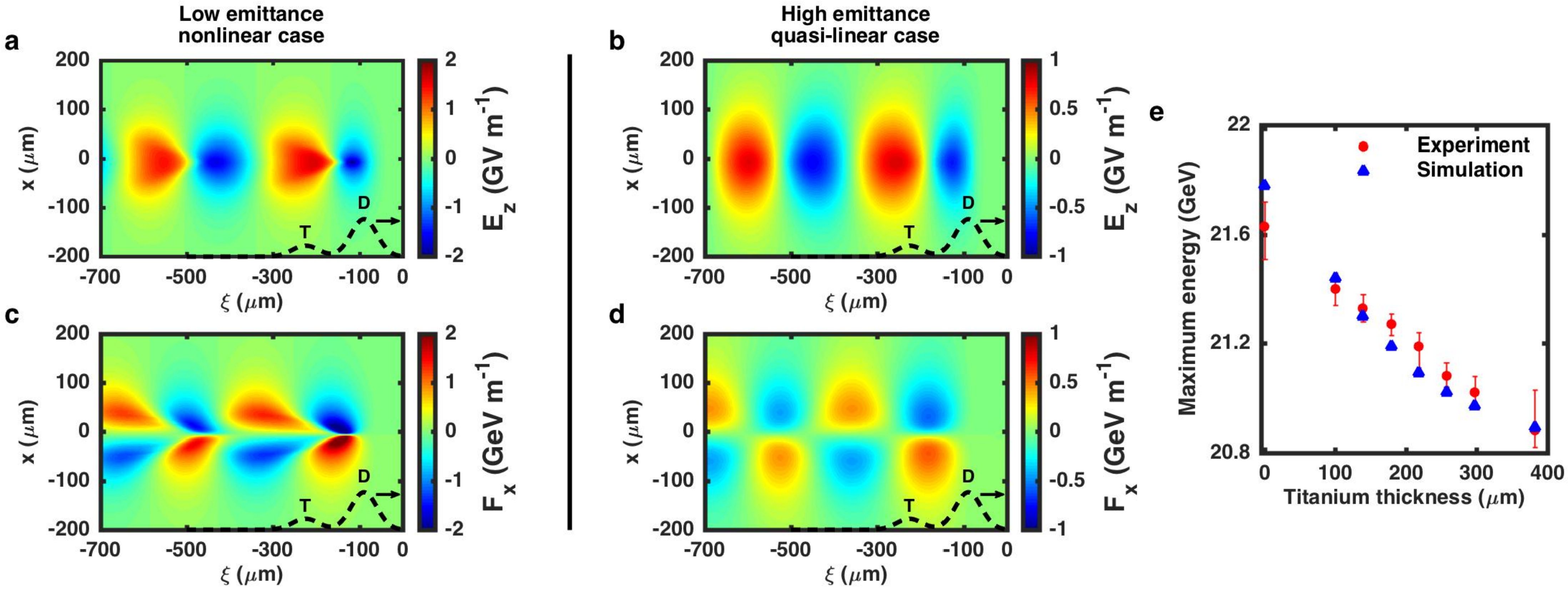


Emittance without Ti: 100 um x 10 um
With Ti 300 um : 270 um x 60 um

A. Doche *et al.*, Scientific Reports (in press)

Influence of driver emittance on plasma wake excitation

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



$$\frac{n_{\mathrm{beam}}}{n_{\mathrm{plasma}}} = 14.2$$

$$\frac{n_{\mathrm{beam}}}{n_{\mathrm{plasma}}} = 1.2$$

A. Doche *et al.*, Scientific Reports (in press)

What we've learned

- Nonlinear regime:
  - ➢ Plasma acceleration possible for positrons
  - ➢ High field and high efficiency
  - ➢ Nonlinear plasma wakes can provide guiding potential well over meter-scale distances
- Quasi-linear regime:
  - ➢ High-emittance particle beams (e^- or e^+) drive quasi-linear wakes and propagate in plasmas over meter-scale distances
  - ➢ Can accelerate positrons
- Other observations:
  - ➢ No evidence of hosing observed in positron plasma acceleration experiments

  [hosing for electrons: not observed experimentally, explained theoretically by T. Mehrling et al., PRL 118, 174801 (2017)]

What's next

- Nonlinear regime:
  - Bunch shaping for radial equilibrium distribution (not gaussian, slice dependent)
  - Trailing bunch emittance preservation?
- Quasi-linear regime:
  - Increase efficiency
  - Independent control of drive and trailing bunches
  - Nonlinear positron beam loading, incl. transverse beam loading
- For both:
  - **Simultaneously achieve preserved emittance and efficiency**
  - Investigate positron acceleration in electron-driven plasma wakes
- Test new ideas, e.g. donut-shaped drivers, etc.

Thank you for your attention