Acceleration of positrons in plasma

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March 21, 2019

Outline

Prerequisites

- Linear wakefields and beam loading: lectures from S. Karsch, A. Thomas, Z. Najmudin
- Nonlinear regime and blowout: lectures from L. Silva
- Beam dynamics and matching: lectures from M. Ferrario
- Collider application: lecture from Z. Najmudin

Outline

- Introduction to the positron challenge
  - ➢ Nonlinear regime: not symmetrical for e^- and e^+
  - ➢ Linear regime: energy efficiency and low emittance very challenging
- The physics of positron acceleration in plasma
  - ➢ Beam loading and transverse dynamics in linear waves
  - ➢ Nonlinear regime: self-loading and donut-shaped wakes
  - ➢ Hollow channel
- Future research towards plasma-based e^-/e^+ collider
  Need to achieve simultaneously: stability, low emittance, high efficiency

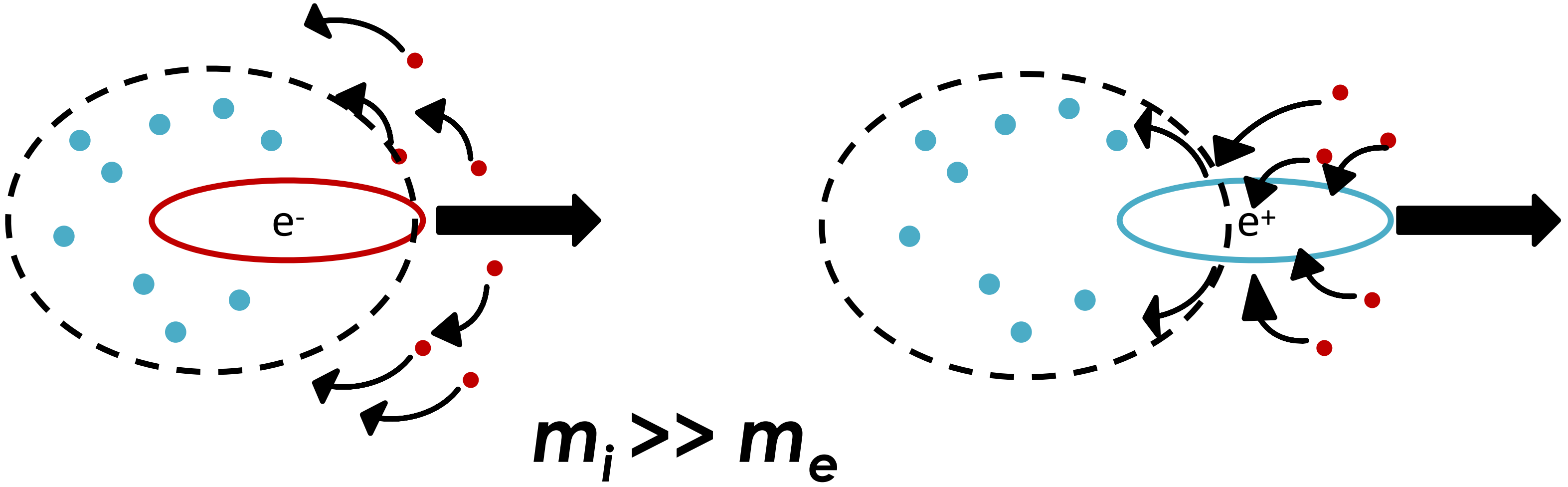
Introduction to the positron challenge

Nonlinear plasma wakefield

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.

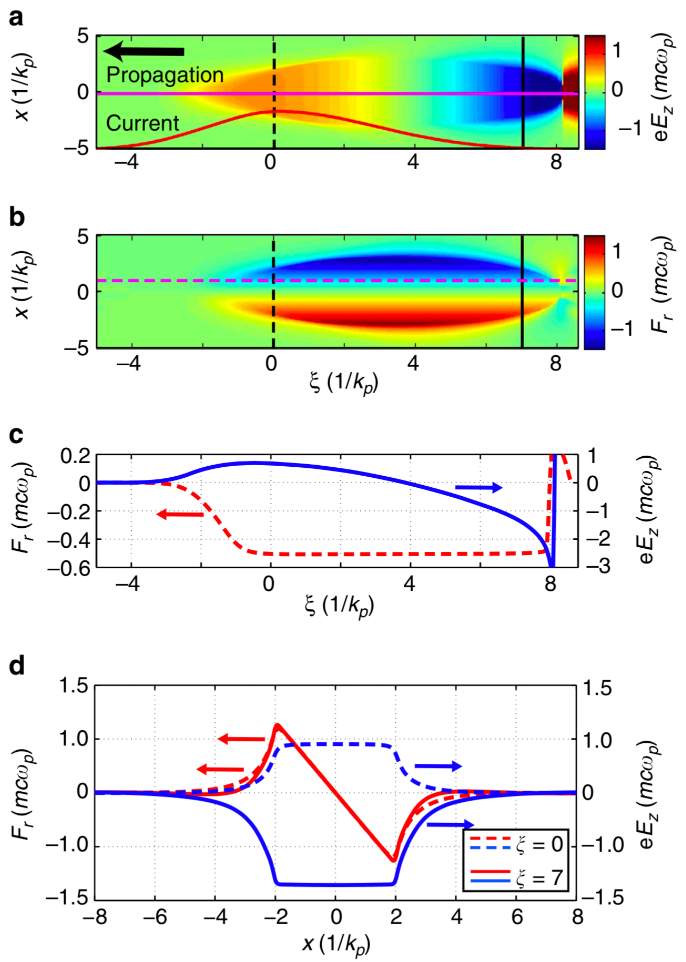


The plasma electrons are mobile but the ions are not.

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

Nonlinear plasma wakefield - electron case

Blow-out regime:



EM fields inside cavity:

$$\mathbf{E}/E_0 = \frac{1}{2}k_p\xi\ \mathbf{e}_z + \frac{1}{4}k_p r\ \mathbf{e}_r$$

$$c\mathbf{B}/E_0 = -\frac{1}{4}k_p r\ \mathbf{e}_\theta$$

Transverse force experienced by an e^-:

$$F_r = -e(E_r - cB_\theta) = -\frac{eE_0k_p}{2}r$$

→ Focusing force linear in *r*

Additional properties:

$$\partial_\xi F_r = 0 \qquad \partial_r F_z = 0$$

The blowout regime has ideal field properties for e^-:

- → emittance preservation is expected to be achievable.
- → beam loading allow for high efficiency, flat E_z field and therefore low energy spread.
- → most studied regime for electron acceleration, in both LWFA and PWFA.
- → hosing instability may be an important limitation for collider beam parameters.
- → ion motion may lead to emittance growth.

Nonlinear plasma wakefield - positron case

EM fields inside cavity:

$$\mathbf{E}/E_0 = \frac{1}{2}k_p\xi\,\mathbf{e}_z + \frac{1}{4}k_p r\,\mathbf{e}_r$$

$$c\mathbf{B}/E_0 = -\frac{1}{4}k_p r\,\mathbf{e}_\theta$$

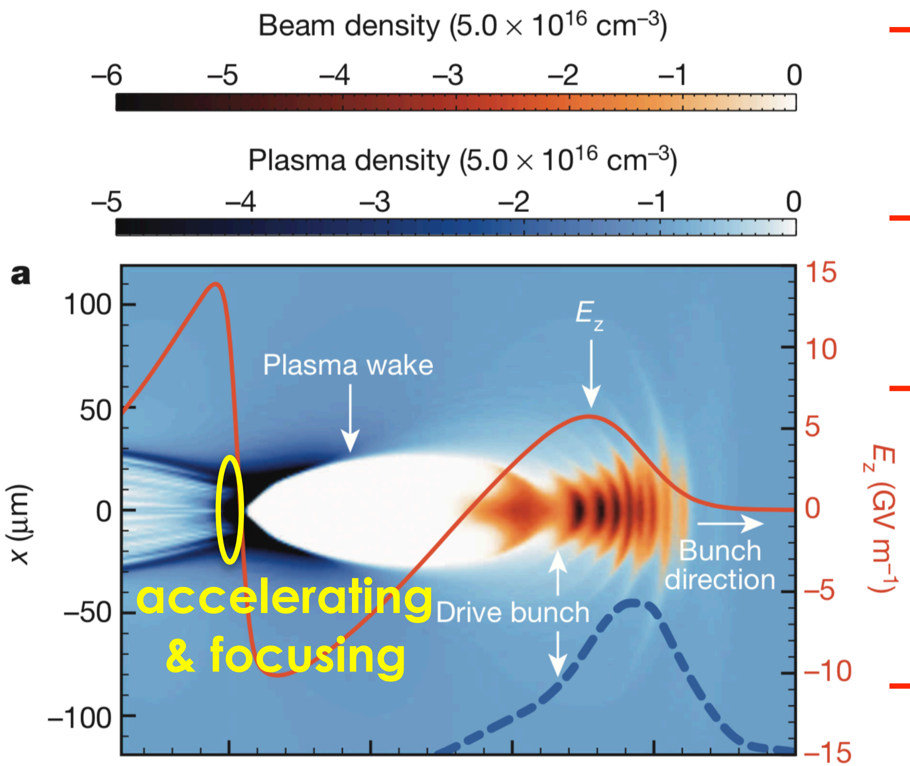
Transverse force experienced by an e⁺:

$$F_r = +e(E_r - cB_\theta) = +\frac{eE_0k_p}{2}r$$

→ Defocusing force

Blow-out ideal field properties:
not applicable for positron acceleration

Is it possible to have accelerating and focusing fields for e⁺ somewhere outside cavity?



→ Very small accelerating-focusing region

→ Nonlinear focusing force

→ E_z varies with r

→ Really not ideal: but still under investigation

Linear plasma wakefield

- Linear plasma wave equation with beam or laser driver: $$\left(\frac{\partial}{\partial t^2}+\omega_p^2\right)\delta n=\omega_p^2\frac{q}{e}n_b+n_0c^2\nabla^2\frac{a^2}{2}$$

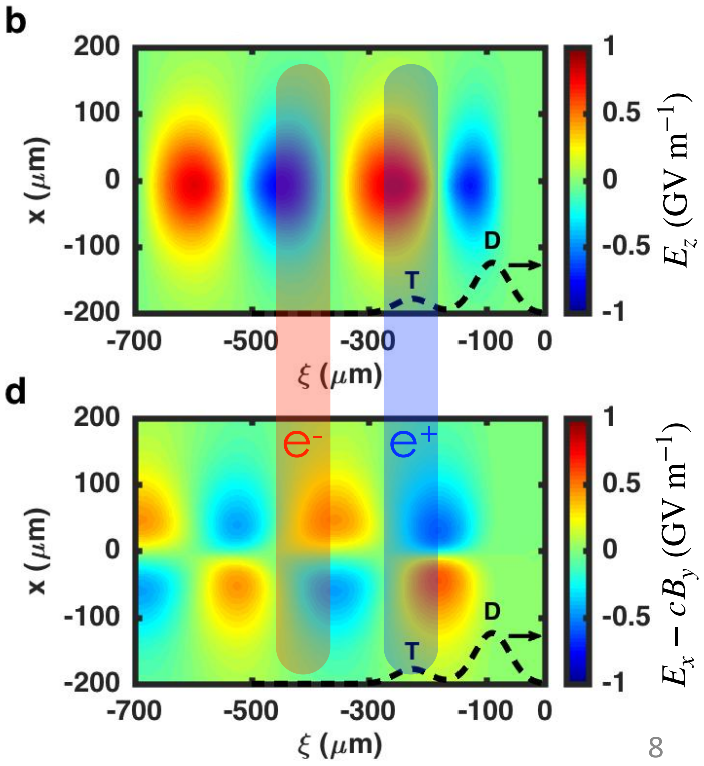
- Plasma density perturbation from a drive particle beam in the linear regime with quasi-static approximation:

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

- Fully symmetric between electrons and positrons: just a sign change

- A quarter of the period is accelerating and focusing for positrons, same for electrons. The fields are separable in ξ and r.

- Quasi-linear regime: increase wake amplitude as high as possible but keep properties of a linear regime.



Linear plasma wakefield

So, what's the problem with the linear regime?

- Need to add the main bunch (often called trailing or witness bunch) to be accelerated in the wakefield.
- If the charge Q_m of the main bunch is very small, its effect on the wakefield (beam loading) is negligible, the main bunch only sees the wakefield from the driver.

$$Q_m \longrightarrow 0 \ : \quad \text{it works!}$$

- But in this limit, the energy efficiency also goes to 0.

- Matched beams:

$$\sigma_{\text{matched}} = \sqrt{\epsilon_g \, \beta_{\text{matched}}}$$

- Low emittance leads to small beam size and large beam density
- Plasma electrons move within the main bunch: « electron motion », much more serious than « ion motion ». Also referred to as transverse beam loading.

→ Energy efficiency and low emittance: extremely challenging in linear regime

Physics of positron acceleration in linear plasma wakefield

Linear plasma wakefield

The scope of our problem:

- We assume that a driver (laser or beam) can excite a linear plasma wave in a stable way and over a long distance. This is not obvious at all, but it's an issue that needs to be addressed separately.
- We add the main positron beam in the linear plasma wakefield.
- The main questions are:

* What charge can be accelerated?
* With which energy efficiency?
* Do we stay linear once the main beam is there?
* How to control final energy spread?
* How low can the initial emittance be?
* What emittance growth is to be expected?
* Is it stable?

Linear plasma wakefield

The 1D case with short bunches

Electric field from a single electron:

$$E_1(\xi) = E_{1,\text{peak}} \cos(k_p \xi)\, \theta(-\xi)$$

Electric field from an electron driver:

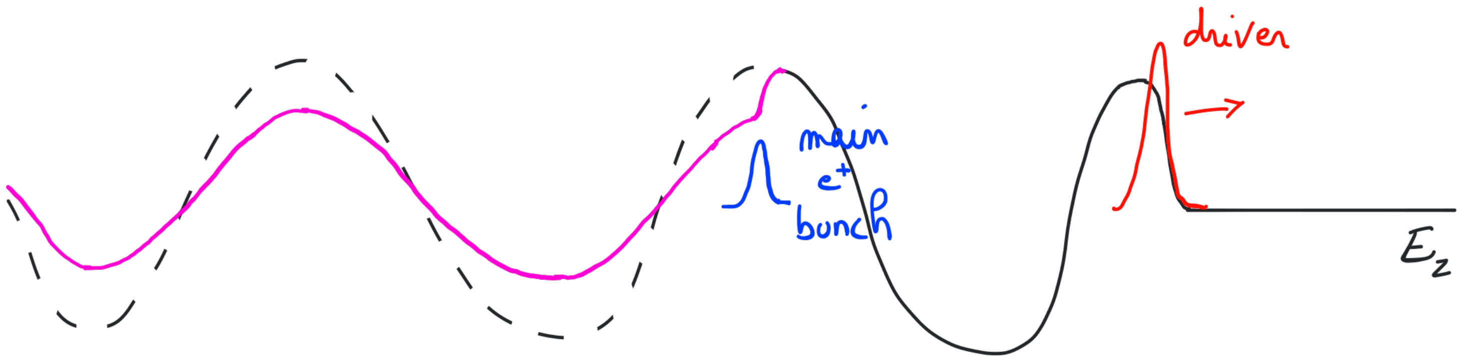
$$E_d(\xi) = N_d E_1(\xi)$$

Electric field from the main positron bunch:

$$E_m(\xi) = -N_m E_1(\xi + \Delta\xi)$$

Total electric field (superposition):

$$E(\xi) = N_d E_1(\xi) - N_m E_1(\xi + \Delta\xi)$$



Average electric field experienced by electron driver:

$$\langle E \rangle_d = N_d E_{1,\text{peak}}/2$$

Average electric field experienced by main e+ bunch:

$$\langle E \rangle_m = N_d E_{1,\text{peak}} - N_m E_{1,\text{peak}}/2$$

for $\Delta\xi = \lambda_p$

Energy transfer efficiency:

$$\eta = \left| \frac{N_m \langle E \rangle_m}{N_d \langle E \rangle_d} \right| = \frac{N_m}{N_d}\left(2 - \frac{N_m}{N_d}\right)$$

Relative energy spread:

$$\sigma_\gamma \sim \frac{N_m E_{1,\text{peak}}}{N_d E_{1,\text{peak}}} = \frac{N_m}{N_d}$$

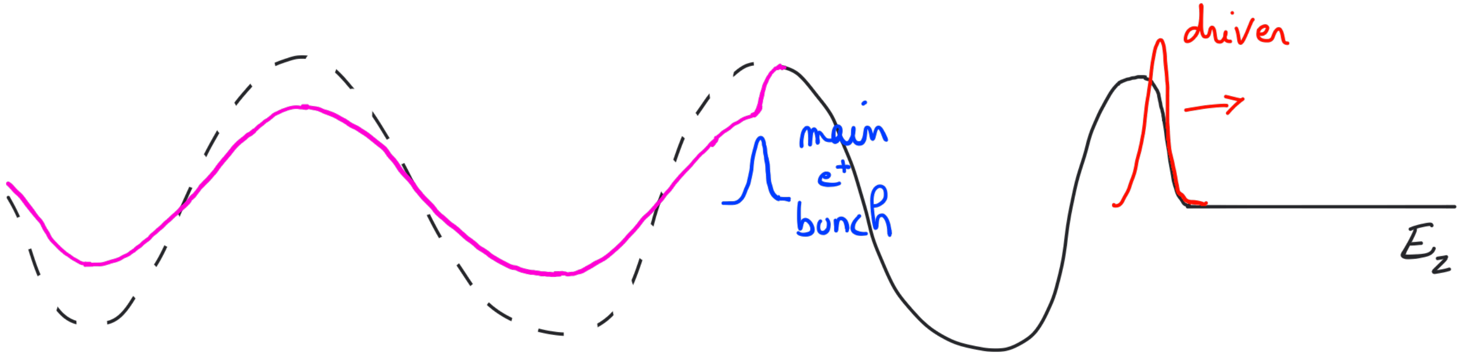
Linear plasma wakefield

The 1D case with short bunches

Example: $$\frac{N_m}{N_d} = 0.2$$

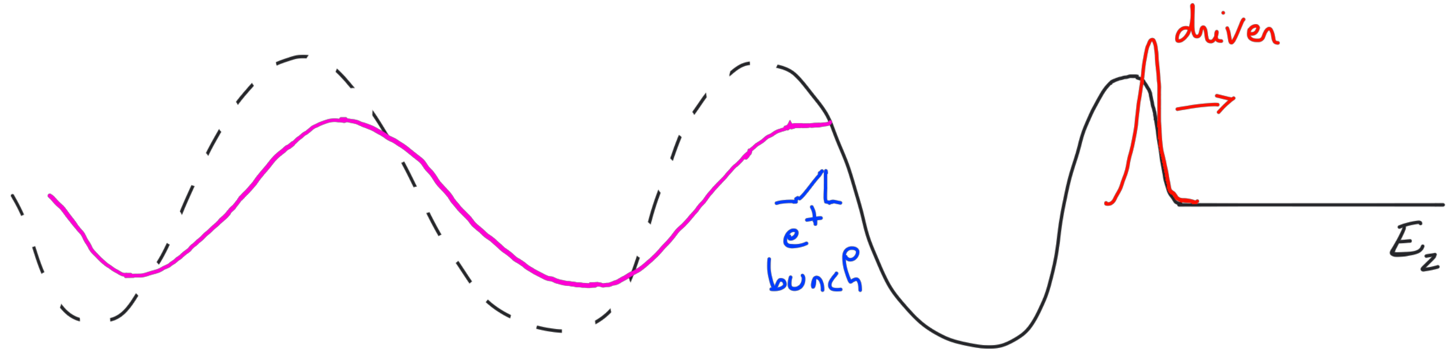
$$\rightarrow \quad \eta = \frac{N_m}{N_d}\left(2 - \frac{N_m}{N_d}\right) = 0.36$$ good

$\sigma_\gamma \sim 0.2$ not good, can be fixed?



Optimised beam loading:

Uniform E_z field experienced by e+ bunch: low final energy spread.



Linear plasma wakefield

The 3D case

➢ The wakefield and the main positron bunch have a finite transverse extent, the main positron bunch beam size can evolve: transverse beam dynamics is important.

➢ Assuming no acceleration, and near the axis, we have:

$$\frac{d}{dt}\left(\gamma m \frac{dx}{dt}\right) = F_x \simeq \frac{dF_x}{dx}\, x \qquad \Longrightarrow \qquad \frac{d^2x}{dz^2} = -\,k_\beta^2 x \qquad \text{with} \quad k_\beta^2 = -\,\frac{1}{E}\frac{dF_x}{dx}$$

➢ This leads to:

$$\Longrightarrow \qquad \frac{d^2\sigma_x}{dz^2} = -\,k_\beta^2 \sigma_x + \frac{\epsilon_g^2}{\sigma_x^3} \qquad \text{with} \quad \sigma_x = \langle x^2 \rangle^{1/2} \qquad \text{(envelope equation)}$$

➢ If the focusing term is not balanced by the emittance term, no stable propagation: the main e+ bunch collapses, nonlinear wavefield may be generated, emittance growth is expected due to mismatch.

➢ Need matched trailing positron bunch: $\dfrac{d^2\sigma_x}{dz^2} = 0 \;\Longrightarrow\; k_\beta^2 \sigma_x^4 = \epsilon_g^2 \;\Longrightarrow\; \beta_{\text{matched}} = \dfrac{\sigma_x^2}{\epsilon_g} = 1/k_\beta$

Linear plasma wakefield

The 3D case

Next question: can the main positron bunch interaction with the plasma wave be described by linear wakefield theory?

Do we have $n_m < n_0$?

$$n_m = \frac{I_{\text{peak}}}{2\pi e c \sigma_r^2} \qquad n_m < n_0 \implies \sigma_r^2 > \frac{I_{\text{peak}}}{2\pi e c n_0}$$

$$\implies \beta_m = \gamma \frac{\sigma_r^2}{\epsilon_n} > \frac{\gamma I_{\text{peak}}}{2\pi e c n_0 \epsilon_n}$$

Requires to work with very large beta function.

Numerical application: 500 GeV, 1 kA, 10^{18} cm^{-3} plasma density, 10 nm emittance:

β_m = 330 m, λ_β = 2 km $\longrightarrow$ main e^+ bunch has to be parallel and to see no transverse force in a plasma stage

Linear plasma wakefield

The 3D case

Next question: can the main positron bunch interaction with the plasma wave be described by linear wakefield theory?

Do we have $n_m < n_0$?

$$n_m = \frac{I_\text{peak}}{2\pi e c \sigma_r^2} \qquad n_m < n_0 \implies \sigma_r^2 > \frac{I_\text{peak}}{2\pi e c n_0}$$

$$\implies \beta_m = \gamma \frac{\sigma_r^2}{\epsilon_n} > \frac{\gamma I_\text{peak}}{2\pi e c n_0 \epsilon_n}$$

Problems with large beta functions:

Much stronger transverse instabilities

Emittance growth due to Coulomb scattering

Betatron cooling unlikely to be a solution as transverse force needs to be very small

Linear plasma wakefield

The 3D case

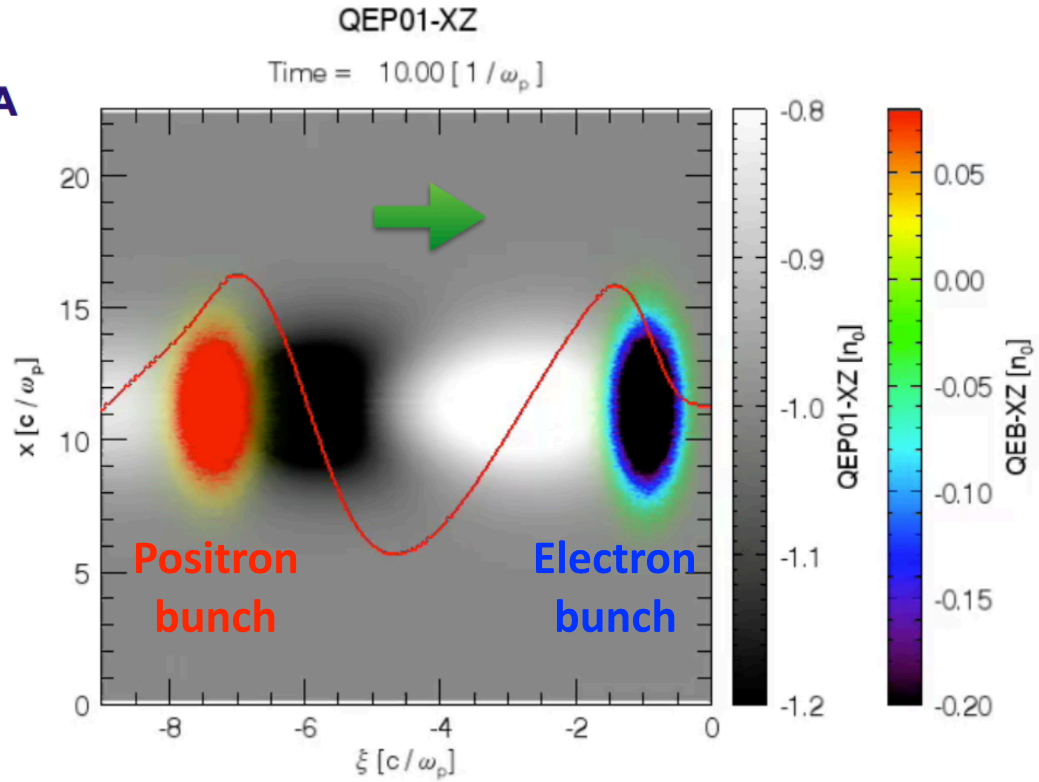
Example with FACET-II parameters
(high charge, high current beams):

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}



- ➢ To prevent collapse and have matched beam, one may conclude we need high emittance
- ➢ Not acceptable solution, colliders need extremely small emittances.

Linear plasma wakefield

The 3D case

$$\beta_m = \gamma \frac{\sigma_r^2}{\epsilon_n} > \frac{\gamma I_{\text{peak}}}{2\pi e c n_0 \epsilon_n}$$

Possible solution: bunch train and energy recovery

- ➢ Low efficiency per bunch, low current, and therefore smaller beta function to allow for emittance preservation

- ➢ Linear regime therefore requires multi-pulse/multi-bunch and/or energy recovery, to accommodate for the low efficiency per bunch / low current and to reach good overall efficiency.

PRL 119, 044802 (2017) PHYSICAL REVIEW LETTERS week ending 28 JULY 2017

Excitation and Control of Plasma Wakefields by Multiple Laser Pulses

J. Cowley,[1] C. Thornton,[1] C. Arran,[1] R. J. Shalloo,[1] L. Corner,[1] G. Cheung,[1] C. D. Gregory,[2] S. P. D. Mangles,[3] N. H. Matlis,[4] D. R. Symes,[2] R. Walczak,[1] and S. M. Hooker[1,*]
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(Received 15 March 2017; revised manuscript received 31 May 2017; published 27 July 2017)

We demonstrate experimentally the resonant excitation of plasma waves by trains of laser pulses. We also take an important first step to achieving an energy recovery plasma accelerator by showing that a plasma wave can be damped by an out-of-resonance trailing laser pulse. The measured laser wakefields are found to be in excellent agreement with analytical and numerical models of wakefield excitation in the linear regime. Our results indicate a promising direction for achieving highly controlled, GeV-scale laser-plasma accelerators operating at multikilohertz repetition rates.

S. Hooker *et al.*, J. Phys. B: At. Mol. Opt. Phys. **47**, 234003 (2014);
J. Cowley *et al.*, Phys. Rev. Lett. **119**, 044802 (2017)

Linear plasma wakefield

The 3D case

Other solution: nonlinear beam loading from main e+ bunch

$$\text{Allow } n_m > n_0$$

- ➢ Linear plasma wave from the driver
- ➢ Nonlinear regime within and behind the main e^+ bunch
- ➢ Plasma electrons are strongly sucked in by the main e^+ bunch
- ➢ Main e^+ bunch sees a strongly modified wakefield:

$\longrightarrow$ Longitudinal and transverse beam loading

Linear plasma wakefield

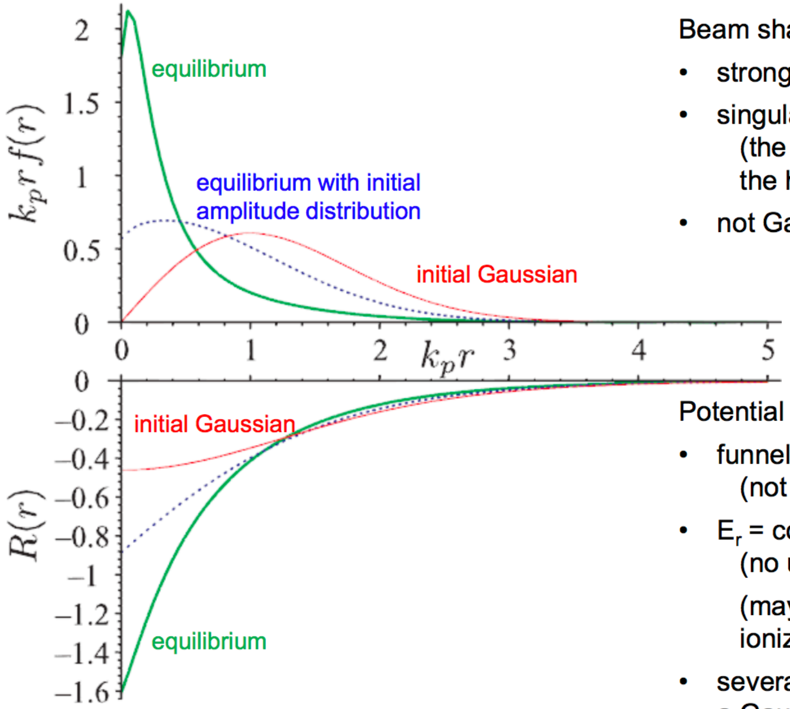
The 3D case

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)

Nonlinear plasma wakefield

If linear regime:

$$\text{Total Wakefield} = \text{Drive Wakefield} + \text{Self Wakefield}$$

from the main e+ bunch, acting on itself

Panofsky–Wenzel theorem (Maxwell-Faraday equation with cylindrical quasi-static symmetry):

$$\partial_r F_z = \partial_\xi F_r$$

$$\partial_\xi F_r \neq 0 \implies \partial_r F_z \neq 0$$

→ Slice energy spread may be compromised by strong self wakefield

Nonlinear plasma wakefield

Possible paths:

- ➢ Single-stage plasma accelerator to avoid emittance growth in multiple stages
- ➢ Minimize initial emittance growth to reach equilibrium, and determine if there are conditions in which emittance has really saturated, without further growth.
- ➢ Bunch train and energy recovery

Physics of positron acceleration in nonlinear plasma wakefield

Nonlinear plasma wakefield

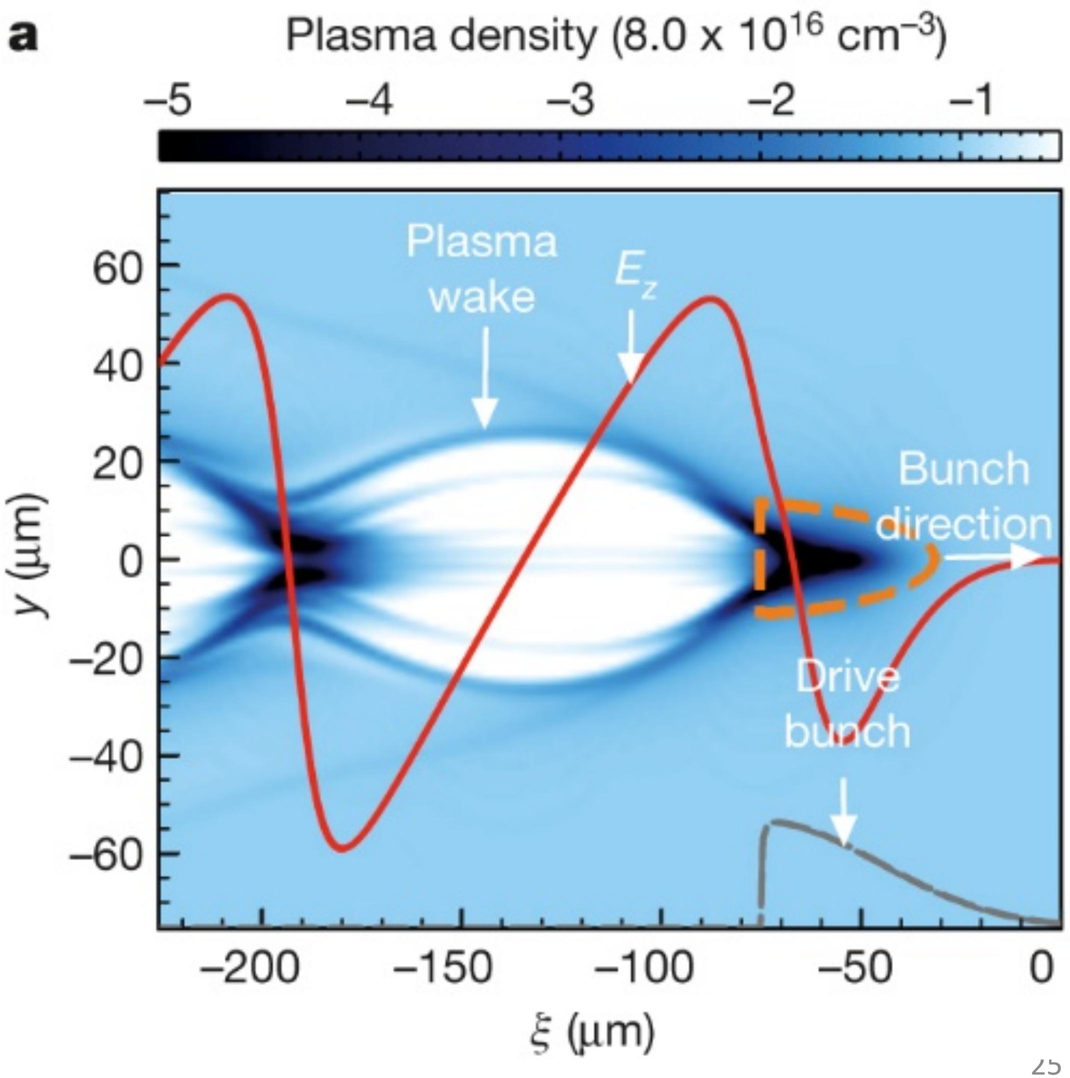
To date:

- 3D nonlinear regime: no analytical solution for wakefield excitation.
- Single e^- sheath phenomenological model of W. Lu *et al.* (Phys. Rev. Lett. 96, 165002, 2006) for blowout regime: not applicable for positrons.
- Would need a multi-sheath or multi-particle model, but this becomes very close to a quasi-static particle-in-cell simulation.
- Rely mainly on PIC simulations to help understand nonlinear positron physics.

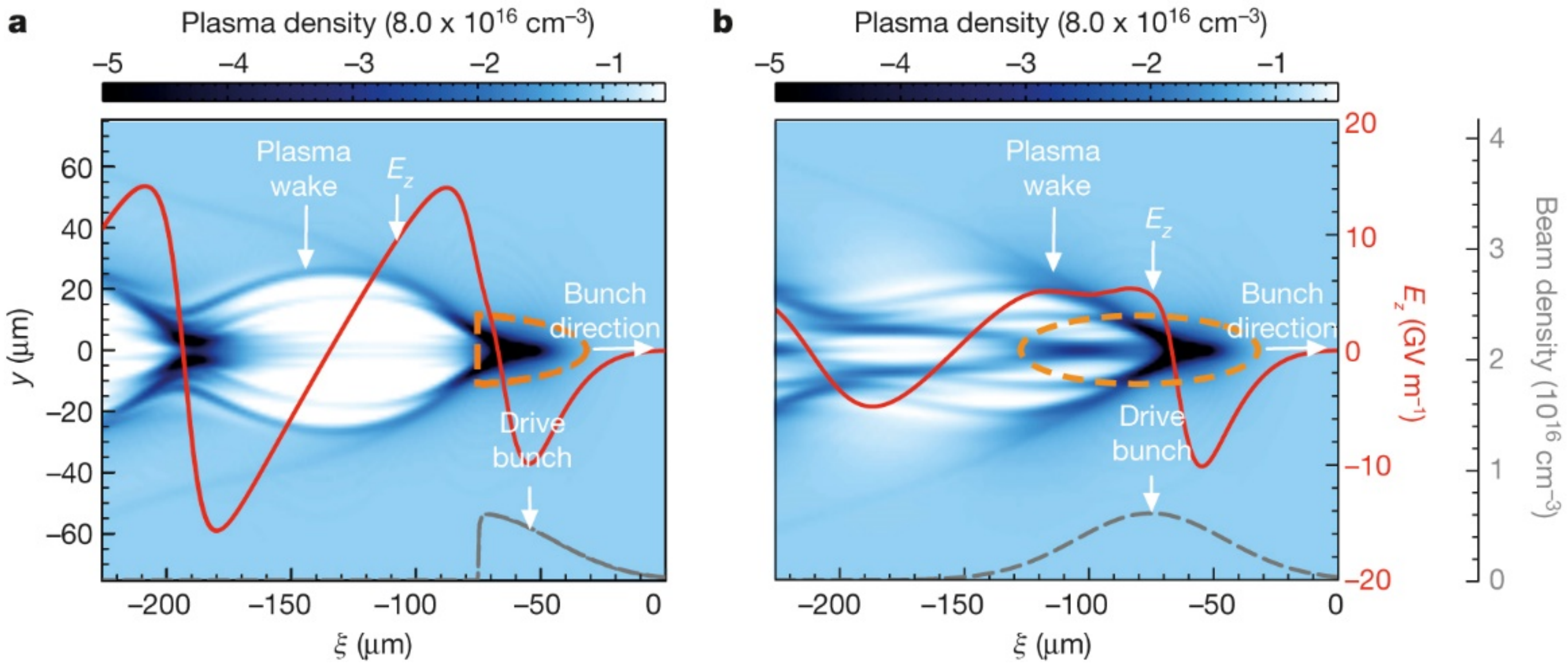
Nonlinear plasma wakefield

Short positively-charged drive bunch:

- ✳ Plasma electrons are sucked in towards the propagation axis.
- ✳ If the bunch is short enough, an ion cavity similar to the blowout regime forms behind the drive bunch.
- ✳ Once plasma electrons have crossed the propagation axis, E_z switches sign and becomes accelerating for positrons.
- ✳ But it's defocusing, seems unlikely to accelerate positrons, similarly to blowout regime.



Nonlinear plasma wakefield



But adding positrons where E_z is positive, the wakefield is strongly modified: longitudinal and transverse beam loading

E_z becomes flat: low energy spread, wakefield becomes focusing for positrons: guiding and positron acceleration is possible.

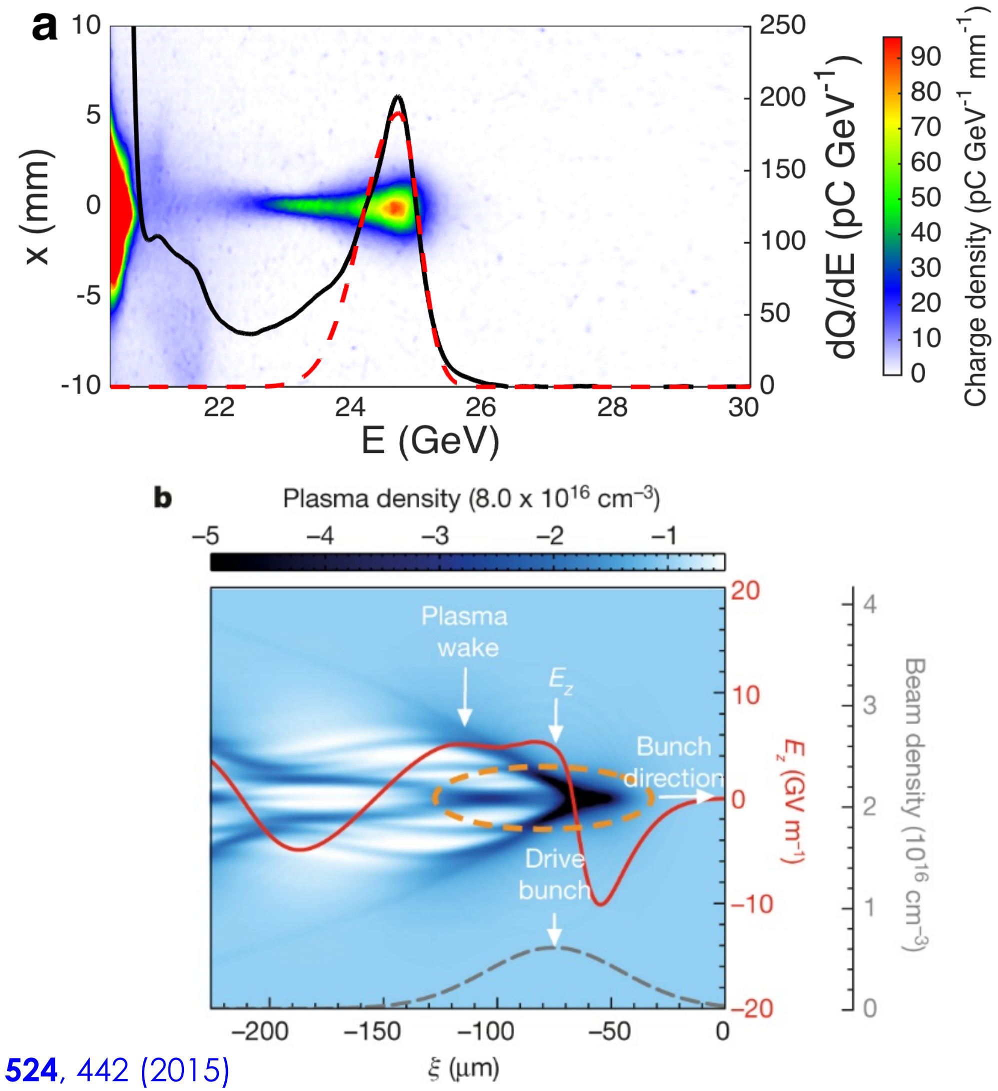
Nonlinear plasma wakefield

Experimental demonstration of positron acceleration in nonlinear plasma wakefield:

- Focusing-accelerating volume for positrons: yes, a large number of positrons are accelerated

- Large field: energy gain of 5 GeV over 1.3 m

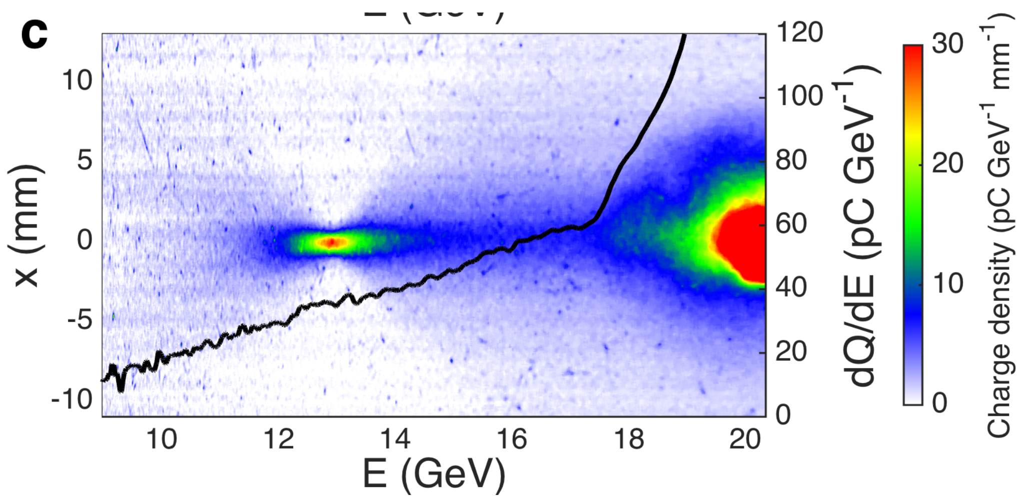
Experimental results in 1.3 m plasma

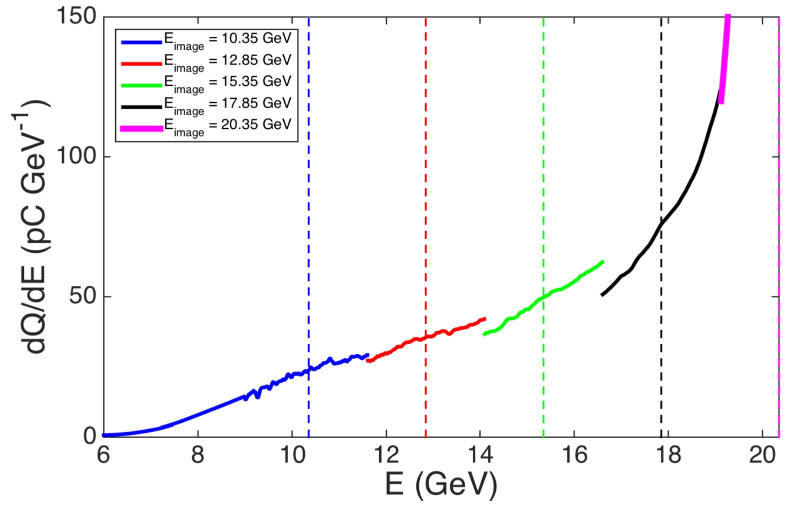


S. Corde *et al.*, Nature **524**, 442 (2015)

Nonlinear plasma wakefield

Experimental results in 1.3 m plasma





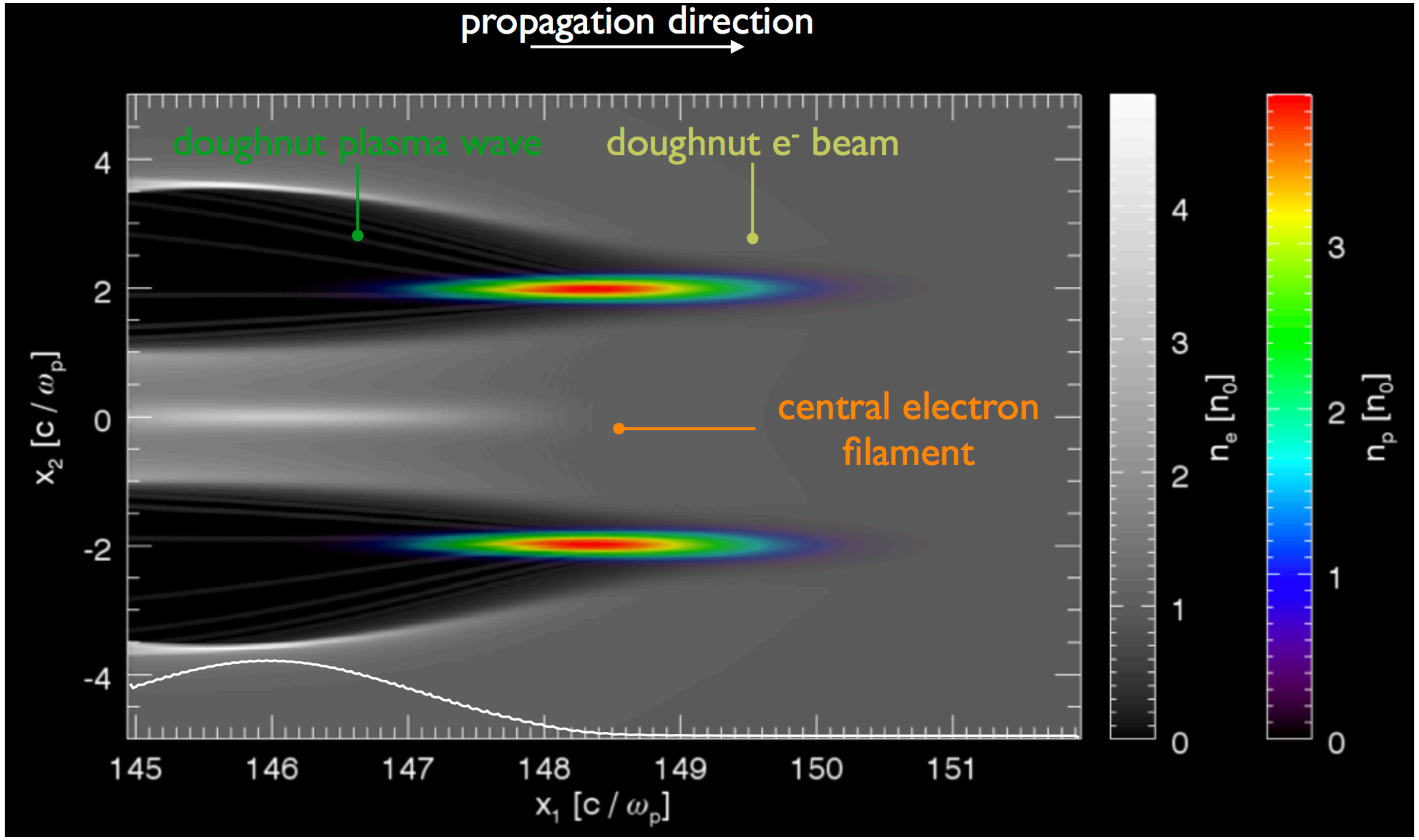
Experimental demonstration of positron acceleration in nonlinear plasma wakefield:

- Positrons decelerated by up to ~10 GeV.
- Can be used to determine energy extraction efficiency.
- Large energy extraction efficiency of about 30% is deduced

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

Nonlinear plasma wakefield

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



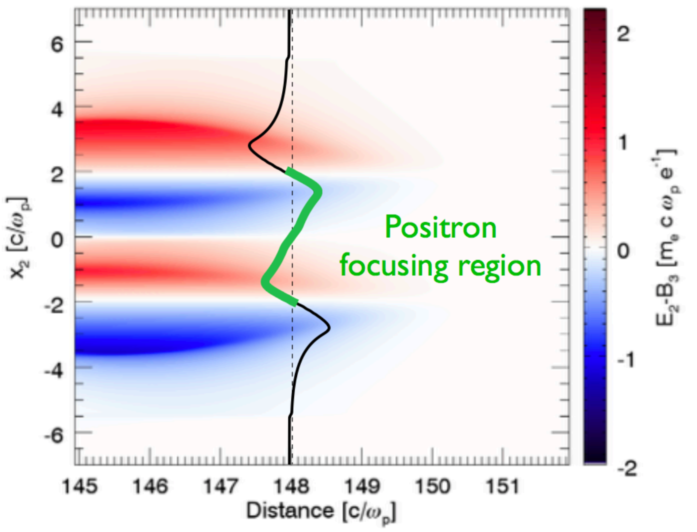
J. Vieira et al Proceedings of AAC (2014); N. Jain et al arXiv (2015)

Nonlinear plasma wakefield

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

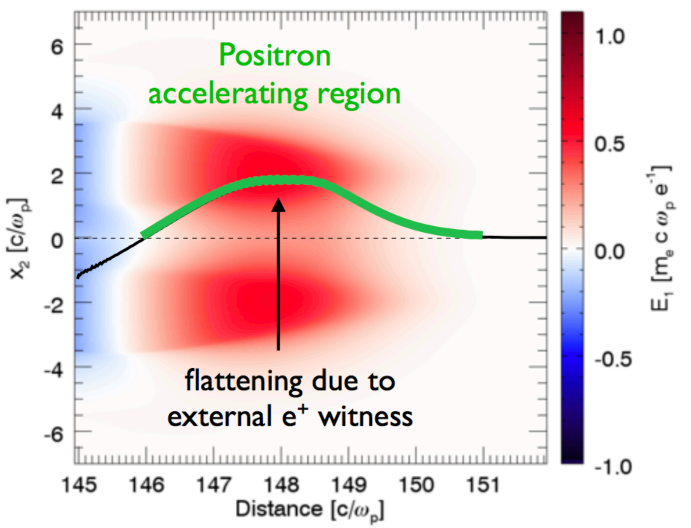
Potential for preserved emittance in nonlinear plasma wakefield?

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**

J. Vieira et al Proceedings of AAC (2014); N. Jain et al arXiv (2015)

Nonlinear plasma wakefield

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

strong self wakefield

electron motion

non-Gaussian radial equilibrium

Nonlinear plasma wakefield

Betatron cooling?

- ➢ Due to their transverse oscillation, positrons emits betatron gamma-rays which reduce their transverse momentum. Leads to cooling and emittance reduction.

- ➢ Compensate and overcome Coulomb scattering?

- ➢ Works with nonlinear field and nonlinear equilibrium? Energy lost by betatron radiation does not compromise overall energy efficiency? Final energy spread acceptable?

PHYSICAL REVIEW E **74**, 026501 (2006)

Radiative damping and electron beam dynamics in plasma-based accelerators

P. Michel, C. B. Schroeder, B. A. Shadwick, E. Esarey,* and W. P. Leemans*

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 081303 (2012)

Electron beam dynamics and self-cooling up to PeV level due to betatron radiation in plasma-based accelerators

Aihua Deng,[1] Kazuhisa Nakajima,[1,2,3,*] Jiansheng Liu,[1,†] Baifei Shen,[1] Xiaomei Zhang,[1] Yahong Yu,[1] Wentao Li,[1] Ruxin Li,[1] and Zhizhan Xu[1]

Promising for nonlinear positron acceleration!

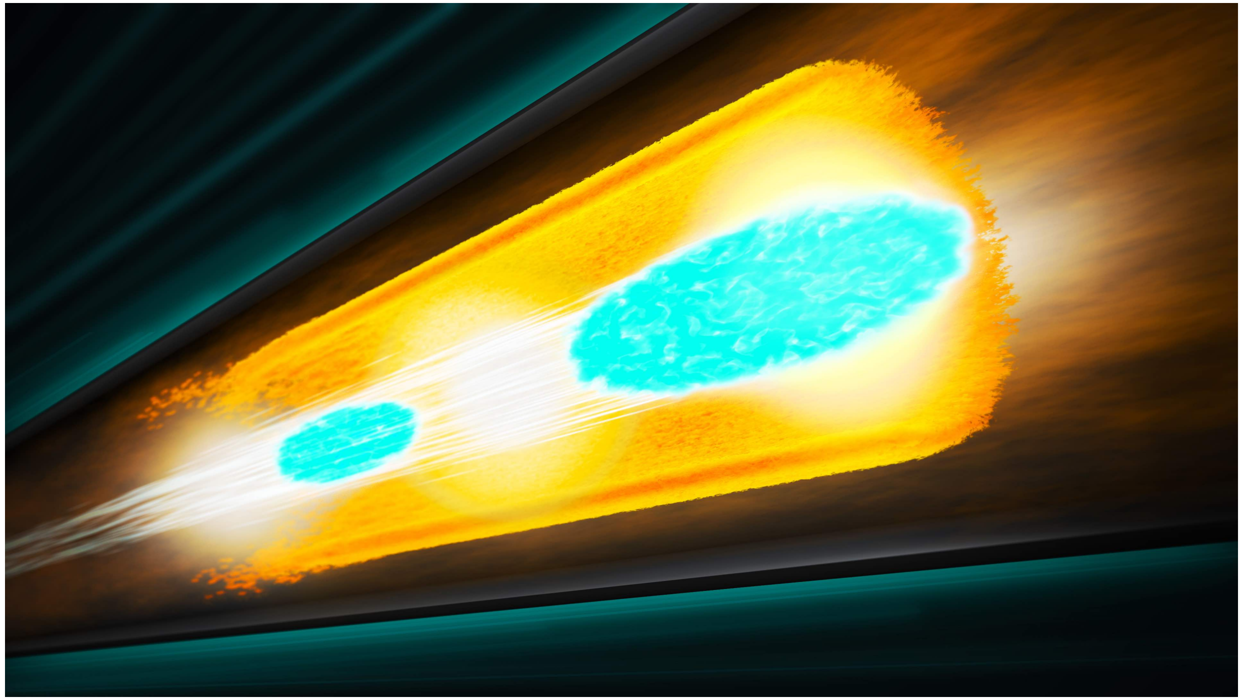
Physics of positron acceleration in hollow plasma channels

References for the theory: PhD thesis of S. Gessner and C. Lindstrøm

Let’s discover it from the experiment

Hollow plasma channels

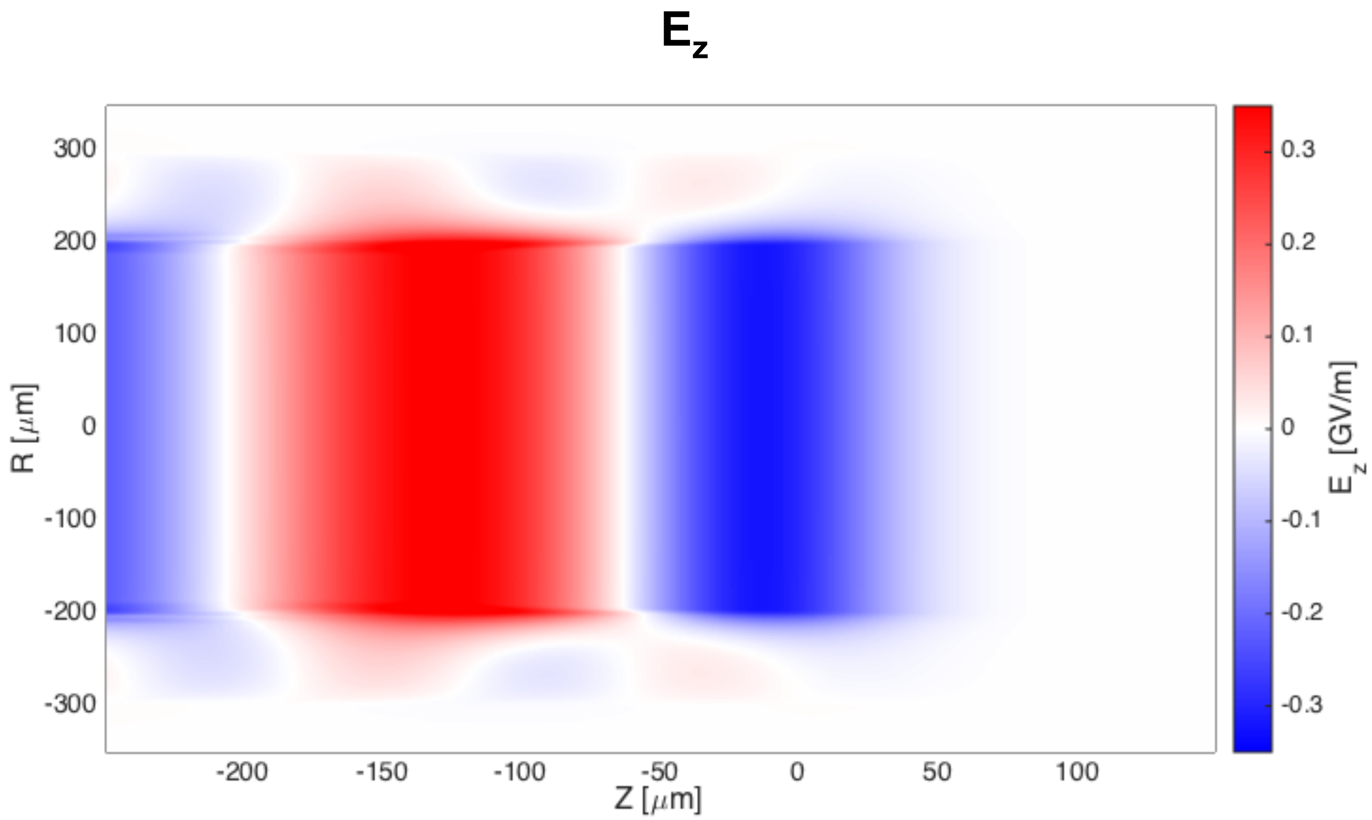
Hollow plasma channels = plasma tubes



Main principle:

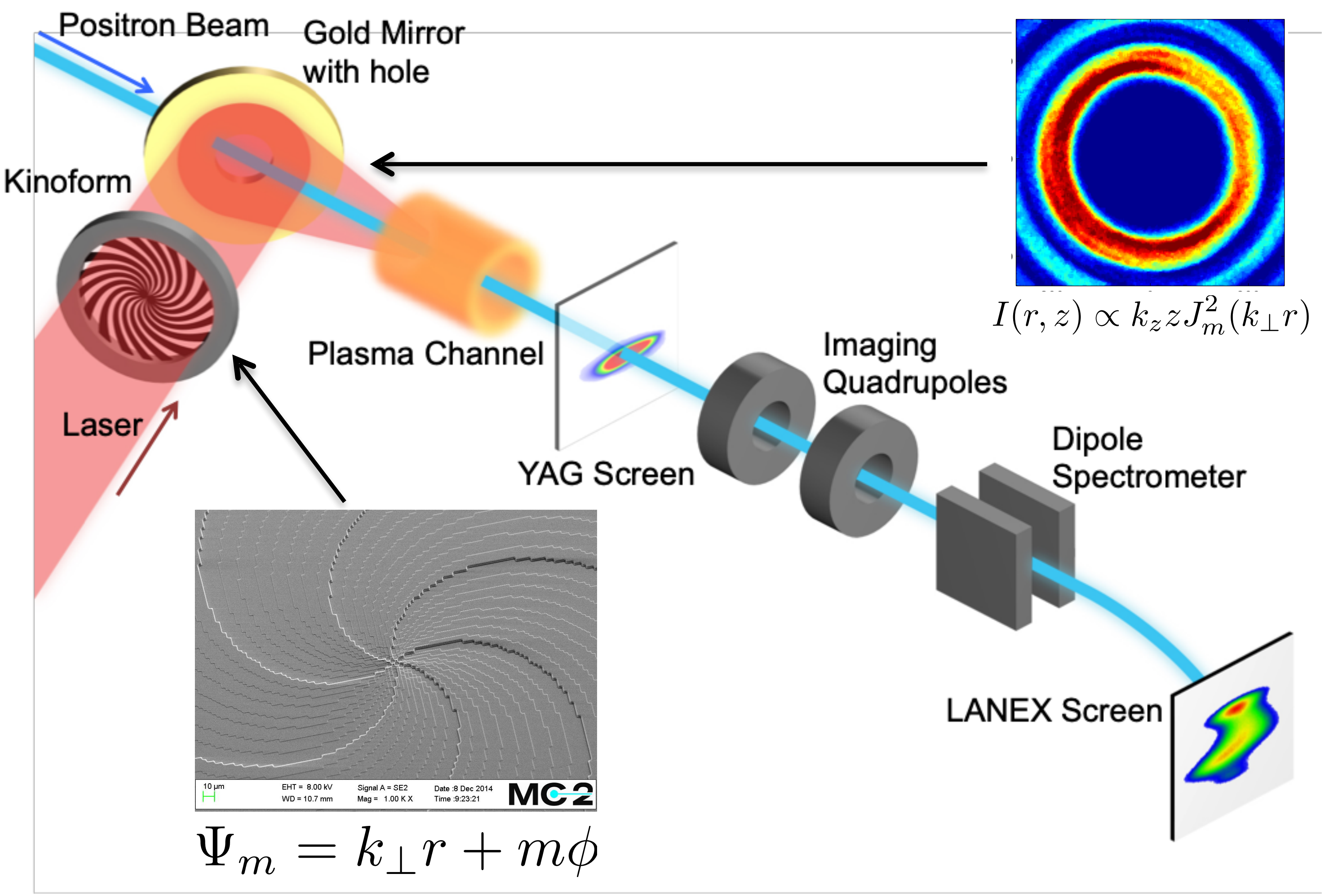
- ✳ Beams propagate in the center, where there is no plasma
- ✳ As a consequence, no focusing or defocusing force, there is only E_z inside the channel
- ✳ No electron motion, because again, no plasma in the center

Hollow plasma channels



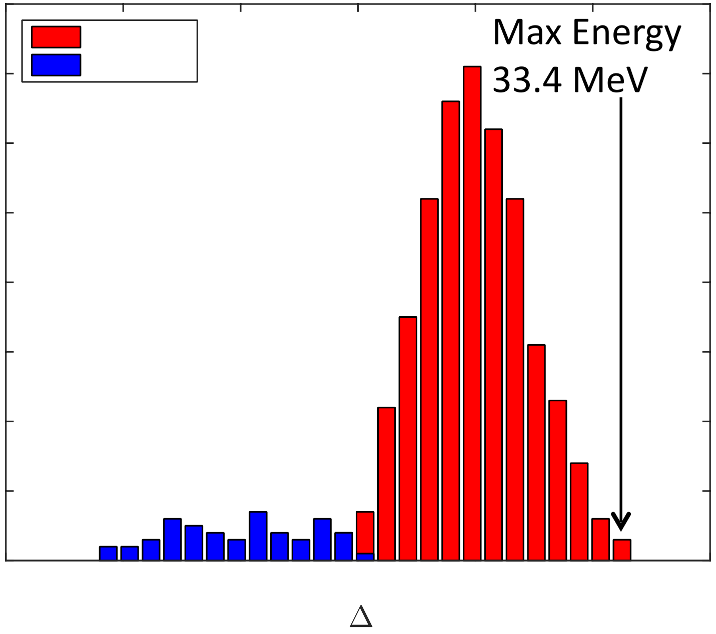
Hollow channels provide large accelerating fields *without* focusing fields.

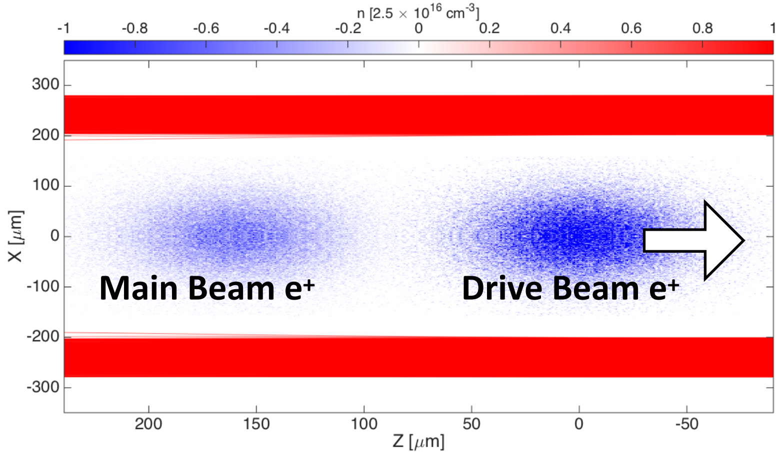
Hollow plasma channels



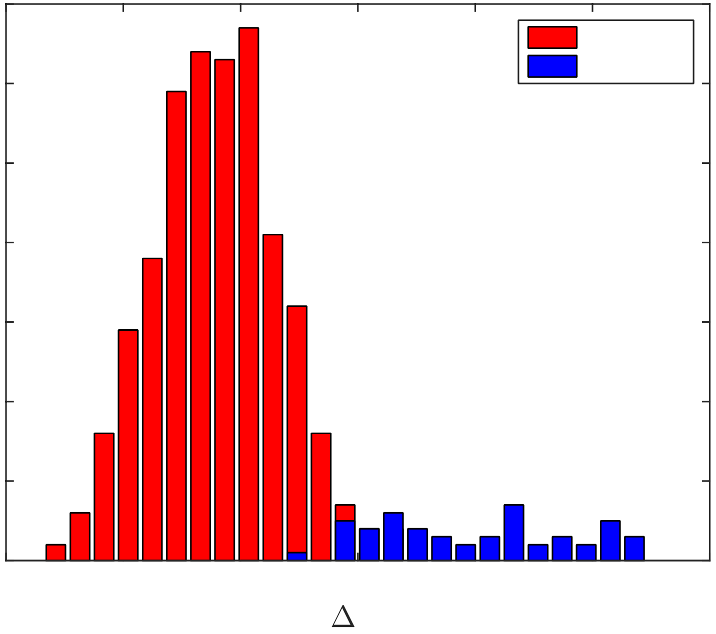
Hollow plasma channels

Mean <ΔE> = 19.9 MeV





Mean <ΔE> = -11.0 MeV



Main beam gains energy from the wake.

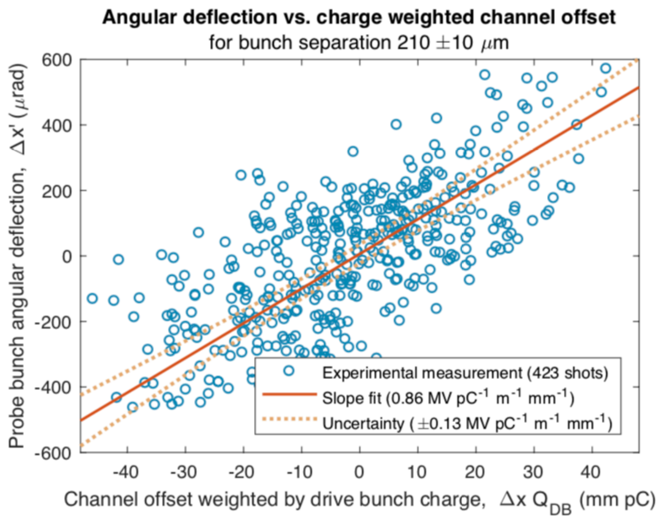
Drive beam transfers energy to witness beam.

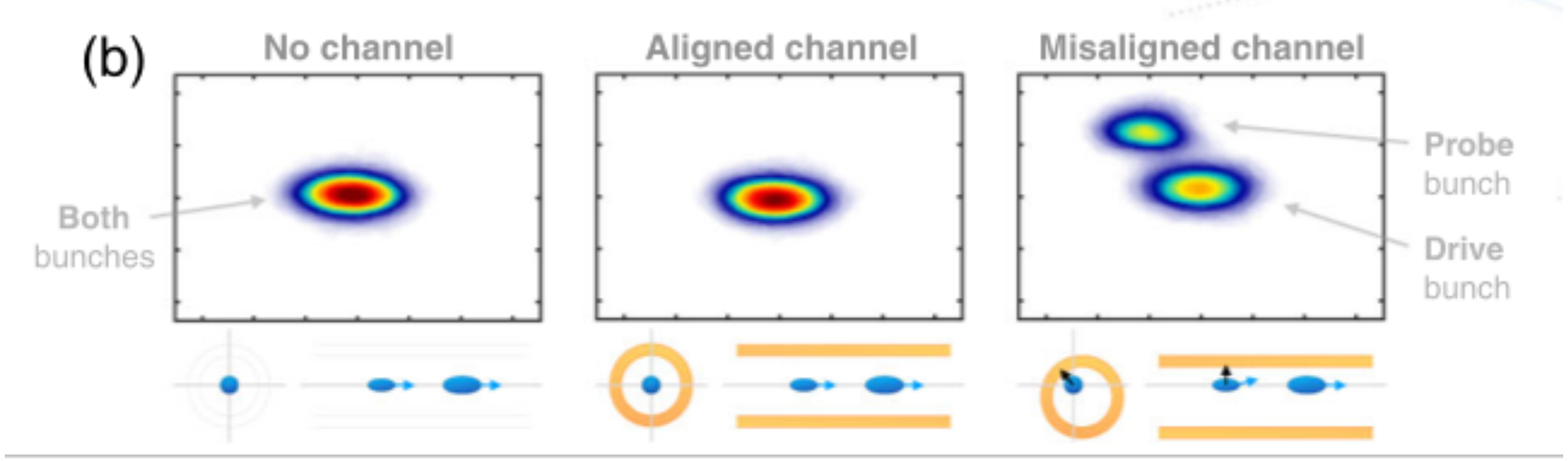
Hollow plasma channels

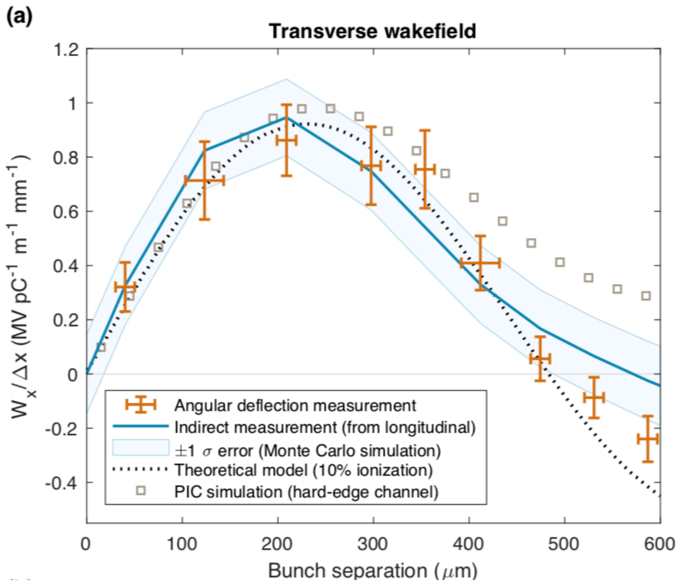
We measured the transverse wakefields in the hollow channel and the result agrees with our theoretical calculation:

10^6 V/(pC m mm)

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







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

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 main 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

(uniform plasma)

beam breakup instability

(hollow plasma)

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