ALEGRO 2018 workshop at Oxford

Positron Acceleration in Plasma
Introduction, Status and Objectives

Sébastien Corde and Spencer Gessner
WG8 coordinators

March 26, 2018

Outline

- Introduction of the scientific context for positron acceleration in plasma
    - Motivation and relationship with LWFA-PWFA WG4 and 5
    - Difficulties for positron acceleration in plasma
    - No self-consistent scheme for simultaneously achieving high efficiency, low preserved emittance and transverse instability mitigation

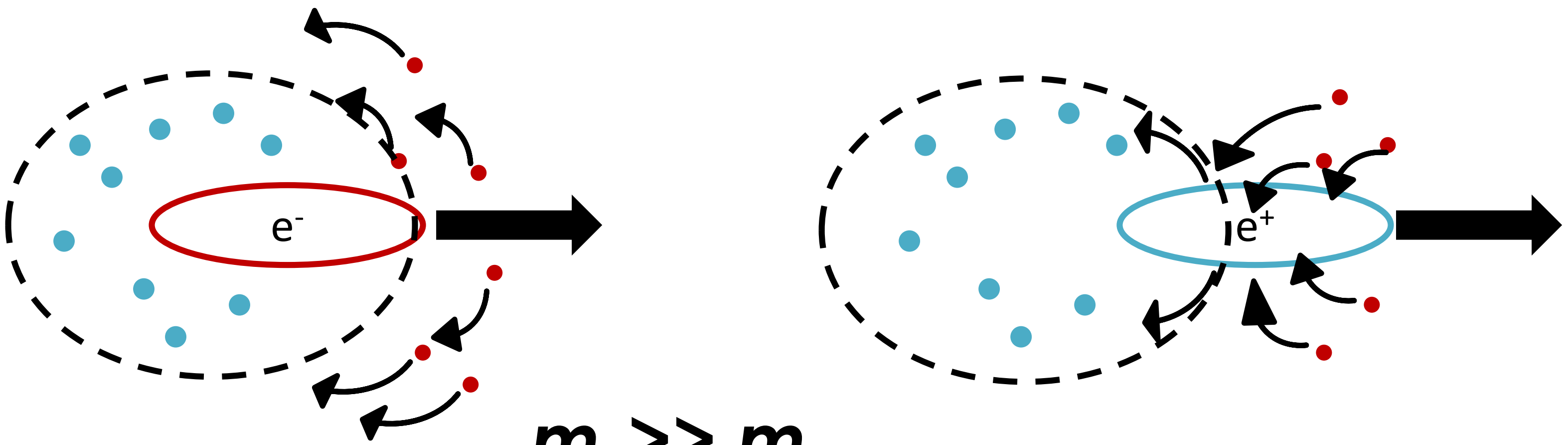
- Paths identified so far (all have major problems for linear colliders)
    - Quasi-linear plasma wakefield
    - Nonlinear plasma wakefield
    - Hollow plasma channels

- WG8 Status and Objectives
    - WG8 CERN mini-workshop
    - WG8 sessions at ALEGRO 2018 workshop
    - Identify path forward, potential issues, and R&D priorities

Introduction to Positron acceleration in Plasma

Plasmas are asymmetric accelerators

Plasma acceleration schemes (both LWFA and PWFA) are promising candidates for an advanced linear collider. But plasmas are asymmetric accelerators: there are profound difference between electron and positron acceleration in plasmas.



$m_i >> m_e$

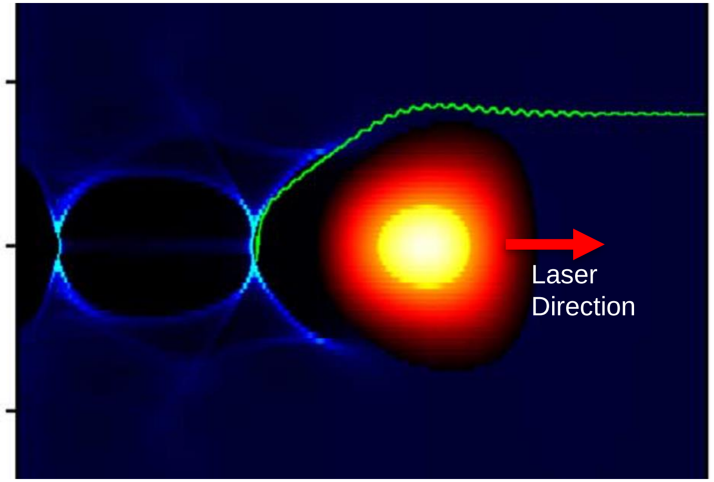
The plasma electrons are mobile but the ions are not.

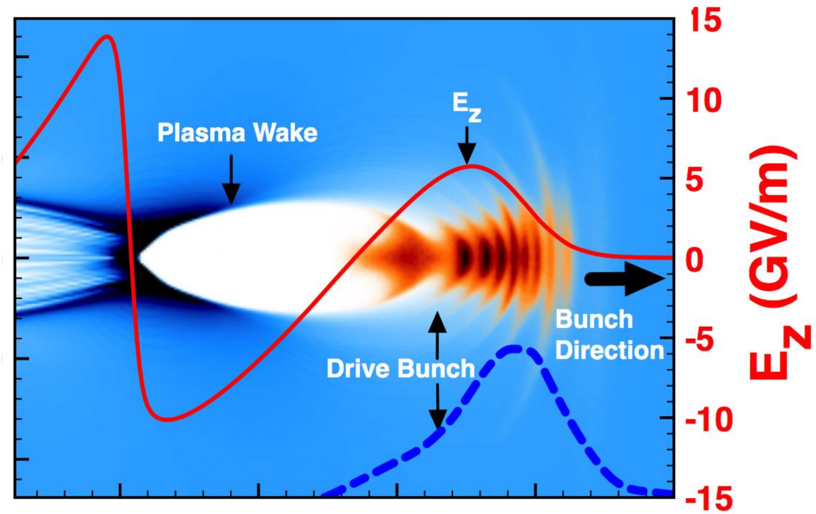
The symmetry of the accelerating mechanism is broken.

Exception

Linear plasma waves are symmetrical.

Plasmas are asymmetric accelerators





LWFA
laser driver

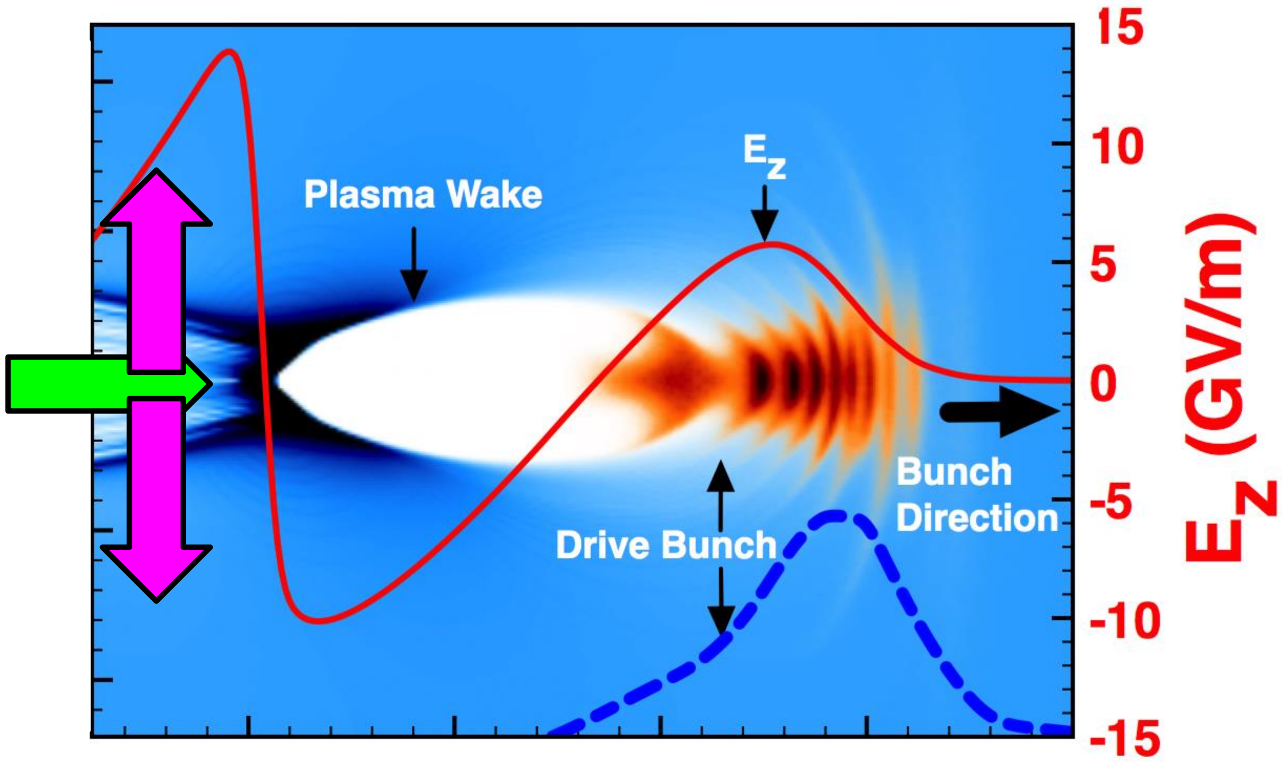
PWFA
particle beam driver

Positron acceleration has very similar difficulties in both LWFA and PWFA. It would be beneficial to tackle the problem across the fields of LWFA and PWFA.

→ WG8 Positron acceleration is a joint sub-WG to LWFA-PWFA WG4 and 5

Plasmas are asymmetric accelerators

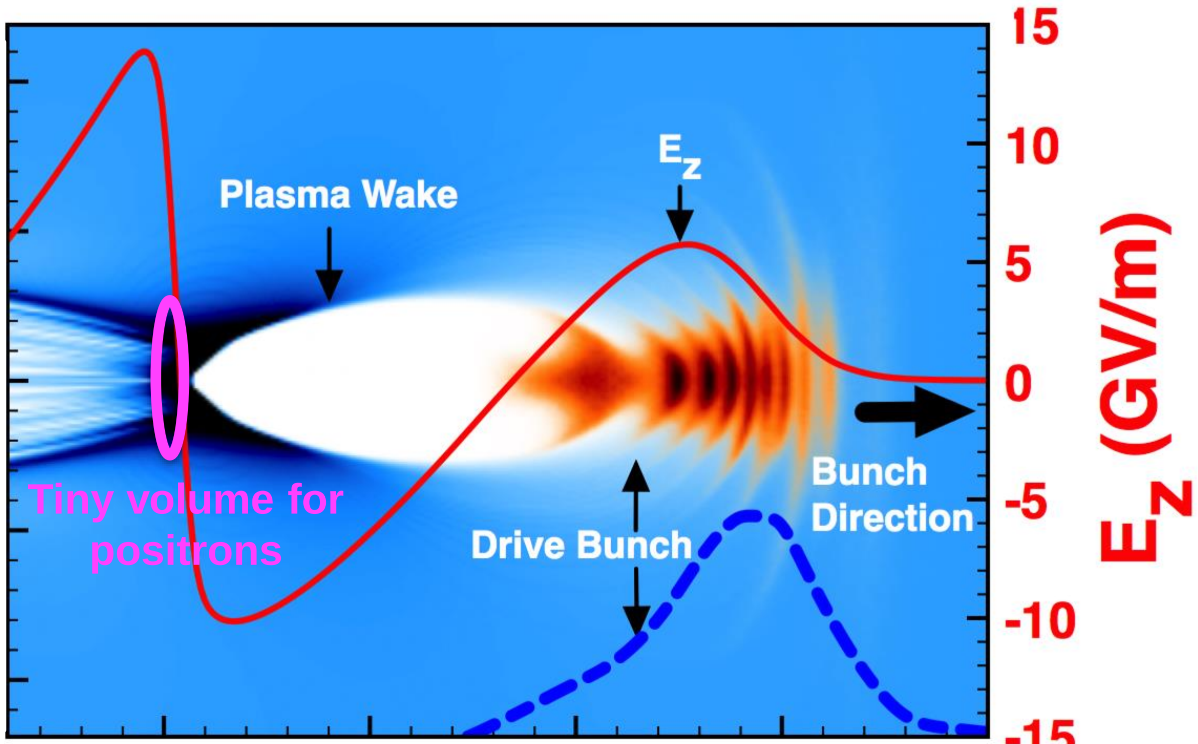
Electron-driven or laser-driven nonlinear blowout wakes:



But the field is defocusing in this region.

Plasmas are asymmetric accelerators

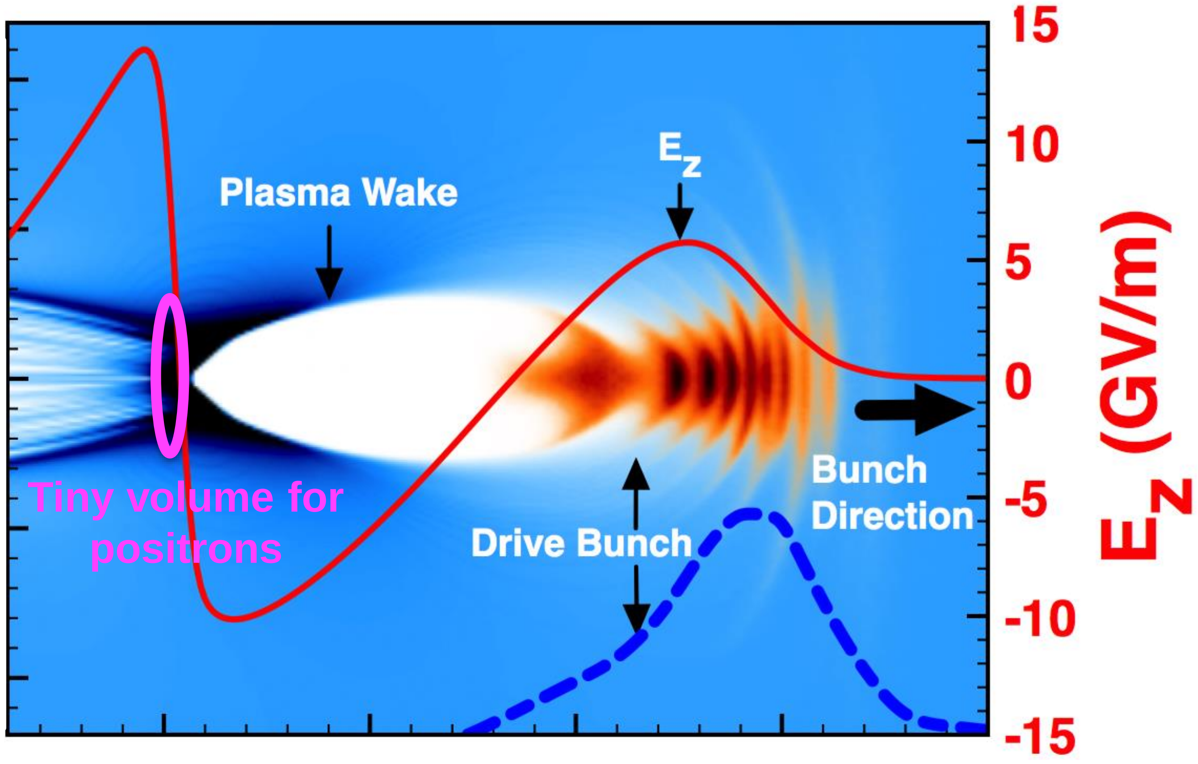
Electron-driven or laser-driven nonlinear blowout wakes:



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

Plasmas are asymmetric accelerators

Electron-driven or laser-driven nonlinear blowout wakes:

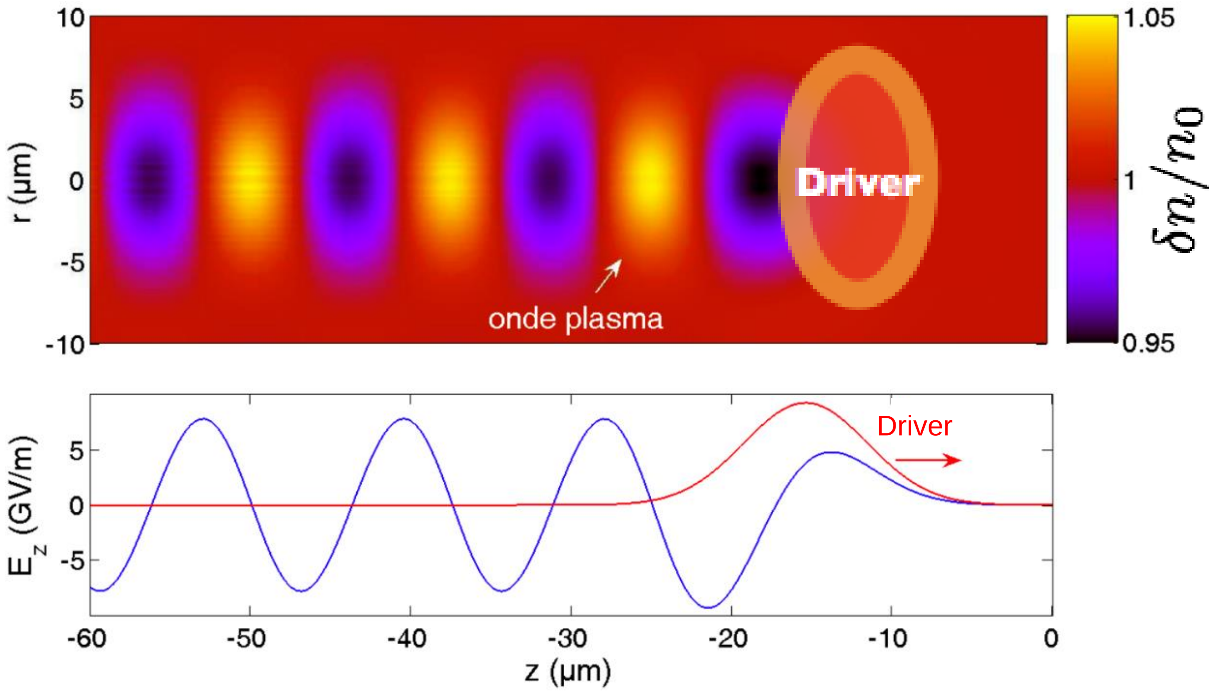


Transverse force is highly nonlinear in r

→ emittance growth

Challenges of Positron acceleration in Plasma

Linear plasma wakes (any driver):

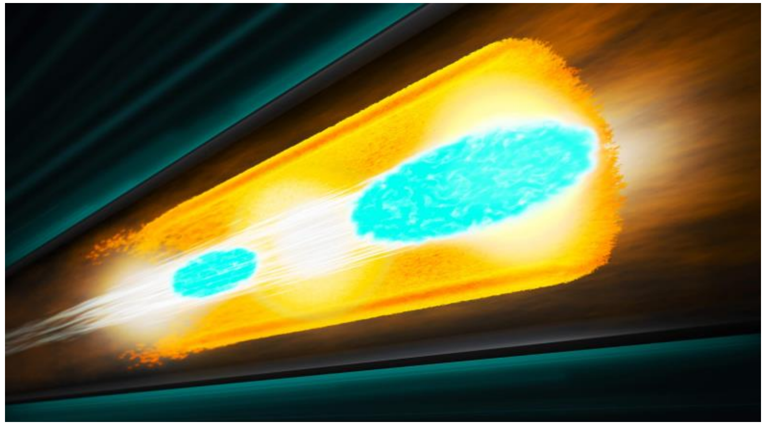


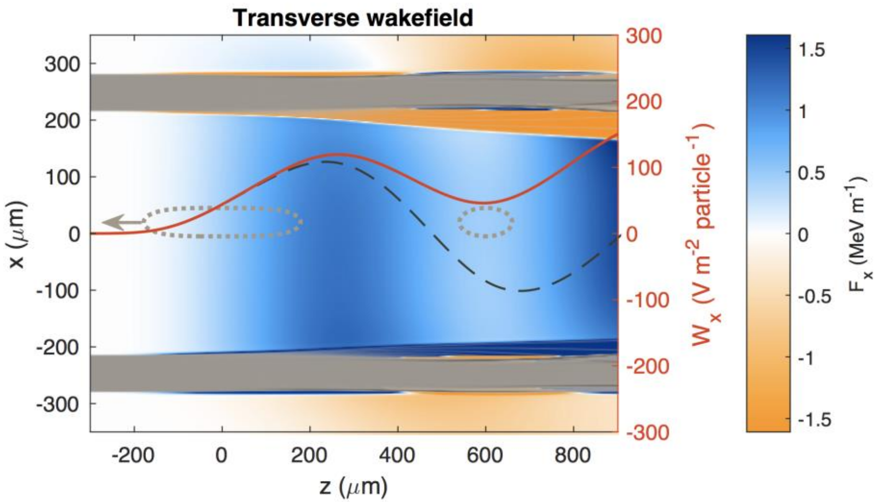
Major problems:

- Efficiency is low
- Stable propagation of a witness positron bunch requires either high emittance or very low charge; otherwise it collapses and drives nonlinear wakefield.

Challenges of Positron acceleration in Plasma

Hollow plasma channels:





Major problem:

- ➢ Transverse instability

Challenges of Positron acceleration in Plasma

Plasma acceleration is being considered for an advanced linear collider, 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.

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

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)].

Challenges of Positron acceleration in Plasma

As of now, no self-consistent scheme for accelerating positrons in plasma that can simultaneously provide:

- High energy efficiency
- Extremely low preserved emittance
- Mitigation of transverse instabilities

Plasma-based particle accelerators face a major challenge:

The positron problem

→ Deserve serious attention

It's all about beam quality and efficiency

Identified paths for positron acceleration in plasma

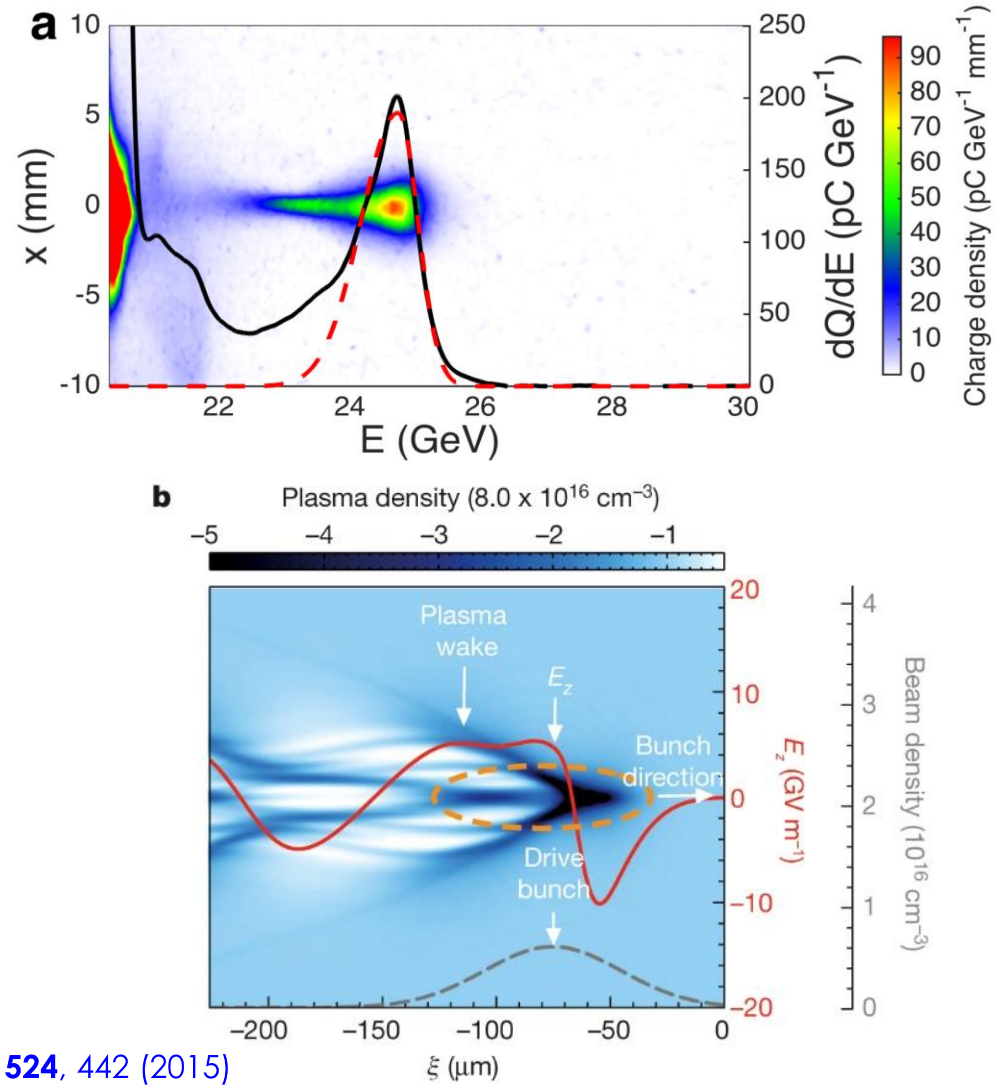
Nonlinear plasma wakefield

Nonlinear plasma wakefield

Positron acceleration in nonlinear plasma wakefield:

- Unexpected result: a large number of positrons are accelerated. Not just a tiny volume being accelerating and focusing for positrons.
- 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.).
- Energy extraction efficiency of about 30% is deduced.

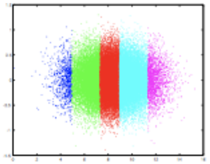
Experimental results in 1.3 m plasma

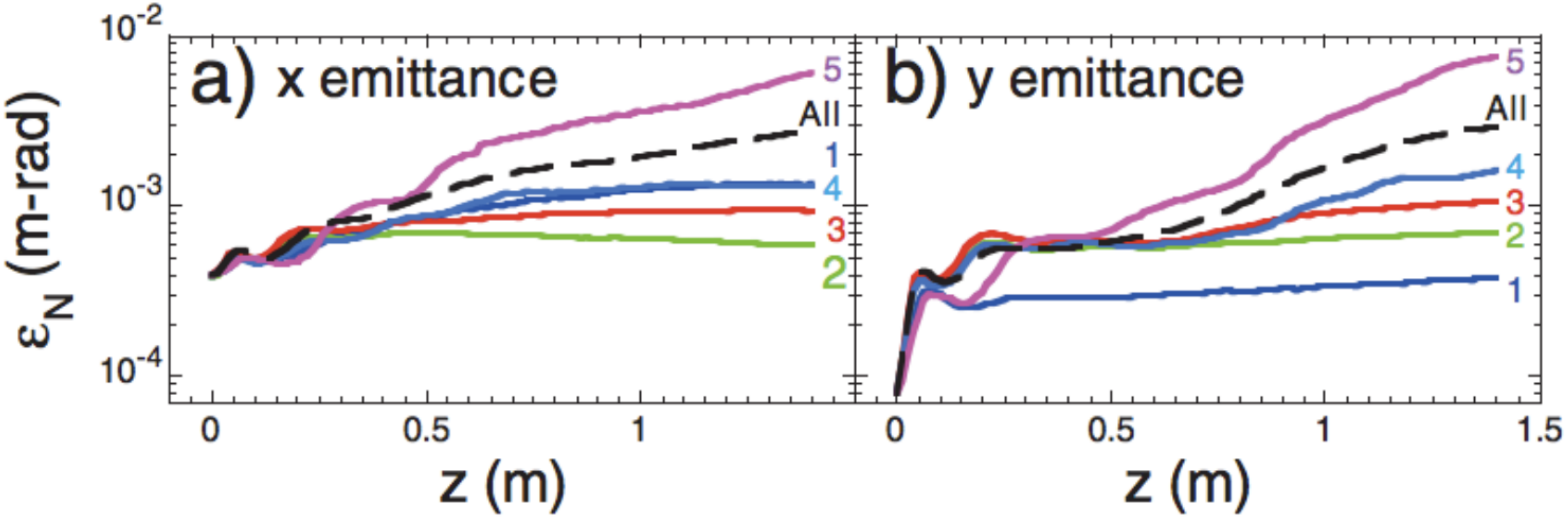


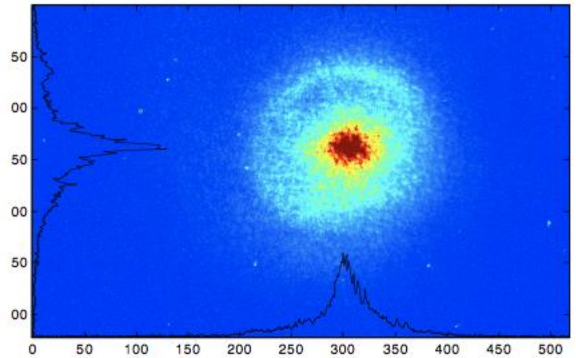
S. Corde *et al.*, Nature **524**, 442 (2015)

Nonlinear plasma wakefield

Transverse force is nonlinear in r,
and is slice dependent.
→ emittance growth

Front  Back





Halo formation

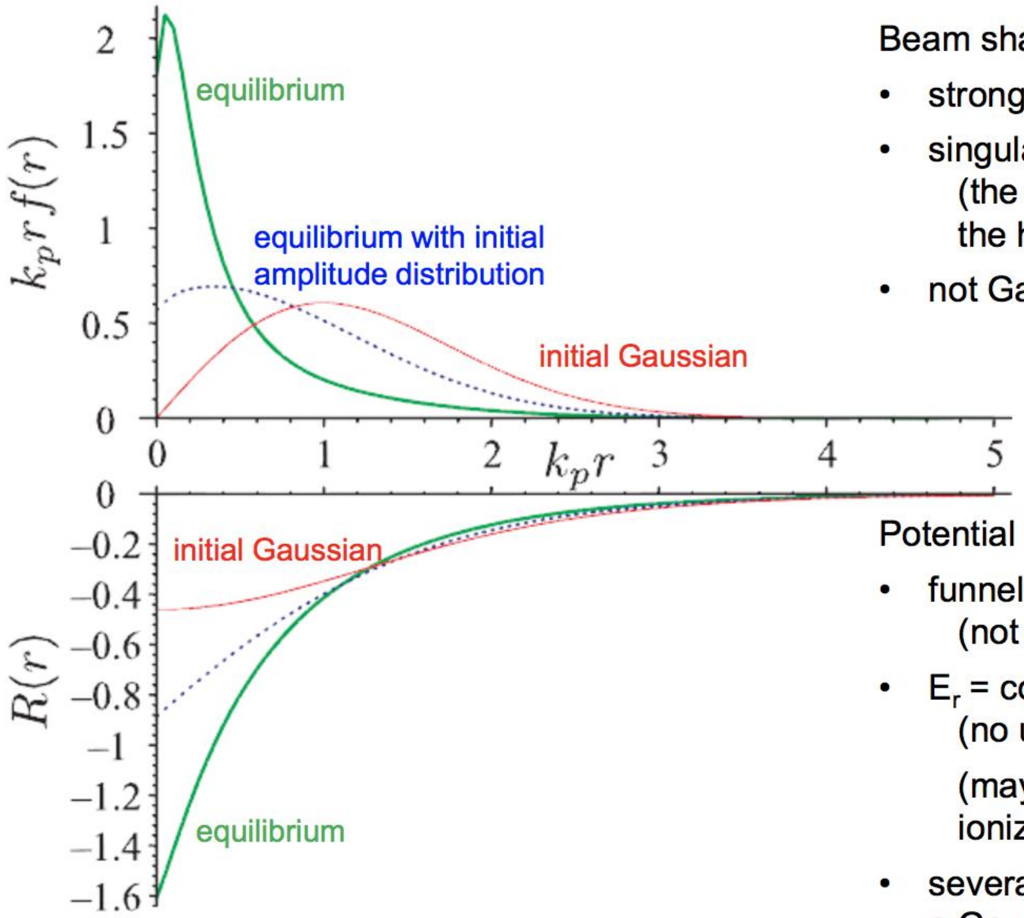
P. Muggli *et al.*, Phys. Rev. Lett 101, 055001 (2008)

Nonlinear plasma wakefield

- “Weird” bunch shape for radial equilibrium
→ no emittance growth

- If initially Gaussian, the bunch evolves with emittance growth until equilibrium (quasi-steady state) is reached, after which emittance is preserved.

- Single-stage plasma accelerator to avoid emittance growth in multiple stages



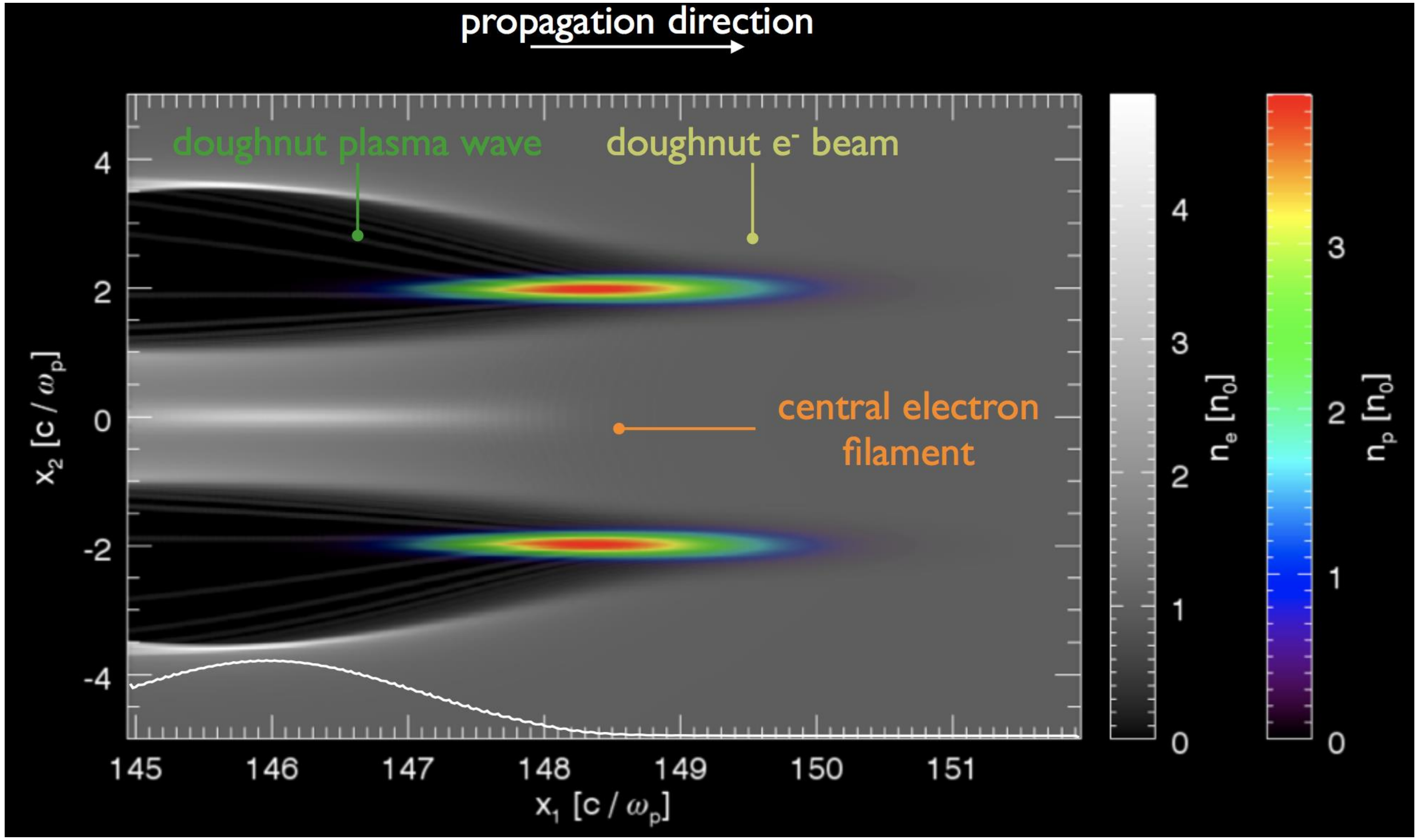
Beam shape:
- strongly peaked near the axis
- singular behaviour (1/r) (the smaller the initial emittance, the higher on-axis density)
- not Gaussian

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

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



Potential for high efficiency and preserved emittance in nonlinear plasma wakefield

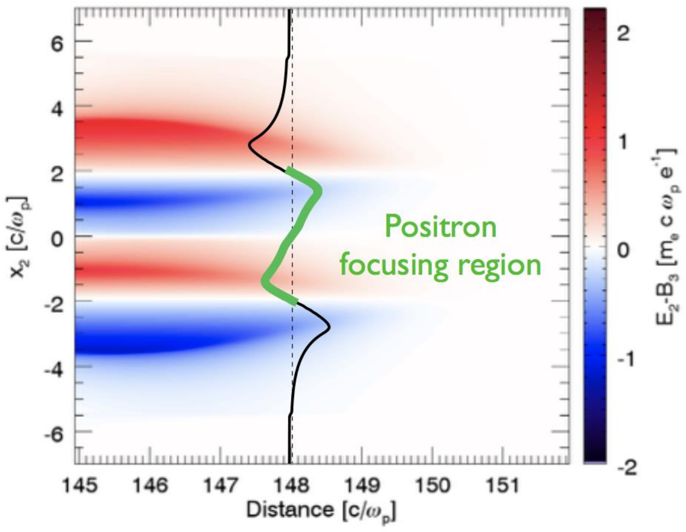
J. Vieira et al Proceedings of AAC (2014); N. Jain et al arXiv (2015)

Nonlinear plasma wakefield

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

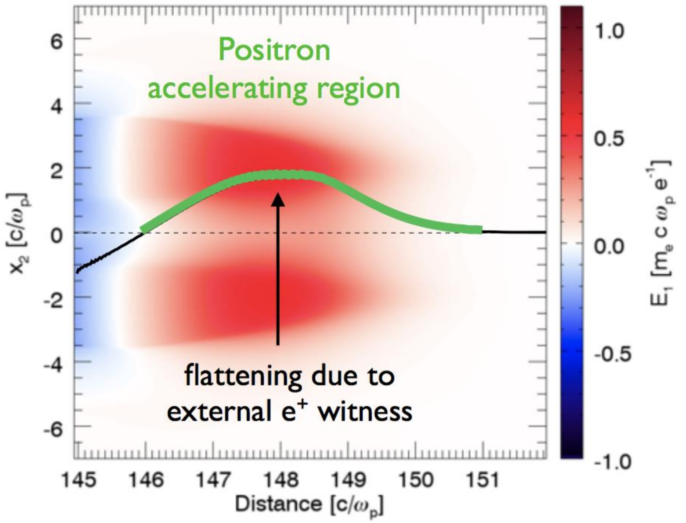
Potential for high efficiency and preserved emittance in nonlinear plasma wakefield

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

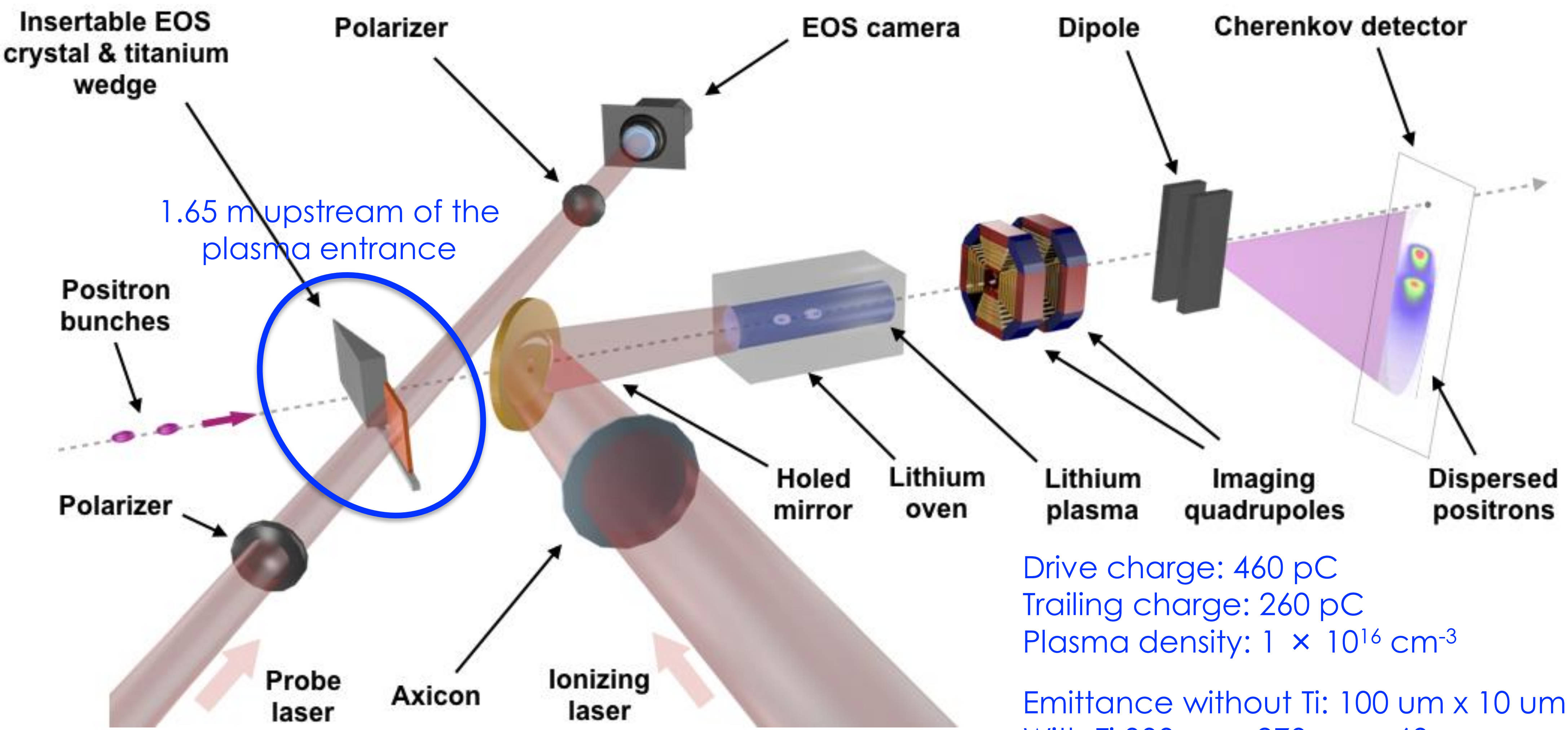


- e+ can **accelerate at the front**
- **Beam loading** is possible
- **Energy spread** growth can be **controlled**

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

Quasi-linear plasma wakefield

Quasi-linear plasma wakefield

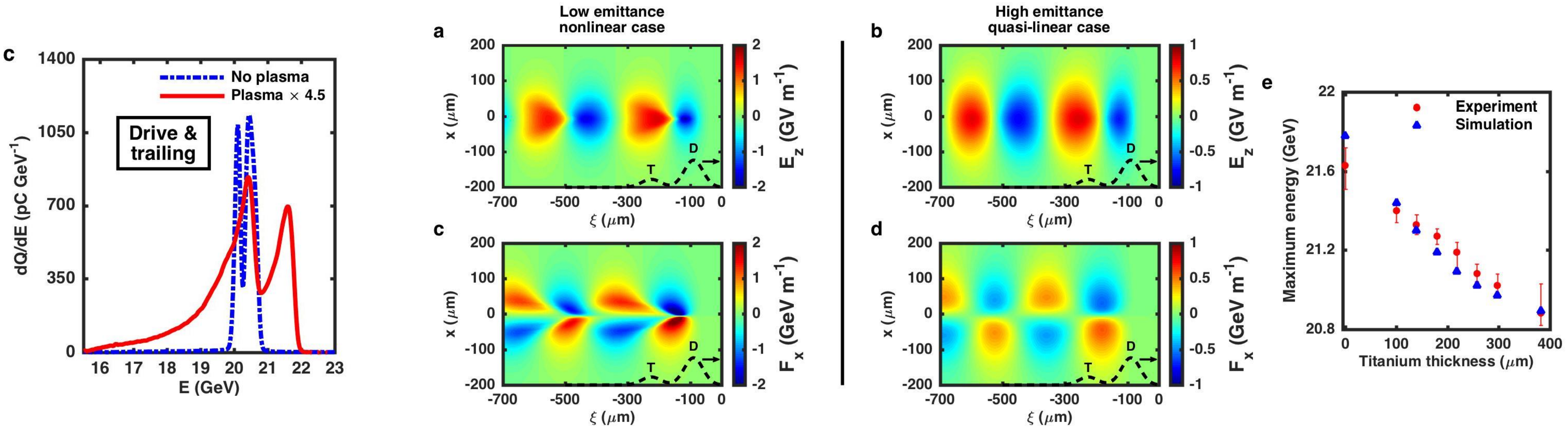


Drive charge: 460 pC
Trailing charge: 260 pC
Plasma density: 1×10^{16} cm^{-3}

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

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

Quasi-linear plasma wakefield



- ➢ Acceleration of a distinct positron bunch in a plasma
- ➢ By varying incoming emittance, experiment spans nonlinear to quasi-linear regime

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

Quasi-linear plasma wakefield

- Stable propagation for trailing positron bunch requires high emittance or low charge.

- Without stable propagation, the trailing positron bunch collapses and a nonlinear wavefield is generated

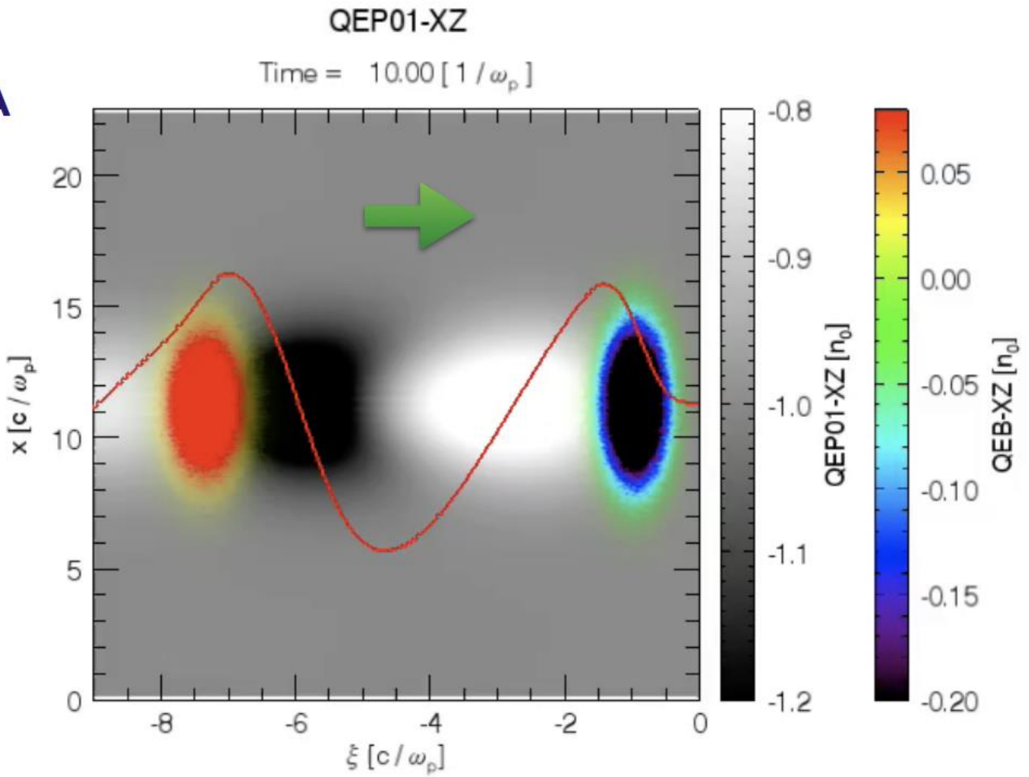
→ same problems as discussed for nonlinear plasma wakefield

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, $\boxed{\varepsilon_N = 4000\ \mu m\ rad}$

Distance between two bunches:
340 µm

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



Quasi-linear plasma wakefield

- Low emittance implies low charge, and therefore low efficiency per bunch.

- “True” quasi-linear regime therefore requires multi-pulse/multi-bunch and/or energy recovery, to accommodate for the low efficiency per bunch 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,*]

[1]*John Adams Institute for Accelerator Science, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom*

[2]*Central Laser Facility, Rutherford Appleton Laboratory, Didcot OX11 0QX, United Kingdom*

[3]*John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom*

[4]*Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, Hamburg 22607, Germany*

(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)

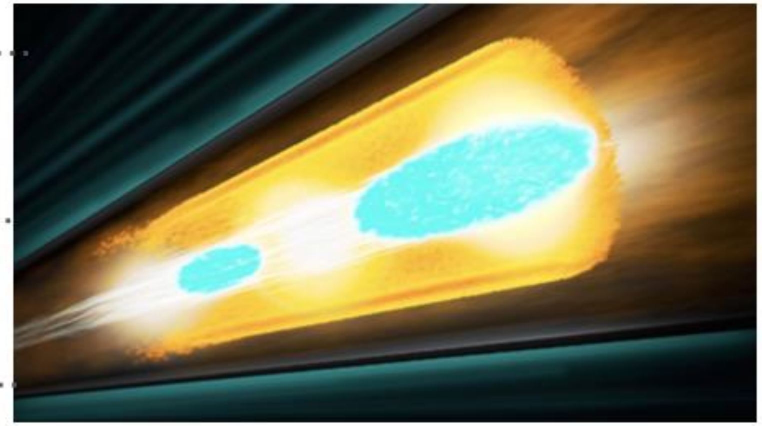
Hollow plasma channels

Hollow plasma channels

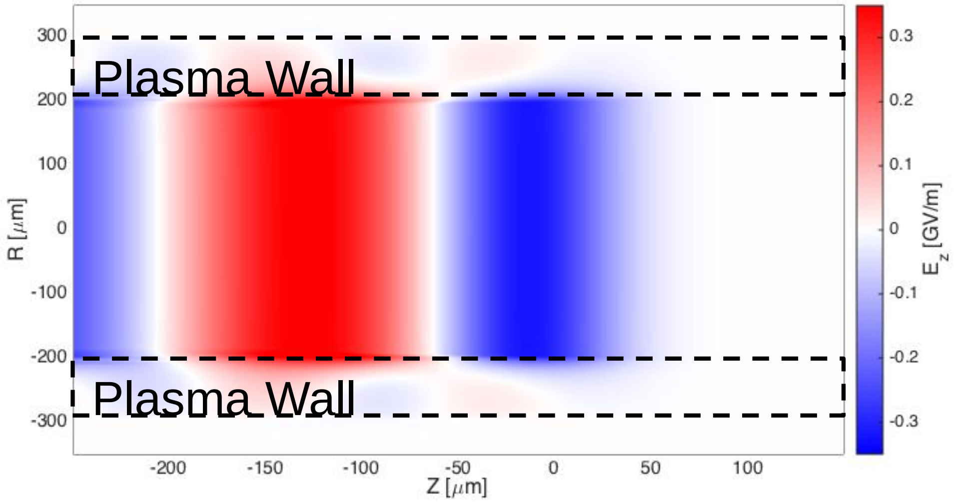
charge symmetry
(works also positrons)

no focusing fields
(no tight beam matching)

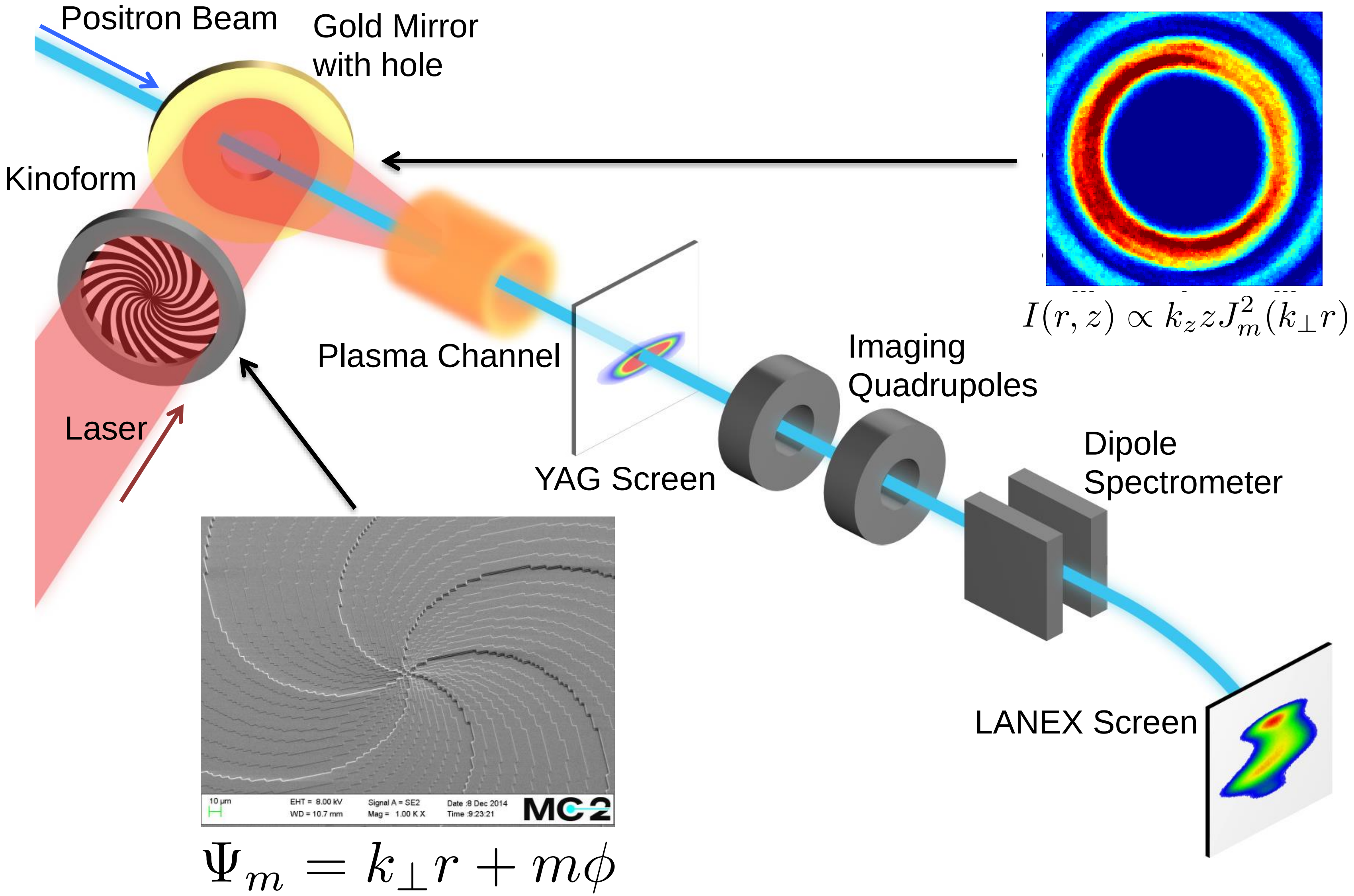
no structure failure
(new channel every time)



The Hollow Plasma Channel 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.



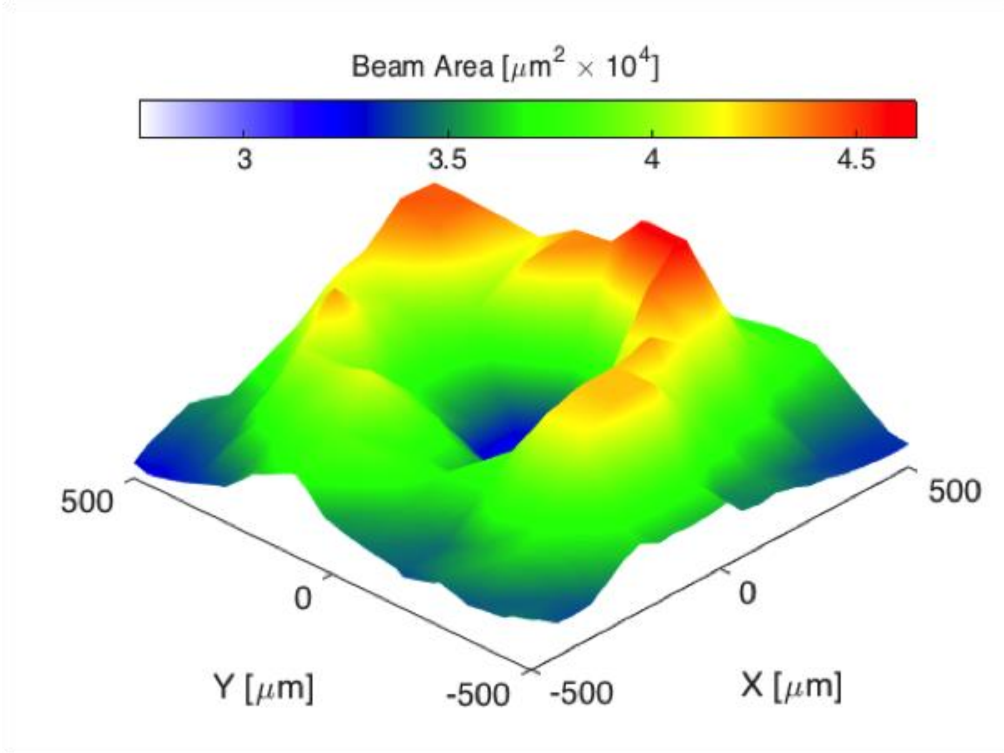
Hollow plasma channels



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.

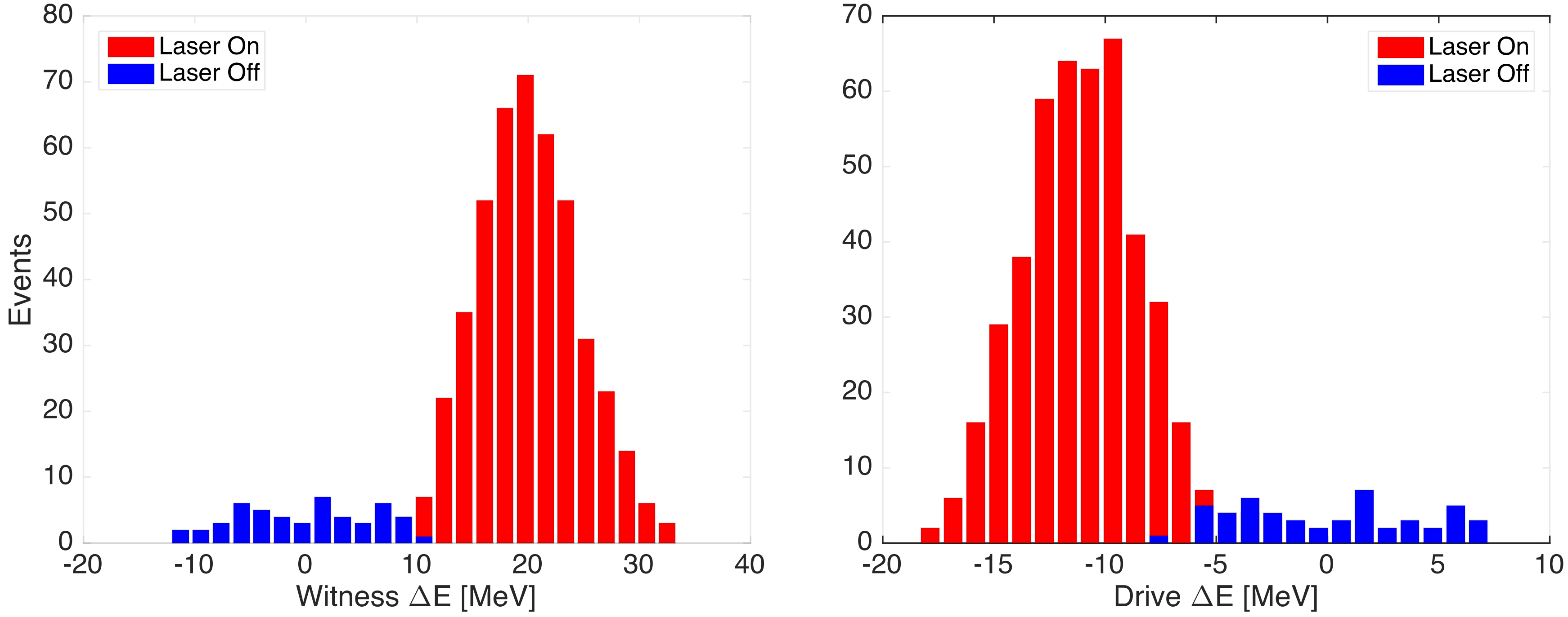
Both the Kick Map and Beam Area Measurement (Volcano Plot) are consistent with an annular plasma channel.



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

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.

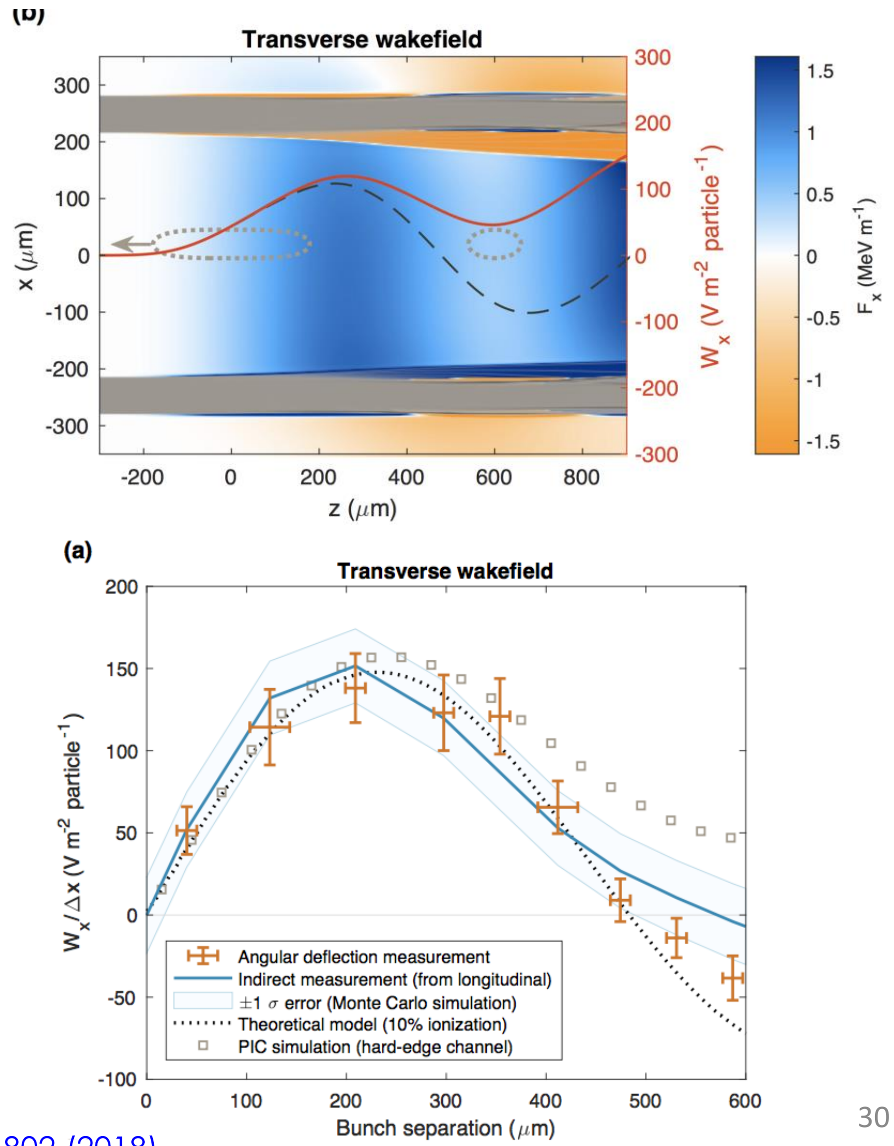
Hollow plasma channels

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

- Hollow channel (500 μm diameter at 3×10^{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)

WG8 Status and Objectives

Working Group 8 sessions

ALEGRO WG8 mini-workshop at CERN (February 9, 2018)

Talks:

- Review results from previous experiments
- Get a common understanding of the challenges and proposed solutions
- Look ahead to future experiments

Discussion:

- What are the major obstacles to accelerating high-quality positron beams in plasma?
- There are many proposed solutions. What are their advantages and drawbacks?
- There aren't many facilities of positron PWFA/LWFA research. Is there anything we can do about it?
- What about novel sources of positron beams for plasma acceleration experiments?

Working Group 8 sessions

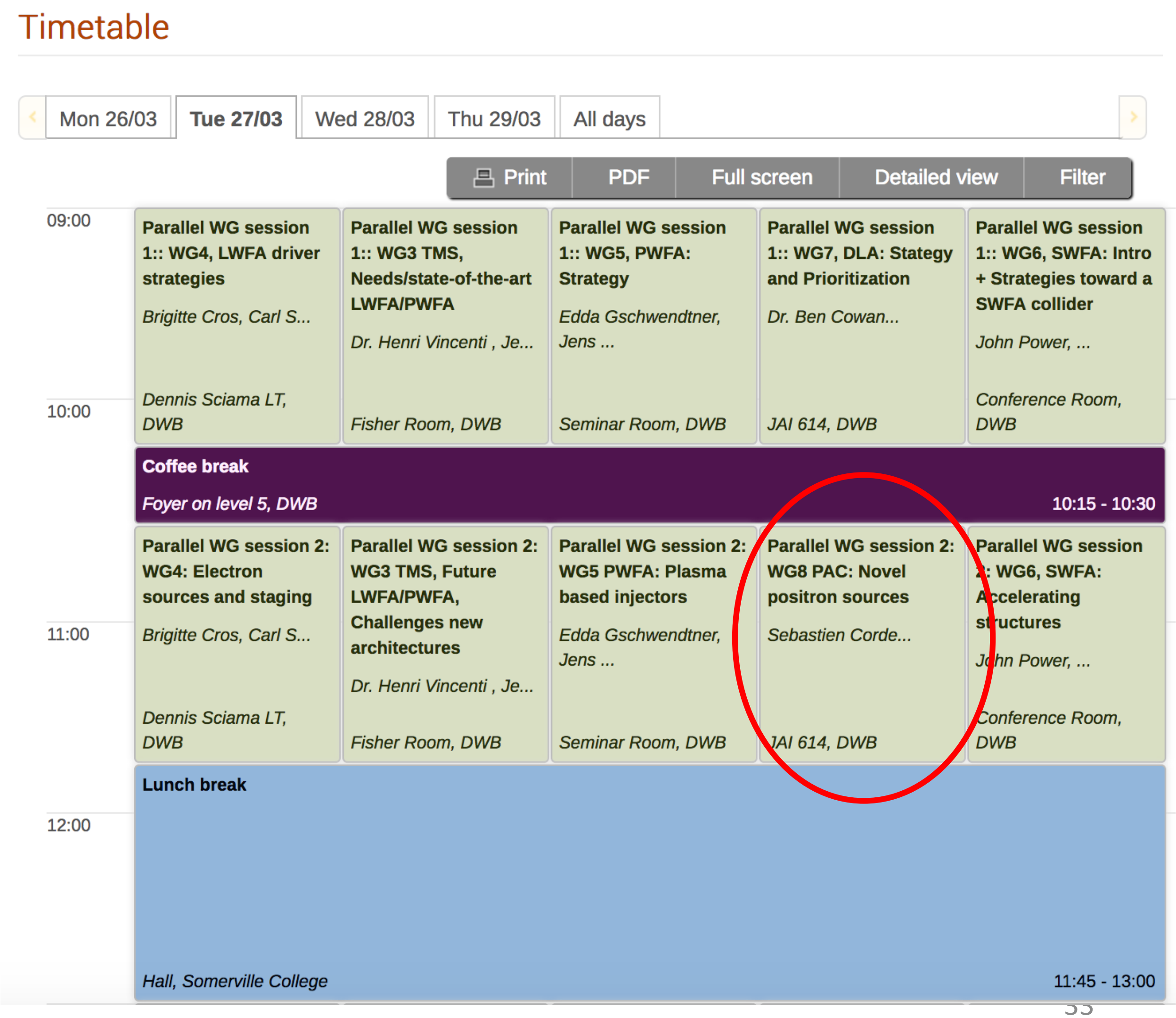
WG8 session on novel positron sources:
Tuesday @10:30

There is only one facility that produces positron beams for plasma acceleration experiments.

Increasing access to positron beams will accelerate positron PWFA/LWFA research.

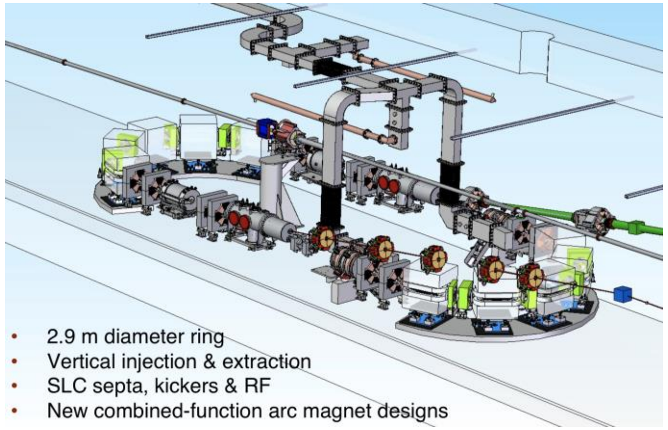
In this session we examine existing and novel technologies for producing positron beams in the context of a PWFA/LWFA research facility.

Looking ahead, the LC community would benefit from compact, low-emittance positron sources if they can replace expensive damping ring complexes.

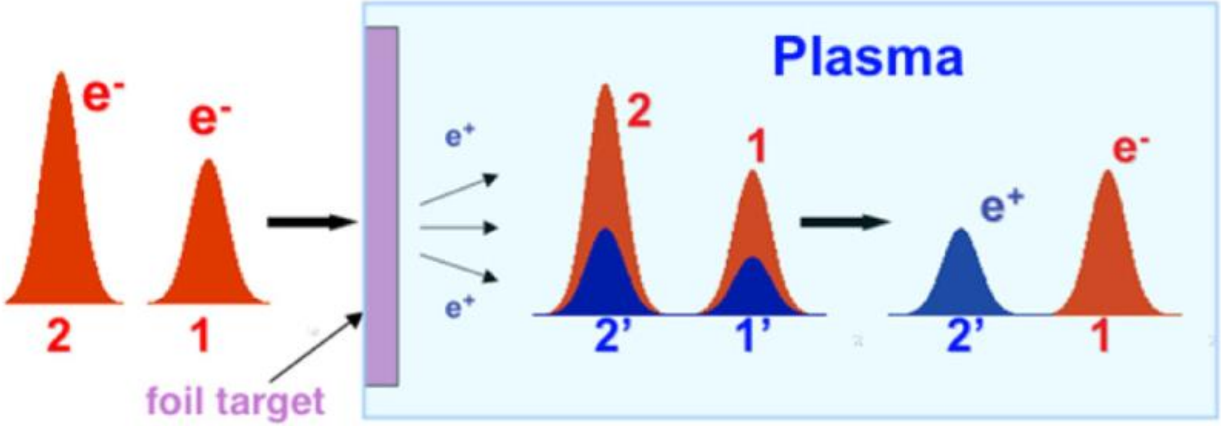


Working Group 8 sessions

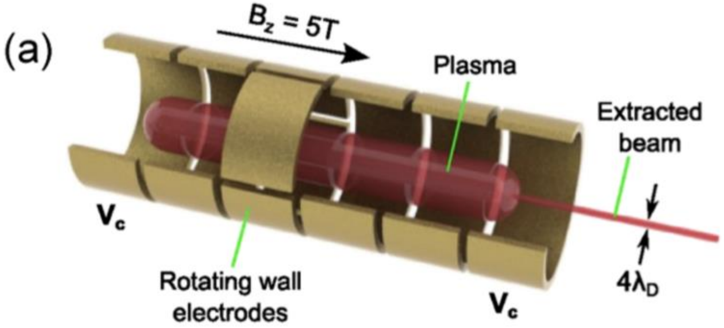
Positron Source Topics



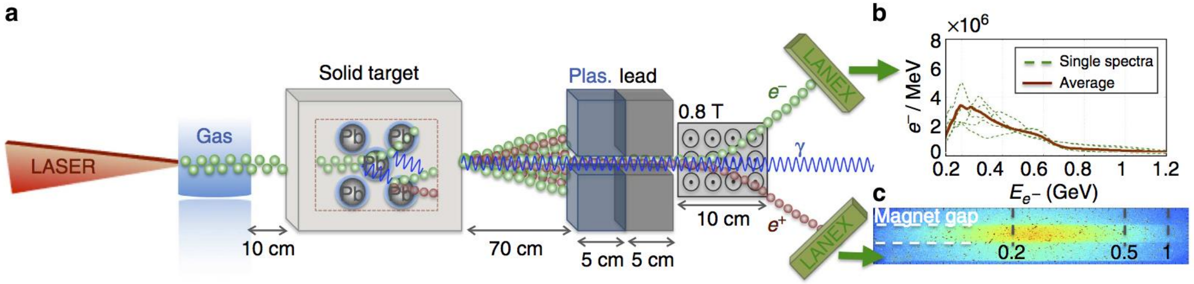
Compact Damping Rings
V. Yakimenko, FACET-II TDR, SLAC-R-1072



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

Working Group 8 sessions

WG8 joint session with LWFA WG4:
Tuesday @15:30

- Detailed report on ALEGRO WG8 mini-workshop at CERN
- Hollow channels for positron acceleration in LWFAs
- Discussion on positron acceleration in LWFA schemes

WG8 joint session with PWFA WG5:
Wednesday @10:30

- Prospects and challenges for positron acceleration in the quasi-linear regime
- Transverse wakefields in hollow plasma channels
- Discussion on most viable paths moving forward for positron acceleration

Objectives

Our goals

- Survey existing work in LWFA/PWFA positron acceleration
- Provide input by identifying most promising path and highlighting their potential limitations
- Prioritize R&D on solving the most important problems and on exploring new promising ideas
- Emphasize need for facilities for positron LWFA/PWFA research

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.

Nonlinear plasma wakefield

How to preserve emittance?

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

It's all about beam quality and efficiency

→ Positron problem deserves serious attention