18th Advanced Accelerator Concepts Workshop, Breckenridge, Colorado

Generation and acceleration of a trailing positron bunch using the drive-trailing electron bunch configuration

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No. DE-SC0010064

Abstract

We numerically study the positron generation and acceleration by injecting two incident electron bunches on thin high-Z target using the Monte Carlo code EGS5 and the 3D particle-in-cell code QuickPIC. An experiment to demonstrate this concept is possible at a new 10 GeV electron beam facility, Facilities for Accelerator Science and Experimental Test (FACET) II, which is under construction at SLAC. Since the beam density at FACET II is expected to reach ~10^{20} cm^{-3} under certain conditions, we also discuss the possibility of strong magnetic field generation inside the high-Z target which enhances the gamma-ray flux and the number of positrons.

Motivation and Outline

Motivation

Knowledge of how to accelerate high-quality positron beams using a plasma wakefield accelerator is necessary for building future plasma-based colliders. In the upcoming FACET-II experiment, we propose to use a two-bucnch configuration to produce and subsequently accelerate positron beams.

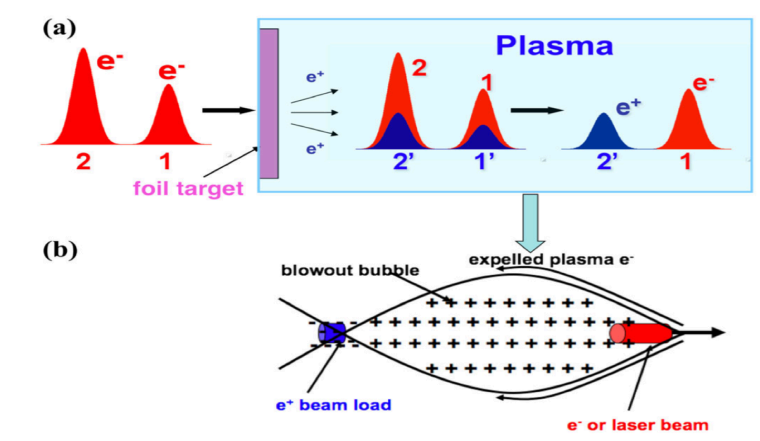
Outline

- Positron acceleration concept
- Experimental setup for two-bunch positron acceleration
- Simulation of positron generation using Monte Carlo code EGS5
- Simulation of the trailing positron acceleration using QuickPIC

EGS5 : EGS5 Web Page. (http://rcwww.kek.jp/research/egs/egs5.html)
QuickPIC : W. An, et al., J. Comp. Phys. 250, 165 (2013). (https://github.com/UCLA-Plasma-Simulation-Group/QuickPIC-OpenSource)

Positron generation and acceleration concept

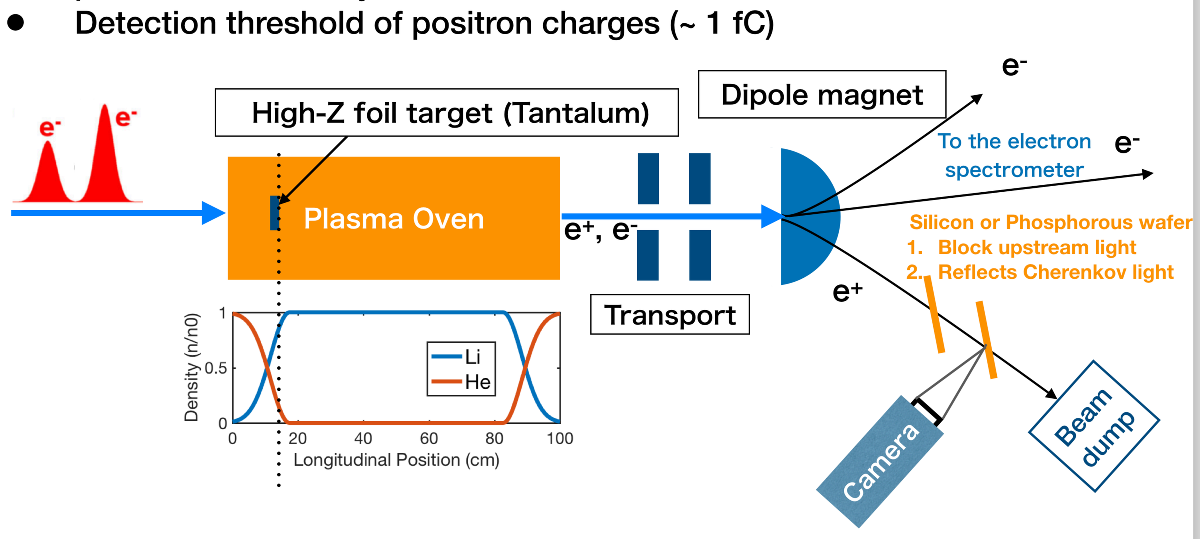
- Drive-trailing electron bunch configuration used for the incident beams.
- Interaction of two beams with High-Z foil target generates positrons within these bunches because of pair-production.
- Drive electron bunch excites plasma wakefield, coincident positrons are defocused.
- Trailing positron bunch at a proper phase is accelerated, coincident electrons are defocused by the wake.



X. Wang, et. al., Positron Injection and Acceleration on the Wake Driven by an Electron Beam in a Foil-and-Gas Plasma, Phys. Rev. Lett. **101**, 124801 (2008)

Experimental setup capable at FACET-II

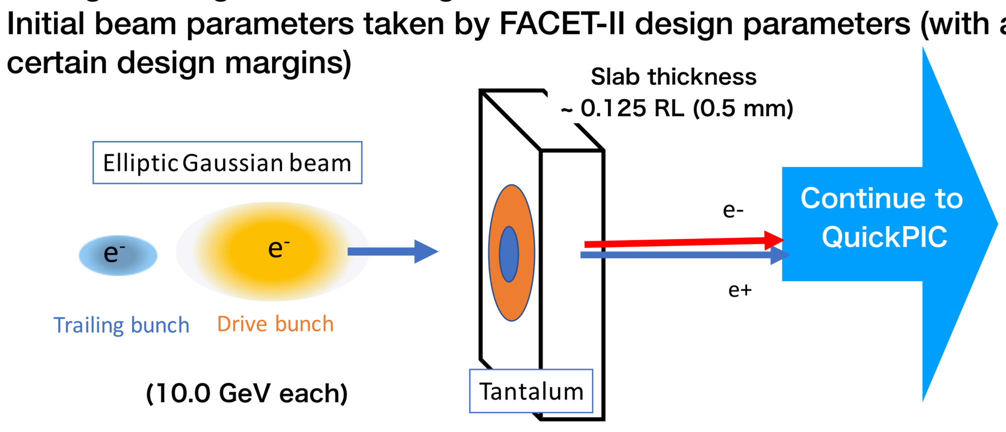
- We utilize two 10 GeV electron bunches (< 40 mm-mrad) provided for the PWFA (talk by C. Joshi) on FACET II.
- High-Z target will be placed inside the plasma oven where the lithium plasma is formed by the self electric field of the drive bunch.
- Detection threshold of positron charges (~ 1 fC)



- Detection of Cherenkov radiation

Monte Carlo simulation configuration

- EGS5 (maintained by KEK) is used for the Monte Carlo simulation
- Two incident electron beams with the energy of 10 GeV passes through the higi-Z thin foil target
- Initial beam parameters taken by FACET-II design parameters (with a certain design margins)

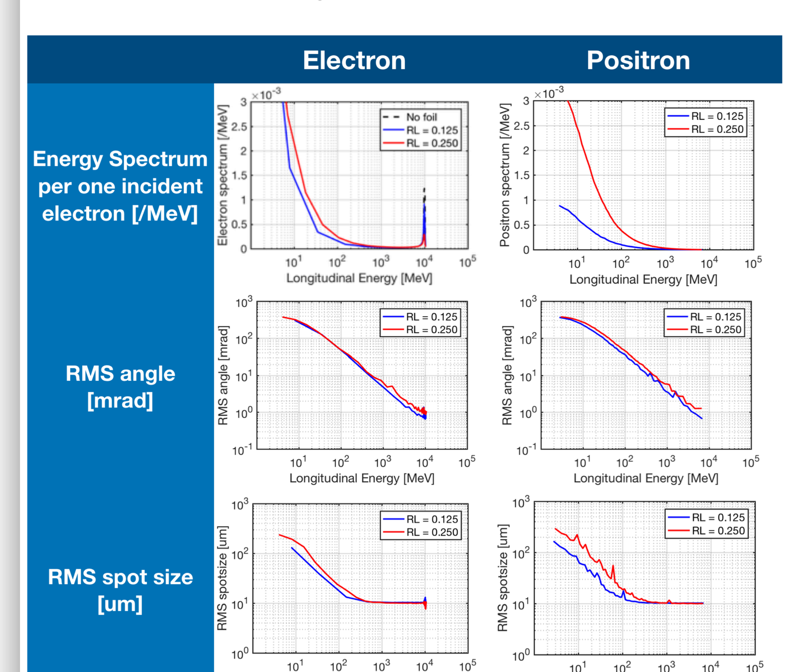


EGS5 configuration (High/Low)	Spot size σ_r [μm]	Length σ_z [μm]	Normalized emittance in x, y [mm-mrad]	Energy [GeV]	Cut off Energy [MeV]	Charge [nC]
Drive electron beam	8.0	13	40	10.0	1.0	1.0 / 025
Trailing electron beam	8.0	6.4	40	10.0	1.0	0.5

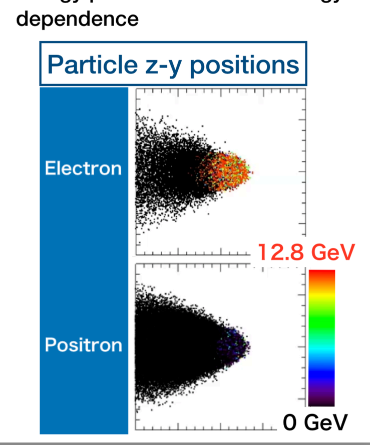
Parameters determined based on C. Joshi, "Plasma Wakefield Acceleration Experiments at FACET II" (2018)

Typical EGS5 results

- Typical EGS5 results after the simulation of 10 GeV electron beams passing through the tantalum target.
- The graph below shows the energy spectrum for two different slab thickness cases. (1 RL (Radiation length)=0.4094 cm for Tantalum)

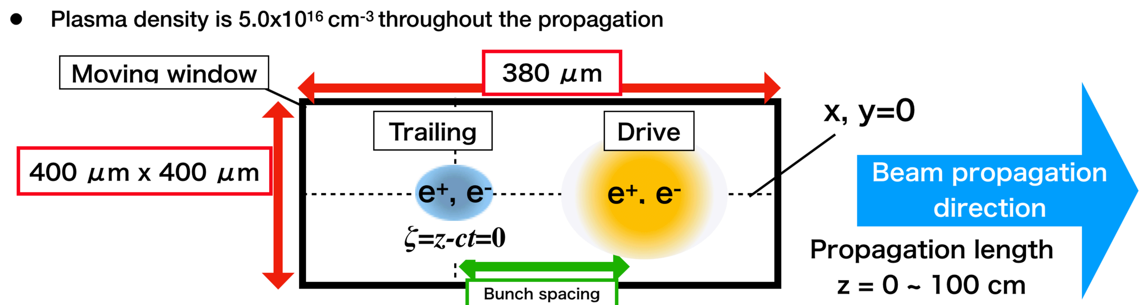


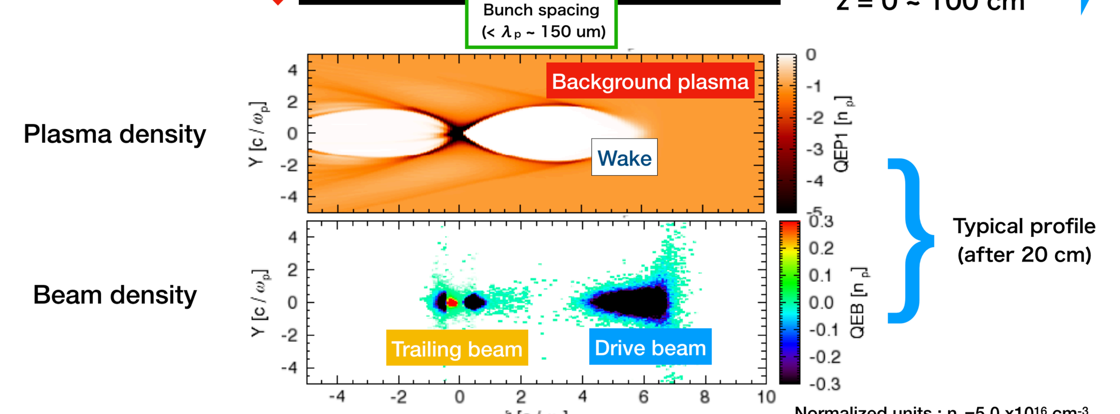
- The foil thickness should be chosen such that the first electron bunch is only mildly scattered, and is still able to excite a large amplitude plasma wake after the foil.
- The spot size seldom changes from the initial state (8 μm) for the high energy particles (>100 MeV), while low energy particle radius has energy dependence



3D QuickPIC simulation configuration

- We performed particle-in-cell simulation using QuickPIC
- Imported 6-dimensional phase space of all drive/trailing electron/positron beams from EGS5 with the slab thickness of RL=0.125
- Plasma density is 5.0x10^{16} cm^{-3} throughout the propagation

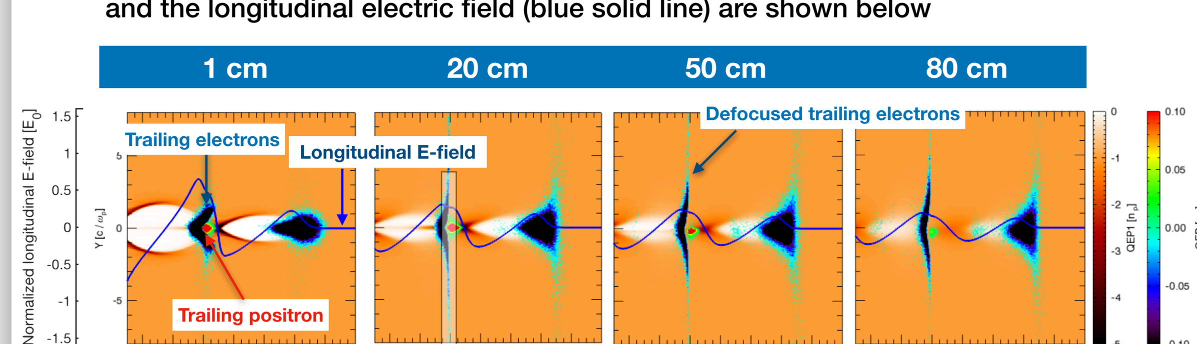


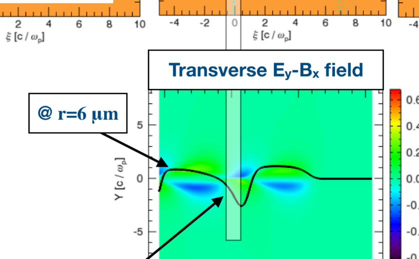


Normalized units : n_p=5.0 x10^{16} cm^{-3}

Wakefield structure

- Time evolution of plasma density (red color scale), beam density (rainbow color scale) and the longitudinal electric field (blue solid line) are shown below





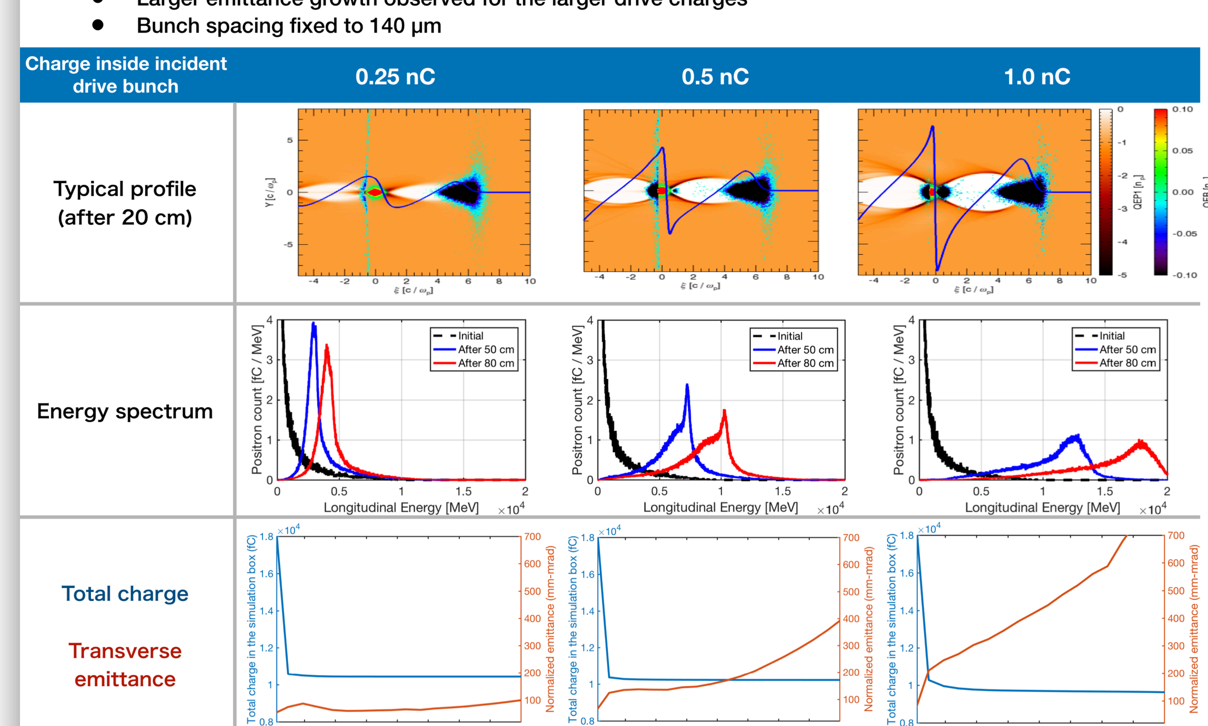
In this ζ range, positron bunch experiences both accelerating field and focusing field

- In the very early phase of the propagation trailing electrons are expelled rapidly.
- The wake structure seldom changes for a while (20 cm ~ 50 cm).
- The drive beam looses energy due to head erosion and the wake structure shifts from nonlinear to linear (> 50 cm)

Normalized units : length c/ω_p~24 [um], time $1/\omega_p$=8 x 10^{-8} [us], field strength $E_0=mc\omega_p/e$=21.5 [GeV/m]

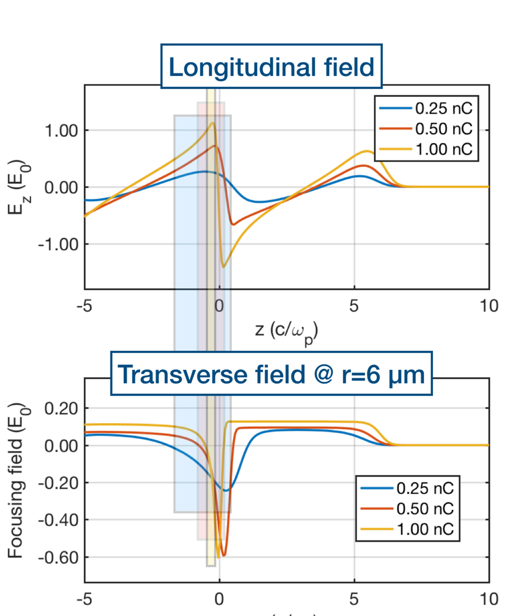
Trailing positron bunch diagnosis

- The trailing charge of the incident electron beam is fixed to 0.5 nC
- Larger emittance growth observed for the larger drive charges
- Bunch spacing fixed to 140 μm



Drive-electron trailing-positron regime scaling

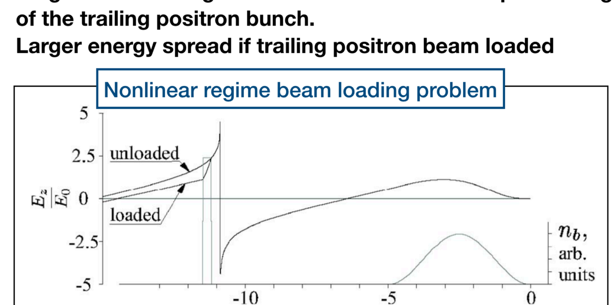
Showing both longitudinal and transverse field after propagating 20 cm



In the available charge range at FACET-II (0.25 nC~1.0 nC), electron-driven trailing-positron acceleration by quasi-linear regime (0.25 nC) to nonlinear regime (1.00 nC) is accessible

For drive-electron trailing-positron scheme, nonlinear regime leads to

- **Larger emittance growth due to the sensitive positioning of the trailing positron bunch.**
- **Larger energy spread if trailing positron beam loaded**

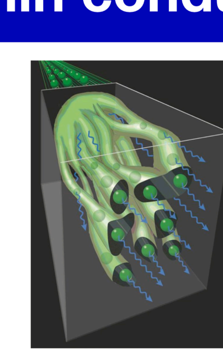


K. V. Lotov, PoP **14**, 023101 2007

Provide us the platform of investigating electron-driven trailing-positron acceleration

Instability growth within conducting material

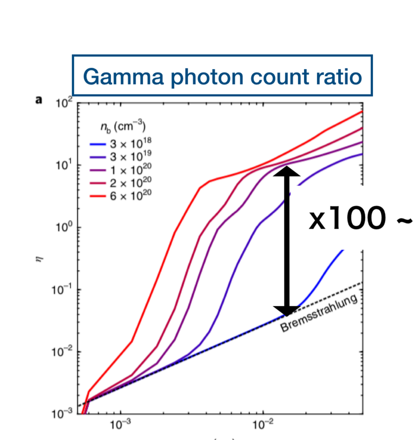
- Positron yield can be further enhanced.
  - Recent study (Benedetti, et. al., 2018) has numerically shown that high intensity beams (~10^{20} cm^{-3}) generates large magnetic field due to the filamentation instability.
  - FACET-II beam density can reach the condition for this instability
- Synchrotron radiation by this large B-field enhances gamma-ray emission, consequently enhances the number of positrons.



Filamentation instability

Instability grows because of the two-stream instability between the filamentation of electron beam by the self B-field and the counter streaming return current by conducting electrons

Andrea Macchi, Instability yields bright gamma emission (2018)



Beneddeti, et. al., Giant collimated gamma-ray flashes (2018)

Parameters comparison

	Target	Beam energy	Beam density
Instability condition reported by Beneddeti. et. al	Sr	2 GeV	3 x 10^{18} ~ 6 x 10^{20} cm^{-3}
FACET-II design parameter ①σ_r=4 μm, σ_z=6.4 μm, 1 nC	Ta	10 GeV	1.7 x 10^{18} cm^{-3}
FACET-II with design margin ②σ_r=8 μm, σ_z=6.4 μm, 1nC	Ta	10 GeV	1.74 x 10^{17} cm^{-3}

When we focus the trailing bunch radius on the target, this effect may enhance the positron yield

Conclusions

- Numerically investigated the trailing positron generation and acceleration scheme
  - Performed Monte Carlo (EGS5) simulations to generate the 6D-phase space distribution of electrons and positrons after the interaction of electron beam with the high-Z target material.
  - Imported the 6D-phase space distribution onto the QuickPIC simulation.
- Simulation results demonstrated
  - Positron acceleration of several GeV for the available beam parameter of FACET-II.
  - Larger emittance and energy spread growth for the nonlinear wake case.
- The drive-trailing electron configuration may allow us to study the drive-electron trailing-positron acceleration scheme.

Acknowledgements

Dr. Vitaly Yakimenko @ SLAC National Accelerator Laboratory
Dr. Mark Hogan @ SLAC National Accelerator Laboratory
Dr. Chaojie Zhang @ University of California, Los Angeles
Funded by the department of energy No. DE-SC0010064

SLAC NATIONAL ACCELERATOR LABORATORY QuickPIC Plasma Accelerator Group led by Prof. Chan Joshi UCLA