Focusing of Positron Bunch when Accelerating in Electron Bunch Wakefield in the Dielectric Waveguide Filled with Plasma*

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* *The work is supported by NRFU, project # 2020.02/0299*

IPAC21

MOPAB145
Monday, May 24, 2021,
Brazil

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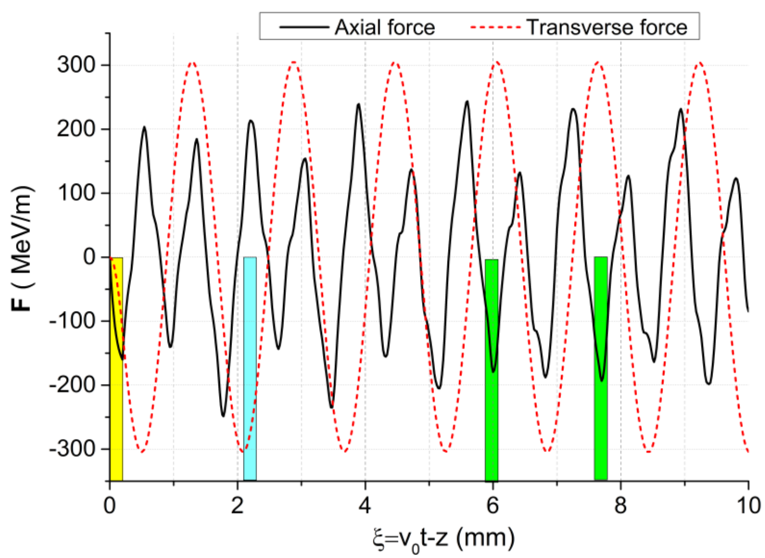
Introduction

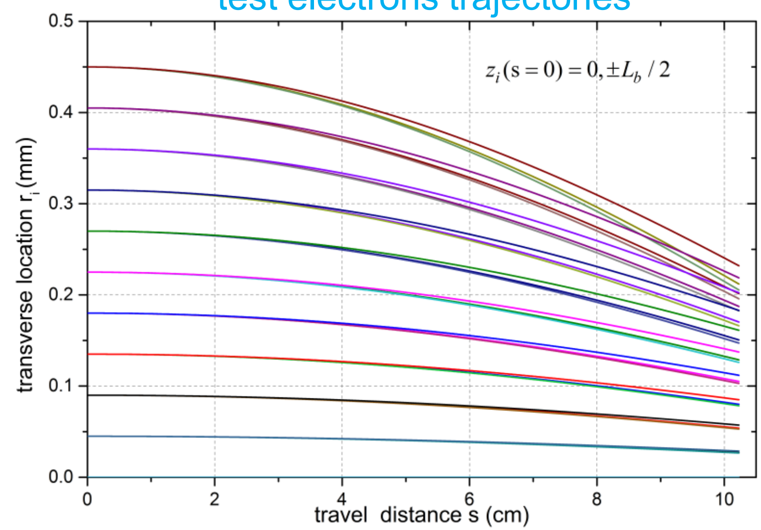
- The dielectric wake accelerator (DWA) is a promising candidate for constructing an electron-positron collider in the TeV energy range

- One of challenges of the DWA is transport of drive and accelerated bunches [*Li C. et al. Phys. Rev. STAB, 17, 091302(2014)*]

- To improve bunch transport and their stability it has been proposed to fill the drift channel of DWA with plasma of certain density [Sotnikov G.V. et al. Nucl. Inst. & Meth. A 2014, V. 740. P. 124-129] — PDWA



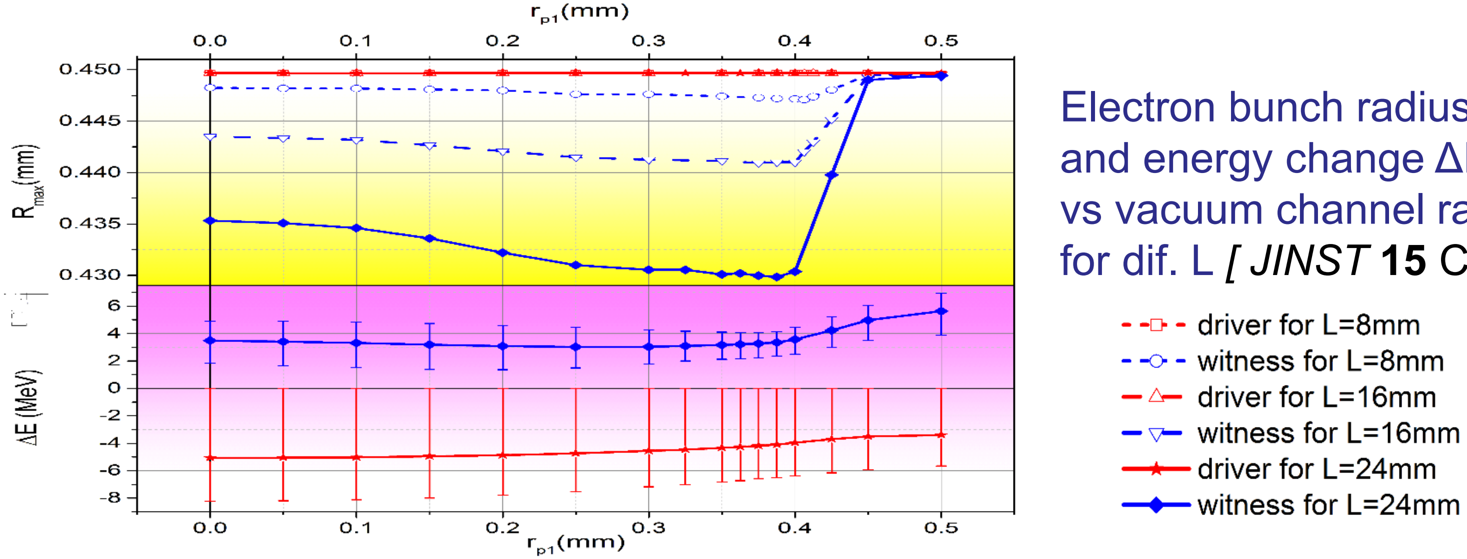
test electrons trajectories



Yellow – drive electron, cyan – test electron, green – test positron bunches

Introduction

- The results of analytical computations of acceleration and transport of electron bunches in PDWA had been already confirmed by direct PIC simulations for different radial plasma density profile (hom. & inhom.)

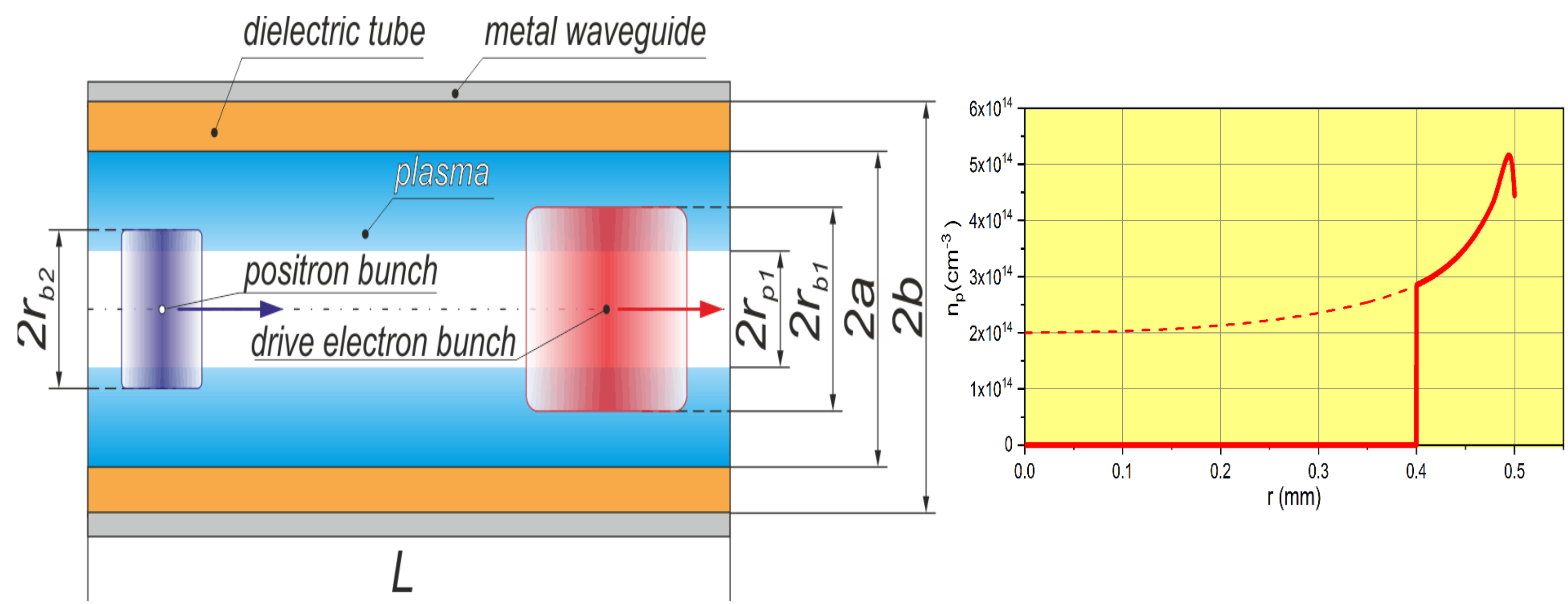


Electron bunch radius Rmax and energy change ΔE vs vacuum channel radius (rp1) for dif. L [*JINST* **15** C09001 (2020)]

- Below we present the results of PIC numerical simulations of acceleration and transport of positron bunches in PDWA with vacuum channel in plasma column (created in result of capillary discharge)

- It should be noted that transport of positron bunches remains a challenge in PWFA studies [see V. Lebedev et al., *Phys. Rev. STAB* 20, 121301(2017); S. Diederichs et al., *Phys. Rev. STAB* 23, 121301(2020) and ref. there]

Statement of the Problem

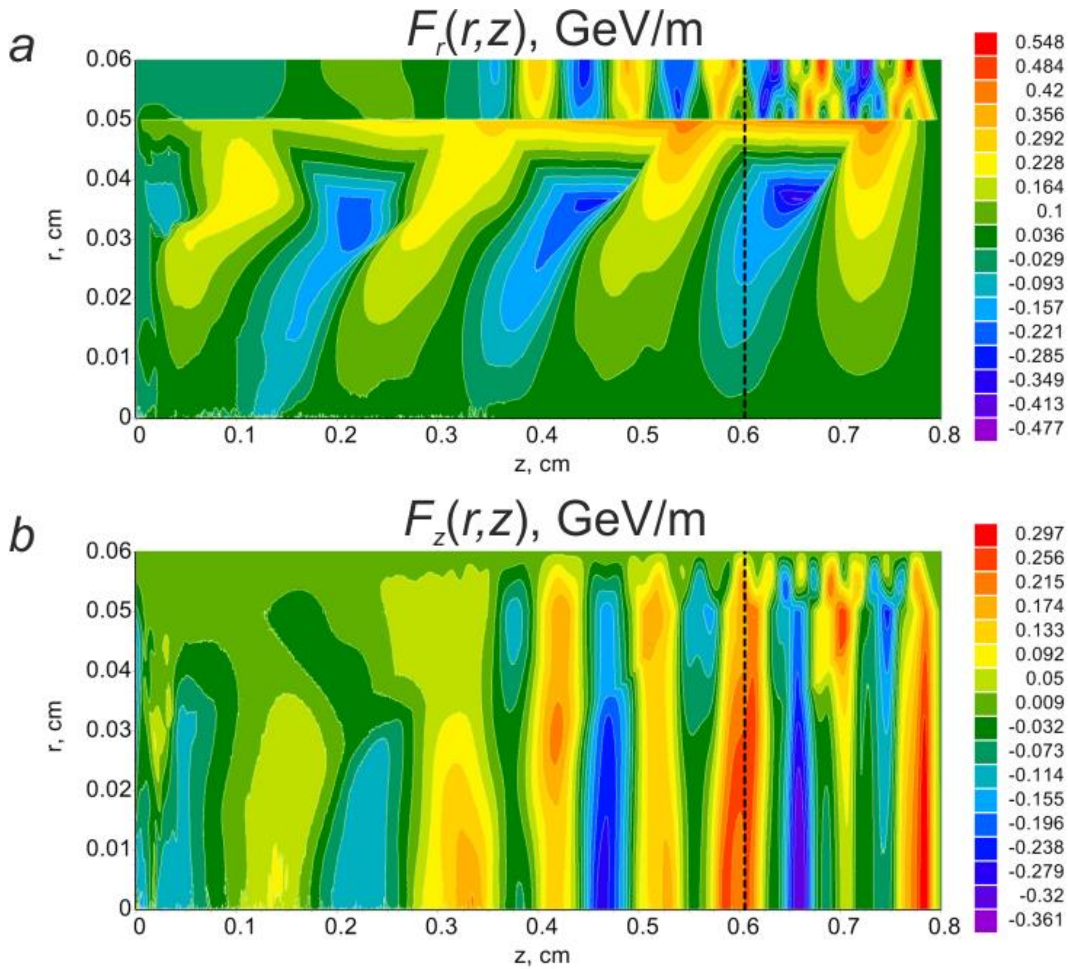


The sketch of the PDWA. Orange area shows dielectric tube, Drift channel of size 2a is partially (inner radius r_{p1}) filled with radially inhomogeneous plasma [blue color, the profile is at the right, Bobrova N.A. et al. PRE, 65, 016407 (2001)]. Drive bunch is pink cylinder and positron bunch is purple cylinder

Parameters of numerical PIC simulations

Waveguide diameter $2b$, mm	1.2
Inner diameter of dielectric tube $2a$, mm	1.0
Dielectric permittivity of the tube ε, fused silica	3.75
Inner diameter of plasma column r_{p1}, mm	0÷1.0
Waveguide length L, mm	8÷24
Energy of drive and test bunches E_0 , GeV	5
Charge of electron drive bunch, nC	-3
Charge of positron test bunch, nC	0.05
Drive bunch diameter $2r_{b1}$, mm	0.9
Axial RMS length of electron drive bunch $2\sigma_1$, mm	0.1
Positron test bunch diameter $2r_{b2}$, mm, mm	0.7
Axial RMS length of positron test bunch $2\sigma_2$, mm	0.05
Extrapolated to the waveguide axis plasma density r_{p1}, cm^{-3}	$2x10^{14}$
Wavelength of E_{01} mode, mm	~1
Wavelength of on-axis plasma wave, mm	2.4

2d-Results of 2.5 dimensional PIC–simulations



t=26.69ps: drive electron bunch is at the output end of the waveguide (8mm)

Delay of positron bunch is 6.34ps (Δz=1.9mm)

$$\boldsymbol{F} = |e|\boldsymbol{E}$$

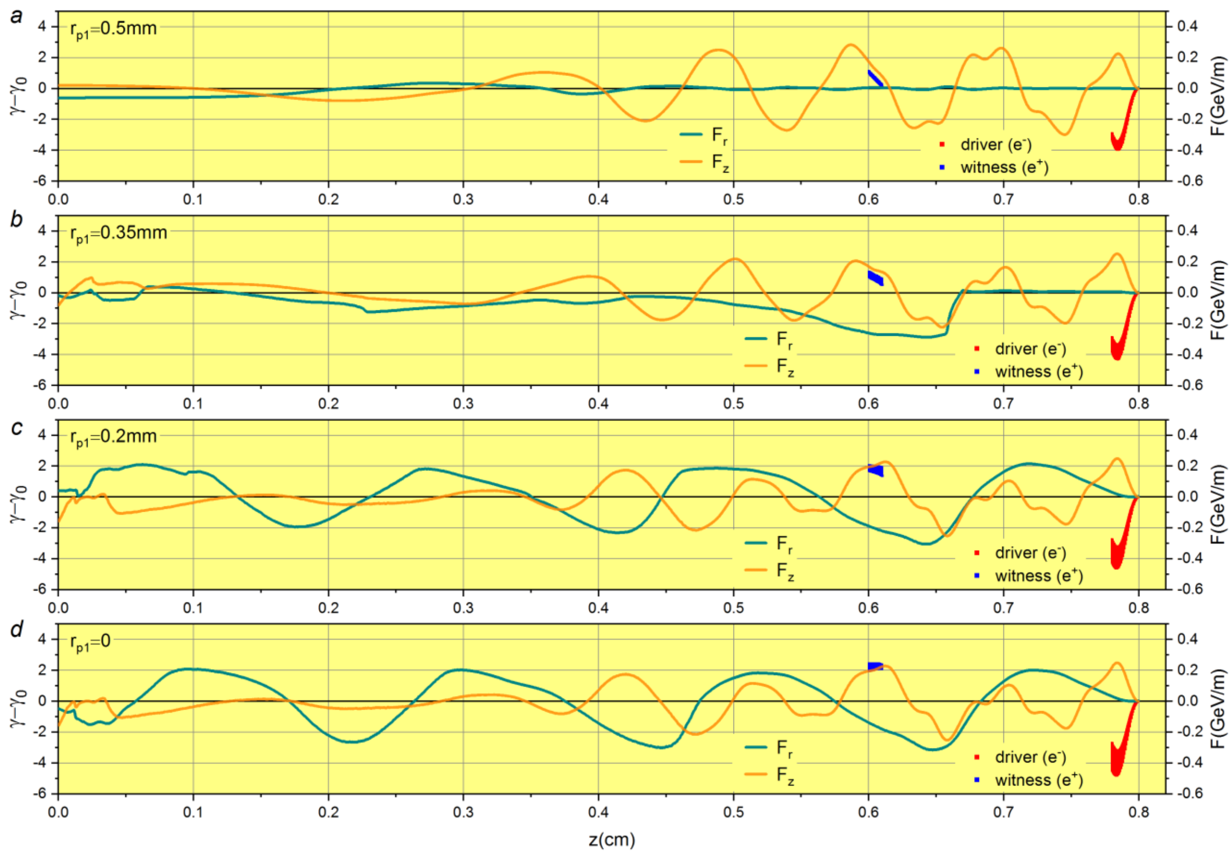
Red color - accelerating (Fz) and defocusing (Fr) for positron bunch

Blue color - decelerating (Fz) and focusing (Fr) for positron bunch

Accelerating positron bunch is focusing

Color maps and level lines for transverse Fr (at the top) and longitudinal Fz (on the bottom) component of Lorentz force, acting on test positron. No vacuum channel in this case, r_{p1}=0. Location of positron bunch shows vertical dash line.

1d-Results of 2.5 dimensional PIC–simulations



t=26.69ps

τ_{del} = 6.34 ps

a) r_{p1}=0.5mm w/o plasma

b) r_{p1}=0.35mm

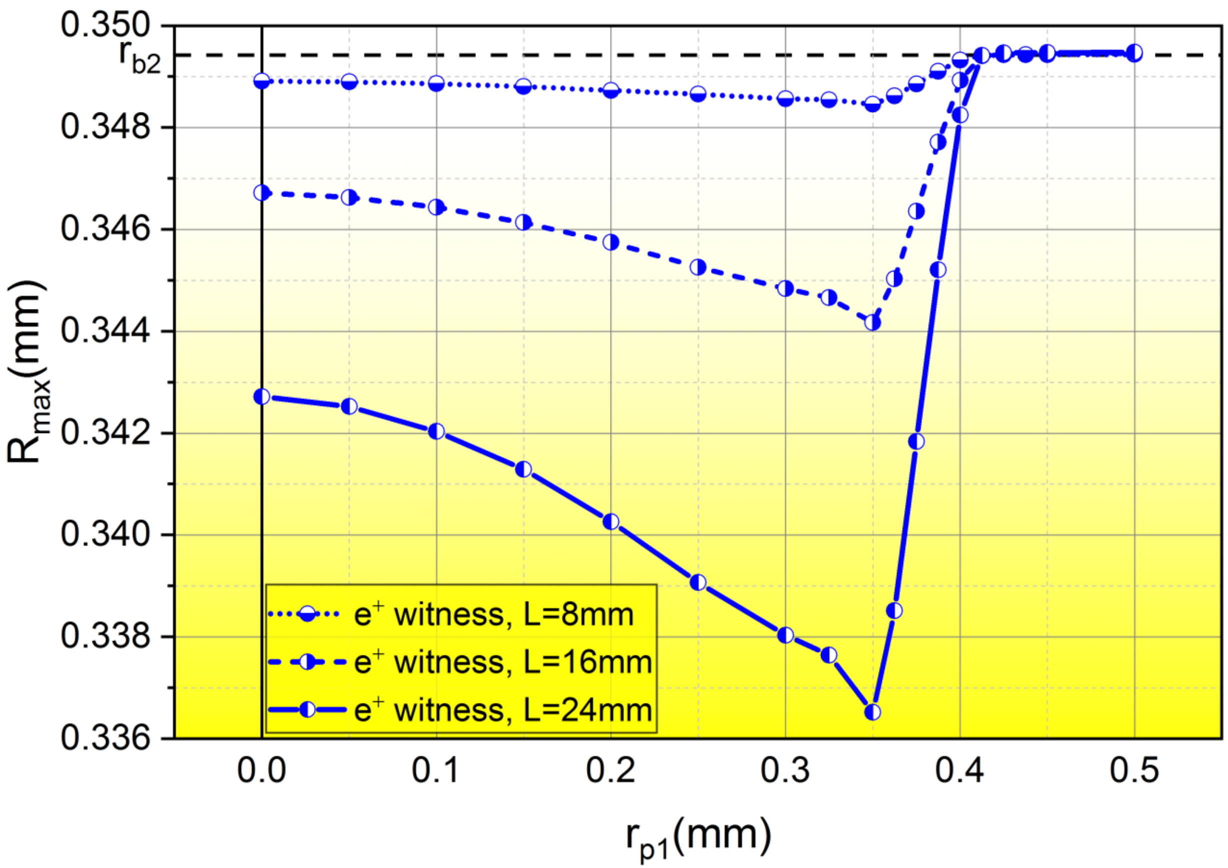
c) r_{p1}=0.2mm

d) r_{p1}=0

no vacuum channel

Phase plane γ-z (energy-z, left axis) of bunch electrons superimposed with Fz(z) and Fr(z) (right axis) at r=r_b=*0.35mm*. Blue dots – test positrons, red dots – drive electrons

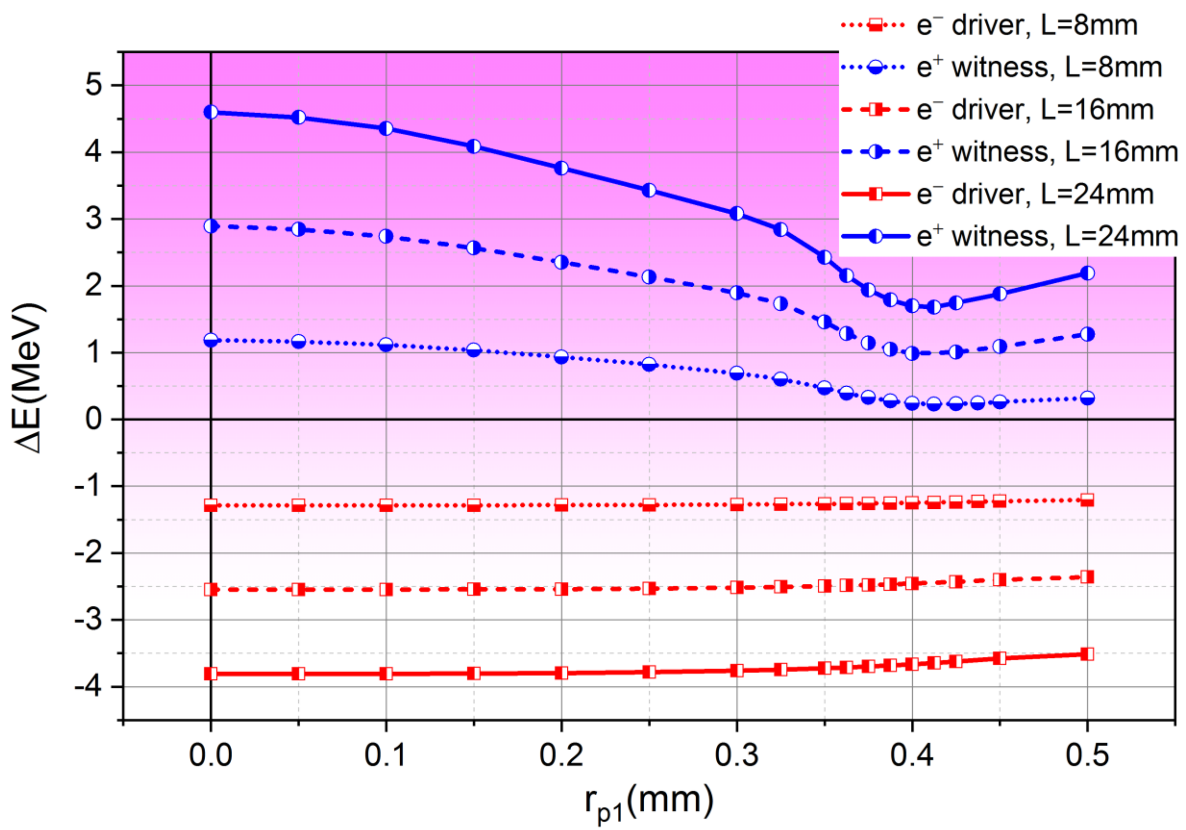
Changing R_{max} at changing plasma size r_{p1}



Positron bunch radius = 0.35mm

Changing r_{p1} from *0* to *0.35*mm (positron bunch radius) leads to an improving of test bunch focusing. At $r = r_{p1}$ is maximal focusing. When size of vacuum channel is greater than transverse bunch size there is disimproved.

Energy change of drive and witness bunches

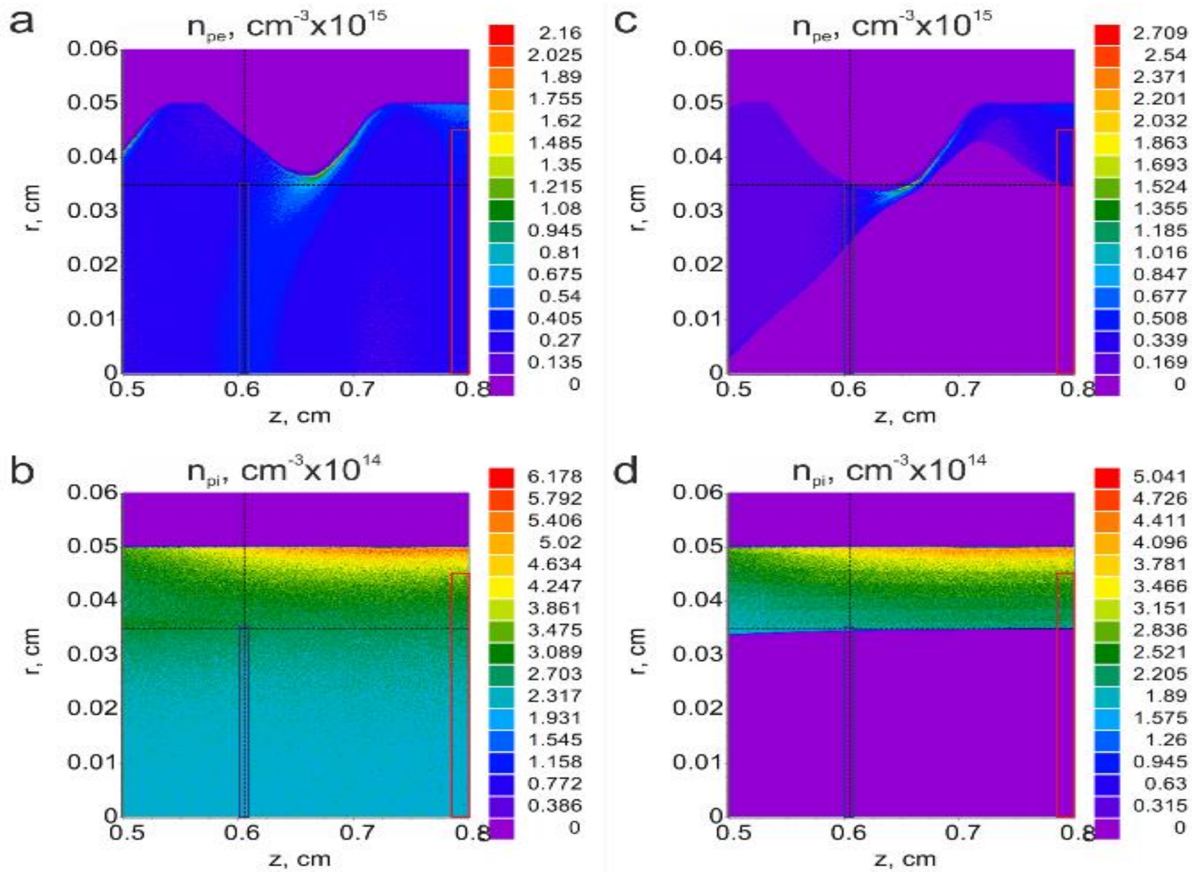


Blue line – positron bunch

Red line – Drive bunch

With increase the radius of vacuum channel the energy gain of test bunch decreases that is connected with the bunch is out from the optimum phase of the longitudinal accelerating force (slide 7)

Electron and ion densities of plasma *for t = 26.69*ps



$n_{pe}(r,z)$ [top]

$n_{pi}(r,z)$ [bottom]

Cases:

No vacuum channel [left]

r_{p1}=0.35mm, best focusing [right].

Red rectangular – drive electron bunch

Blue rectangular – test positron bunch

Explanation of positron focusing:

a) Drive bunch pushes out the plasma electrons to the periphery
b) The excess of plasma ions is formed behind the drive bunch. Ions attract the plasma electrons and they move back to the waveguide axis.
c) An excess plasma electrons density where the positron bunch travels is formed.
d) In addition, the plasma ion excess at positron bunch location push positrons to the waveguide axis

Conclusion

- PIC simulation of the wake field excitation and a dynamics of electron drive and positron accelerated bunches in a plasma-dielectric cylindrical structure of THz frequency range with a plasma density profile of a capillary discharge is carried out.
- Numerical simulation has confirmed predictions of the analytical theory, having shown acceleration of test positron bunch with its simultaneous focusing.
- A vacuum channel in the plasma improves focusing of the positron bunch. There is the optimum vacuum channel radius, at which the positron bunch focusing is the best, but an energy gain is not highest.
- The highest energy gain of positron bunch is in case when plasma completely fills the drift channel, however at that positron bunch focusing is weaker in comparison with optimal case.

THANK YOU FOR YOUR INTREST TO THE PRESENTATION

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