Acceleration and Focusing Electron/Positron Bunches in Plasma-Dielectric Wakefield Accelerator

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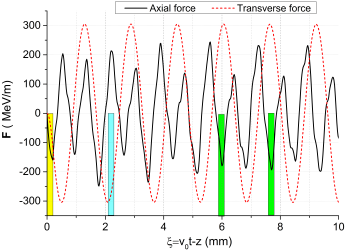
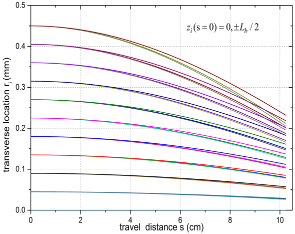
Introduction

- The dielectric wake accelerator (DWA) is a promising candidate for constructing an electron-positron collider in the TeV energy range
- One of shortcomings of the DWA is susceptibility of bunches to beam breakup (BBU) instability [Li C. et al. Phys. Rev. STAB, 17, 091302(2014)]
- To suppress this instability recently 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





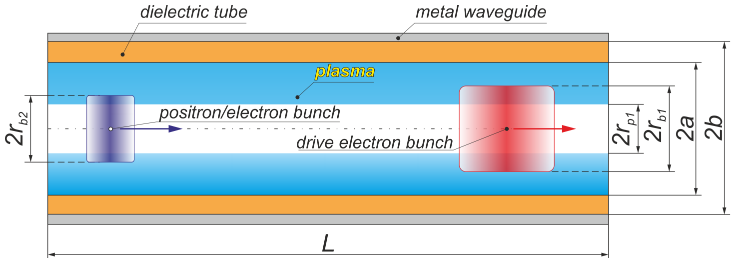
Analytical example of wakefield excitaion and transport of test electrons :

$n_p = 4 \cdot 10^{14} cm^{-3}$, *a=0.5mm, b=0.6mm,* $W_b = 5\ GeV$, $Q_b = 3nC$, $\varepsilon = 3.75$

Introduction cont.

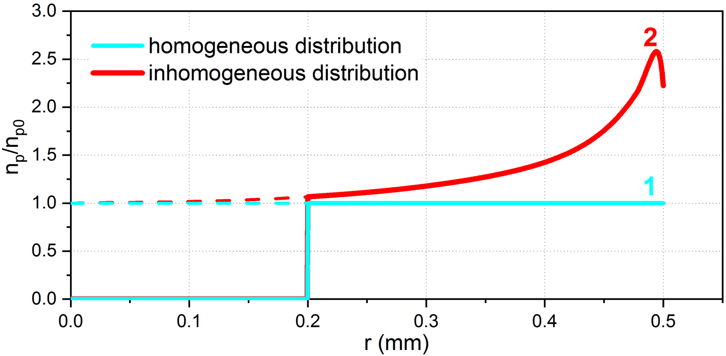
- However, plasma is good medium for a transport and focusing of electron bunches. The positron witness bunch focusing in PDWA may face the same problems which exist in beam-driven plasma wakefield accelerators (PWFA)
- To improve the transport of positron bunches in PWFA, it is proposed to use various methods [V. Lebedev et al., S. Gessner et al. , S. Diederichs et al., S. Zhou et.al]
- One of them is to use a vacuum channel inside the plasma [S. Gessner PhD thesis]. However hollow core plasma channel is intrinsically unstable because of the BBU instability of drive bunch [C.B. Schroeder et al]
- In this presentation we report the results of PIC simulations of electron and positron bunches transport in PDWA with hollow plasma channel

Geometry of the problem



Schematic view of longitudinal section of the plasma dielectric wakefield accelerator (PDWA) with hollow plasma channel. In general case drive electron bunch and witness electron/positron bunches can partially located in plasma region $r_{p1} < r_{b1}, r_{b2}$

Profiles of plasma density

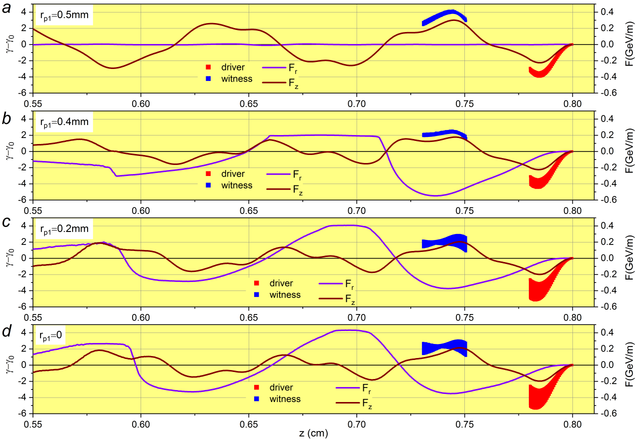


Models of plasma density-radius relationship $n_p(r)$ for two cases: the plasma fills completely the interior of the dielectric tube (dash lines) and the plasma cylinder of internal radius $r_{p1} = 0.2\,mm$ (solid lines). Red line (2) corresponds to the inhomogeneous distribution of plasma density [N.A. Bobrova et al., PRE 2006], cyan line (1) is for the homogeneous one.

PIC simulations parameters

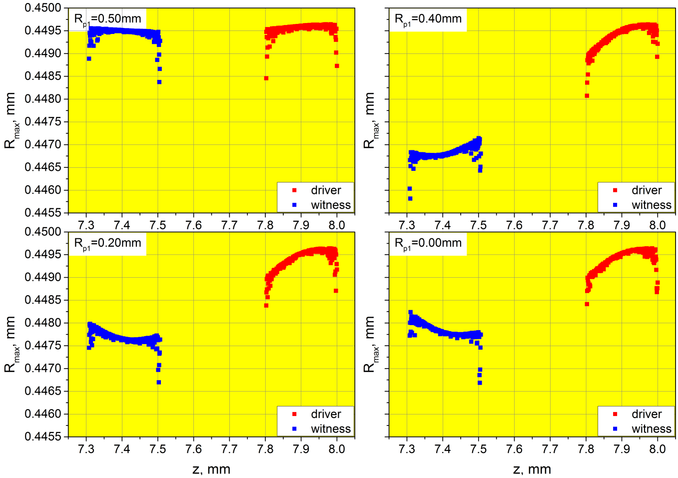
Item	Value	Units
Waveguide diameter $2b$	1.2	mm
Inner diameter of dielectric tube $2a$	1.0	mm
Dielectric permittivity of the tube ε	3.75	fused silica
Diameter of plasma channel r_{p1}	$0 \div 1.0$	mm
On-axis plasma density n_{p0}, e^-/e^+ case	4.4/2	$10^{14} cm^{-3}$
Initial energy of drive and test bunches	5	GeV
Charge of drive bunch	3.0	nC
Charge of test bunch e^-/e^+	0.3/0.05	nC
Drive Bunch diameter r_{b1}	0.9	mm
Test bunch diameter e^-/e^+	0.9/0.7	mm
Axial RMS length of drive bunches, $2\sigma_1$	0.1	mm
Axial RMS length of test bunches, $2\sigma_2$	0.05	mm
Wavelength of E_{01} mode	~ 1	mm
Wavelength of on-axis plasma wave, e^-/e^+	$\sim 1.6/2.3$	mm

Electron bunch energy and Forces



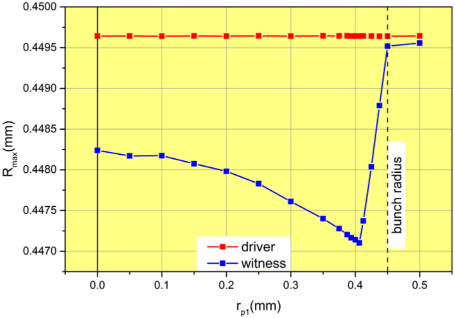
Phase plane $\gamma - z$ (Energy-z, left axis) of bunch electrons superimposed with $Fz(z)$ and $Fr(z)$ (right axis) at $r = rb = 0.45mm$. Blue dots – test bunch, red dots – drive bunch electrons

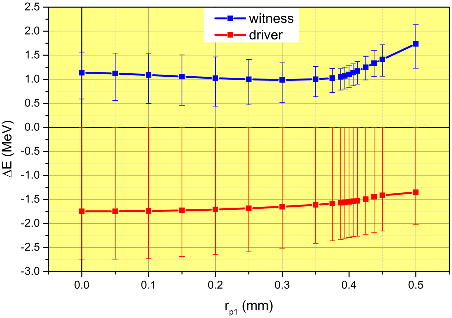
Position of witness and drive bunch electrons



Configuration space representing the position of the bunch electrons being at the periphery for different size of vacuum channel r_{p1}

Transverse size and energy change of witness and drive bunches

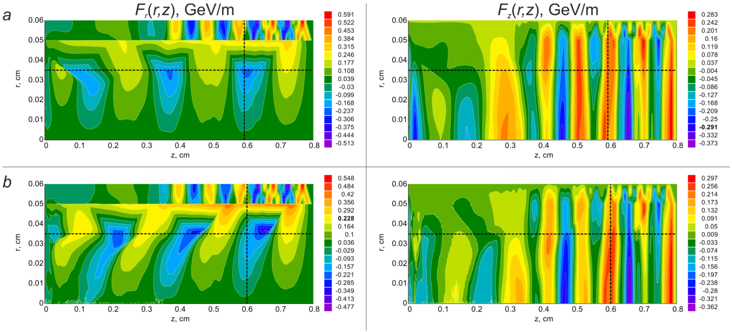




Left (bunch radius): Changing plasma channel from 0 to 0.4 mm leads to an improving of test bunch focusing, at next increasing of vacuum channel size the focusing is disimproved. When size of vacuum channel is greater than transverse bunch size there is no focusing.

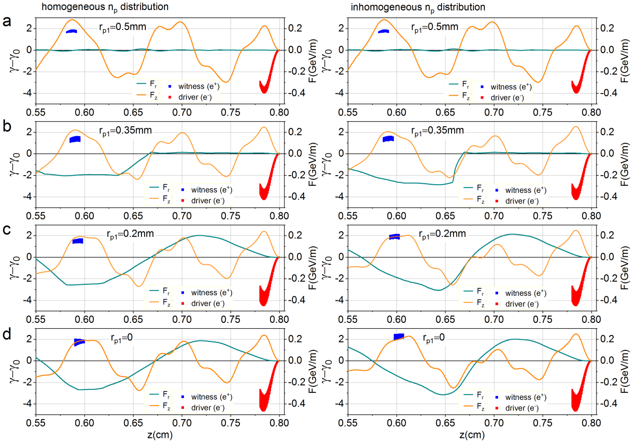
Right (energy change): Increasing r_{p1} from 0 to 0.3mm leads to small decreasing of energy gain of test bunch, at next increasing r_{p1} the energy gain grows. In vacuum case one we observed the best energy gain of test bunch at minimal energy losses of drive bunch.

Maps for Fr and Fz forces behind drive electron bunch



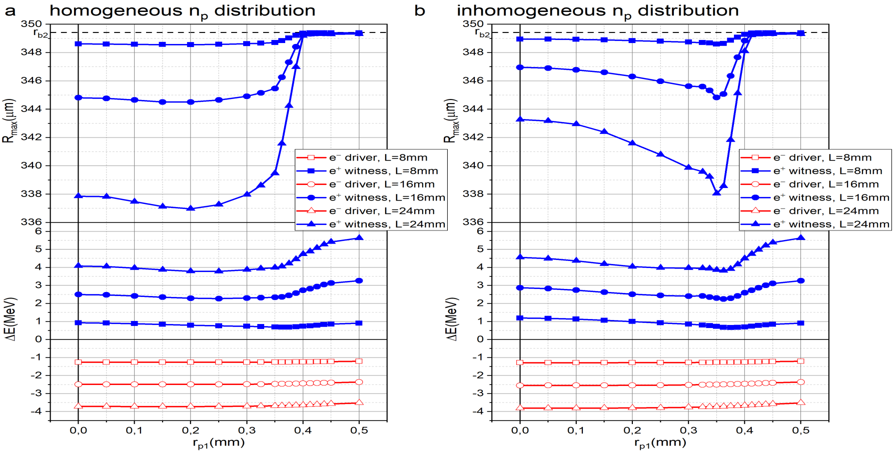
Color maps and level lines for transverse (at the left) and longitudinal (at the right) components of the Lorentz force acting on test positron at time $t = 26.69\,ps$ *for different plasma density-radius relationships: a) homogeneous model and b) the dependence realized in capillary discharge for the case* $r_{p1} = 0$.

Bunch energy and Forces



Phase plane $\gamma - z$ (Energy-z, left axis) of drive (electron) and witness (positron) particles superimposed with $Fz(z)$ and $Fr(z)$ (right axis) at $r = r_b = 0.35$mm. Blue dots – test bunch positrons, red dots – drive bunch electrons.

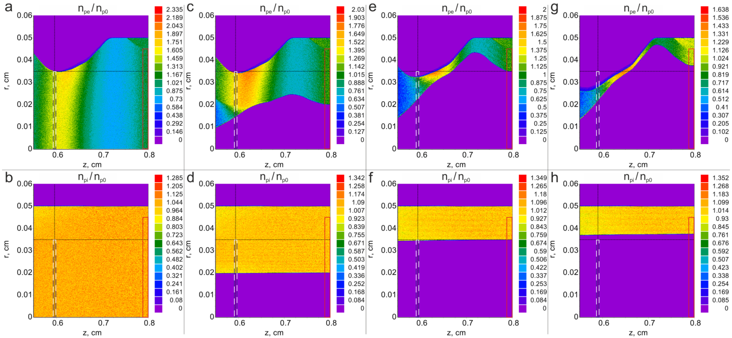
Transverse size and energy change of bunches



Positron bunch radius R_{max} (top) and energy gain ΔE of the accelerated positron bunch (middle) and the drive bunch (bottom) vs. the plasma channel radius r_{p1} for the waveguide lengths $L = 8, 16, 24$mm. Left - homogenous plasma density, Right - capillary discharge.

Explanation of positron focusing in PDWA

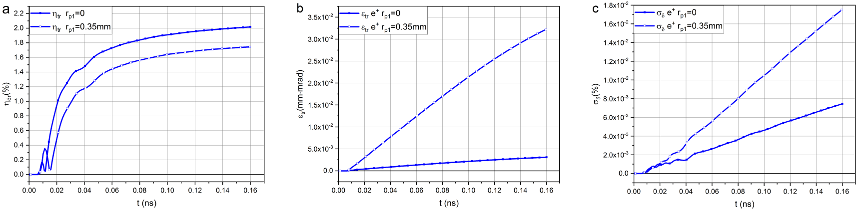
The focusing of the positron bunch occurs due to the excess of returning plasma electrons at its location



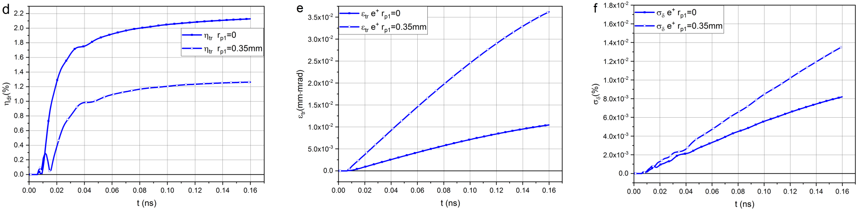
The plasma electron density (top) and plasma ion density (bottom) for $r_{p1} = 0$(a, b), $r_{p1} = 0.2$(c, d), $r_{p1} = 0.35$(e, f) and $r_{p1} = 0.375$ (g, h). Rectangles show the position of drive and test bunches. Initially plasma is homogeneous in transverse section

Characteristics of the accelerated positron bunches versus time

constant plasma density

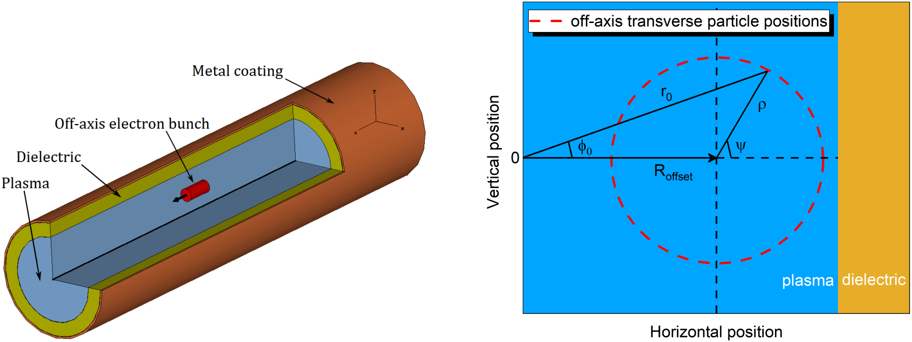


capillary discharge plasma density



Left column — transfer energy efficiency; Middle — trace emittance; Right — energy spread for 2 cases: no plasma channel and radius plasma channel is equal to positron bunch radius

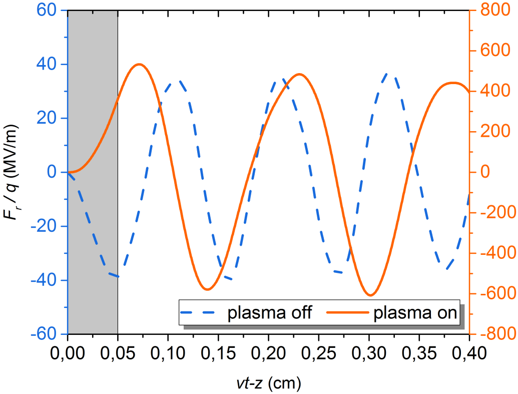
Off-axis drive bunch transport: Geometry of the problem



General view (left) cross view (right): coordinate "0"corresponds waveguide axis

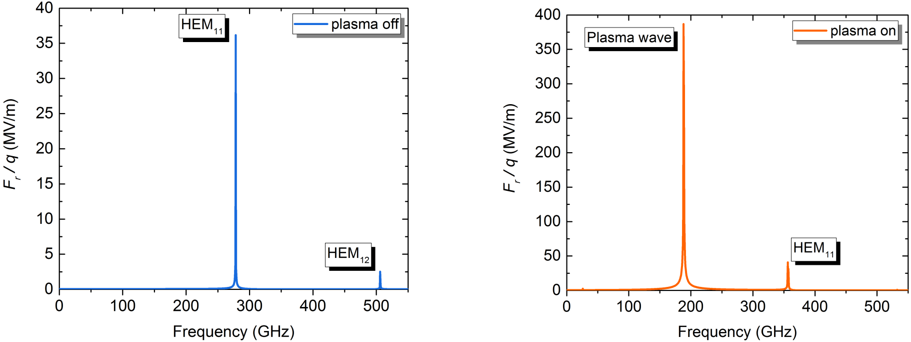
Transverse wakefield for vacuum DWA and PDWA

Analytical theory of wakefield excitation by off-axis bunch is built.



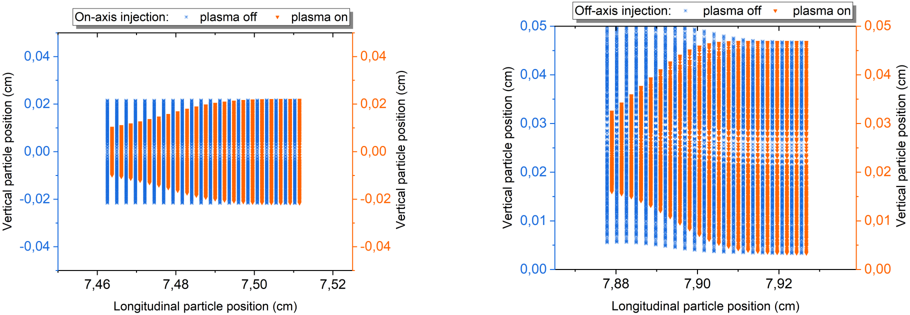
Longitudinal profiles of the transverse wakefield at the lateral bunch surface for the plasma DWA, and for vacuum DWA. Grey rectangle shows the drive bunch location. Note the opposite signs of forces on drive bunch and great difference in amplitudes

Transverse wakefield (spectrum)



Transverse wakefield spectra (calculated at the drive bunch lateral surface) excited by the off–axis drive electron bunch for the plasma off and plasma on cases.

Transverse bunch dynamics: PIC simulation



The on–axis (left) and off–axis (right) injected drive bunch particle distribution on the $z - r$ *plane at the structure exit for the plasma–on and plasma–off cases.*

Conclusion

1. Numerical PIC simulation a transport of electron and positron accelerated bunches confirm the results of analytical theory about possibility of their focusing. Plasma channel can improve the transport, however
2. The parameters of accelerated electron and positron bunches (emitttance, energy spread) do not contradict the collider requirements. The plasma channel improves transport, but it worsens the emittance and energy spread.
3. There a small difference in choose initial parameters $e^{-}/e+$ bunches, plasma density, delay time, transverse size
4. Plasma filling DWA suppress the BBU instability of drive electron bunch

Thank you for your attention!

On behaf of our team