Analytical and Numerical Studies of Underdense and Overdense Regimes in Plasma-Dielectric Wakefield Accelerators*

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Outline

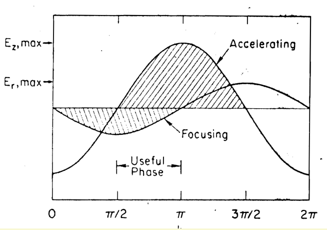
Motivation

- The use of DWA structures excited by REB is an actively developing direction of new methods of acceleration. Experimental research carried out in ANL and SLAC has shown that DWA can be considered as a promising candidate for future e-p colliders of TeV energy range.
- There is one problem that is not solved completely - difficulties with stabilization of transverse motion of the drive and accelerated bunches and, thus obtaining the accelerated bunches of particles with a small emittance.
- In a DWA drive bunch under defocusing action of wakefield, an accelerated bunch placed at the maximum of accelerating field is at zero focusing field.
- We propose to use for focusing of drive and witness bunch a plasma filling the drift channel of DS

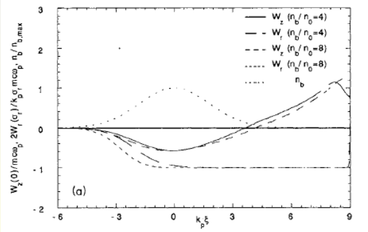
Focusing in PWFA

Using a plasma for focusing of an accelerated bunch is not a new proposition. Focusing properties of plasma were investigated in PWFA:

1. for the linear plasma condition [R. D. Ruth et al. Part. Accelerators, 1985.]
2. and for a non-linear regime [J.B. Rosenzweig et al. PRA, 1991; N. Barov and J. B. Rosenzweig. PRE, 1994]



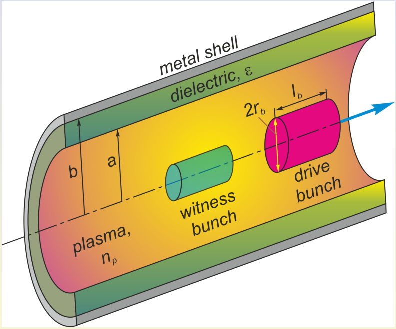
R. D. Ruth et al.[1985]



J.B. Rosenzweig et al.[1991]

PDWA under investigation

In our opinion, using a plasma filling the accelerating channel helps to avoid above mentioned restrictions. A plasma can be created by a capillary discharge in a dielectric tube.



PDWA unit. Isotropic plasma fills transport channel entirely.

Governing Equations

Having solved Maxwell equations we obtain next equations for the field excited by drive bunch :

$$E_z = E_z^L + E_z^d + E_z^C$$

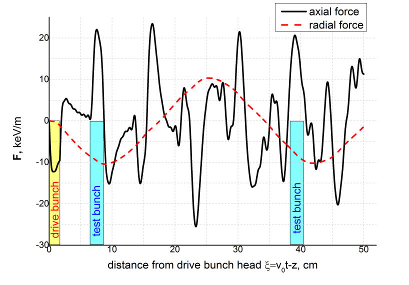
$$E_r = E_r^L + E_r^d + E_r^C$$

$$H_\varphi = H_\varphi^d + H_\varphi^C,$$

- $E_{r,z}^d$ and H_φ^d — wakefield in dielectric waveguide modified by presence of plasma in transport channel (DW); its period is defined by eigen frequency ω_s
- $E_{r,z}^C$ and H_φ^C — quasistatic field (Coulomb field); it is very small for ultra-REB and high density of plasma [*R.R. Kniaziev et al., IPAC13, TUPEA055*]
- $E_{r,z}^L$ — plasma wakefield (PWF); its period is defined by plasma frequency ω_p

$\sim 3\,GHz$ example of focusing in PDWA

Because of different periods of dielectric wakefield and plasma wakefield it is rather easy to place an accelerated bunch in a focusing phase.



GHz PDWA suitable for an experiment at KIPT: OD=8.65cm, ID=2.2cm, $\varepsilon = 2.1$, $L_b = 1.7cm$, $2r_b = 2.2cm$, *Bunch energy=4.5MeV*, $Q_b = 0.32nC$, $n_p = 10^{10}cm^{-3}$; $n_b/n_p = 0.04$

Here the acceleration is provided by DW, and the focusing – by PWF.

Transition to HF PDWA

As the field frequency increases, it becomes more and more difficult to fulfill the strong inequality $n_b/n_p \ll 1$.
The reason is the unequal growth rate of density of electrons in a bunch n_b and required plasma density n_p.
Really:

1. Wavelenghth of DW $\lambda_s \sim (b-a)$
2. At optimal condition $L_b < \lambda_s/2$ from above eq. follows $n_b \sim 1/(b-a)^3$
3. From condition $\omega_p a \sim 1$ [maximum of plasma wave amplitude] it follows $n_p \sim 1/a^2$

Thus, when increasing the operating frequency of a linear PDWA the bunch density grows more quickly then the plasma density. Therefore THz PDWA can work at not very strong inequality $n_b/n_p < 1$ only.

Parameters used for THz PDWA

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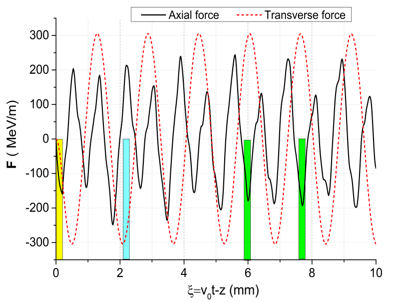
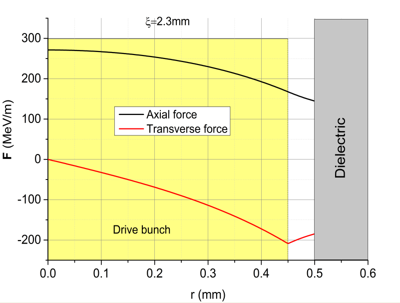
Wavelength of E_{01} mode	$\approx 1\,mm$
OD of dielectric tube	$1.2\,mm$
ID of dielectric tube	$1.0\,mm$
Relative dielectric constant, ε	3.75
Bunch energy	$5\,GeV$
Bunch charge	$3\,nC$
Bunch diameter	$0.9\,mm$
Density of drive bunch electrons, n_b	$1.47 \cdot 10^{14}\,cm^{-3}$
Plasma density, n_p	$4.41 \cdot 10^{14}\,cm^{-3}$
Wavelength of plasma wave	$1.6\,mm$

Thus, $n_b/n_p = 1/3$

$\sim THz$ example of focusing in PDWA





Axial (at left, r=0.45mm) and transverse (at right, $\xi = 2.3mm$) profiles of the axial force (black line) and transverse force (red line). Yellow/blue/green rectangles are locations of drive/witness electron/witness positron bunches

Thus this PDWA can be used both for acceleration of electron bunches, and for acceleration of positron bunches.

Profiles of forces for $n_b/n_p = 1/3$

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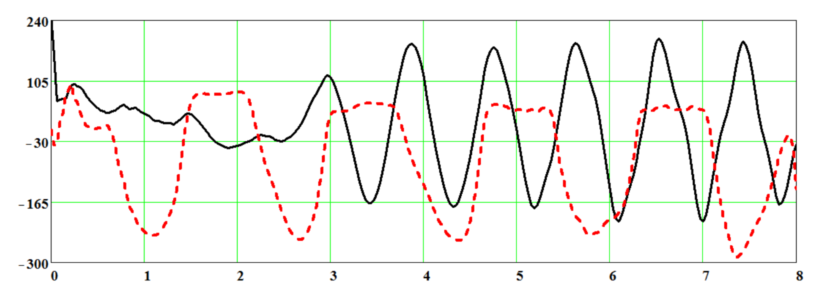
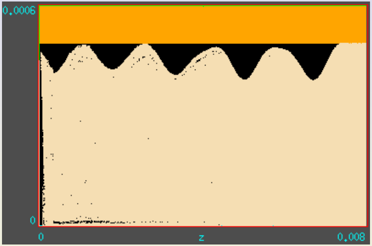
Is $n_b/n_p = 1/3$ small value? Are the previous results valid?
Yes, the simulations using the XOOPIC code confirm this.



Axial profiles of the axial force (black line) and transverse force (red line) at r=0.45mm. Drive bunch moves from left to right, its head is located at z=8mm. Distance (x-axis) is measured in mm, forces (y-axis) are in MeV/m.

Perturbation of plasma particles

The difference in defocusing areas of the wakefield can be explained by the pushing out of plasma electrons to the dielectric surface.

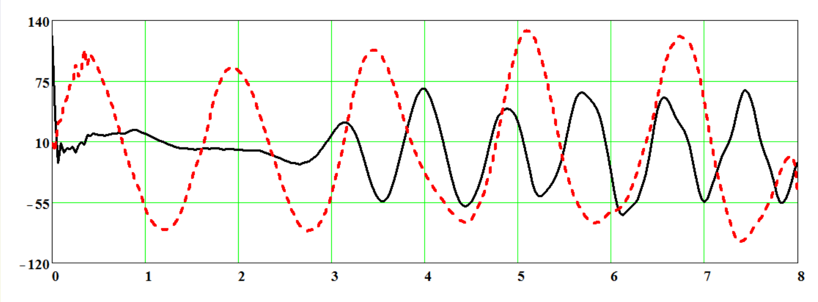


Configuration space (z,r), of plasma electrons (yellow dots) and plasma ions (green dots) at time t=26.688psec, when the head of drive bunch came to output end. Dielectric tube is shown by orange color. Dimensions are in m.

Near the dielectric surface, periodic positive charged cavities arise. They decrease the defocusing force acting on test electrons.

Profiles of forces for $n_b/n_p = 1/9$

By decreasing the ratio n_b/n_p the truncation of the defocusing part of F_r disappears, and a more exact coincidence of the simulation result with the analytical calculation is obtained.



Axial profiles of the axial force (black line) and transverse force (red line) at r=0.45mm. The plasma density is the same $n_p = 4.41 \cdot 10^{14}$*, but* $n_b = 0.49 \cdot 10^{14}$ *- bunch charge is decreased by 3 times*

Parameters underdense PDWA

Previously, the underdense or blowout regime in unbounded plasma has been investigated by J.Rosenzweig et al. The transition to THz frequencies this case can be realized in PDWA easily. One example:

OD of dielectric tube	$1.0\,mm$
ID of dielectric tube	$0.4\,mm$
Relative dielectric constant, ε	3.75
Bunch energy	$5\,GeV$
Bunch charge	$3\,nC$
Bunch diameter	$1.0\,mm$
Density of drive bunch electrons, n_b	$3 \cdot 10^{15}\,cm^{-3}$
Plasma density, n_p	$10^{14}\,cm^{-3}$
Nonrelativistic plasma wavelenghth	$3.36\,mm$

Thus, $n_b/n_p = 30$

Focusing in PDWA for underdense plasma

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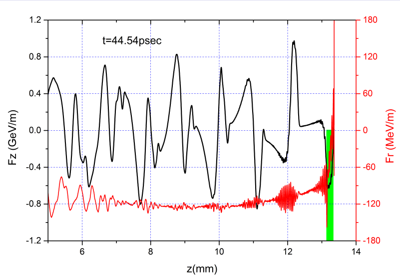
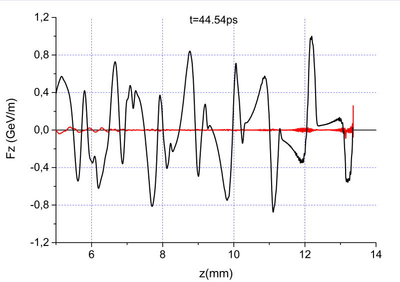
$n_p = 10^{14}$, $n_b/n_p = 30$



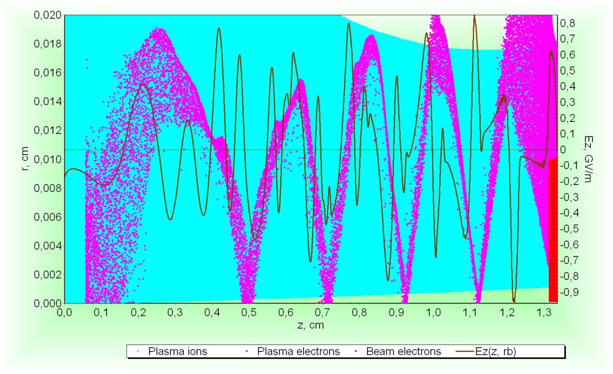
$n_p = 0$



Axial profile of the axial force (black line) and axial profile of transverse force (red line) at $r = 0.1\,mm$ for $t = 44.54\,psec$. Drive bunch moves from left to right, its location is shown green rectangle.

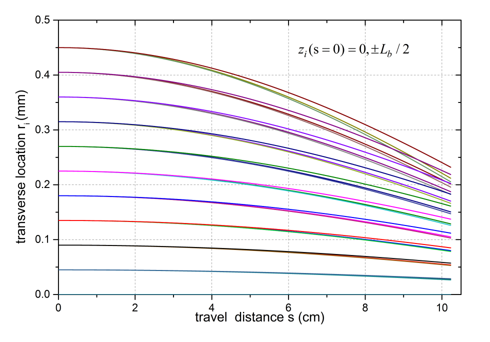
Acceleration is due to the dielectric wave and focusing is due to the plasma ions. At $n_p = 4.4 \cdot 10^{14}$ it may be anticipated that the focusing force is equivalent B=1.8T

Plasma and beam particles



Configuration space of plasma electrons (magenta dots) and plasma ions (cyan dots) in the transport channel after travelling in it electron bunch (red dots) at t=44.54ps. Black line shows axial electric field.

Focusing of test electrons



Radii of witness bunch electrons during the acceleration by wakefield of drive bunch. Initially (at s=0) center of witness bunch is located at the distance of 2.2cm behind of drive bunch head.

For the distance 10 cm the accelerated electron bunch is focused ∼twice.

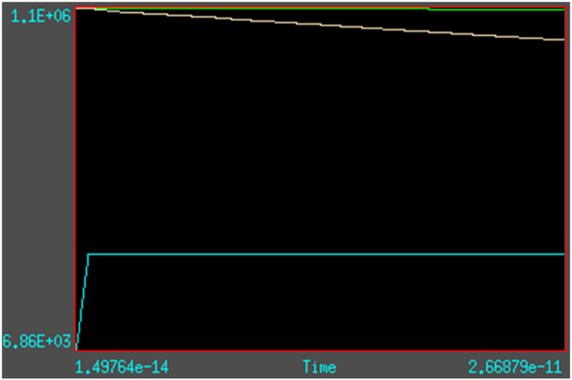
Summary

Researches of wakefields excited by the electron bunch in PDW showed:

- Filling up the dielectric waveguide vacuum transport channel with isotropic plasma having a definite density sets up a focusing wakefield which accelerates a witness bunch
- For the case of a linear plasma, the focusing of witness bunch particles is provided by the plasma wave, and acceleration is provided by the eigen waves of the empty dielectric waveguide
- Focusing mechanism is charge symmetrical: it can be used both for accelerated electron bunches and for accelerated positron bunches
- For case of nonlinear plasma, focusing is provided by plasma ions remaining in transport channel after pushing out the plasma electrons. Acceleration, as before, is provided by dielectric wave

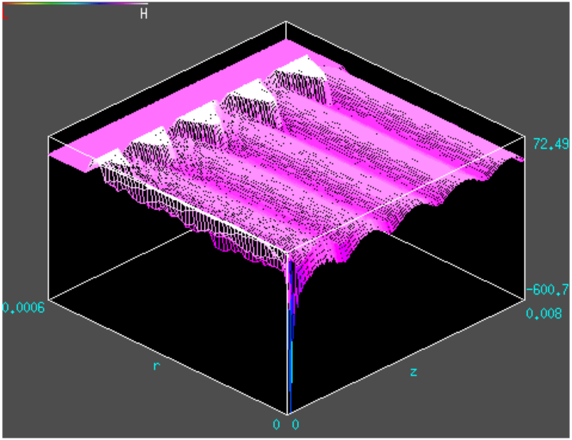
Thank you for your attention

Loss of particles $n_b/n_p = 1/3$



Number of plasma electrons (yellow line), number of ions (green line) and bunch electrons in the unit versus time of simulations. Particles which hit the dielectric surface were removed from the unit. During the simulation period about $\sim 8\%$ *of plasma electrons was lost*

Charge density in PDWA $n_b/n_p = 1/3$



Total charge density of all particles (nC/m^3) at time t=26.6879psec.