ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB165

IDENTICAL FOCUSING OF TRAIN OF RELATIVISTIC POSITRON GAUSSIAN BUNCHES IN PLASMA*

D. S. Bondar[1], V. I. Maslov[1], I. N. Onishchenko
Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
[1]also at V. N. Karazin Kharkiv National University, Kharkiv, Ukraine

Abstract

Focusing of both electron and positron bunches in electron-positron collider is necessary. The focusing mechanism in the plasma, in which all electron bunches are focused identically, has been proposed earlier. This mechanism is considered for positron bunches by using simulation with LCODE. Three types of lenses with different trains of cosine pro-file positron bunches are considered depending on the bunch length, the distance between bunches and their charge. It has been shown that all positron bunches are focused identically at special parameters of the first positron bunch, wherein the middles of bunches are focused weaker than their fronts.

INTRODUCTION

Plasma wakefield is important lens for focusing bunches of electrons and positrons [1-7]. In [1] plasma lens under consideration was based on the charge compensation by the positive charge of plasma ions, arisen due to repulsion of plasma electrons by an injected electron bunch. Another lens using plasma wake-field has been investigated for identical focusing of electron bunches [7].

In this paper, the focusing of a sequence of positron bunches by the wakefield, excited by the first bunch, is considered. Cosine profile positron bunches focusing is quantitatively investigated by particle-in-cell simulation by 2.5D LCODE [8]. This code threats plasma as a cold electron fluid and bunches as ensembles of macro-particles. Cylindrical coordinate system (r, φ, x) is used. Time t and bunch longitudinal momentum P_z are normalized on ω_{pe}^{-1}, mc; densities of plasma electrons n_e and of bunches n_b are normalized on unperturbed plasma electron density n_0, radius r and longitudinal coordinate x - on $c\omega_{pe}^{-1}$; fields - on $E_0 = cm\omega_{pe}e^{-1}$, m, e are the electron mass and charge, c is the light speed, $\omega_{pe} = (4\pi n_0 e^2 m_e^{-1})^{0.5} = 1.78 \cdot 10^{10}$ rad/s is the plasma frequency. I_b maximal bunch current normalized on 17 kA. Unperturbed plasma density is $n_0 = 10^{11}$ cm^{-3}. The purpose is to determine the conditions under which the train of relativistic cosine profile positron bunches is focused by identical forces. The averaged focusing force F_r means the averaged over radius value between values at $r = 0$ and $r = r_b$. Averaged value of the wakefield E_z means $< E_z >= \int E_z n_b r dr \,/\, \int n_b r dr$.

*The study is supported by the National Research Foundation of Ukraine under the program “Leading and Young Scientists Research Support” (project # 2020.02/0299).

RESULTS OF SIMULATION

First Type Lens

We consider the following train of short positron cosine profile bunches: the charges of all bunches are in $\sqrt{2}$ times larger than the charge of the first bunch. The interval between the first and second bunches is $(k + 8^{-1})\lambda$, $k = 1, 2, \ldots$ Below the case $k = 1$ is presented. The interval between other bunches equals excited wakefield wavelength $\lambda = 10.6$ cm. The length of all bunches is $L_b = \lambda/2$.

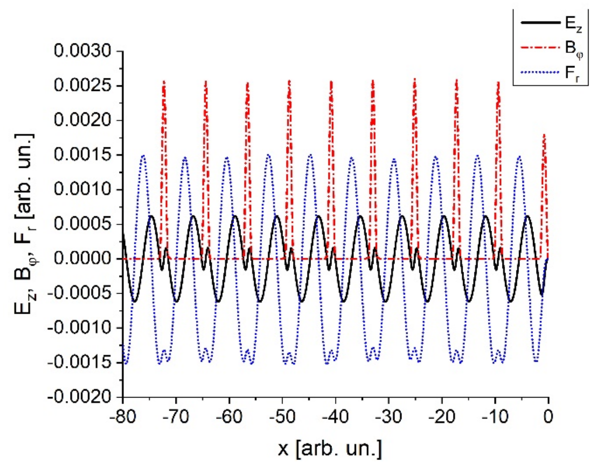

Figure 1: Averaged focusing force F_r, magnetic field B_φ, and longitudinal electric field E_z at $r = r_b$, $\gamma_b = 5$, $I_b = 0.3 \cdot 10^{-3}$ (first bunch), $r_b = 0.1$, γ is the relativistic factor of bunches, I_b is the maximal bunch current.

In Fig. 1 magnetic field component B_φ shows bunches location. One can see that the fronts of all bunches are under higher focusing force than middles of the bunches. Positron bunches are located in wider focusing regions where plasma electron density exceeds the unperturbed density $n_e > n_{0e}$ compared with more narrow defocusing regions where $n_e < n_{0e}$ (Fig. 2). The bunches (except the first bunch) approximately do not exchange energy with wakefield, because they are in a periodical longitudinal wakefield (see Fig. 2). Only the first bunch excites the wakefield and all other bunches are focused in it.

Second Type Lens

We consider (Fig. 3) the spatial distribution for another train of positron cosine profiled bunches. The length of bunch L_b (at half height) is selected to be equal to $L_b = \lambda/2$. Also, we choose charge of the 1st bunch $Q_1 = Q_i/2$, $i = 2,3,\ldots$ (where i are the numbers of the

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB165

other following bunches) (Fig. 3). The distance between bunches equals to 2.5λ.

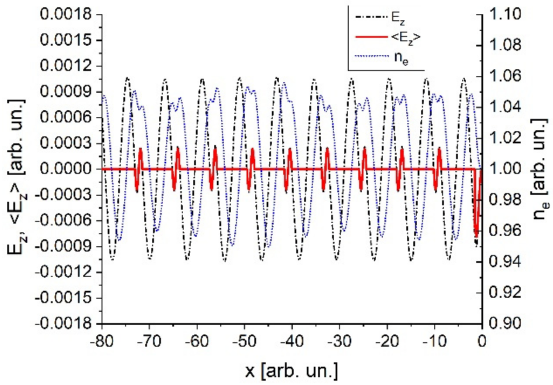

Figure 2: Plasma electron density n_e at $r = 0$, longitudinal wakefield E_z at $r = 0$ and $< E_z >$ averaged E_z for $\gamma_b = 5$, $I_b = 0.3 \times 10^{-3}$ (first bunch), $r_b = 0.1$.

A positron bunch passing through the plasma violates the quasi-neutrality, as a result of which the plasma electrons move to the axis of the bunch. The focusing force for positrons appears, and its value increases. At some point, approaching the axis, the electrons, continuing to move by inertia, scatter away. The value of the focusing force decreases. At some point, the system comes to its original quasi-neutral state. However, the electrons continue to move, scattering from the axis of the bunch. A focusing force begins to act on the plasma electrons, due to the formation of a volume ion uncompensated charge because of the plasma electron expansion. At a certain point, the value of this focusing force becomes such that it prevents further expansion of the electrons. The electrons begin returning to the axis, and the value of the focusing force for the plasma electrons decreases. The dynamics of the system becomes oscillatory. At some time, the plasma electron bunch reaches the axis and the process, described above, would have to be repeated, but this does not happen. The second positron bunch, injected into the plasma, prevents electrons from the scatter again from the axis by compensating their charge. At this moment, as described earlier, the focusing force for positrons is maximal. When the bunch leaves the plasma, the electrons begin to scatter and the process, described at the beginning, repeats, considering the injection at the right time of the third bunch, etc.

The middle of only first bunch (see Fig. 3) is in non-zero longitudinal wakefield. Hence first bunch mainly forms focusing wakefield. Middles of all bunches with the exception of the first bunch of the train are in zero average longitudinal wakefield. We see that wakefield does not change from one bunch to another.

Focusing is provided by the wide areas of increased plasma density n_e in regions of bunches (Fig. 4). In region of the 1st bunch, one can see strongly non-identical areas of increased plasma density of density of plasma electrons. That’s why nonidentical focusing of the 1st bunch should be developed.

In the long regions of high plasma electron density, the bunches are located. The long elevations of n_e (regions of bunches) are alternated by short perturbations of n_e.

Similar wakefield distribution is formed also for seven Gaussian bunches with $L_b = \lambda/2$, $Q_1 = Q_i/2$, $i = 2,3,\ldots$ (Fig. 5).

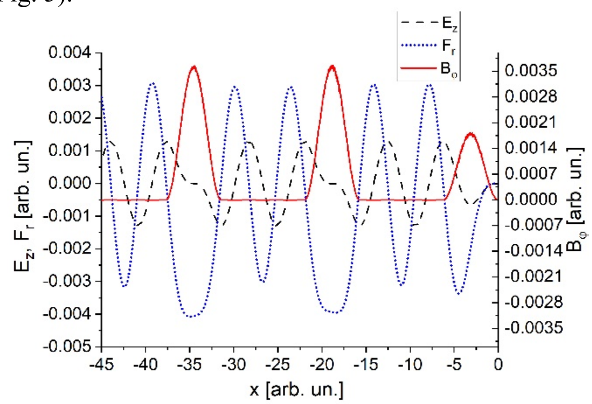

Figure 3: Longitudinal wakefield E_z at $r = r_b$, averaged focusing force F_r, and magnetic field B_φ at $r = r_b$ for $\gamma_b = 5$, $I_b = 0.3 \times 10^{-3}$ (first bunch), $r_b = 0.1$.

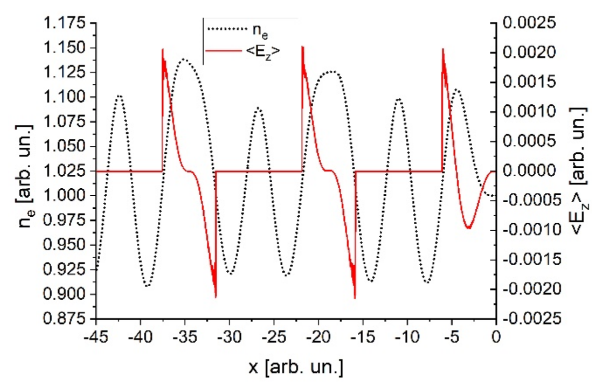

Figure 4: Plasma electron density n_e at $r = r_b$, $< E_z >$ is averaged wakefield E_z, $\gamma_b = 5$, $I_b = 0.3 \times 10^{-3}$ (first bunch), $r_b = 0.1$. $< E_z >$ shows bunch location.

Third Type Lens

Because in Fig. 3-5 the focusing force is non-identical, we consider a train with more identical focusing force distribution (see Fig. 6). The first five cosine profiled positron bunches of the train are shaped (Fig. 6) with increasing charge along the train according to: $2k - 1$ charges of the first bunch, $k \leq N, k = 1,2,\ldots$ The charges of next bunches equal $2N$ charges of the first bunch, $k > N$. The positron bunches with 1.5λ spacing, have cosine profile in the longitudinal and Gaussian profile in the transverse directions. The length of the bunch (on the basis) is equal to $\lambda/2$.

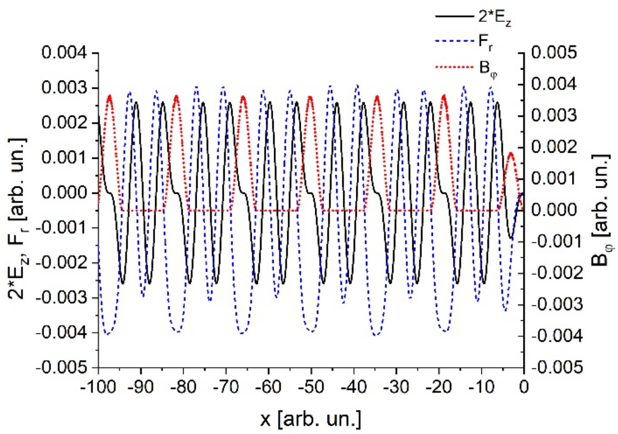

Figure 5: longitudinal wakefield E_z, averaged focusing force F_r and magnetic field B_φ at $r = r_b$, $\gamma = 5$, $I_b = 0.3 \times 10^{-3}$ (first bunch), $r_b = 0.1$.

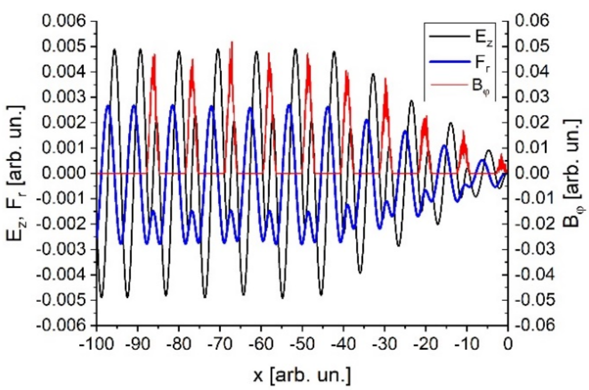

Figure 6: longitudinal wakefield E_z ($r = r_b$), the average focusing force F_r, magnetic field B_φ ($r = r_b$).$I_b = 0.3 \times 10^{-3}$ (first bunch), $\gamma_b = 1000$, $r_b = 0.1$.

The positron bunches have Gaussian profiles in the longitudinal and transverse directions. The charges of first N=5 Gaussian bunches are shaped. One can see (Fig. 6) that radial wake force is identical for all bunches (after 5th bunch). But the middles of bunches are focused weaker than their fronts. The profiling made it possible to provide the identical focusing force. We considered several positron train cases. Each of them has advantages and disadvantages and, at the same time, can be used for focusing a train of bunches.

CONCLUSION

The identical focusing of a train of relativistic positron bunches was considered. First bunch excites the wakefield and all other bunches are focused in it. Three types of lenses for identical focusing of positron bunches train were studied. For the first type of lenses all bunches after the first bunch are focused identically, but the middles of bunches are focused weaker than their fronts. The second lens allows identical focusing along the entire length of the bunches. In the case of the third lens, identical focusing is achieved for shaped bunches.

All three lenses provide identical positron focusing under different conditions and allow achieving the stated research goal.

ACKNOWLEDGEMENTS

The study is supported by the National Research Foundation of Ukraine under the program "Leading and Young Scientists Research Support" (project # 2020.02/0299).

REFERENCES

[1] G. Hairapetian, P. Devis, C. Joshi, C. Pelegrin, and T. Katsouleas, "Transverse dynamics of a short, relativistic electron bunch in a plasma lens", *Phys. Plasma*, vol. 2, p. 2555, 1995. doi:10.1063/1.871217

[2] E. Esarey, C. B. Schroeder, and W. B. Leemans, "Physics of laser-driven plasma-based electron accelerators", *Rev. Mod. Phys.*, vol. 81, pp. 1229-85, 2009. doi:10.1103/RevModPhys.81.1229

[3] A. Pukhov and J. Meyer-ter-Vehn, "Laser wake field acceleration: the highly non-linear broken-wave regime", *Apl. Phys. B*, vol. 74, pp. 355-61, 2002. doi:10.1007/s003400200795

[4] M. J. Hogan *et al.*, "Ultrarelativistic-Positron-Beam Transport through Meter-Scale Plasmas", *Phys. Rev. Lett.*, vol. 90, p. 05002, 2003. doi:10.1103/PhysRevLett.90.205002

[5] P. Muggli *et al.*, "Halo Formation and Emittance Growth of Positron Beams in Plasmas", *Phys. Rev. Lett.*, vol. 101, p. 055001, 2008. doi:10.1103/PhysRevLett.101.055001

[6] N. Barov *et al.*, "Observation of plasma wakefield acceleration in the underdense regime", *Phys. Rev. ST Accel. Beams*, vol. 3, p. 011301, 2000. doi:10.1103/PhysRevSTAB.3.011301

[7] V. I. Maslov, I. N. Onishchenko, and I. P. Yarovaya, "Fields excited and providing an identical focusing of short relativistic electron bunches in plasma", *East European Journal of Physics*, vol. 2, pp. 92-95, 2014.

[8] K. V. Lotov, "Simulation of ultrarelativistic beam dynamics in plasma wake-field accelerator", *Phys. Plasmas*, vol. 3, pp. 785-91, 1998. doi:10.1063/1.872765