MECHANISMS OF SYNCHRONIZATION OF RELATIVISTIC ELECTRON BUNCHES AT WAKEFIELD EXCITATION IN PLASMA

K.V. Lotov[1], V.I. Maslov, I.N. Onishchenko, I.P. Yarovaya[2]

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine;

[1]Budker Institute of Nuclear Physics and Novosibirsk State University, Novosibirsk, Russia;

[2]V.N. Karazin Kharkov National University, Kharkov, Ukraine

E-mail: vmaslov@kipt.kharkov.ua

Using code Lcode the mechanisms of defocusing of electron bunches at wakefield excitation in plasma have been demonstrated.

PACS: 29.17.+w; 41.75.Lx;

INTRODUCTION

Resonant excitation of wakefield by a long sequence of relativistic electron bunches is difficult, because it is difficult in an experiment to support homogeneous and stationary plasma. In [1] the resonant mechanism of wakefield excitation has been studied by the nonresonant sequence of short electron bunches. Synchronization of frequencies has been realized due to (self-cleaning of sequence of bunches) defocusing and shift on the radius of some bunches (being in "bad" phases of wave). In this article the results of numerical simulation of defocusing mechanisms of electron bunches by the 2d3v code lcode [2] are presented. In the dielectric accelerator and plasma the electrons of bunches are defocused:

- due to shift of bunches relatively to a wave in nonresonant case due to difference between repetition frequency of bunches and eigenfrequency of wave $\omega_m \neq \omega_0$ some bunches get in the areas of large radial forces;
- due to finite length of bunches $\Delta\xi_b$ their one fronts are focused, and second fronts are defocused;
- misalignment of bunches at their inhomogeneous focusing/defocusing leads to misalignment of wave and, consequently, to the change of conditions of focusing/defocusing;
- due to finite radius of bunches $r_b \neq 0$ some their electrons get in the finite radial field;
- bunches, getting in the focusing phases of the field, are broaden at certain conditions due to broadening of the betatron oscillations;
- electrons of bunches are also defocused due to misalignment of wave because plasma electron leaving, compensating a charge of bunches, from the axis results in that plasma frequency on the axis $\omega_{pe}(r=0)$ is less than plasma frequency on periphery $\omega_{pe}(r=0) \neq \omega_{pe}(r \neq 0)$.

DEFOCUSING MECHANISMS OF ELECTRON BUNCHES AT WAKEFIELD EXCITATION BY THEM IN PLASMA

We consider defocusing mechanisms of electron bunches at wakefield excitation by them in plasma.

Firstly, in nonresonant case due to the lack of coincidence of repetition frequency of bunches and plasma frequency $\omega_m \neq \omega_{pe}$ the bunches are shifted relatively to a wave and some of them get in areas with a large value of radial force F_r (Figs. 1-5). Secondly, at finite length of bunches $\Delta\xi_b$ their first fronts are defocused, but their back fronts are focused.

We consider the criterion of differentiation of contributions to defocusing of these two mechanisms. The effects of these two mechanisms are depended on observation period t_{ob}. Qualitatively the effects of two mechanisms (due to $\omega_m \neq \omega_{pe}$ and due to $\Delta\xi_b \neq 0$) are the same, if during the time t_{ob} "point" bunches, $\Delta\xi_{bp} \approx 0$, are shifted relatively to a wave on $t_{ob}|\omega_m-\omega_{pe}| \approx (\Delta\xi_b/\lambda)2\pi$ length of lengthy bunch $\Delta\xi_b \neq 0$. If $t_{ob} << (\Delta\xi_b/\lambda)2\pi|\omega_m-\omega_{pe}|$, then defocusing is determined by $\Delta\xi_b \neq 0$. If $\Delta\xi_b << \lambda$ and $\omega_m \neq \omega_{pe}$, then defocusing is determined mainly by $\omega_m \neq \omega_{pe}$, if $2\pi(\Delta\xi_b/\lambda) < t_{ob}|\omega_m-\omega_{pe}|$, even if $t_{ob}|\omega_m-\omega_{pe}| << \pi/2$. If $\Delta\xi_b \approx \lambda/4$, and $t_{ob} \geq (\Delta\xi_b/\lambda)\pi/2|\omega_m-\omega_{pe}|$, then effects of two are the same.

Thirdly, defocusing is also determined by the finite radius of bunches $r_b \neq 0$. The phenomenon is determined by that if a point bunch is in the maximal longitudinal $E_z^{(max)}$ and zero radial $F_r=0$ fields, then a bunch of finite radius $r_b \neq 0$ even short, $\Delta\xi_b << \lambda$, at certain conditions gets in $F_r \neq 0$.

Fourthly, at leaving of compensative plasma electrons from the axis a wave is warped, so that it becomes non-planar, and in kind of a sequence of cones. Then the fields E_z and F_r are shifted along z relatively to each other (Fig. 8). Then, if before warping the bunches-pancakes were in $E_z^{(max)}$ and $F_r \approx 0$, then after warping of wave the periphery (on r) of bunches-pancakes gets in $F_r \neq 0$.

One can note that a wave can be also warped due to that at focusing of back fronts of bunches and at defocusing of their first fronts the bunches, exciting a wave, are warped.

Fifthly, even if bunches are in focusing phases, they can at the certain conditions are defocused (Figs. 10, 11) at expansion of the betatron oscillations (the oscillations in Fig. 9).

Thus, to defocusing of electron bunches the next mechanisms can result:

1) Shift of bunches relatively to a wave due to $\omega_m \neq \omega_{pe}$ in nonresonant case. Thus the bunches are warped simultaneously (Fig. 7). This warping can effect on the wave warping.

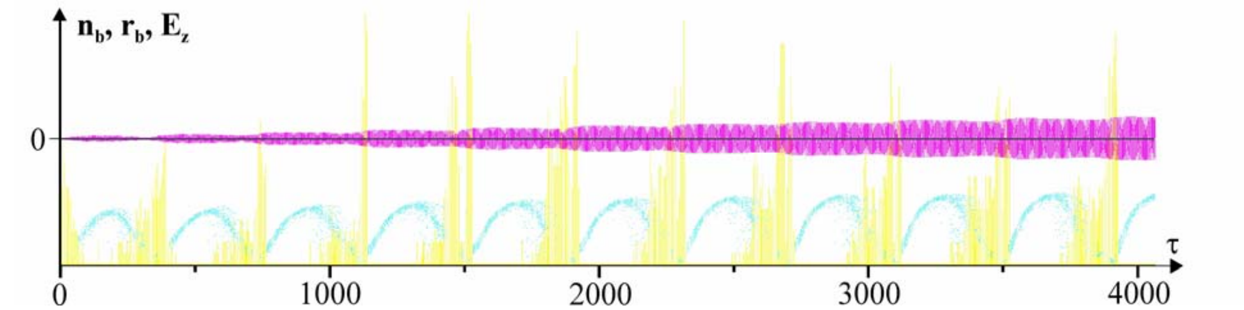

Fig. 1. Longitudinal wakefield E_z (red), density n_b (yellow) and radius of 675 short bunches r_b (blue) in nonresonant case (electron plasma density is smaller on 3% than resonant one)

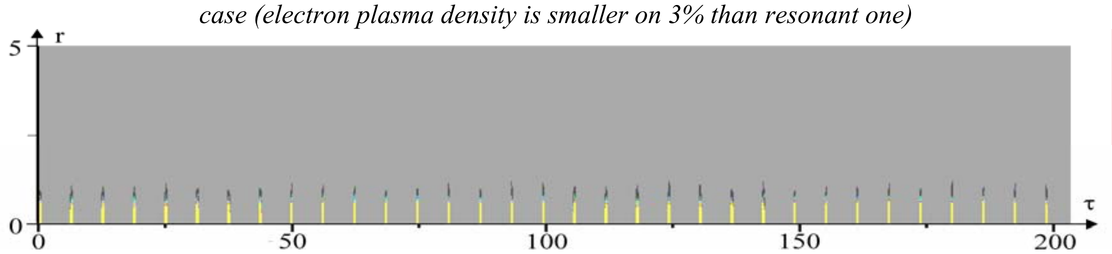

Fig. 2. The density of 33 "point" bunches on boundary of injection in nonresonant case (electron plasma density is smaller on 3% than resonant one)

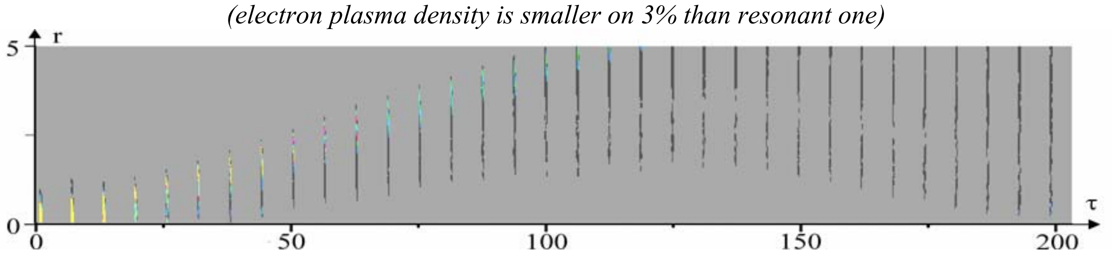

Fig. 3. The density of 33 "point" bunches far from the boundary of injection in nonresonant case (electron plasma density is smaller on 3% than resonant one)

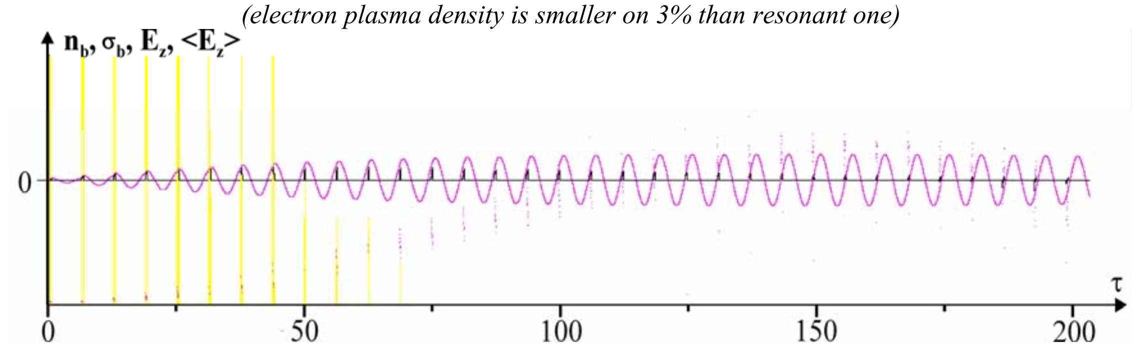

Fig. 4. Longitudinal wakefield E_z (red), coupling rate $<E_z>$ (black) of bunches with wakefield E_z, density n_b (yellow) and radius r_b (red) of 33 "point" bunches in nonresonant case (electron plasma density is smaller on 3% than resonant one)

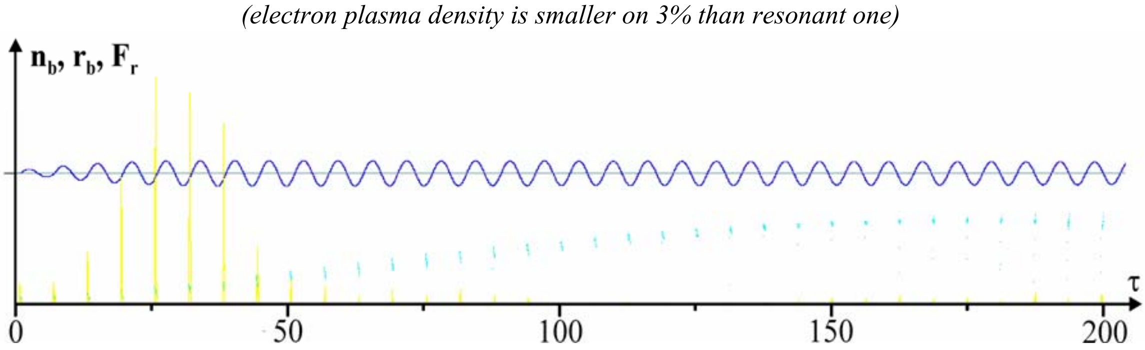

Fig. 5. The density (yellow) and radius r_b (blue) of 33 "point" bunches, radial wakeforce far from the boundary of injection in nonresonant case (electron plasma density is smaller on 3% than resonant one)

2) Finite length of bunches $\Delta\xi_b \neq 0$ leads to that their first fronts are defocused and back fronts are focused (Figs. 6, 7). Thus also the bunches are simultaneously warped. This can effect on the wave warping.

3) Dependence on $r_b \neq 0$. Even if bunches are short on z (i.e. they are pancakes), at wave warping (due to leaving of compensative plasma electrons) fields E_z and F_r are shifted relatively to each other in longitudinal direction (see Fig. 8). Thus, if before warping bunches-

pancakes were in $E_z^{(max)}$ and $F_r \approx 0$, then after wave warping the periphery (on r) of bunches-pancakes gets in $F_r \neq 0$.

4) Warping of bunches at focusing/defocusing effects on wave warping.

5) Broadening of betatron oscillations (see the betatron oscillations in Figs. 9 - 11).

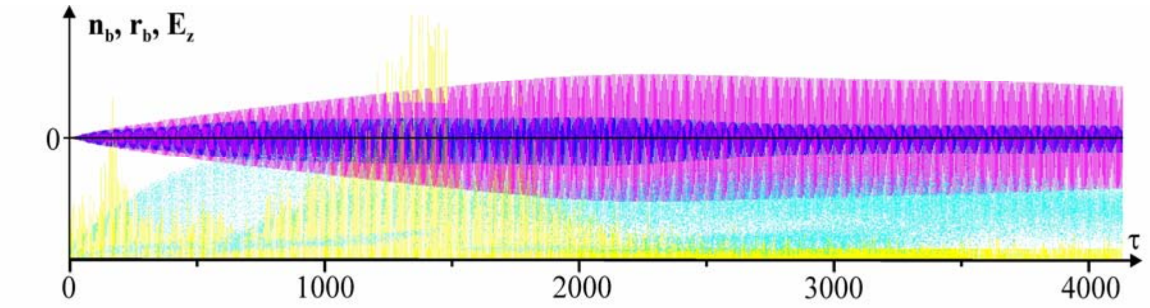

Fig. 6. Longitudinal wakefield E_z (red), density n_b (yellow) and radius r_b (blue) of 675 short bunches in resonant case

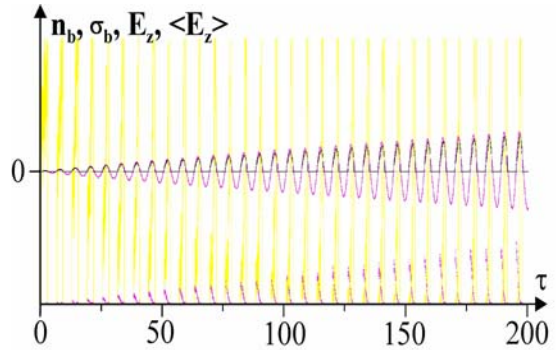

Fig. 7. Warping of bunches at excitation of wakefield in resonant case. The density and radius r_b (red) of 33 "point" bunches, longitudinal wakefield E_z (red) and $<E_z>$ (black) coupling rate of bunches with wakefield E_z in resonant case

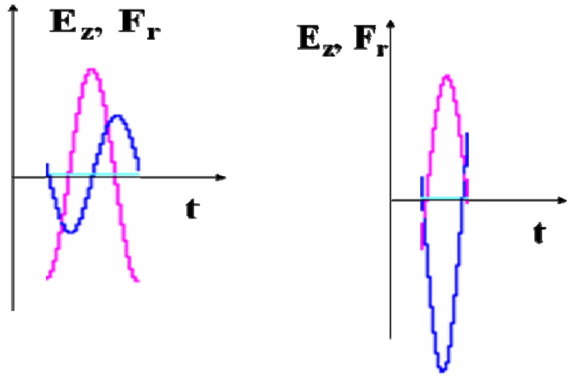

Fig. 8. Shift of E_z and F_r relatively to each other in longitudinal direction

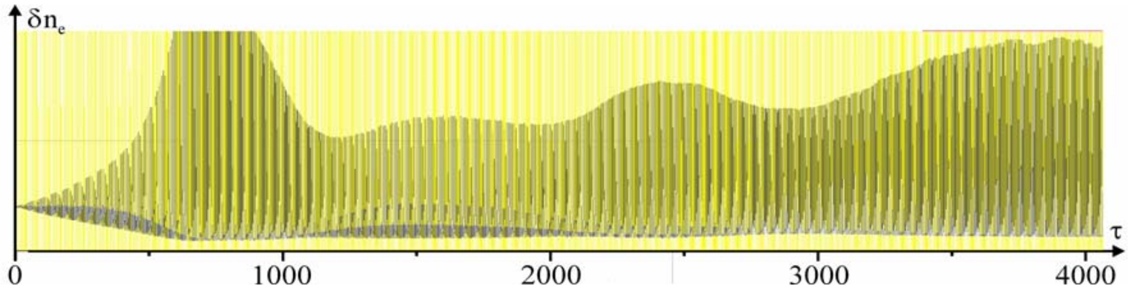

Fig. 9. Perturbation of plasma electron density δn_e (black) in wakefield, excited by 675 resonant electron bunches far from the boundary of injection. γ_b=5

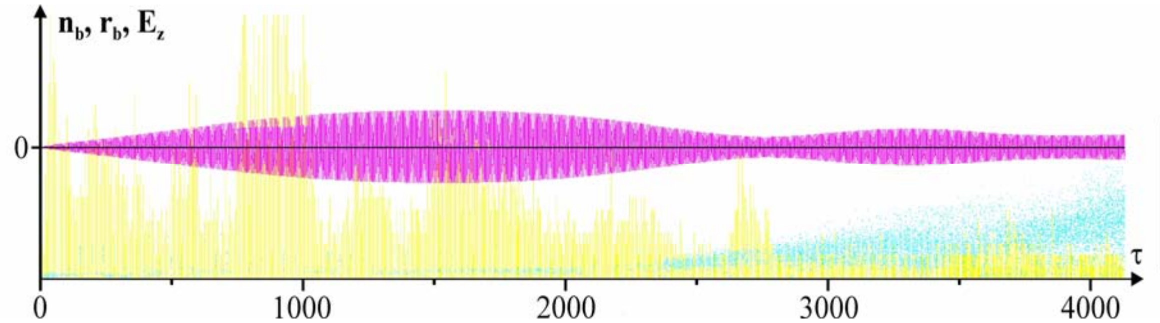

Fig. 10. Longitudinal wakefield E_z (red), excited by 675 resonant electron bunches far from the boundary of injection, density n_b (yellow) and radius r_b (blue) of "point" bunches

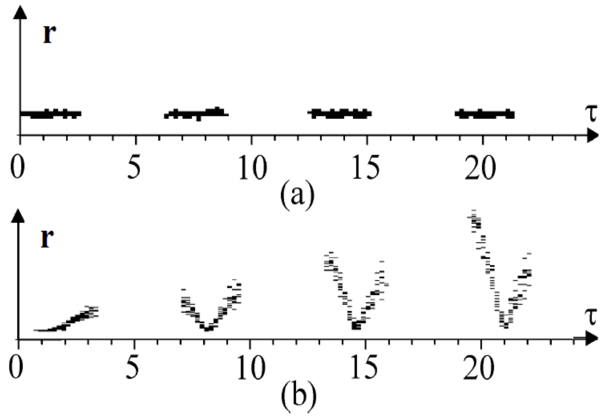

Fig. 11. Electron beam defocusing and over-focusing

I.e. explanation of "rapid" radial evolution of bunches, "point" on z of finite radius, is following. Wave warping results in relative shift of E_z and F_r. Consequently, bunches get in maximal E_z and in large F_r.

At $\gamma_b \rightarrow \infty$ or in the case of strong external magnetic-field focusing of electron bunches is damped, and $E_z^{(max)}$ becomes smaller, but amplitude is homogeneous along the system.

The betatron oscillations are expanded as follows. At first the bunches are focused. Then the bunches are defocused because the wakefield amplitude is spatially inhomogeneous. Namely, the wakefield decreases to the first front of sequence of bunches.

One can note that the wave warping is a charge-depending phenomenon. Really, in the case of electron bunches the wave is warped in one side (Fig. 12), and in the case of positron bunches the wave is warped in other side (Fig. 13).

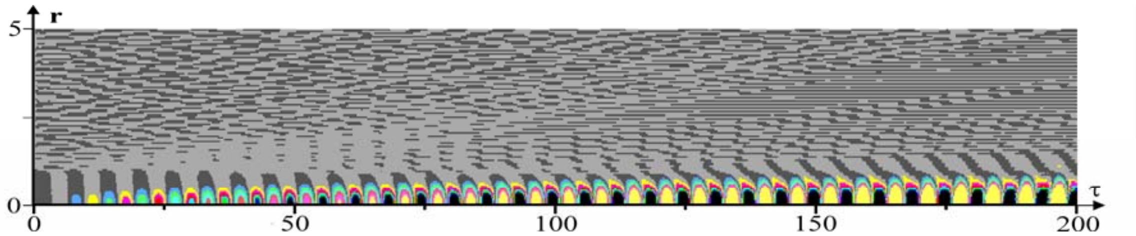

Fig. 12. Wave of n_e in the case of electron bunches

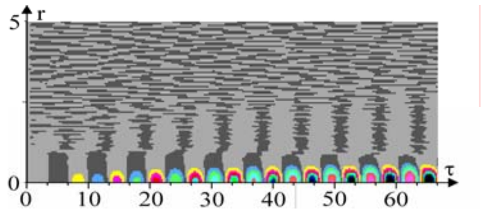

Fig. 13. Wave of n_e in the case of positron bunches

CONCLUSIONS

It has been shown that the following mechanisms can lead to defocusing of electron bunches: firstly, shift of bunches relatively to the wave in nonresonant case; secondly, finite length of bunches $\Delta\xi_b \neq 0$ results in that their first fronts are defocused and back fronts are focused; thirdly, at the finite radius of bunches even if they are short, at a wave warping due to leaving of compensative plasma electrons from the axis the fields E_z and и F_r are shifted relatively to each other in longitudinal direction and bunches gets in $F_r \neq 0$; fourthly, the bunch warping at focusing/defocusing can effect on the wave warping; fifthly, if bunches are in focusing phases, they can be defocused at the certain conditions due to expansion of the betatron oscillations.

ACKNOWLEDGEMENTS

This work was performed with the support of Department of Education and Science of Russian Federation, agreement 14.B37.21.0784.

REFERENCES

1. K.V. Lotov, V.I. Maslov, I.N. Onishchenko, E. Svistun. Resonant excitation of plasma wakefields by a nonresonant train of short electron bunches // *Plasma Phys. Cont. Fus.* 2010, v. 52, № 6, p. 065009.
2. K.V. Lotov. Simulation of ultrarelativistic beam dynamics in plasma wake-field accelerator // *Phys. Plasmas*. 1998, v. 5, № 3, p. 785-791.

Article received 18.04.2013

МЕХАНИЗМЫ СИНХРОНИЗАЦИИ ПОСЛЕДОВАТЕЛЬНОСТИ СГУСТКОВ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОНОВ ПРИ ВОЗБУЖДЕНИИ КИЛЬВАТЕРНОГО ПОЛЯ В ПЛАЗМЕ

К.В. Лотов, В.И. Маслов, И.Н. Онищенко, И.П. Яровая

Используя код Lcode, продемонстрированы механизмы дефокусировки электронных сгустков при возбуждении кильватерного поля в плазме.

МЕХАНІЗМИ СИНХРОНІЗАЦІЇ ПОСЛІДОВНОСТІ ЗГУСТКІВ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОНІВ ПРИ ЗБУДЖЕННІ КІЛЬВАТЕРНОГО ПОЛЯ В ПЛАЗМІ

К.В. Лотов, В.І. Маслов, І.М. Оніщенко, І.П. Ярова

Використовуючи код Lcode, продемонстровані механізми дефокусування електронних згустків при збудженні кільватерного поля в плазмі.