TO THE PLASMA WAKEFIELD EXCITATION BY A NONRESONANT SEQUENCE OF RELATIVISTIC ELECTRON BUNCHES AT PLASMA FREQUENCY ABOVE BUNCH REPETITION FREQUENCY

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By using 2d3v code LCODE the investigation of plasma wakefield excitation by a nonresonant sequence of relativistic electron bunches for the case of bunch repetition frequency lower plasma frequency is carried out. Contrary to the case of nonresonant sequence with bunch repetition frequency higher plasma frequency the picture of field and bunches evolution is more complicated with no linear field growth. Nevertheless the asymmetry between the energy loss of decelerated bunches in the front half of beats and the energy gain of accelerated bunches in the rear half of beats, caused by different bunch-field coupling gives on average the growth of wakefield amplitude.

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1. INTRODUCTION

Resonant plasma wakefield excitation by long sequence of relativistic electron bunches simulated in [1] for parameters of experiment [2], is difficult to realize because we need to keep plasma frequency with precession 1/M, where M is number of bunches in the sequence. Results of 2.5D simulation by LCODE [3] of plasma wakefield excitation by a nonresonant long sequence (repetition frequency ω_m is not coincided with plasma frequency ω_p) have been early presented in [4]. Frequency detuning $\Delta\omega=\omega_p-\omega_m$ causes beats in wakefield excitation. The mechanism of the wakefield excitation is the asymmetry appearance between energy exchange of bunches with wakefield at first and second halves of beats due to different radial dynamics of bunches. Moreover it was shown that for $\omega_p<\omega_m$ the bunches occurred in maxima of beats are defocused and leave the region of excited wakefield so the sequence "self-cleans" becoming resonant one (so called frequency synchronization) though with only 1/6 beam intensity.

In this paper we consider more detaily the case when the plasma frequency is larger than the repetition frequency $\omega_p>\omega_m$ In this case bunches occurred in maxima of beats are focused and there are no bunches which are irreversibly defocused by the wakefield. Contrary to case $\omega_p<\omega_m$ evolution of wakefield and bunches is more complicated. However due to radial dynamics of bunches and their phase shifting asymmetry between energy exchange in first and second halves of each beat arises that leads to the growth of wakefield. It is important since in experiment inhomogeneity of plasma density embraces both considered cases.

2. ASYMMETRY OF ENERGY EXCHANGE IN HALVES OF EACH BEAT

2d3v simulation of nonresonant case $\omega_p>\omega_m$ in cylindrical coordinate system (r, z) were performed for parameters of experiment [2]: sequence of $M=6\cdot10^3$ electron bunches each of energy W=2MeV, charge Q=0.32 nC, rms length $2\sigma_z=1.7$ cm, rms radius $\sigma_r=0.5$ cm, rms angular spread $\sigma_\theta=0.05$ mrad, bunch repetition period 360 ps, resonant plasma density $n_p=10^{11}$ cm^{-3}.

At first we consider 500 electron bunches. Number of the beats, excited by sequence of 500 bunches, contrary to nonresonant case $\omega_p<\omega_m$, to the end of the plasma decreases in comparison with the number of the beats near injection boundary. Amplitude of the on-axis electric field as a function of the coordinate along the plasma and the number of injected bunches are shown in Fig. 1 for two nonresonant cases $\omega_p\approx1.025\omega_m$ and $\omega_p\approx0.97\omega_m$.

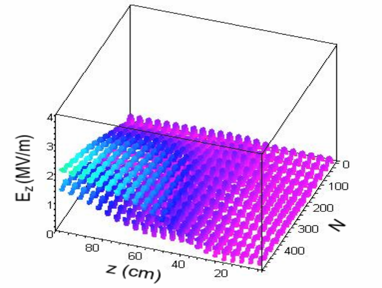

Fig. 1. The amplitude of the on-axis electric field as a function of the coordinate along the plasma and the number of injected bunches for $\gamma_b=5$; $\omega_p\approx1.025\omega_m$ (below) and $\omega_p\approx0.97\omega_m$. (upper)

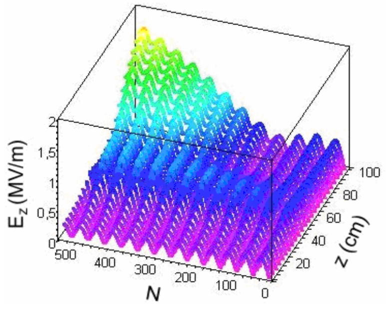

Fig. 2. The amplitude of the on-axis electric field as a function of the coordinate along the plasma and the number of injected bunches for $\gamma_b=5$; $\omega_p\approx1.025\omega_m$

Fig. 1 demonstrates wakefield growth with increase of number of bunches and plasma length for both cases. However for ;$\omega_p \approx 1.025\omega_m$ picture of wakefield and bunch evolution is complicated [4] (Fig. 2). Further we are investigating in detail the mechanism of wakefield growth for the case of $\omega_p > \omega_m$.

For cogency that radial dynamics is decisive in wakefield growth for nonresonant case we performed 2d3v-simulation the case of ultra relativistic bunches (γ_b=1000) for which radial motion is suppressed (Fig. 3). It is seen that wakefield growth is absent for this case.

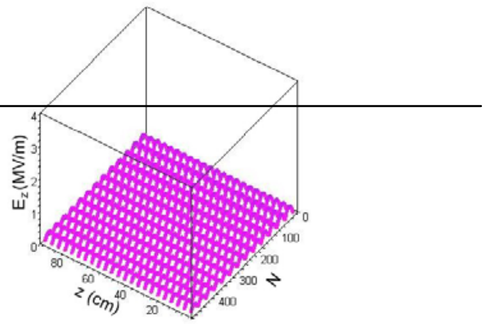

Fig. 3. On-axis electric field versus z and N for γ_b=1000

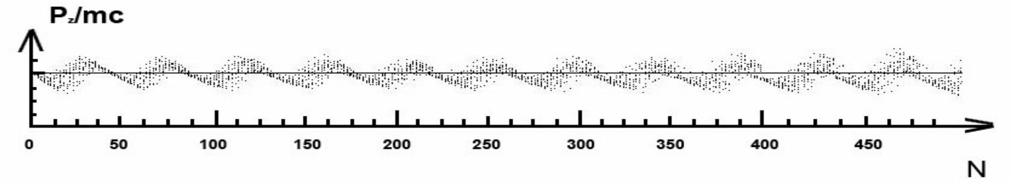

Fig. 4. Longitudinal momentum of 500 bunches on the end of the system (z=100 cm) for γ_b=5; $\omega_p \approx 1.025\omega_m$

It is seen on phase plane (Fig. 4) that number of decelerated electrons exceeds the number of accelerated electrons in each beat of wakefield. This explains averaged wakefield growth accompanied by wakefield beating.

Let us consider mechanism of plasma wakefield excitation on example of sequence of 32 bunches in the case $\omega_p \approx 1.025\omega_m$. From Figs. 5, 6, 8-10 one can see that the radial distribution of bunch density is asymmetrical relatively to maximum of beat. In maximum of beat bunches experiences focusing contrary to the case of $\omega_p < \omega_m$ [4]. In front half of a beat, where bunches are decelerated, focusing of bunch electrons are stronger and in the rear half of beat, where bunches are accelerated, their focusing are smaller. Moreover, in the rear half of beat, as one can see from Fig. 6, the bunches can get in defocusing phase of wakefield. So decelerated electrons occur in higher wakefield comparatively to accelerated electrons. Thus energy losses by decelerated electrons exceed energy gain by accelerated electrons.

From Figs. 8, 9 one can see that the middle radii of bunches are larger (see Fig. 9) and the coupling of bunches with wakefield is smaller (see Fig. 8) in rear half of beat (phases of electron acceleration) in comparison with front half of beat (phases of electron deceleration).

Because the wakefield is excited by nonresonant sequence the wakefield represents beats. Near injection boundary the symmetry between phases of decelerated electrons in wakefield in front half of beat and phases of accelerated electrons in wakefield in rear half of beat is realized. As a result of bunch radial dynamics the wavelength changes far from the injection boundary. This leads to phase symmetry braking, i.e. accelerated bunches in rear part of beat get in another radial fields comparatively to decelerated bunches in front half of beat. Therefore middle radii of bunches are larger in rear half of beat, than in front half of beat. It decreases coupling of bunches with wakefield in rear half of beat in comparison with front half of beat. So the sequence continues to excite the wakefield.

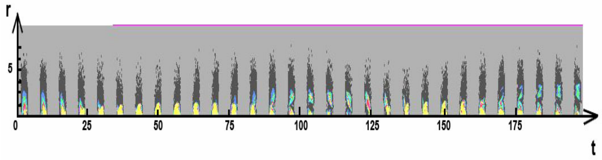

Fig. 5. Evolution of bunch density on the plasma end (z=100 cm) for $\omega_p \approx 1.025\omega_m$

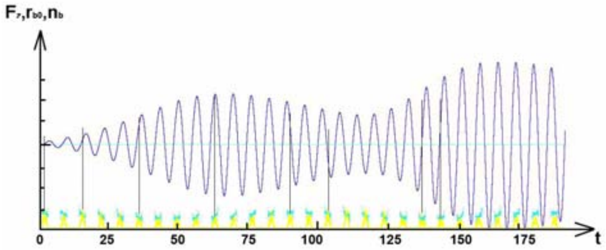

Fig. 6. The radial wake force F_r,(blue) averaged radius of bunches r_{b0} (green), and density of bunches on the axis (yellow) for $\omega_p \approx 1.025\omega_m$

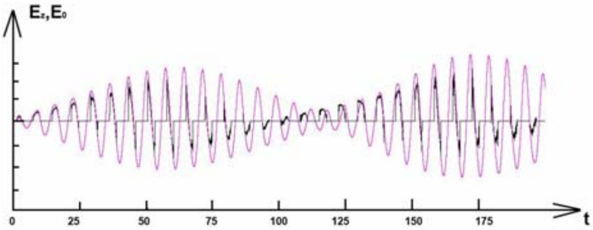

Fig. 7. The on-axis wakefield excitation E_z (red) by a sequence of 32 bunches (z=100 cm) $\omega_p \approx 1.025\omega_m$. The averaged field E_0 (black)

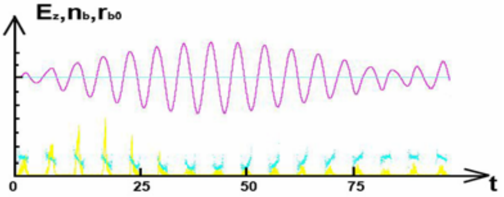

Fig. 8. E_z,(red), averaged radius of bunches r_{b0} (green), and density of bunches on the axis (yellow) for $\omega_p \approx 1.025\omega_m$

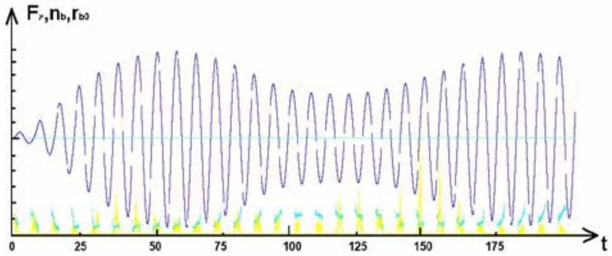

Fig. 9. The radial wake force F_r,(blue) averaged radius of bunches r_{b0} (green), and density of bunches on the axis (yellow) for $\omega_p \approx 1.025\omega_m$

From Figs. 8-10 one can see that the density of bunches near axis is larger in first half of beat, where bunches are slowing down, than in second half of beat, where bunches are accelerated.

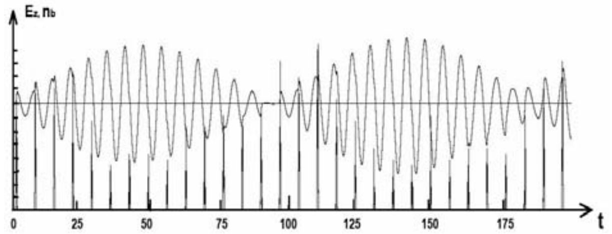

Fig. 10. E_z and density of electron bunches on the distance from axis, equal beam radius r_b (vertical lines) at z=50cm for $\omega_p \approx 1.025\omega_m$

3. CONCLUSIONS

At wakefield excitation by nonresonant sequence of electron bunches the wavelength changes far from the injection boundary as a result of bunch radial dynamics. This leads to bunch phase shift, in rear half of beat accelerated bunches get in another radial fields comparatively to decelerated bunches in front half of beat. The sequence continues to excite the wakefield.

In front half of beat, where bunches are decelerated, focusing of bunch electrons are stronger and in the rear half of beat, where bunches are accelerated, their focusing is smaller. Moreover, in the rear half of beat the bunches can get in defocusing field.

The averaged radii of bunches are larger and the coupling of bunches with wakefield is smaller in rear half of beat in comparison with front half of beat.

The densities of bunches near axis are larger in front half of beat, where bunches are decelerated, than in rear half of beat, where bunches are accelerated.

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ВОЗБУЖДЕНИЕ КИЛЬВАТЕРНОГО ПОЛЯ В ПЛАЗМЕ НЕРЕЗОНАНСНОЙ ЦЕПОЧКОЙ РЕЛЯТИВИСТСКИХ СГУСТКОВ ЭЛЕКТРОНОВ

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С использованием 2d3v-кода LCODE проведены исследования возбуждения кильватерного поля в плазме нерезонансной цепочкой релятивистских электронных сгустков в случае, когда частота следования сгустков меньше плазменной частоты. В отличие от случая нерезонансной цепочки с частотой следования сгустков, большей плазменной частоты, картина эволюции поля и сгустков более сложная, без линейного роста поля. Тем не менее, асимметрия между потерей энергии тормозящимися сгустками в первой половине биений и приобретением энергии ускоряемыми сгустками во второй половине биений, вызванная различной связью сгустков с полем, приводит, в среднем, к росту амплитуды кильватерного поля.

ЗБУДЖЕННЯ КІЛЬВАТЕРНОГО ПОЛЯ В ПЛАЗМІ НЕРЕЗОНАНСНИМ ЛАНЦЮЖКОМ РЕЛЯТИВІСТСЬКИХ ЗГУСТКІВ ЕЛЕКТРОНІВ

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З використанням 2d3v-коду LCODE проведено дослідження збудження кільватерного поля у плазмі нерезонансним ланцюжком релятивістських електронних згустків у випадку, коли частота слідування згустків в плазму менше плазмової частоти. На відміну від випадку нерезонансного ланцюжка з частотою слідування згустків, більшою за плазмову частоту, картина еволюції поля та згустків більш складна, без лінійного зростання поля. Тим не менше, асиметрія між втратами енергії згустками, що гальмуються в першій половині биття та здобутком енергії згустками, що прискорюються у другій половині биття, спричинена різним зв'язком згустків з полем, призводить, у середньому, до зростання амплітуди кільватерного поля.