WAKEFIELD EXCITATION IN NONLINEAR PLASMA BY SEQUENCE OF RELATIVISTIC ELECTRON BUNCHES

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The plasma wakefield excitation by long sequence of relativistic electron bunches is considered. It has been shown that taking into account ionization of the residual gas partially compensates resonance nonlinear detuning and the wakefield amplitude increases in comparison with the case of constant plasma density. Certain small excess of the plasma density on the resonant value also leads to focusing of more part of bunches, to extend the existence of the resonance and, as a result, to increase of the amplitude of the excited wakefield.

PACS: 29.17.+w; 41.75.Lx;

INTRODUCTION

For intense plasma wakefield excitation in experiment [1] and in numerical simulation [2] a long resonance sequence of low-density electron bunches has been used. However, it appears that there is a limiting wakefield amplitude. It is determined by the fact that with wakefield amplitude increase the nonlinear shift of frequency of wake wave appears. Due to this the resonant interaction of bunches with wakefield is destroyed. This resonance destroying is delayed in time, if, as was done in [3], initially selected a small excess of the plasma density over the resonant value. In this paper the plasma wakefield excitation by long sequence of electron bunches is considered. Taking into account ionization of the residual gas and the fact that the intensity of ionization is proportional to the amplitude of the exciting wakefield, the plasma density increases with time. With plasma density increase the electron plasma frequency increases. Because with wakefield amplitude increase the negative nonlinear correction to the frequency of the wake wave increases, the ionization partially compensates resonance nonlinear detuning. In other words, the ionization leads to the resonance adjustment as in the development of the beam-plasma discharge [4]. Using code lcode [5], the numerical simulation of the wakefield amplitude growth has been performed at slow temporal grow of the plasma density. The second case of the wakefield excitation, when initially the plasma density n_{0e} is larger than resonant one $n_{0e}>n_{rez}(=\omega_m^2 m_e/4\pi e^2)$ (ω_m is the repetition frequency of bunches) and plasma density grows slowly in time, has been also numerically simulated. It has been shown that the wakefield amplitude increases in comparison with the case of constant plasma density, neglecting the energy loss on ionization.

RESULTS OF SIMULATION

For beginning we consider dynamics of first 32 bunches in the plasma. We use the cylindrical coordinate system (r, z) and plot plasma and beam densities at some z as functions of the dimensionless time $\tau=\omega_p t/2\pi$ (ω_p is the plasma electron frequency). We do not taking into account longitudinal dynamics of bunches, because at considered times and beam energies, radial relative shifts of beam particles prevail. From Figs. 1, 2 we see that in the resonant case at the middle of the plasma, the bunches are already focused by the wakefield, and the focusing is non-uniform. Namely, the first fronts of the bunches are defocused and their back fronts are focused. Then the mean field $E_0=\int E_z n_b dr/\int n_b dr$ (which is proportional to coupling factor of bunches with wakefield) on the first front of the bunch is less, and on the back front is more (Fig. 3).

In the case, when initially the plasma density is larger than resonant one $n_{0e}>n_{rez}$, one can see in Fig. 4 that bunches are shifted in the focusing phases. In this case, at a certain excess of n_{0e} over n_{rez} bunches are focused entirely. This should lead to an increase of the excitation intensity of the wakefield. Also, the ratio $n_{0e}>n_{rez}$ should lead to a prolongation of the time of the resonant interaction of bunches with wakefield.

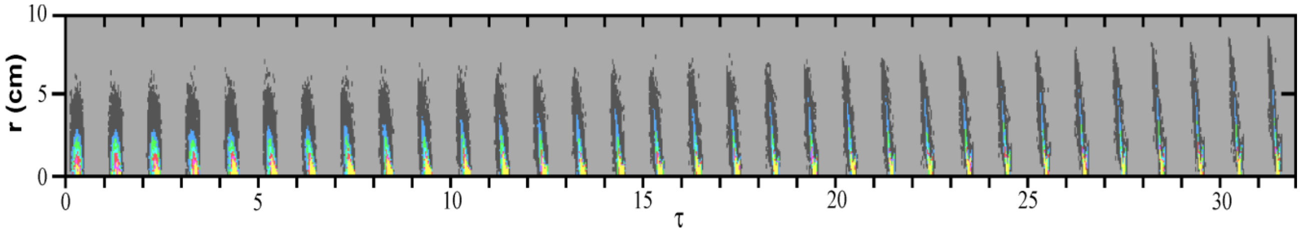

Fig. 1. Temporal evolution of the beam density in the middle of the plasma (at z=50 cm from the injection point) at wakefield excitation by resonant sequence of electron bunches

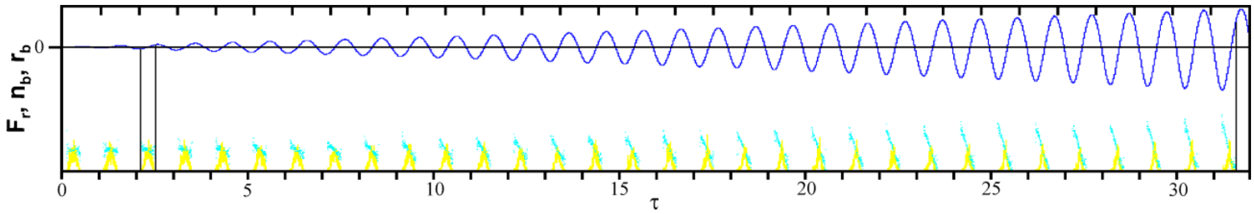

Fig. 2. Temporal evolution of the beam radius (blue) in the middle of the plasma (at z=50 cm from the injection point) at wakefield excitation by resonant sequence of electron bunches

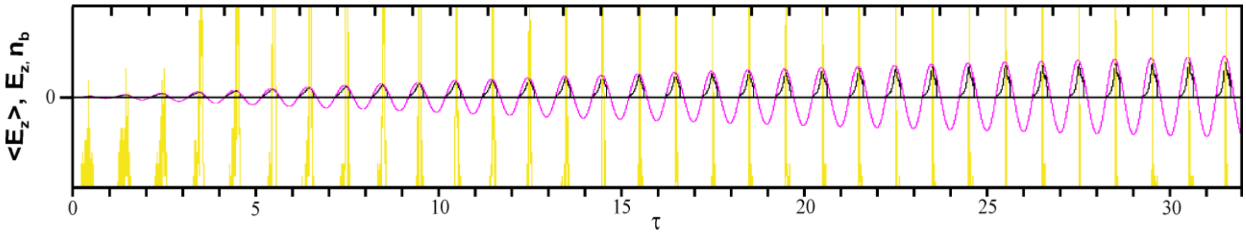

Fig. 3. Temporal evolution of coupling factor (black) of the beam with wakefield in the middle of the plasma at wakefield excitation by resonant sequence of electron bunches

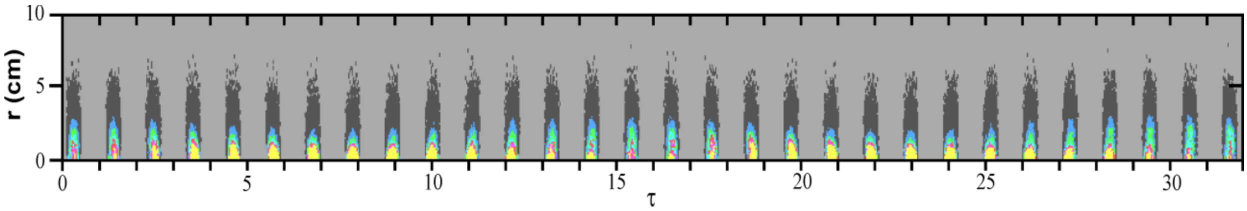

Fig. 4. Temporal evolution of the beam density in the middle of the plasma (at z=50 cm from the injection point) with n_e>n_{rez} at wakefield excitation by sequence of electron bunches

Now we consider the results of these two factors of increase of the maximum excited wakefield on the example of sequence of 500 resonant bunches.

Because bunches near injection boundary are not yet focused and at the end of plasma are over-focused the wakefield amplitude is larger into the plasma. From Figs. 5 and 6 one can see that each of the approximately 100 first resonant bunches lose only part of its energy and wakefield increases approximately linearly with time. Further about 300 bunches lose almost all their energy, and the wakefield amplitude continues to grow, but more slowly. The maximal wakefield amplitude in the case of resonant sequence is equal to E_z=0.14059 in the middle of the plasma. E_z is normalised on $m_e\omega_pc/e$. Then, due to the appearance of negative nonlinear correction to frequency of wake wave, bunches ahead of it, so that about half of the electrons lose energy, and half of their takes energy.

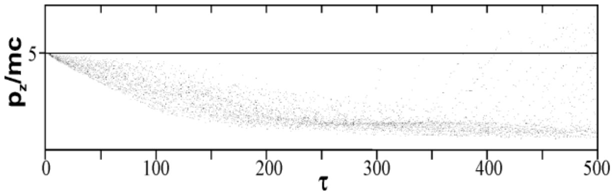

Fig. 5. Longitudinal momenta of 500 bunches

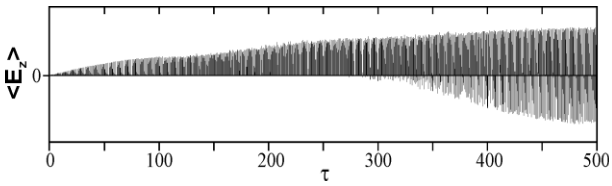

Fig. 6. Temporal evolution of the mean field $<E_z>$ in the middle of the plasma (at z=50 cm from the injection point) at wakefield excitation by sequence of 500 resonant electron bunches

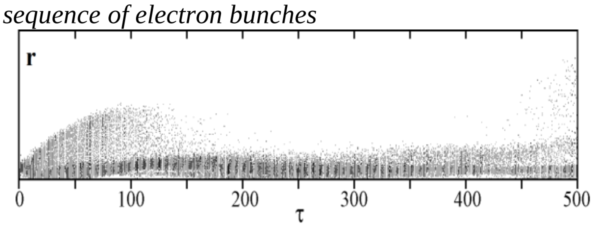

Fig. 7. Temporal evolution of radius of the bunches into the plasma at wakefield excitation by sequence of 500 nonresonant electron bunches (ω_m<ω_p)

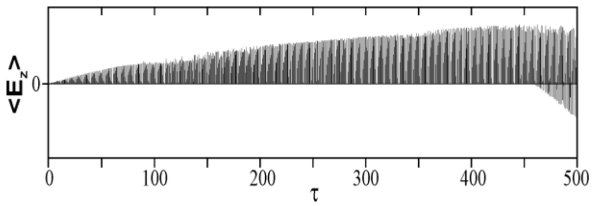

Fig. 8. Temporal evolution of the mean field $<E_z>$ into the plasma at wakefield excitation by sequence of 500 nonresonant electron bunches (ω_m<ω_p) with slow temporal growth of plasma density

In the case of initial non-resonant sequence (ω_m<ω_p) at the beginning the electron bunches are defocused, as in the case of resonance. Then, as a result of the shift of the bunches with respect to the wave due to the initial mismatch n_e>n_{rez} the bunches fall more into the focusing phases (Fig. 7), that leads to increase the intensity of the wakefield excitation. The condition ω_m<ω_p also leads to the prolongation of the existence of resonance. Then with time, under certain small n_e-n_{rez}<<n_{rez} nonlinear frequency shift $\Delta\omega_{NL}$ begins to prevail. This leads to a shift of bunches relative to wave into the small E_z and large F_r. As a result, bunches strongly expand (see Fig. 7). The maximal wakefield amplitude in the case of nonresonant sequence ($\omega_m<\omega_p$) equals E_z=0.18318 and is more than in resonant case.

From Fig. 8 one can see, that in the case of nonresonant sequence ($\omega_m<\omega_p$) with slow temporal growth of plasma density the resonance is braked and some of the electron bunches fall into accelerating fields (see. Fig. 8) on more bunches in comparison with initially resonance case. In the case of nonresonant sequence ($\omega_m<\omega_p$) with slow temporal growth of plasma density more than 500 bunches lose energy (Fig. 9), while in initially resonance case they are about 400. The maximal wakefield amplitude in the case of nonresonant sequence ($\omega_m<\omega_p$) with slow temporal growth of plasma density is equal to E_z=0.19046 in the first half of the plasma (z=12.5. The plasma length is equal to L=60. z is normalised on c/ω_p). I.e. the wakefield amplitude is larger and longitudinal point of maximal amplitude achieving is closer to the boundary of the injection, because in the nonresonant case E_z is more and focusing force F_r is more. Thus, more longer time of bunches location in focusing phases and more longer support of resonance lead to larger wakefield amplitude.

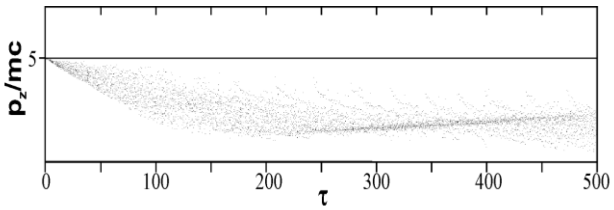

Fig. 9. Longitudinal momenta of 500 bunches

CONCLUSIONS

It is shown that more long sequence of relativistic electron bunches contributes to wakefield growth in some nonresonant case and in some nonresonant case with slow temporal growth of plasma density in comparison with initially resonant sequence.

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Article received 25.09.2014

ВОЗБУЖДЕНИЕ КИЛЬВАТЕРНОГО ПОЛЯ В НЕЛИНЕЙНОЙ ПЛАЗМЕ ПОСЛЕДОВАТЕЛЬНОСТЬЮ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОННЫХ СГУСТКОВ

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Рассматривается возбуждение кильватерного поля в плазме длинной последовательностью релятивистских электронных сгустков. Показано, что учет ионизации остаточного газа частично компенсирует нелинейную расстройку резонанса, и амплитуда кильватерного поля увеличивается по сравнению со случаем постоянной плотности плазмы. Определенное малое превышение плотности плазмы над резонансным значением также приводит к фокусировке большей доли сгустков, к продлению существования резонанса и, как результат, к увеличению амплитуды возбуждаемого кильватерного поля.

ЗБУДЖЕННЯ КІЛЬВАТЕРНОГО ПОЛЯ В НЕЛІНІЙНІЙ ПЛАЗМІ ПОСЛІДОВНІСТЮ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОННИХ ЗГУСТКІВ

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

Розглядається збудження кільватерного поля в плазмі довгою послідовністю релятивістських електронних згустків. Показано, що врахування іонізації залишкового газу частково компенсує нелінійну розстройку резонансу, і амплітуда кільватерного поля збільшується порівняно з випадком постійної густини плазми. Певне мале перевищення густини плазми над резонансним значенням також призводить до фокусування більшої частини згустків, до продовження існування резонансу і, як результат, до збільшення амплітуди збуджуваного кільватерного поля.