TRANSFORMATION RATIO AT INTERACTION OF LONG SEQUENCE OF ELECTRON BUNCHES WITH PLASMA

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The efficiency of wakefield excitation in plasma by sequence of electron bunches is determined by transformation ratio. Using code LCODE, the 2d3v-numerical simulation has been performed and transformation ratio has been investigated for long train of electron bunches. The cases of shift of bunches on phases relative to excited wave, shaping of densities of bunches in nonlinear regime and combined case have been considered, which lead to values of transformation ratio, essentially exciding the limiting value 2.

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1. INTRODUCTION

Advantage of electron acceleration by wakefield is large accelerating field [1], providing possibility of essential decrease of dimensions of colliders and accelerators [2]. The transformation ratio is important at electron acceleration by wakefield. It is determined T_W by ratio of energy, gained by accelerated bunches, to energy, lost by long sequence of electron bunches, slowed down and exciting wakefield in plasma. The transformation ratio can be determined as ratio $T_E = E_2/E_1$ of wakefield, which is excited in plasma by electron bunch E_2 to field, in which the electron bunch slows down E_1.

In one-dimensional case of two bunches: slowed down and accelerated, lengths of which are smaller than wavelength in plasma [3], the transformation ratio is smaller or equals two $T \leq 2$. It is result of Wilson theorem. The sequence use of bunches for wakefield excitation leads to possibility to get round restriction, determined by Wilson theorem. In one-dimensional case this possibility has been researched for sequence of bunches, exciting wakefield in plasma [3,4].

The sequence, in which the distance between bunches equals to excited wavelength, is used for maximum wakefield excitation. In this case the repetition frequency of bunches equals to plasma frequency for wakefield excitation in plasma. It provides possibility to add coherently the excited fields and to increase the amplitude of wakefield in N times (N is the number of identical bunches in sequence) in comparison with wakefield, excited by single bunch [1,3]. Thus, however, the transformation ratio grows with bunch number growth essentially slow.

More fast growth of T with bunch number growth in sequence can be achieved [5], if all bunches are placed in phases, where the amplitude of wakefield, excited by previous bunches, equals zero. Then all bunches are slowed down by identical fields, equal half wakefield, excited by each bunch.

The previous case concerns to "point" bunches. The method of increase of transformation ratio is offered in [6] and researched in [7-9] for the case of bunches of finite dimensions. In this case the transformation ratio grows as 2N in the case of small amplitudes. N is the number of bunches in sequence. For this it is necessary that the bunches, the length of each bunch equals half of wavelength, are placed after one and a half of wavelength and are slowed down by fields, identical to field in which the first bunch is slowed down. The charge of first bunch is the smallest one. The charges of bunches should grow along sequence as 1:3:5:7 et al. Thus accelerating wakefield grows as

$$E_N = NE_1, \tag{1}$$

where E_1 is the wakefield, excited by first bunch. The transformation ratio equals

$$T_N = 2N\,. \tag{2}$$

The methods of the transformation ratio increase are researched by numerical simulation, using 2.5-code LCODE [10], in this paper.

Increase of the transformation ratio has been researched in nonlinear regime. First successful investigation of transformation ratio increase in nonlinear regime was performed in [7]. Also increase of the transformation ratio has been researched in this paper in combined case. In combined case the first part

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(ten bunches) of sequence is shaped on charge and second part of sequence is in phased regime. Namely, the charges of first ten bunches of sequence grow according to 1:3:5:7:9:11:13:15:17:19 and next finite number of identical ≪point≫ bunches are placed in phases, where wakefield, excited by previous bunches, equals zero.

2. *2.5D* - NUMERICAL SIMULATION OF WAKEFIELD EXCITATION IN PLASMA AND ENERGY TRANSFER

2.1. RESONANT SEQUENCE OF BUNCHES

Now we simulate at first known case [11] of resonant sequence (the repetition frequency of bunches equals to frequency of wakefield), when maximum wakefield is excited. We consider the wakefield excitation in plasma of density $n_0 = 10^{11}\ cm^{-3}$ by sequence of 49 bunches (Fig.1), lengths of which approximately equal 1/6 of wavelength. The bunches are placed in slowing down phases of wakefield. The radius of bunches equals 0.5cm, the maximum current equals 4.47A. Fiftieth accelerated bunch is placed in phase of accelerating wakefield (Fig.2). From Fig.2 one can see that in this case the coupling of bunches with longitudinal wakefield is maximum. The wakefield grows linearly with number of bunches.

From Fig.2 and Fig.3 one can see that the transformation ratio is small and approximately equals $T_E \simeq 1$.

2.2. SHIFT OF BUNCHES OF SEQUENCE ON PHASE

We consider now the shift of N=16 [8] "point" bunches (of length 0.3mm, radius 1.7mm) on phases relative to wave that they are getted approximately in wakefield, equal zero, excited by, previous bunches (Fig.4-6). Then bunches slow down approximately by identical wakefield, which they themselves excite (see Fig.5). Then $T_E \simeq 8$. It corresponds to $T_E = 2N^{1/2}$. One can see that the maximum possible transformation ratio $T_E \gg 2$ is obtained at used parameters.

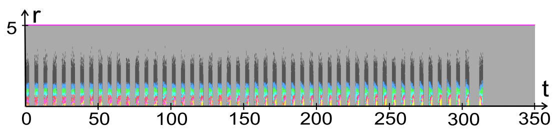

Fig.1. *Density distribution of sequence of electron bunches. r in cm, t is normalized on* ω_{pe}^{-1}

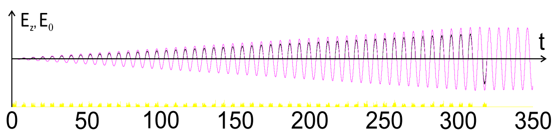

Fig.2. *The on-axis longitudinal electric wakefield* E_z *(red line), value, proportional to coupling rate* $E_0 = \int dr\, r\, E_z n_b / \int dr\, r\, n_b$ *of electron beam with* E_z *(black line), density of sequence of electron bunches (yellow)*

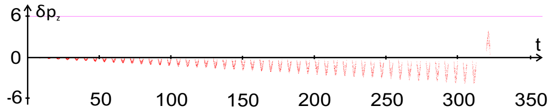

Fig.3. *Change of longitudinal momenta of bunches as they excite wakefield.* p_z *is normalized on* $m_e c$

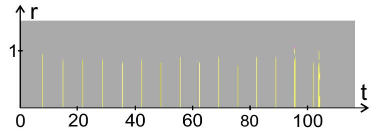

Fig.4. *Density distribution of sequence of electron bunches*

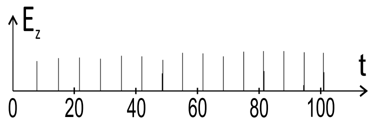

Fig.5. *The longitudinal electric wakefield* E_z *in regions of localization of electron bunches- drivers*

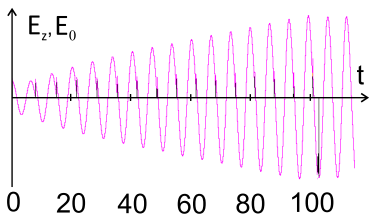

Fig.6. *The on-axis longitudinal wakefield* E_z *(red line),* E_z *in regions of localization of electron bunches (black)*

2.3. SHAPING OF BUNCHES OF SEQUENCE ON CHARGE

In [12,13] it has been obtained that single long bunch, density of which grows linearly along it, can provide the transformation ratio up to

$$T = 2\pi L_b/\lambda\,, \tag{3}$$

where L_b is the bunch length, λ is the wavelength.

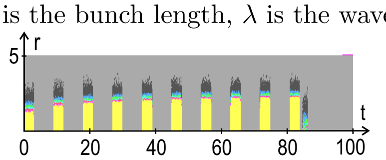

Fig.7. *Density distribution of sequence of electron bunches*

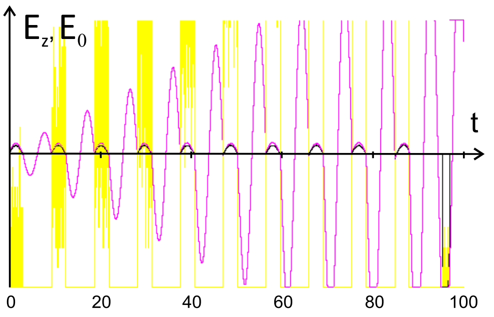

Fig.8. *The on-axis longitudinal wakefield E_z (red line), value, proportional to coupling rate of electron beam with E_z (black line), density of sequence of electron bunches (yellow)*

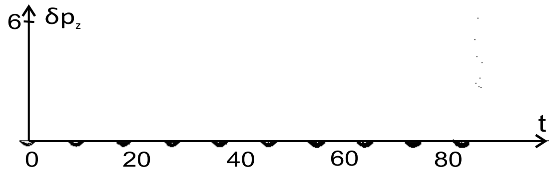

Fig.9. *Change of longitudinal momenta of bunches as they excite wakefield*

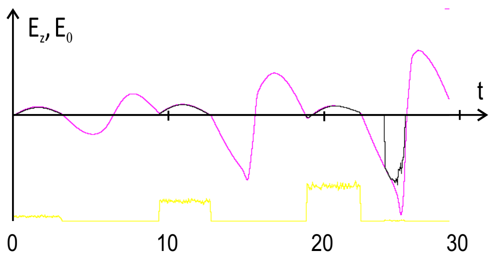

Fig.10. *The on-axis longitudinal wakefield E_z (red line), value, proportional to coupling rate of electron beam with E_z (black line), density of sequence of electron bunches (yellow)*

Now we consider shaping of charge of bunch sequence. We consider ten bunches with ratio of their charges 1, 3, 5, 7, 9, 11, 13, 15, 17, 19; 0.5, i.e. $Q_n = (2n-1)Q_1$, which are injected in plasma of density $n_0 = 10^{11}\ cm^{-3}$. The longitudinal coordinates of bunches equal $\xi_n = \xi_1 + 3\lambda(n-1)/2$. The bunch lengths equal $\lambda/2$. The radius of bunches and their maximum current equal $0.5\,cm$, $71.5\,A$. The fronts of bunches (rectangular in longitudinal direction and Gauss shape on radius) are placed in slowing down field, equal zero (Fig.7-9). In this case $T_E \simeq 20$; $T_E \simeq 2N$. Now we consider shaping of charges of bunch sequence in nonlinear regime. We take into account that in nonlinear wave regions of focusing force are wider than regions of defocusing force. We distribute three bunches (Fig.10-11) and select their charges that the fronts of bunches are getted in slowing down field, excited by previous bunches, equal zero and all of them are slowed down by identical fields.

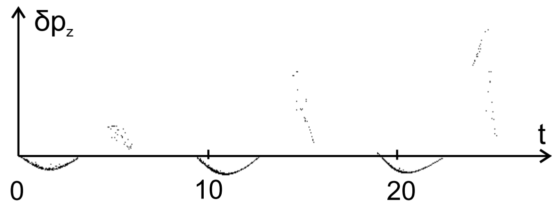

Fig.11. *Change of longitudinal momenta of bunches as they excite wakefield*

It has been shown by numerical simulation that approximately the bunch lengths, equal to lengths of regions of slowing down fields, and ratio of bunch densities, equal 0.25; 1; 1.73, corresponds to this case. Thus the transformation ratio equals $T_E \simeq 2.67$, 8, 12. $T_E \simeq 4N$ reaches after third bunch. This ratio of transformation ratios is larger than 2N. On energy loss the ratio of transformation ratios equals $T_W \simeq 2$, 6, 8, i.e. this ratio is larger than 2N but it is smaller than T_E.

Though in the case of shaping sequence the bunches are slowed down by identical fields, the focusing force, acting on bunches, grows quickly along sequence (Fig.12), and dependence $T_E = 2N$ is broken. In the case of small amplitudes the maximum transformation ratio reaches for sequence of N=10 bunches with charge shaping.

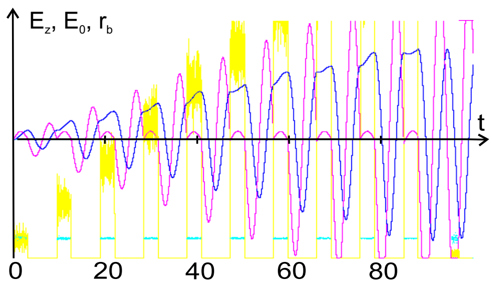

Fig.12. *The on-axis longitudinal wakefield E_z (red line), value, proportional to coupling rate of electron beam with E_z (black line), density of sequence of electron bunches (yellow), middle radii of bunches (light blue), focusing force F_r (blue)*

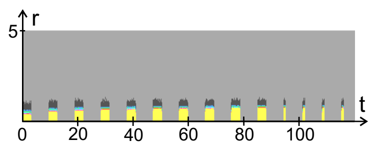

Fig.13. *Density distribution of sequence of electron bunches*

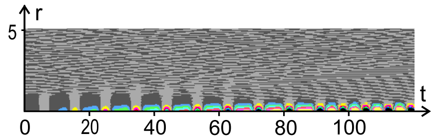

Fig.14. *Density distribution of plasma electrons*

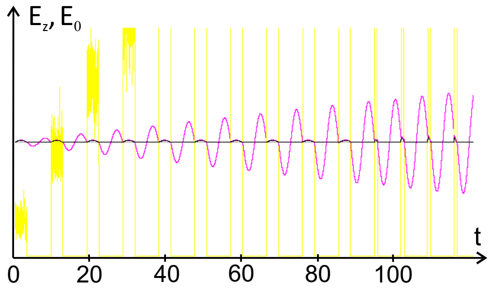

Fig.15. *The on-axis longitudinal wakefield E_z (red line), value, proportional to coupling rate of electron beam with E_z (black line), density of sequence of electron bunches (yellow)*

At number of bunches $N \geq 10$ one can use the combined sequence, namely, sequence of ten shaped on charge bunches and next bunches are shifted on phases (Fig.13-17).

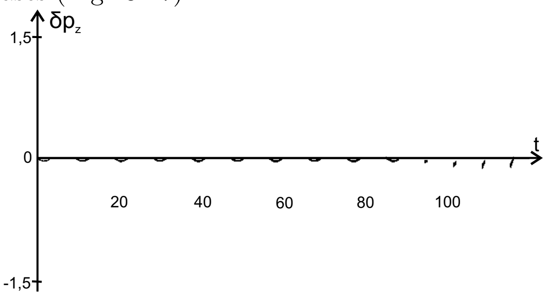

Fig.16. *Change of longitudinal momenta of bunches as they excite wakefield*

3. CONCLUSIONS

It has been shown that the sequence of bunches, shaped on charge, leads to transformation ratio in nonlinear regime considerably larger than in linear regime. For long sequences useful to use combination of ten bunches, shaped on charge and next bunches, shifted on phases.

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КОЭФФИЦИЕНТ ТРАНСФОРМАЦИИ ПРИ ВЗАИМОДЕЙСТВИИ ДЛИННОЙ ПОСЛЕДОВАТЕЛЬНОСТИ ЭЛЕКТРОННЫХ СГУСТКОВ С ПЛАЗМОЙ

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

Эффективность возбуждения кильватерного поля в плазме последовательностью электронных сгустков определяется коэффициентом трансформации. Используя код LCODE, проведено $2d3v$-численное моделирование и исследован коэффициент трансформации для длинной последовательности электронных сгустков. Рассмотрены случаи смещения сгустков по фазе относительно возбуждаемой волны, профилирования плотности сгустков в нелинейном режиме и комбинированный случай, которые приводят к величинам коэффициента трансформации, существенно превышающим предельное значение 2.

КОЕФІЦІЄНТ ТРАНСФОРМАЦІЇ ПРИ ВЗАЄМОДІЇ ДОВГОЇ ПОСЛІДОВНОСТІ ЕЛЕКТРОННИХ ЗГУСТКІВ З ПЛАЗМОЮ

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

Ефективність збудження кільватерного поля в плазмі послідовністю електронних згустків визначається коефіцієнтом трансформації. Використовуючи код LCODE, проведено $2d3v$-числове моделювання і досліджено коефіцієнт трансформації для довгої послідовності електронних згустків. Розглянуті випадки зміщення згустків по фазі відносно збуджуваної хвилі, профілювання густини згустків у нелінійному режимі і комбінований випадок, які приводять до величин коефіцієнту трансформації, значно перевищуючих значення 2.