WAKE WAVE EXCITED BY THE SEQUENCE OF RELATIVISTIC ELECTRON BUNCHES: INITIAL STAGE

O.K. Vynnyk, I.O. Anisimov

Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

Email: alexander.vynnyk@gmail.com

This report is devoted to the study of initial stage of the wake wave excited by the sequence of the short relativistic electron bunches. We used the modernized simulation package described in and based on the particle-in-cell method. Spectra for electromagnetic field components were obtained for the single bunch and both for non-resonant and resonant bunches` sequences.

PACS: 29.17.+w;41.75.Lx

INTRODUCTION

A problem on plasma wake fields excitation by electron bunches and reverse influence of these wake fields on the bunch dynamics is very interesting. This effect can be used to construct the next generation of compact particle accelerators. Possibilities to excite wake waves in plasmas (e.g., [1, 2]) and dielectrics [3, 4] were discussed. Electron on ion bunches or sequences of such bunches [5-10], as well as ultra-short powerful laser pulses [11] can be an instrument for wake waves excitation. The possibility to construct the plasma wake waves' accelerators was confirmed experimentally (e.g., [12]). A problem on plasma wake field excitation is also interesting due to the possibility of the inhomogenous plasma diagnostics via transition radiation of charged particles and bunches [13].

This paper is dedicated to the study of the initial stage of the plasma wake field excitation by sequence of short relativistic electron bunches. The study was carried out via computer simulation using PIC method on modernized package, described in [14]. Similar problem for late stages was considered in [17-22].

1. SIMULATION PACKAGE AND PARAMETERS SELECTION

Simulation was performed using electromagnetic code PDP3, modernized for the bunch sequence and multithread execution. PDP3 is 2.5D (2d3v) electromagnetic code in cylindrical geometry, which used PIC method. PDP3 uses FDTD method for solving Maxwell equations and classical Boris pusher for calculation of particles position and velocity, modified for relativistic velocities (relativistic Boris pusher) and cylindrical geometry.

The simulation was carried out for the cylindrical volume of the low temperature plasma. Sequence of homogenous disk shaped electron bunches is injected along the system axis (Fig. 1). An interval between bunches was varied, but the corresponding repetition frequency remained close to the frequency of plasma oscillations. Simulation model is axially symmetric. Macroparticles were considered as a rings of certain radius with the center that coincides with cylinder axis. As described model simulates interaction of sequence of electron bunches with plasma, we chose parameters with respect to real laboratory experiments with "Almaz-2" electron accelerator [15]. Plasma density was 10^{11} cm^{-3}, bunches' density – $5\cdot10^{10}$ cm^{-3}, bunches' duration – $2\cdot10^{-11}$s. Initial bunch velocity is $2.8\cdot10^{8}$ m/s, and its radius is 0.5 cm. Simulation time is 10^{-8} s. Perfectly matched layer [16] was used for the walls of the simulation volume for the suppression of numerical instabilities.

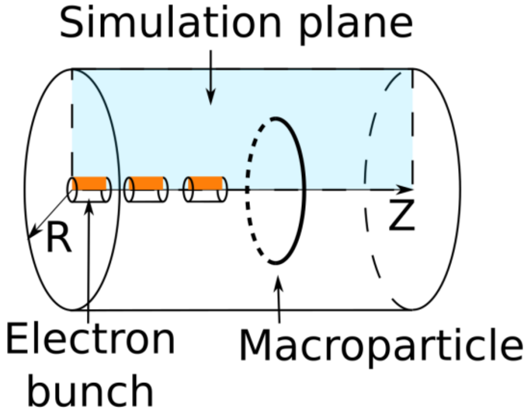

Fig. 1. Generic scheme of simulation

2. SINGLE BUNCH DYNAMICS

Single bunch injection was used to study the plasma eigenmodes. Single electron bunch excites wake wave package during injection. Components of electric field E_r and E_z were exited in antiphase, as expected (Fig. 2). Gradual longitudinal and radial defocusing of the bunch took place due to the reverse wake field influence on the bunch. The excited package had quasi-harmonic shape. The possible source of perturbations is the numerical noise. Nevertheless, spectra maxima for both field components coincide ($2.3\cdot10^{9}$ Hz) but differ from the electron plasma frequency.

3. NON-RESONANT BUNCH SEQUENCE

Injection of the electron bunches' sequence to plasma was also studied. The repetition frequency was equal to the electron plasma frequency $2.3\cdot10^{9}$Hz.

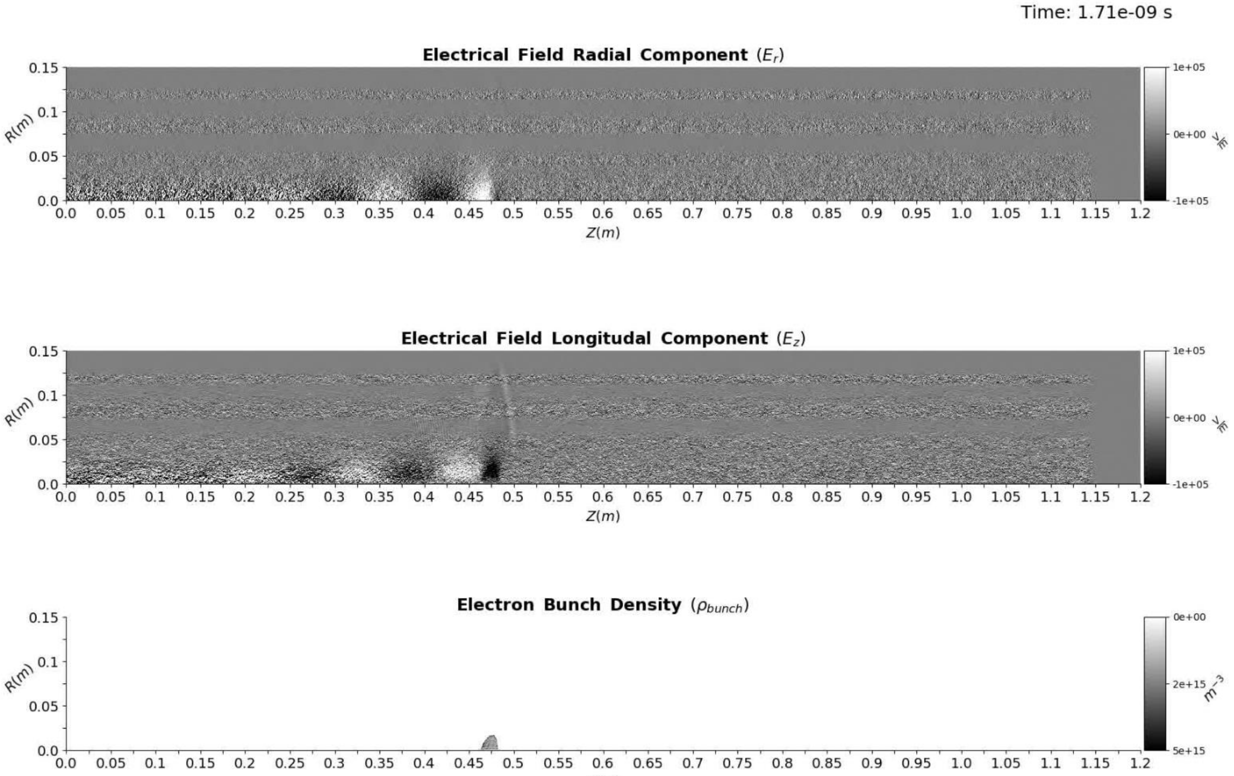

Fig. 2. Electrostatic field components and electron bunch density (single-bunch case)

Electric field excited in such system contains the eigen field of the bunches (mainly longitudinal component) and field of the excited wake wave (mainly radial component). Eigen field of the bunches near injector did not vary substantially with time (Fig. 3). Far from injector the bunches' defocusing moved to the decrease of their eigen field.

Both field components have the discrete spectra. Distance between lines correspond to the bunches' repetition frequency. Spectra contain the low frequency part with maxima at the zero frequency and the high frequency part with substantially lower intensity. The high frequency part of spectra hypothetically corresponds to numerical instability. The low frequency part at the vicinity of zero frequency corresponds to plasma noise.

Both spectra contain clear maxima at $2.8 \cdot 10^9$Hz (repetition frequency of the bunch sequence) and its harmonics (Fig. 4). It is also present in the magnetic field spectrum (azimuthal component). It is caused by the field of the bunches' sequence.

Lower maxima at the frequency $2.3 \cdot 10^9$ Hz and their second harmonic were also observed in the spectra of electric field components. This frequency coincides with the frequency excited by the single bunch. It was not observed in the magnetic field spectrum. This component can be interpreted as the wake wave excited by the bunches' sequence.

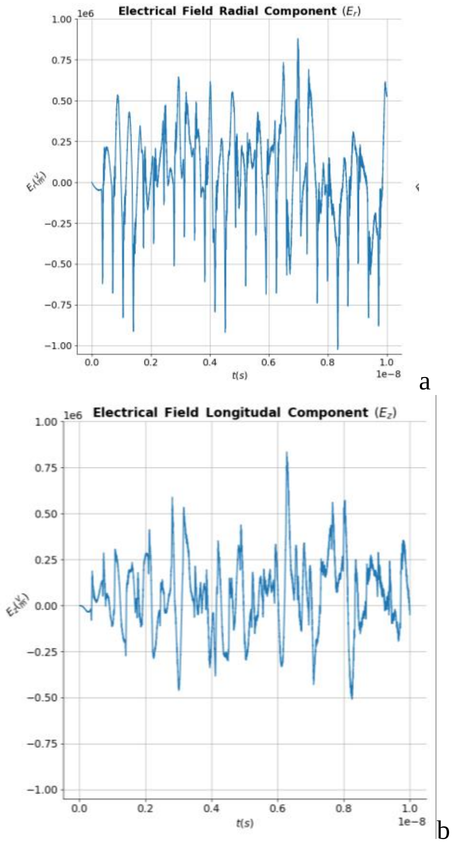

Fig. 3. Electrical field components at probe point r=1cm (a) z=10 cm (b) (non-resonant case)

4. RESONANT BUNCH SEQUENCE

The next simulation was carried out for the bunches' repetition frequency equal to the wake wave frequency. Defocusing of electron bunches was more intensive relatively to the previous case. The bunches' field disappeared at the distance 60…80 cm from the injector (in the previous case this distance was 70…90 cm). On the other hand, substantial growth of the spectral component at the repetition frequency was observed

(Fig. 5) relatively to the previous case (from 1.0 to 1.4 a.u. for the longitudinal field and from 1.5 to 4.2 a.u. for the transversal field). Mechanism of this growth can be interpreted as Cherenkov resonant excitation of the wake wave by the sequence of electron bunches.

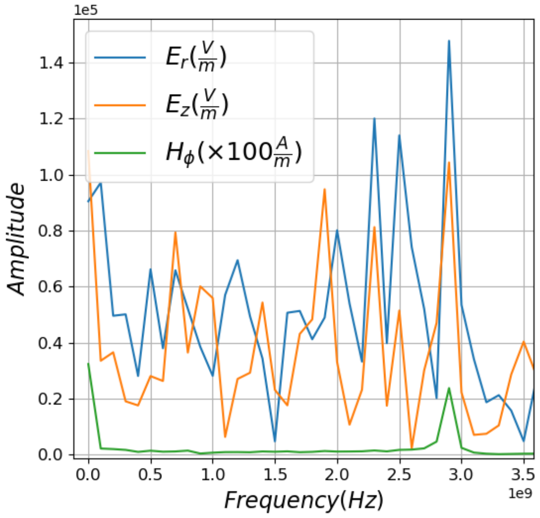

Fig. 4. Electric and magnetic field spectra (non-resonant case) with local maxima at $2.3\cdot10^9$ Hz (for electric field components) and $2.8\cdot10^9$ Hz (for all)

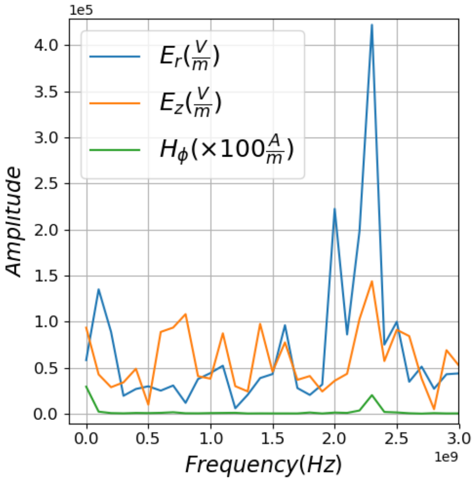

Fig. 5. Electrical and magnetic field spectra (resonant case) with local maxima at $2.3\cdot10^9$Hz Maxima amplitude grows up to 4.2 and 1.5 a.u

CONCLUSIONS

Simulation of the initial stage of the wake wave excitation by non-resonant and resonant sequence of the relativistic electron bunches.

1. For non-resonant case the electric field spectrum contains the components corresponding to the bunch sequence and to the wake wave. Magnetic field spectrum contains only the components corresponding to the bunch sequence.
2. Substantial growth of the excited field was observed for the case when the repetition frequency of the bunches' sequence coincides with the frequency of the field excited by the single bunch. On the other hand, the bunches' defocusing was more intensive in this case.

Further simulation will be devoted to the study of the mechanism of the wake wave amplitude saturation for the case of the resonant bunches' sequence.

REFERENCES

1. P. Chen, J.M. Dawson, R.W. Huff, T. Katsouleas // *Phys. Rev. Lett*. 1985, v. 54, p. 693.
2. M.J. Hogan, T.O. Raubenheimer, A. Seryi, P. Muggli, T. Katsouleas, C. Huang, W. Lu, W. An, K.A. Marsh, W.B. Mori, C.E. Clayton, C. Joshi // *New J. Phys*. 2010, v. 12, 5, p. 055030.
3. A. Tremaine, J. Rosenzweig, P. Schoessow // *Phys. Rev. E*. 1997, v. 56, 6, p. 7204.
4. V.I. Maslov, I.N. Onishchenko // *Problems of Atomic Science and Technology. Ser. "Plasma Physics"*. 2013, № 4, p. 69.
5. A. Bazzania, M. Giovannozzic, P. Londrillob, S. Sinigardia, G. Turchettia // *C. R. Mecanique*. 2014, v. 342, p. 647.
6. A. Caldwell, K.V. Lotov // *Phys. Plasmas*. 2011, v. 18, p. 103101.
7. K.V. Lotov // *Phys. Plasmas*. 2013, v. 20, p. 083119.
8. L. Yi, B. Shen, K. Lotov, L. Ji, X. Zhang, W. Wang, X. Zhao, Y. Yu, J. Xu, X. Wang, Y. Shi, L. Zhang, T. Xu, Zh. Xu. Accelerators and Beams // *Physical Review Special Topics*. 2013, v. 16, p. 071301.
9. K.V. Lotov, V.I. Maslov, I.N. Onishchenko, I.P. Yarovaya // *Problems of Atomic Science and Technology. Ser. "Plasma Physics"*. 2013, v. 4, p. 73.
10. J. Vieira, Y. Fang, W.B. Mori, L.O. Silva, P. Muggli // *Phys. Plasmas*. 2012, v. 19, p. 063105.
11. T. Tajima, J. M. Dawson // *Phys. Rev. Lett*. 1979, v. 43, p. 267.
12. I Blumenfeld, C.E. Clayton, F.J. Decker, M.J. Hogan, C. Huang, et al. // *Nature*. 2007, v. 445, p. 741.
13. I.O. Anisimov, K.I. Lyubich // *J. Plasma Phys*. 2001, v. 66, p. 157.
14. Yu.M. Tolochkevych, T.Eu. Litoshenko, I.O. Anisimov // *Journal of Physics: Conference Series* 2014, v. 511, p. 012001.
15. V.A. Kiselev, A.F. Linnik, V.I. Mirny, et al. // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration*". 2008, v. 6, p. 73.
16. J. Berenger // *Journal of Computational Physics*. 2004, v. 114, p. 185.
17. A.K. Berezin, Ya.B. Fainberg, V.A. Kiselev, A.F. Linnik, V.V. Uskov, V.A. Balakirev, I.N. Onishchenko, G.L. Sidel'nikov, G.V. Sotnikov // *Plasma Physics Reports*. 1994, v. 20, p. 596.
18. K.V. Lotov, V.I. Maslov, I.N. Onishchenko, E.N. Svistun // *Plasma Physics and Controlled Fusion*. 2010, v. 52, p. 065009.
19. K.V. Lotov, V.I. Maslov, I.N. Onishchenko, E.N. Svistun // *Problems of Atomic Science and Technology. Series "Plasma Physics"*. 2008, v. 6, p. 114.
20. K.V. Lotov, V.I. Maslov, I.N. Onishchenko // *Problems of Atomic Science and Technology. Series "Plasma Physics"*. 2010, №. 6, p. 103.

21. K.V. Lotov, V.I. Maslov, I.N. Onishchenko, E.N. Svistun // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2010, № 2, p. 122.

22. V.I. Maslov, I.N. Onishchenko, I.P. Yarovaya // *Problems of Atomic Science and Technology. Series "Plasma Physics"*. 2014, №. 6, p. 101.

Article received 30.09.2018

КИЛЬВАТЕРНАЯ ВОЛНА, ВОЗБУЖДЕННАЯ ПОСЛЕДОВАТЕЛЬНОСТЬЮ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОННЫХ СГУСТКОВ: НАЧАЛЬНАЯ СТАДИЯ

А.К. Винник, И.А. Анисимов

Статья посвящена изучению начальной стадии возрастания кильватерной волны, возбужденной последовательностью коротких релятивистских электронных сгустков. Используется модернизированный программный пакет моделирования методом крупных частиц. Получены спектры компонент электромагнитного поля для одиночного сгустка, для нерезонансной и резонансной последовательностей сгустков.

КІЛЬВАТЕРНА ХВИЛЯ, ЗБУДЖЕНА ПОСЛІДОВНІСТЮ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОННИХ ЗГУСТКІВ: ПОЧАТКОВА СТАДІЯ

О.К. Винник, І.О. Анісімов

Стаття присвячена вивченню початкової стадії зростання кільватерної хвилі, збудженої послідовністю коротких релятивістських електронних згустків. Використовується модернізований програмний пакет моделювання методом крупних частинок. Отримано спектри компонент електромагнітного поля для одиночного згустка, для нерезонансної та резонансної послідовностей згустків.