INFLUENCE OF THE EXTERNAL MAGNETIC FIELD ON THE CYLINDRICAL ELECTRON BUNCH INJECTED INTO PLASMA

M.A. Shcherbinin, I.O. Anisimov

Taras Shevchenko National University of Kyiv, Ukraine

E-mail: ioa@univ.kiev.ua

Dynamics of the initially cylindrical electron bunch injected into plasma along the external magnetic field was studied via PIC simulation. Time evolution of the spatial distributions of electric field, magnetic field and bunch electron density is analyzed. The influence of the external magnetic field on the bunch shape and wake field excitation is treated. The correlation between azimuthal magnetic field distribution and wake field shape is discussed.

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INTRODUCTION

Study of electron bunches' and beams' dynamics in plasma is important for plasma electronics, in particular, for construction of the compact wake field accelerators of electrons. Magnetic field is used for plasma confinement and beams' control, therefore the study of electron bunch dynamics in plasma with the external magnetic field appears to be a topical problem. The objective of this paper is to study the influence of the longitudinal magnetic field on the dynamics of cylindrical electron bunch injected into the homogeneous plasma along magnetic field using PIC simulation via 2.5 D electromagnetic code [1].

While the electron bunch enters plasma, its forefront excites the wake wave, so the bunch moves in the wake field [2]. Due to this field electrons form the microbunches' sequence [3]. Further increase of the wake field amplitude is caused both by the longitudinal focusing and Cherenkov resonance (if the bunch is significantly longer then the wake wave) [4].

For the bunch of finite radius the wake field has a radial component and its sign varies along the bunch. Radial focusing and defocusing of the bunch is caused by this component. Without magnetic field the average bunch density rapidly decreases far from injector due to the particles' radial defocusing, and the wake wave is no more excited. Strong magnetic field ($\omega_{ce} \geq \omega_{pe}$, where ω_{ce} and ω_{pe} are electron cyclotron and Langmuir frequencies of the ambient plasma, respectively) suppresses the radial defocusing of the bunch. Consequently the wake wave amplitude grows far from injector, compared to its value without magnetic field.

Simulation is carried out for the following parameters: length of the cylindrical camera is 1.5 m; it's radius is 0.2 m; bunch is injected along it's axis. Plasma density is $5 \cdot 10^8 cm^{-3}$, ion and electron temperatures are 0.2 eV and 2 eV, respectively. The bunch initial radius is 0.02 m; it's initial velocity is $3 \cdot 10^7$ m/s; and its duration is $2 \cdot 10^{-8} s$.

1. SIMULATION PACKAGE

The simulation was carried out using the PIC method applied to the cylindrical geometry [1] – particles and cells had a shape of rings. Simulation program deals with 2.5 dimensions: particles have two cordinates (radial and axial) and three components of velocity (including azimuthal component); electric and magnetic fields and electric current also have three components. The simulation algorithm includes the charge weighting (using the large particles' coordinates) – procedure is similiar to the 2D case. Current weighting (using the large particles velocities) is the first order weighting used in program. Large particles' cross-section has the square shape in the plane (r,z). So called Courant condition must be sutisfied: maximum distance that particle can passes during one time step should not exceed the half cell size. That's why the particle can give the contribution to 4, 7 or 10 sides during its motion per time step. It's also necessary to consider that large particle charge density is a function of its radius, in the contrast to the case of rectangular geometry where it remains constant. Maxwell equations are solved in order to obtain the field values. Each point where electric field is calculated is surrounded by four points where magnetic field is calculated. For each point where magnetic field is calculated situation is the same. The difference schemes for E and H are described in [4].

2. WAKEFIELD DISTRIBUTION AND THE BUNCH SHAPE

The output of simulation is the set of distributions of charge, current and components of electrical and magnetic fields in the half-plane of system axis.

Fig. 1 shows the spatial distribution of the electron bunch density for various values of the parameter $a = \omega_{ce}/\omega_{pe}$ at the time point $\omega_{pe}t = 50$. It is clear from this figure that the bunch radial defocusing substantially reduces for a> 0.15. Fig. 2 demonstrates the spatial distribution of the wake field radial component for *a*=0.15. One can see that area of the wake wave excitation grows in presence of the magnetic field. Fig. 3 represents the spatial distribution of the wake field radial component near the systems' axis at the same time point for various magnetic fields. The wave excited by beam weakly depends on magnetic fields at least at the distance less than 70 cm. At larger distances the amplitude grows with the magnetic field increase. The measured length of the wake wave

(13 cm) corresponds to the Langmuir wave in the background plasma moving with the bunch velocity. Increase of the longitudinal size of the wake field area can be explained by suppression of the bunch radial defocusing by the longitudinal magnetic field, and, as result, the slowdown of the bunch density decrease. Consequently the electron bunch moving along the strong magnetic field can excite the wake field at the longer distance along its trajectory.

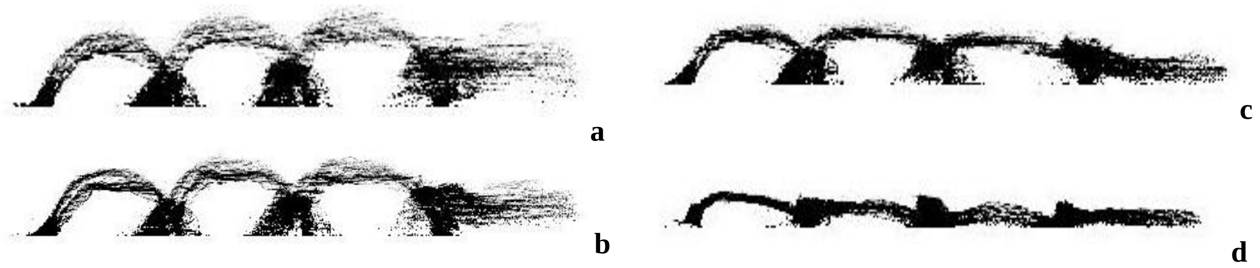

Fig. 1. The bunch charge density distributions in the r-z plane for time point t=40 ns ($\omega_{pe}t=56$) and a=0 (a); a=0.03 (b); a=0.06 (c); a=0.12 (d)

Fig. 2. Spatial distribution of the wake field radial component a – $B_z=0$; b – $B_z=1$ mTl (a=0.12)

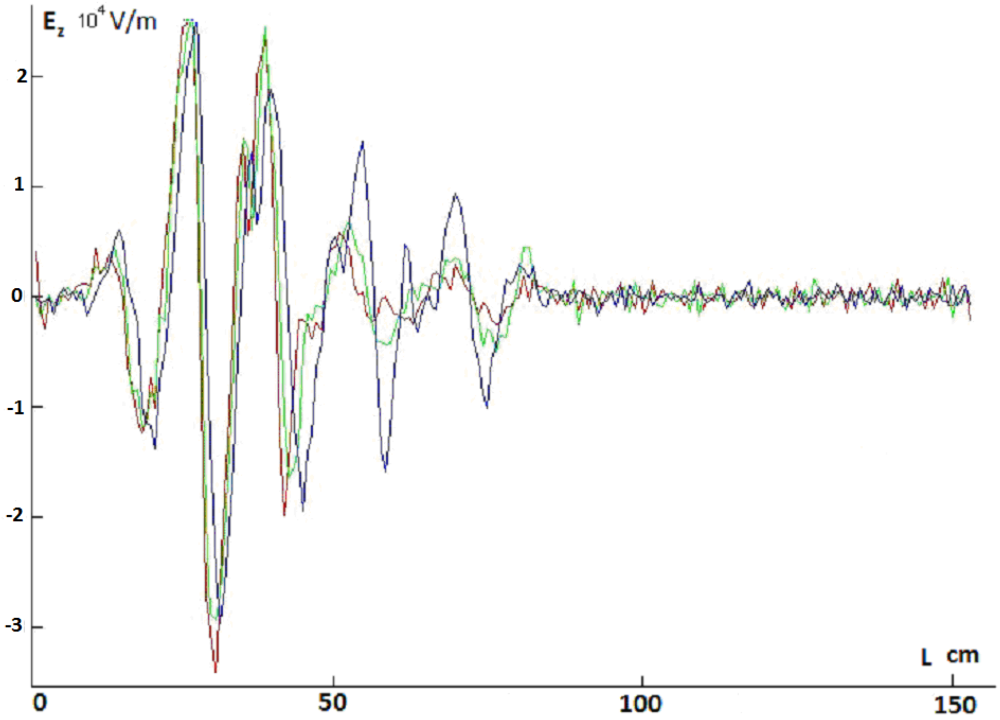

Fig. 3. Spatial distribution of the wake field radial component near the systems' axis; red – B=0; green – B=1 mT; blue – B=2 mT

3. DISTRIBUTION OF AZIMUTHAL MAGNETIC FIELD AND ELECTRONS OF THE BUNCH

Fig. 4 shows the spatial distributions of the azimuthal magnetic field, longitudinal electric field and electron bunch density without external magnetic field for two different time points. Comparing two graphs one can see that spatial distribution of electron bunch density has several peaks which appear to be a microbunches' sequence. At the later time point peaks become lower due to the radial defocusing of the bunch. The azimuthal magnetic field has local maxima corresponding to the bunch density peaks – larger bunches' current produces

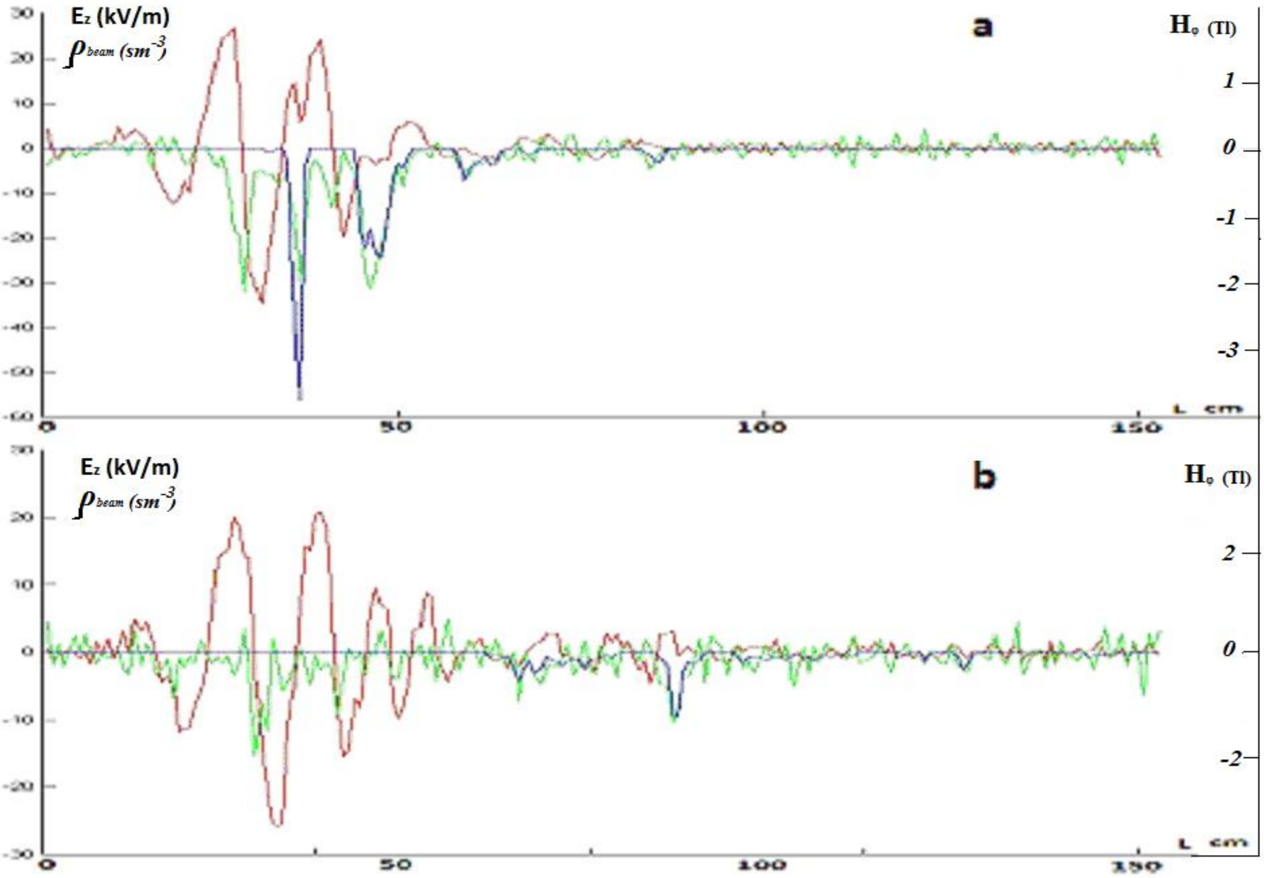

Fig. 4. Spatial distributions of the azimuthal magnetic field, longitudinal electric field and electron bunch density. $B_z = 0$; a – time: 30 ns; b – time: 50 ns; Red – (E_z /1000 (V/m)); Green – (H_φ x15(Tl)); Blue – (ρ_{beam} x 10^6 (m^{-3}))

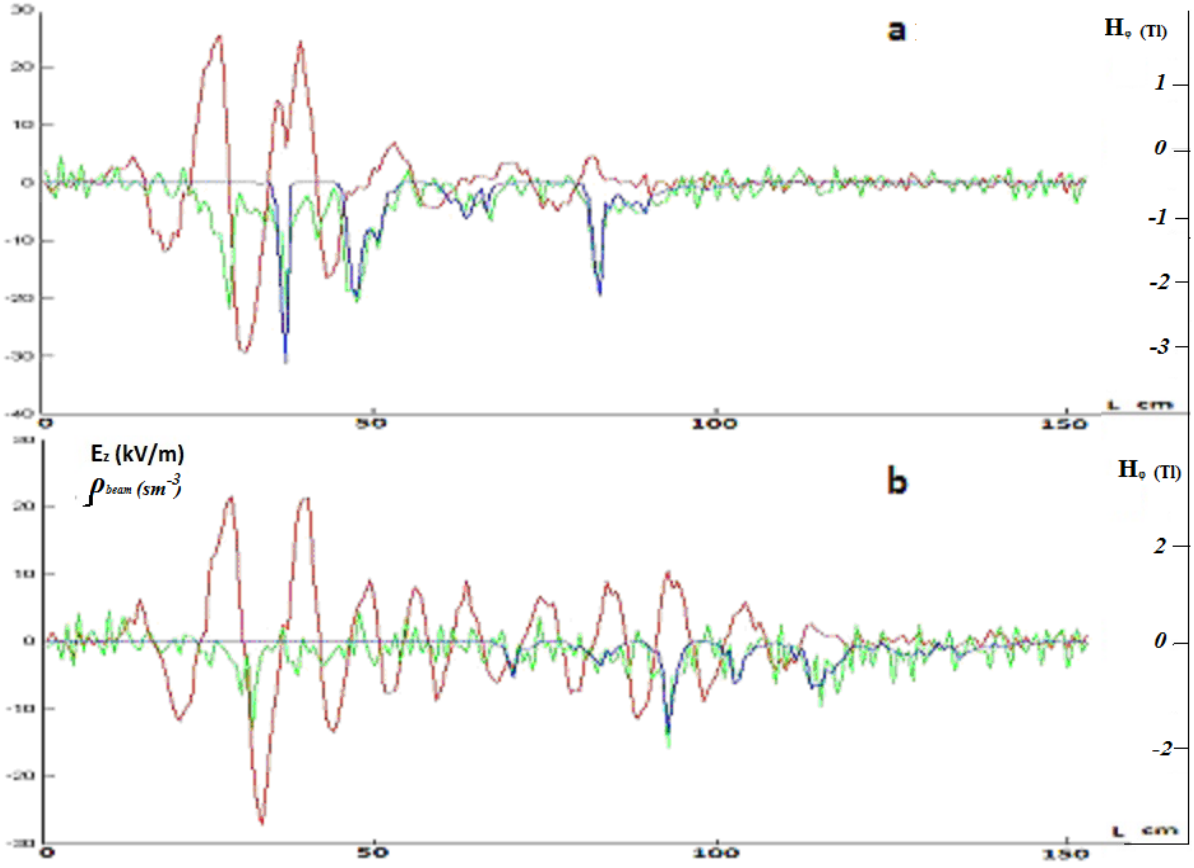

Fig. 5. Spatial distributions of the azimuthal magnetic field, longitudinal electric field and electron bunch density. B_z = 1 mTl; a – time: 30 ns; b – time: 50 ns; Red – (E_z /1000 (V/m)); Green – (H_φ x15(Tl)); Blue – (ρ_{beam} x 10^6 (m^{-3}))

stronger magnetic field at these points. Also one can see that magnetic field spatial distribution has more peaks in the area bunch has passed, despite there's no bunch current in that area. These peaks are shifted with respect to maxima of the longitudinal electric field for the quarter of the wakewaves' length. This fact allows to conclude, that wakewave creates the azimuthal magnetic field due to the Ampere's circuital law, and it's value is of the same order with the field excited by the electron bunch.

Fig. 5 shows the same distributions as see Fig. 4 but for the case of the longitudinal external magnetic field 1 mTl for two different time points. From the graphs for electron bunch density distribution one can see that peaks which correspond to the microbunches' sequence remain higher, and also keep the shape better then without external magnetic field. It is a result of suppressing of the radial defocusing of the bunch by the longitudinal magnetic field – it increases the bunch density near the system axis. The azimuthal magnetic field distribution contains the peaks created both by bunches' current and wake wave field. In some areas superposition of magnetic fields excited by the bunch and by the wake wave can take place.

CONCLUSIONS

1. The longitudinal magnetic field suppresses radial defocusing of electron bunch, injected along its lines of force, in plasma, if the electronic cyclotron frequency is the same or higher degree then electron plasma frequency. The result is an increasing of the amplitude of the wakefield wave with the distance from the injector.
2. Analysis of distributions of the azimuthal magnetic field in plasma leads to the conclusion that the background plasma current produced by the wake wave is of the same order with the microbunch current.
3. The presence of longitudinal magnetic field makes the division of initial bunch on microbunches more clear-cut near the system axis at later time points.

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ВЛИЯНИЕ ПРОДОЛЬНОГО МАГНИТНОГО ПОЛЯ НА СГУСТОК ЭЛЕКТРОНОВ ЦИЛИНДРИЧЕСКОЙ ФОРМЫ, ДВИЖУЩИЙСЯ В ПЛАЗМЕ

Н.А. Щербинин, И.А. Анисимов

С помощью численного моделирования методом частиц в ячейках исследуется динамика сгустка электронов, изначально имеющего форму цилиндра, влетающего в плазму в присутствии продольного внешнего магнитного поля. Анализируются изменения пространственных распределений электрического и магнитного полей, а также плотности электронов в сгустке. Обсуждается влияние продольного магнитного поля на форму сгустка и возбуждение кильватерной волны. Исследуется зависимость между формой сгустка, полем кильватерной волны и распределением азимутальной составляющей магнитного поля.

ВПЛИВ ПОЗДОВЖНЬОГО МАГНІТНОГО ПОЛЯ НА ЗГУСТОК ЕЛЕКТРОНІВ ЦИЛІНДРИЧНОЇ ФОРМИ, ЩО РУХАЄТЬСЯ В ПЛАЗМІ

М.А. Щербінін, І.О. Анісімов

За допомогою чисельного моделювання методом частинок у комірках досліджується динаміка згустка електронів, що початково має циліндричну форму, та влітає в плазму у присутності зовнішнього поздовжнього магнітного поля. Аналізуються зміни просторового розподілу електричного та магнітного полів, а також густини електронів у згустку. Обговорюється вплив зовнішнього магнітного поля на форму згустка та збуджувану кільватерну хвилю. Показана залежність між формою згустка, полем кільватерної хвилі та розподілом азимутальної складової магнітного поля.