TO THE MECHANISM OF INSTABILITY OF CYLINDRICAL RELATIVISTIC ELECTRON BEAM IN PLASMA

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The instability of relativistic electron beam of finite radius in plasma caused by predominantly transversal dynamics of electrons is investigated. The formation of a sequence of short relativistic electron bunches from a long bunch including shaped one is 2d3v-simulated.

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1. INTRODUCTION

The essence of beam-plasma instability [1] in 1D-consideration consists in selfconsistent exponential growth of plasma oscillations amplitude and longitudinal bunching of the charged particle beam. For relativistic electron beam both in linear [2,3] and nonlinear theory [4] the main mechanism of the instability is also longitudinal bunching. Meanwhile for beams of finite radius in 2D-consideration transversal dynamics of beam particles (focusing/defocusing) should be taken into account. Moreover in relativistic case (relativistic factor of the beam γ_b>>1) due to the asymmetry of transversal and longitudinal masses $m_{||}=m_0\gamma_b<<m_\perp=m_0\gamma_b^3$, longitudinal dynamics in excited fields occurs "frozen" and transversal dynamics becomes predominant. For cylindrical relativistic electron beam radial focusing/defocusing leads to longitudinal bunching, which exceeds bunching by longitudinal component of excited field. More bunched beam higher plasma field is excited. Thus feedback providing instability development is mainly based on radial dynamics of beam electrons. It means that linear increment and nonlinear saturation of the instability will differ from ones obtained in [2-4].

In [2] mass asymmetry influence on beam-plasma instability was taken into account in 1D consideration and it was only shown that maximum increment of the instability takes place for $k_r>>k_z$. In [5] 2D consideration of finite radius beam instability was performed but beam radius was fixed. Appearance of goffer on nonfixed radius beam due to the instability was studied in [6] but it is not considered as an instability mechanism. Formation of a train of short ion bunches for wakefield accelerator by modulation of a long relativistic ion bunch using considered principle are investigated in [7].

In this paper the instability development of relativistic electron beam of finite radius in plasma due to transversal dynamics of beam electrons is simulated using LCODE [8]. Early [9] we have studied radial dynamics of bunches to clarify physics of synchronization of bunch repetition frequency and plasma frequency for the nonresonant train of bunches.

The mechanism of beam modulation through transverse electron dynamics allows formation of a sequence of short electron bunches for multibunch plasma wakefield accelerator [10-11]. Simulation results on "cutting" a long bunch into a train of short bunches by means transversal mechanism of relativistic beam-plasma instability.

2. INSTABILITY OF FINITE RADIUS RELATIVISTIC BEAM IN PLASMA

2.1. LOW DENSITY BEAM

To illustrate the instability development we begin with low density beam ($n_b<<n_0$, n_b and n_0 are beam and plasma densities). The results of simulation in the cylindrical coordinate system (*r,z*) are presented in Figs. 1-3 as plots of temporal evolution of beam and plasma densities, excited electric field, averaged field (field coupling with beam, averaged over cross-section), and radial force acting on beam electrons. All variables are dimensionless ($\tau=\omega_p t$, density is in units n_0, field is in units of wavebreaking field).

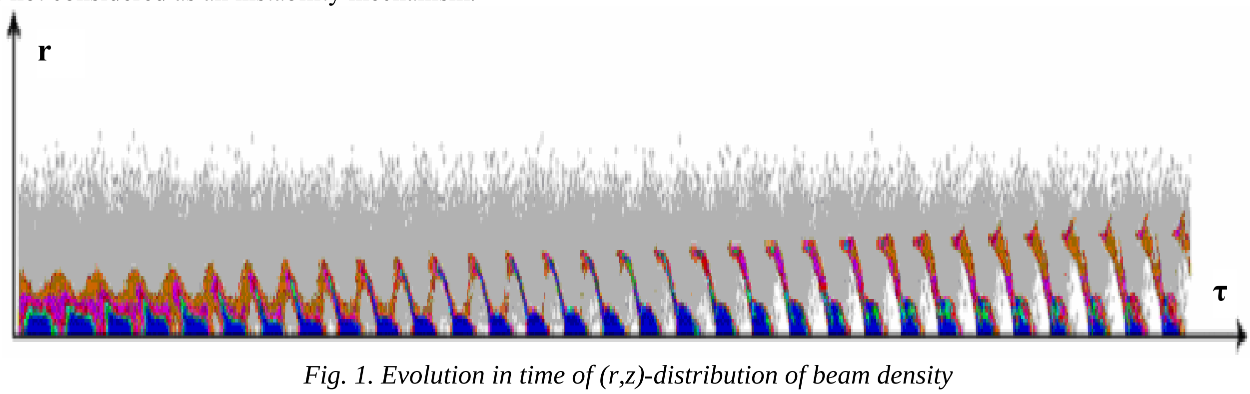

Fig. 1. Evolution in time of (r,z)-distribution of beam density

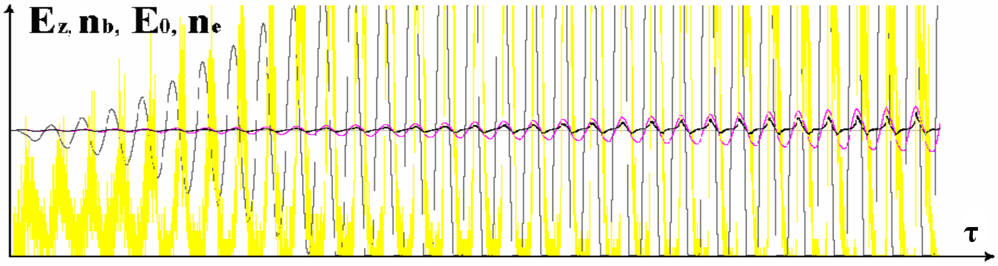

Fig. 2. Temporal development of on-axis beam density (yellow), longitudinal field E_z (red), the plasma density (grey) and coupling E_z with beam density, averaged over cross-section (black)

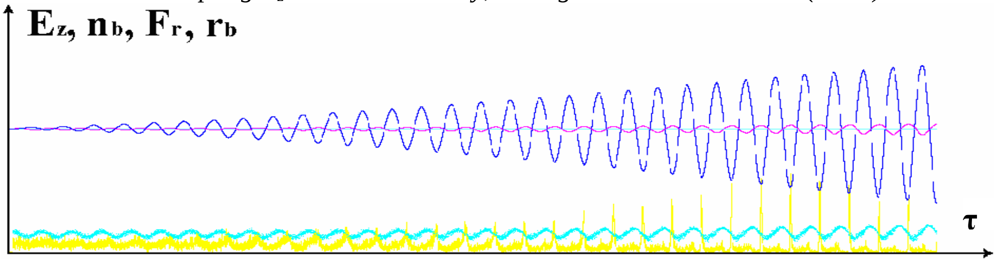

Fig. 3. Temporal development of beam density (yellow), longitudinal field E_z (red), radial force (dark blue), averaged beam radius (blue) on distance from axis, equal beam radius

From Figs. 1, 2 one can see the instability development accompanied by exponential growth of electric field and beam modulation. In Fig.2 it is seen plasma density modulation (gray line) in accordance with electric field growth. Black line (especially at late time) shows higher beam coupling with field, averaged over cross-section, in decelerating phase region. It means that beam predominantly loses its energy on electric field growth. Fig.3 demonstrates strong bunching of the beam (yellow colour) in the regions of focusing and decelerating phases of F_r and E_z, correspondingly. Note that the averaged radius of beam (blue line) is smaller in decelerating phases of E_z and in focusing phases of F_r. All of these results evidence typical features of 2D relativistic beam-plasma instability.

2.2. LONG SHAPED BUNCH

Now we consider the possibility to obtain ramped sequence of bunches for plasma wakefield acceleration by means of "cutting" long bunch with linearly growing density using considered instability. In Fig. 4 simulated ramped sequence of short bunches obtained from a long bunch is presented.

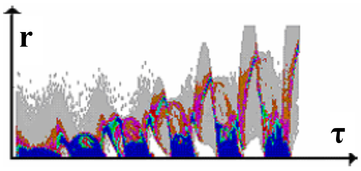

Fig. 4. Spatial (r, z) distribution of density of obtained electron bunches sequence

In Fig. 5 temporal evolution of longitudinal wakefield E_z (upper halves of oscillations correspond decelerated field) and averaged field E_0 (coupling E_z, with beam density, averaged over cross-section) are shown. From Fig. 5 one can see that E_0 is larger (smaller) in decelerating (accelerating) phases. From Fig. 6 one can see that radius of beam electrons is smaller (larger) in decelerating (accelerating) phases. It provides instability development and sequence of electron bunch formation.

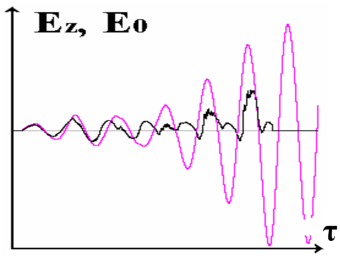

Fig. 5. On axis E_z (red) and coupling E_z, with beam density, averaged over cross-section (black)

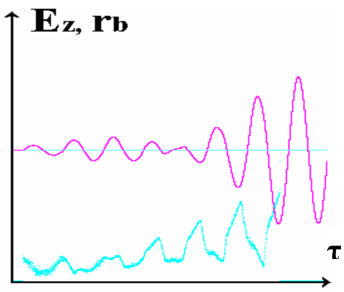

Fig. 6. E_z on distance from axis (red), equal beam radius, and averaged beam radius (blue)

2.3. HIGH DENSITY BEAM

We consider the instability development of dense beam, $n_b > n_0$, and formation of sequence of bunches through appearance of a chain of wakefield bubbles (bubble investigations see [8, 10, 11]). At first a goffered hollow channel is arisen and then a chain of bubbles is formed (Fig. 7).

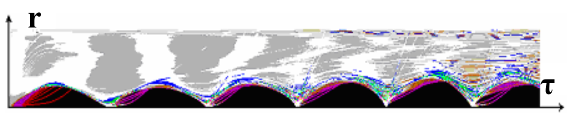

Fig. 7. Spatial (r, z) distribution of plasma electrons in the field of chain of the bubbles

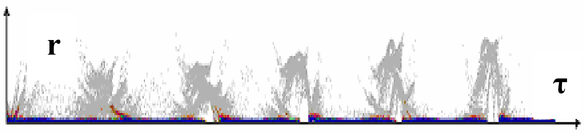

Fig. 8. The sequence of dense relativistic electron bunches, formed from dense beam

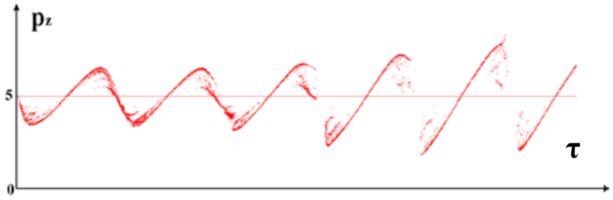

Fig. 9. Longitudinal momenta of bunches at excitation of chain of plasma electron bubbles

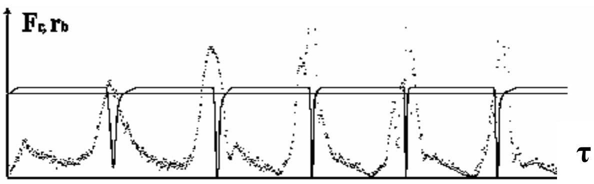

Fig. 10. The spatial distribution of averaged electron beam radius (dotted) and radial force, acting on dense electron beam (line)

In Fig. 8 the focused bunches and electrons thrown out by outburst like way are shown. During instability development the density of formed bunches increases due to focusing. The heads of bunches are decelerated and tails are accelerated (Fig. 9). Evolution of bunches formation is illustrated by Fig. 10 where the spatial distribution of radial force is shown. One can see that radial force in focusing regions approximately does not depend on longitudinal coordinate z that promotes formation of qualitative bunches. Regions of defocusing fill small place so beam loss is negligible.

3. CONCLUSIONS

New mechanism of beam-plasma instability for relativistic beam of finite radius is revealed and investigated by 2d3v-simulation. Basing on this mechanism the formation of a sequence of relativistic electron bunches from the beam of low and high densities has been considered. Formation of ramped sequence of short bunches from a long shaped bunch is investigated that is needed for enhancement of transformer ratio in plasma wakefield acceleration.

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МЕХАНИЗМ РАЗВИТИЯ НЕУСТОЙЧИВОСТИ ЦИЛИНДРИЧЕСКОГО РЕЛЯТИВИСТСКОГО ЭЛЕКТРОННОГО ПУЧКА В ПЛАЗМЕ

К.В. Лотов, В.И. Маслов, И.Н. Онищенко, М.С. Весновская

Исследовано развитие неустойчивости релятивистского электронного пучка конечного радиуса в плазме, вызванной преимущественной поперечной динамикой электронов. Проведено 2d3v-моделирование формирования последовательности коротких релятивистских электронных сгустков из длинного сгустка, включая профилированный сгусток.

МЕХАНІЗМ РОЗВИТКУ НЕСТІЙКОСТІ ЦИЛІНДРИЧНОГО РЕЛЯТИВІСТСЬКОГО ЕЛЕКТРОННОГО ПУЧКА У ПЛАЗМІ

К.В. Лотов, В.І. Маслов, І.М. Онищенко, М.С. Весновська

Досліджено розвиток нестійкості релятивістського електронного пучка кінцевого радіусу у плазмі, що спричинюється переважною поперечною динамікою електронів. Проведене 2d3v-моделювання формування послідовності коротких релятивістських електронних згустків із довгого згустку, включаючи профільований згусток.