

Electron Bunch Compression in Laser Wakefield Acceleration

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A new approach to effective compression of electron bunches in the process of laser wakefield acceleration is proposed and analyzed. Three-dimensional test particle simulations confirm the analytical predictions and demonstrate extremely high bunching and monoenergetic acceleration of electrons to a few GeV energies.

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The progress in laser-plasma accelerators depends substantially on the possibility to provide extended quasi-monoenergetic acceleration of short electron bunches. The inhomogeneity of a comparatively short-wavelength laser wakefield tends to increase the energy spread of finite length electron bunches [1], but at the same time it is responsible for the effects of electron bunching in the energy distribution [2]-[4] and in space [5]-[9].

In the present paper we analyze a new scheme of electron beam injection into a laser wakefield accelerator, which provides a super high compression of the injected beam and highly monoenergetic acceleration [10]. A comparatively long low-energy electron bunch injected in front of the laser pulse can be trapped and accelerated in the plasma wakefield behind the pulse (see Fig. 1). Under certain conditions (on the injection energy and wakefield potential) the electron bunch compression is extremely high (more than two orders of magnitude) and the relative energy spread is damped away up to 0.1% in the process of electron bunch acceleration to GeV energies.

For bunch injected in front of the pulse to be trapped velocity of injected electrons should be less than the group velocity of the laser pulse, which is assumed to be equal to the phase velocity of the wakefield V_{ph} :

$$u_{inj} = c\sqrt{1 - m^2 c^4 / E_{inj}^2} < V_{ph}, \quad E_{inj} < \gamma_p mc^2, \quad (1)$$

where E_{inj} is the injection energy, which is small in comparison with the resonant one determined by the γ -factor associated with the wakefield phase velocity:

$$\gamma_p = 1/\sqrt{1 - \beta_p^2} = \omega_0/\omega_p, \quad \beta_p = V_{ph}/c, \quad (2)$$

where ω_0 and ω_p are the laser carrier and electron plasma frequencies.

The dynamics of an electron bunch can be determined using the energy conservation law in the commoving with the laser pulse frame [8] that gives in the one-dimensional limit the following compression ratio at the acceleration stage when the electron energy $E(\xi)$, where $\xi = z - V_{ph}t$ is the commoving variable, starts to exceed substantially the resonant energy ($E(\xi) \gg \gamma_p mc^2$) [10]:

$$\frac{L_b}{L_{b0}} = \frac{1 - \beta_p}{\beta_p - u_{inj}/c}, \quad (3)$$

where L_{b0} and L_b are the initial and compressed bunch lengths. This equation shows that the bunch length is subject to strong decreasing after the bunch is trapped and the bunch compression is higher for faster wakefield (i.e. lower plasma density, when $\beta_p \rightarrow 1$) and lower injection energy. For example, Eq. (3) predicts that the bunch length can be compressed by a factor of 100 for the injection energy $E_{inj} = 5$ MeV and $\gamma_p = 100$. It should be noted however that with decreasing injection energy and increasing wakefield phase velocity the amplitude of the wakefield potential should be higher to trap the bunch in the focusing phase of the wake wave.

While the absolute energy spread $\Delta E(\xi)$ evidently increases during compression of the bunch length, the relative value $\Delta E(\xi)/E(\xi)$ decreases substantially at the acceleration stage when $E(\xi) \gg \gamma_p mc^2$ and $k_p L_b(\xi) \leq 1$ ($k_p = \omega_p/c$ is the plasma wave number):

$$\frac{|\Delta E(\xi)|}{E(\xi)} = \frac{L_b(\xi)}{1 - \beta_p} \frac{d\phi}{d\xi} \frac{mc^2}{E(\xi)}, \quad (4)$$

where $\phi(\xi)$ is the wakefield potential normalized to $mc^2/|e|$. This equation shows that the energy spread scales linear with the compressed bunch length and decreases especially at the end of accelerating phase where the wakefield potential approaches maximum.

To demonstrate the potentials and practical applicability of the proposed injection scheme, and also availability of the simple analytical predictions (3), (4) we present the results from simulations of the electron bunch compression and acceleration in the wakefield excited by a laser pulse propagating in a preformed plasma channel with the parabolic density increasing with radius:

$$n(r) = n_0 \left[1 + \frac{r^2}{R_{ch}^2} \right], \quad (5)$$

where the channel radius R_{ch} is matched to the laser spot radius r_L by the condition $R_{ch} \cong k_p r_L^2$ [11], [12], and the initial laser envelope was assumed to be Gaussian:

$$a = \frac{eE_L}{mc\omega} = a_0 \exp\left[-r^2/2r_L^2 - 2 \ln 2 (\xi - \xi_0)^2 / (k_p L)^2\right]. \quad (6)$$

The plasma density along the channel axis n_0 is chosen to be in the resonance with the laser pulse duration: $k_p L = 2\sqrt{2 \ln 2}$ [13], where $k_p = \omega_p / c = \sqrt{4\pi e^2 n_0 / m_e} / c$. The nonlinear structure of the wakefield and laser pulse dynamics in the channel were modeled on the base of equations described in [14]. The dimensionless axial and radial components of the force acting upon an accelerating electron were determined through the normalized wakefield potential as follows:

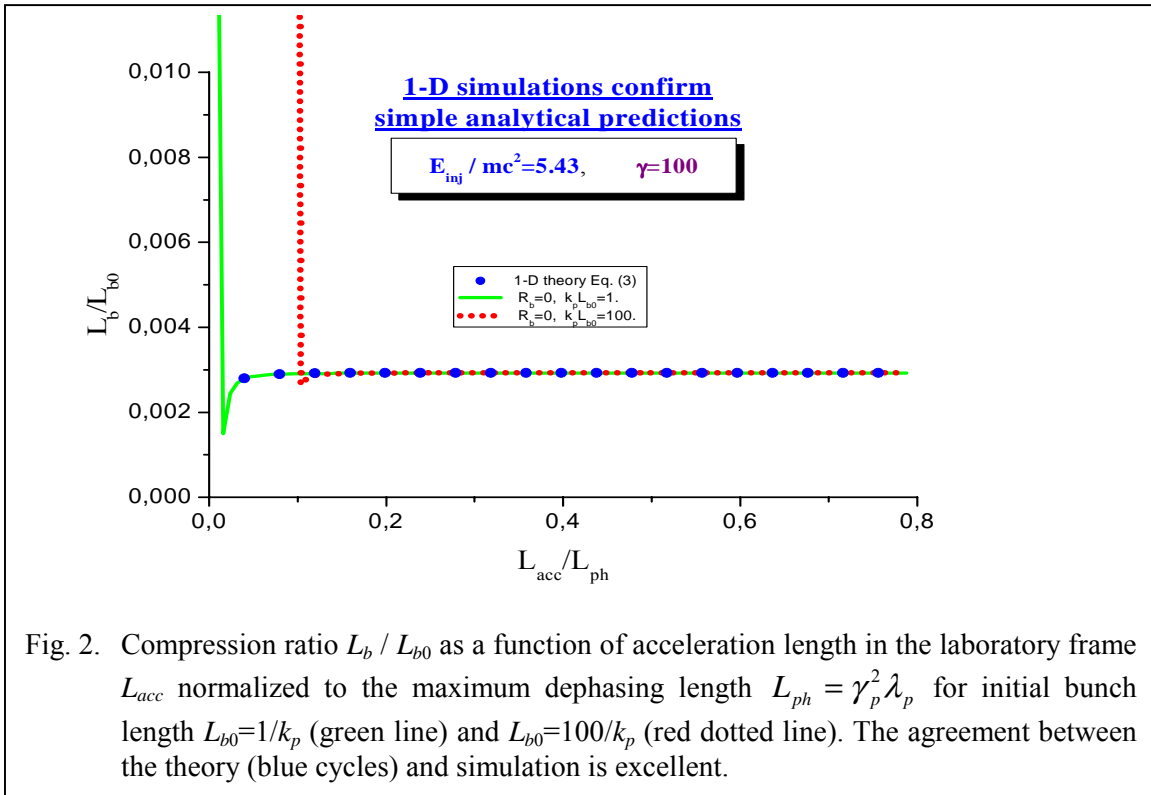
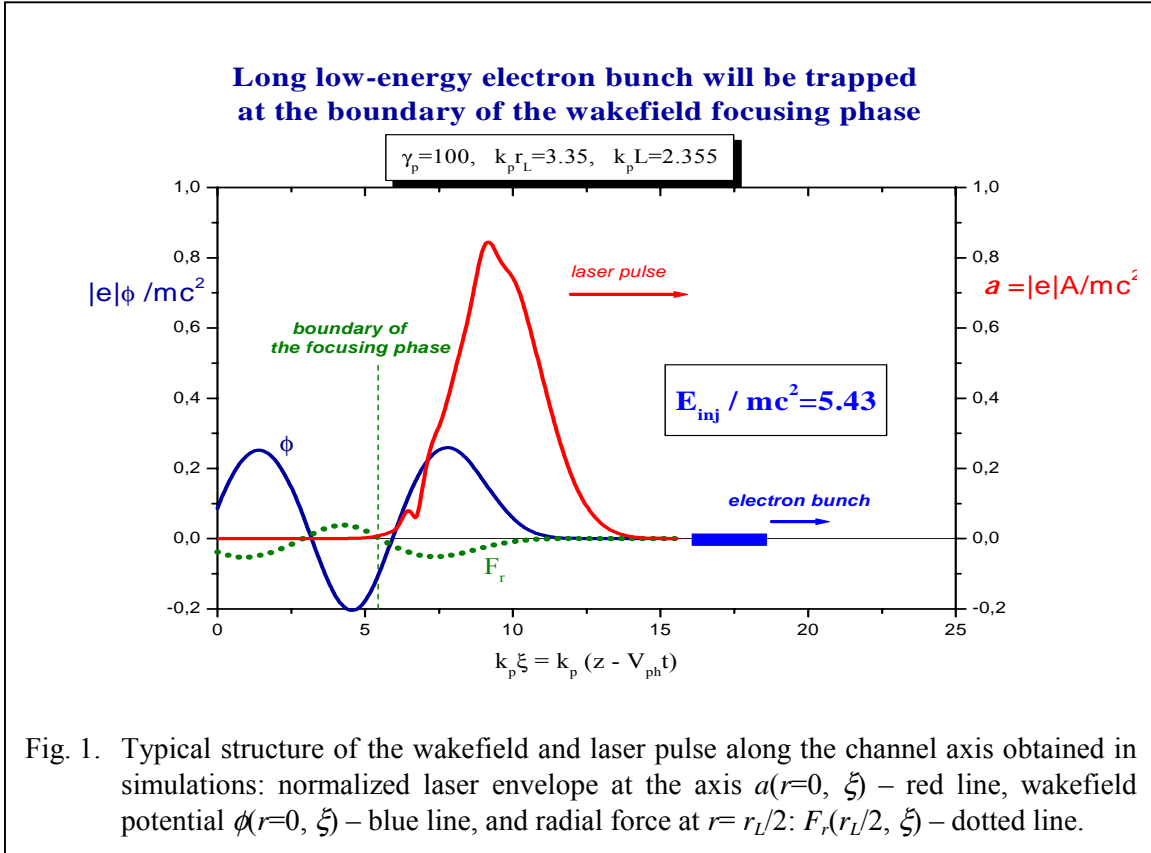
$$F_z \equiv \frac{eE_z}{mc\omega_p} = \frac{1}{k_p} \frac{\partial \phi}{\partial \xi}, \quad (7)$$

$$F_r \equiv \frac{eE_r}{mc\omega_p} - \frac{eB_\phi}{mc\omega_p} = \frac{1}{k_p} \frac{\partial \phi}{\partial r}. \quad (8)$$

These expressions were used for three dimensional test particle simulations of bunch compression and acceleration. Note that small-scale forces acting to the bunch while it passes along the laser pulse were also included in the code. For the presented below results $a_0 = 0.8$, $k_p r_L = 3.35$, $\gamma_p = 100$, and $E_{inj} = 5.43 mc^2 = 2.78 \text{ MeV}$.

Figure 1 illustrates the proposed scheme of injection and the typical structure of the wakefield and laser pulse along the channel axis obtained in simulations. The injection energy was adjusted with the excited wakefield potential so that the electron bunch was trapped at the boundary of the focusing phase, which is marked by the dotted vertical line in the figure.

Fig. 2 demonstrates an excellent agreement between one-dimensional modeling (with electron beam radius R_b tends to zero) and an analytical result of bunch compression given in Eq. (3). The compression ratio L_b / L_{b0} is plotted as a function of acceleration length in the laboratory frame L_{acc} normalized to the maximum dephasing length $L_{ph} = \gamma_p^2 \lambda_p = 2\pi \gamma_p^2 / k_p$, for different initial bunch lengths: $L_{b0} = 1/k_p$ and $L_{b0} = 100/k_p$.



The effect of finite beam radius to the bunch compression is shown in Fig. 3. The results of tree-dimensional test particle simulations are in a good agreement with a simple analytical prediction of Eq. (3) for the initial bunch radiuses less than plasma skin depth $1/k_p = \lambda_p/2\pi$. The energy of accelerated bunch doesn't depend on its radius and for discussed example reaches 3 Gev as is shown in Fig. 4.

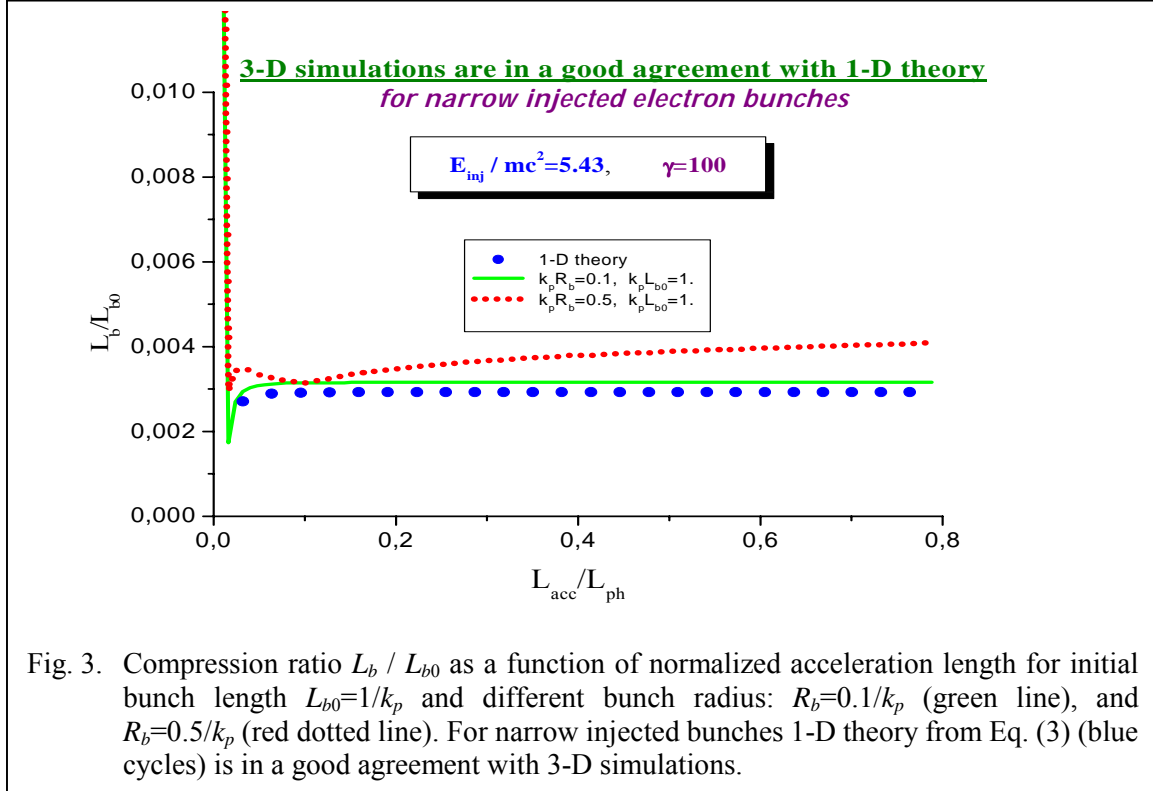


Fig. 3. Compression ratio L_b / L_{b0} as a function of normalized acceleration length for initial bunch length $L_{b0}=1/k_p$ and different bunch radius: $R_b=0.1/k_p$ (green line), and $R_b=0.5/k_p$ (red dotted line). For narrow injected bunches 1-D theory from Eq. (3) (blue cycles) is in a good agreement with 3-D simulations.

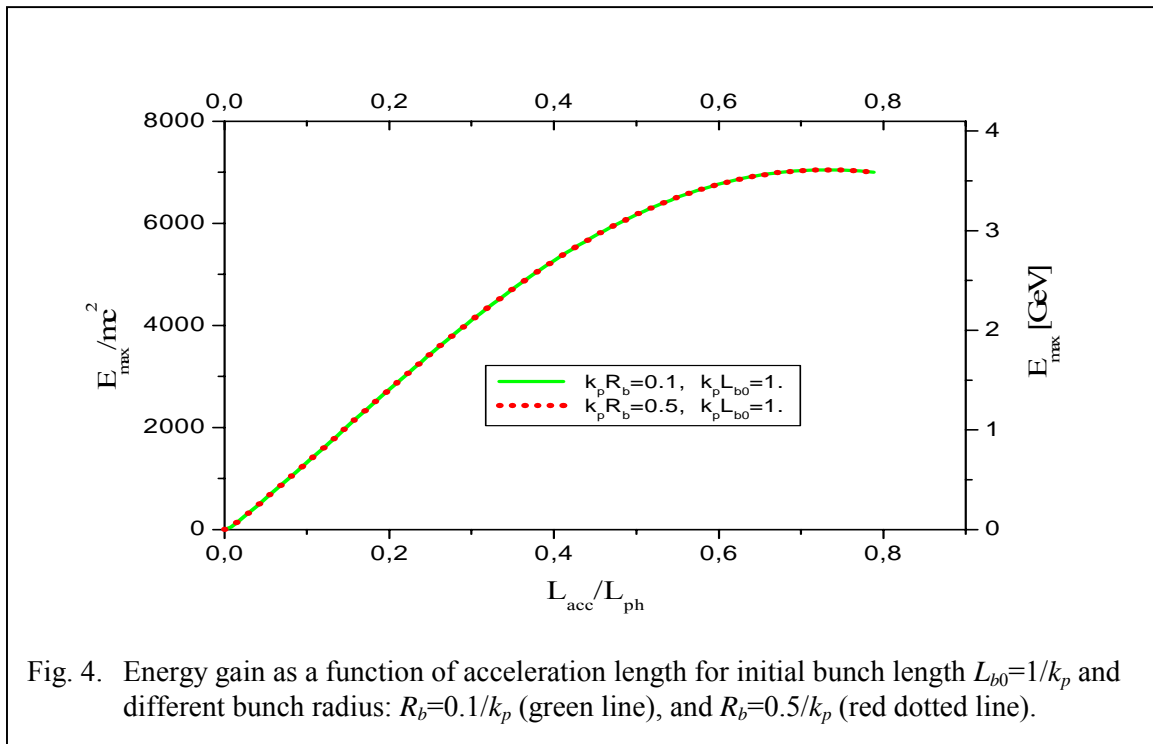


Fig. 4. Energy gain as a function of acceleration length for initial bunch length $L_{b0}=1/k_p$ and different bunch radius: $R_b=0.1/k_p$ (green line), and $R_b=0.5/k_p$ (red dotted line).

An ability of the proposed scheme to provide a highly monoenergetic acceleration of compressed electron bunches is demonstrated in Fig. 5. While the energy spread increases substantially during the bunch compression (a peak in Fig. 5 corresponding to the bunch trapping in the wakefield), the relative value $\Delta E / E$ rapidly falls down in the process of bunch acceleration and reaches a minimum at the end of acceleration phase in conformity with an analytical prediction given in Eq. (4).

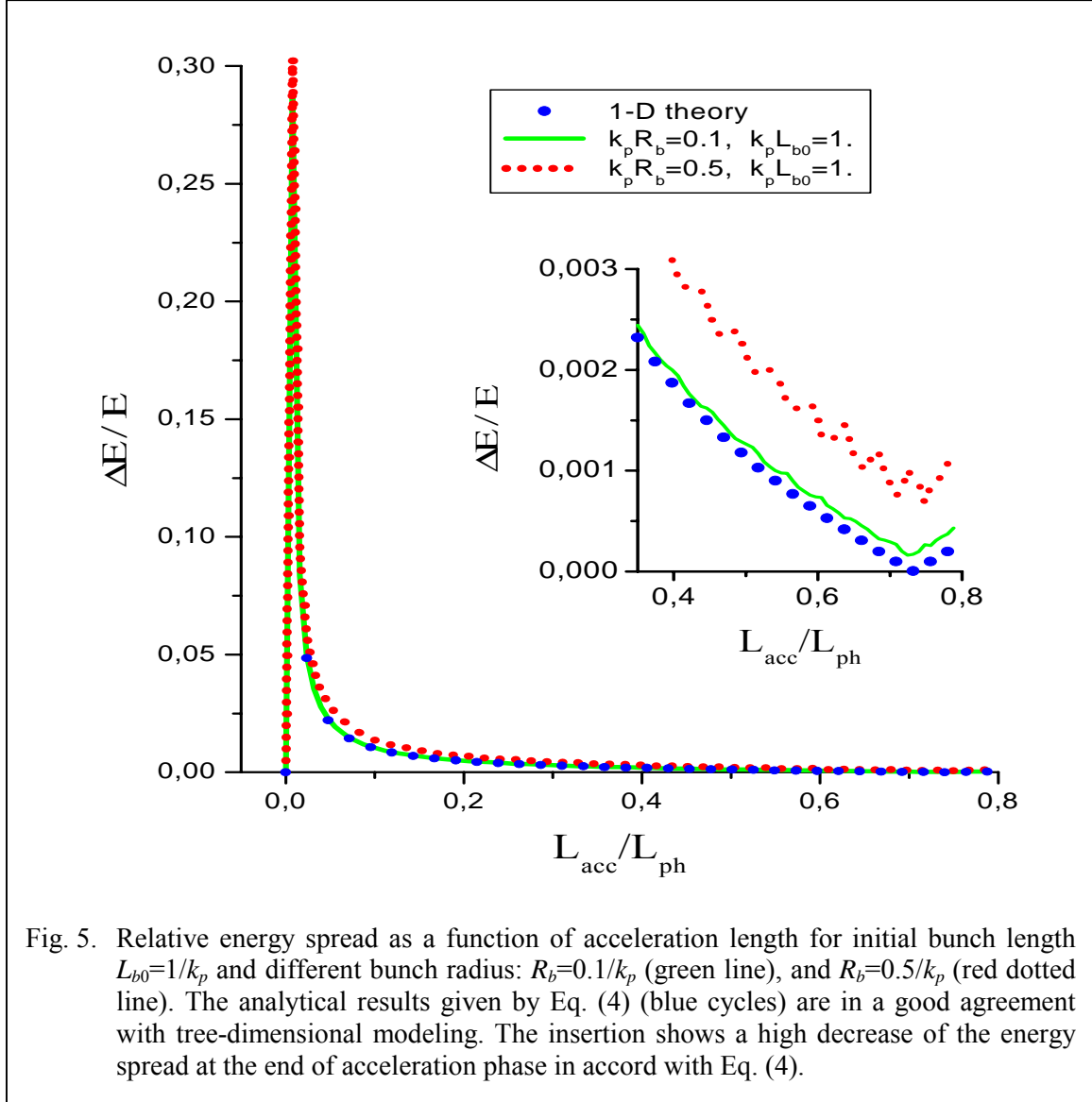


Fig. 5. Relative energy spread as a function of acceleration length for initial bunch length $L_{b0}=1/k_p$ and different bunch radius: $R_b=0.1/k_p$ (green line), and $R_b=0.5/k_p$ (red dotted line). The analytical results given by Eq. (4) (blue cycles) are in a good agreement with tree-dimensional modeling. The insertion shows a high decrease of the energy spread at the end of acceleration phase in accord with Eq. (4).

In conclusion, we present and analyze a new injection scheme for the laser wakefield accelerators, which provide very effective electron bunch compression and monoenergetic acceleration. The analytical estimates confirmed by tree-dimensional test particle simulations predict the extremely high electron bunch compression, more than two orders of magnitude, and the relative energy spread less than 1%. The considered practical example of channel guided LWFA demonstrates a possibility to produce (for 1 μm laser driver) a single 0.1- μm long electron bunch at the energy of 3 GeV with 0.1% of relative energy spread.

REFERENCES

- [1] N.E. Andreev, S.V. Kuznetsov, I.V. Pogorelsky, "Monochromatic laser wakefield acceleration", *Phys. Rev. Special Topics-Accelerators and beams*, vol. **3**, p. 021301 (2000).
- [2] N.E. Andreev, L.M. Gorbunov, S.V. Kuznetsov, "Acceleration of a relativistic electron bunch in linear and nonlinear plasma waves", *Plasma Phys. Reports*, vol. 21, pp. 1037-1041 (1995); "Energy spectra of electrons in plasma accelerators", *IEEE Trans. On Plasma Sci.*, vol. **24**, pp. 448-452 (1996).
- [3] N.E. Andreev, S.V. Kuznetsov, "Acceleration of electron beams in finite-amplitude wake waves", *Plasma Phys. Reports*, vol. 25, pp. 746-752 (1999).
- [4] A. Reitsma, R. Trines, and V. Goloviznin, "Energy spread in plasma-based acceleration", *IEEE Trans. On Plasma Sci.*, vol. **28**, pp. 1165-1169 (2000).
- [5] T. Katsouleas, "Physical mechanism in the plasma wake-field accelerators", *Phys. Rev. A*, vol. **33**, pp. 4412-4414 (1986).
- [6] T. Katsouleas, C. E. Clayton, L. Serafini, C. Pellegrini, C. Joshi, J. Dawson, and P. Castellano, "A plasma klystron for generating ultra-short electron bunches", *IEEE Trans. On Plasma Sci.*, vol. **24**, pp. 443-447 (1996).
- [7] A. Ogata, K. Nakajima, N. Andreev, "Production of femtosecond single-bunched electrons by laser wakefield acceleration", *Journal of Nuclear Materials*, vol. **248**, pp. 392-399 (1997).
- [8] N.E. Andreev, S.V. Kuznetsov, "Effect of electron bunching during acceleration in a wake plasma wave", *Bulletin of the Lebedev Physics Institute (RAS)*, No. 1, pp. 6-12 (1999); [Translated from: *Kratkie Soobshcheniya po Fizike*, No. 1, pp. 9-17 (1999)]; "Laser wakefield acceleration of short electron bunches", *IEEE Trans. On Plasma Sci.*, vol. **28**, pp. 1170-1176 (2000).
- [9] M. Ferrario, T.C. Katsouleas, L. Serafini, and I. Ben Zvi, "Adiabatic plasma buncher", *IEEE Trans. On Plasma Sci.*, vol. **28**, pp. 1152-1158 (2000).
- [10] S.V. Kuznetsov, N.E. Andreev, "Super bunching of electrons in laser wakefield accelerator", *Plasma Phys. Reports*, to appear.
- [11] E. Esarey, P. Sprangle, J. Krall, and A. Ting, "Overview of plasma-based accelerator concepts", *IEEE Trans. on Plasma Sci.*, vol. **24**, pp. 252-288 (1996).
- [12] N.E. Andreev, V.I. Kirsanov, and L.M. Gorbunov, "Stimulated processes and self modulation of short intense laser pulses in laser wake field accelerator", *Physics of Plasmas*, vol. **2**, part 2, № 6, pp. 2573-2582 (1995); N.E. Andreev, L.M. Gorbunov, V.I. Kirsanov, K. Nakajima, and A. Ogata, "Structure of the wakefield in plasma channels", *Phys. Plasmas*, vol. **4**, pp. 1145-1153 (1997); N.E. Andreev, L.M. Gorbunov, "Laser-plasma acceleration of electrons", *Physics-USpekhi*, vol. **42**, pp. 49-53 (1999).
- [13] L.M. Gorbunov, V.I. Kirsanov, *Sov. Phys. JETP*, vol. **66**, p.290 (1987).
- [14] N.E. Andreev, E.V. Chizhonkov, A.A. Frolov, L.M. Gorbunov, "On laser wakefield acceleration in plasma channels", *Nuclear Instruments & Methods in Physics Research, Section A*, vol.**410**, no.3, pp. 469-476 (1998).