TRANSVERSE DEFOCUSING STUDY IN LPWA CHANNEL FOR LINEAR AND BUBBLE MODES

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Abstract

Laser plasma wakefield acceleration (LPWA) is one of most popular novel trends of acceleration. The LPWA has two serous disadvantages as very high energy spread and low part of electrons capturing into acceleration. The waveguide and klystron type beam pre-modulation schemes were proposed [1-3] to growth capturing and to limit the energy spectrum of 2-3 % for 200-300 MeV beam. One interesting effect was shown due to numerical simulation of beam dynamics in plasma channel. Not captured electrons are escape to the channel border fast and this effect should be explained. It was shows that such effect is caused by effective potential function which forms very high defocusing transverse field after its trailing edge. The results of such explanation verification by numerical simulations discuss in report.

INTRODUCTION

A few methods for improving the energy spread in the non-linear LPWA regime have been proposed. The first is to use two plasma stages with constant but not equal plasma densities and a transient stage with varying density between them for the beam modulation [4]. An energy spectrum better than 3 % for a 1 GeV beam has been numerically and in experiment has demonstrated a low energy spectrum < ± 3 % [5] for a similar distribution of the plasma density (decreasing in the first stage and constant in the second one). A ponderomotive injection using two synchronized laser pulses was proposed in [6]. Two lasers can also excite a beat wave in the plasma, which is then used for capturing of the shot bunch [7]. All these methods improve the energy spread to about 3 % for a 1 GeV beam for bubble mode LPWA. Still, this result is too high for many applications. The electron capturing efficiency also remains problematic.

The linear LPWA mode is also interesting for practical use. The rate of the energy gain can still be very high, while the laser power requirements are comparatively moderate, meaning that compact, laboratory scale facilities could be designed for accelerating electron beams to hundreds of MeV.

Two methods for the energy spread and capturing efficiency improving were proposed early for linear LPWA mode acceleration [1-3]. These beam pre-modulation schemes are similar to waveguide and klystron type bunchers of conventional RF linac. In the first the bunching scheme similar to waveguide buncher the plasma channel is divided into two stages. The plasma density slowly decreases in the first, pre-modulation stage, and is constant in the second, the main accelerating stage. In contrast to conventional RF accelerators, the phase velocity $\beta_v(\xi)$ and amplitude of the accelerating field $E(\xi)$ are not independent variables, but functions of the plasma electron density $n_0(\xi)$ and are related as $E = mc\omega_p / e$. Therefore, conventional methods of the beam dynamics optimization in waveguide bunchers directed to the capturing coefficient growth and/or energy spread minimization can not give tolerable result for LPWA. Thus the other beam pre-modulation method was discussed [1, 2]. This scheme is similar to the multigap klystron buncher of conventional RF linac and based on a number of short plasma sub-stages (several λ_l long each) separated by drift gaps. This scheme is suitable to growth capturing and to limit the energy spectrum of 2-3 % for 200-300 MeV beam.

Later the 2D beam dynamics in linear mode LPWA channel was studied by means of numerical simulation [3]. The new code version BEAMDULAC-LWA2D was developed to study the 2D electrons dynamics both in pre-modulation stage and main acceleration stage. One interesting and not explained then effect was observed due to simulations. It was shown that externally injected electrons which are not captured into LPWA acceleration (about 25-30 %) are not only leave the bunch but undergoes the intensive transverse defocusing. Such electrons are going to the plasma channel boundary very fast (along a number of tens of λ_l). This effect is presented in Fig. 1. To understand this dynamical process and to propose methods of more effective electrons capturing are main aims of this paper.

CHANNEL WITH ASSIGNED PLASMA DENSITY SIMULATION

To simulate plasma channel PIC code SUMA was used [8], [9]. In [10] it was shown the possibility to keep synchronism between injected to plasma channel electron bunch and plasma wave potential well by decreasing plasma density along the channel. The correct chose of plasma density gradient allows to keep electrons in the potential well and exclude defocusing area influence at the edge of the well. Another way to obtain similar result is to put inhomogeneity in to the capillary near the plasma channel. It might be the iris, which sizes and position should be chosen to achieve the effect we need. Figure 2 shows evolution of the electron bunch (green dots) injected to the plasma channel. Red and blue dash lines correspond to longitudinal and transverse plasma wave electric field distribution in channel at the mean beam radius. Plasma density is equal to 1024 m3, laser field 4x1011 V/m, laser pulse duration 40 fs, laser spot radius r=30 μm, capillary radius 120 μm. External electron current pulse duration is 0.15 ps. Electron bunch is injected 60 fs after laser pulse. Now clearly, that using iris we don't allow electron bunch sizes increase in both directions that leads to improving its characteristics.

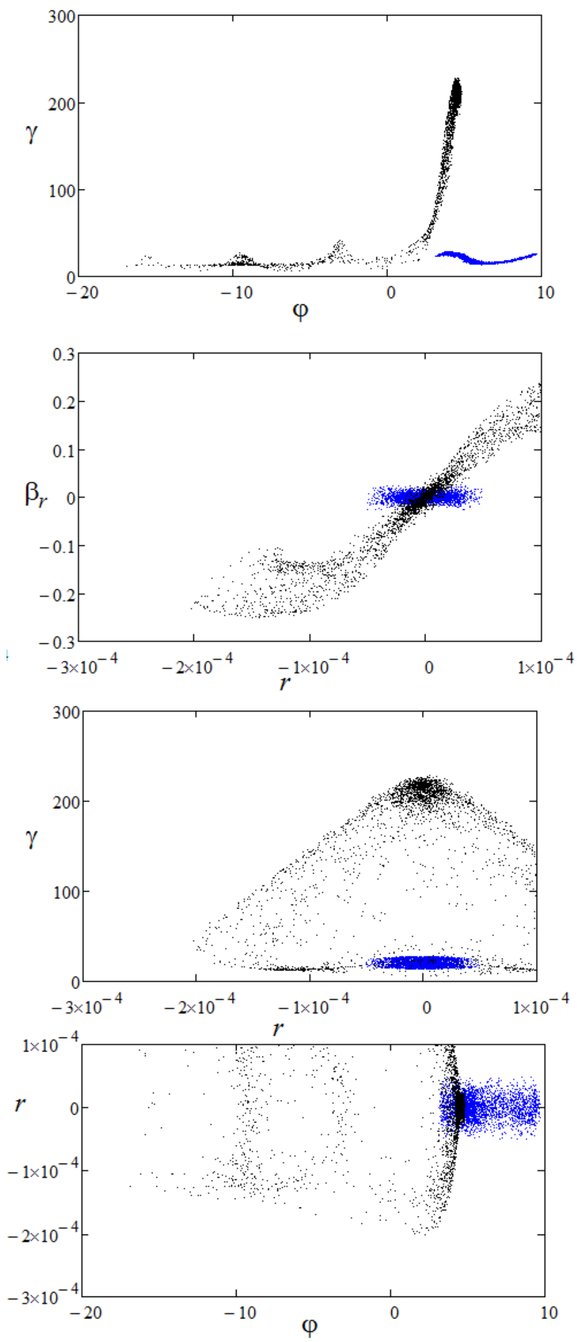

Figure 1: Results of 2D electrons dynamics simulation [3] for beam after pre-modulation for z=1000 λ_l; are sown (top to bottom): particles distribution in conventional (γ, φ) and (β_r, r [m]) phase planes and in non-conventional (γ, r) and (r, φ) planes, Injection distributions after pre-modulation are plotted by blue points and output by black.

Figure 3 shows that energy spectrum considerably improves with iris included. Compare electron bunch evolution we can make the following conclusions. Passing through the iris electrons are under influence of focusing plasma wave electric field which amplitude increases with radius (Fig. 4). So, in other words, iris acts

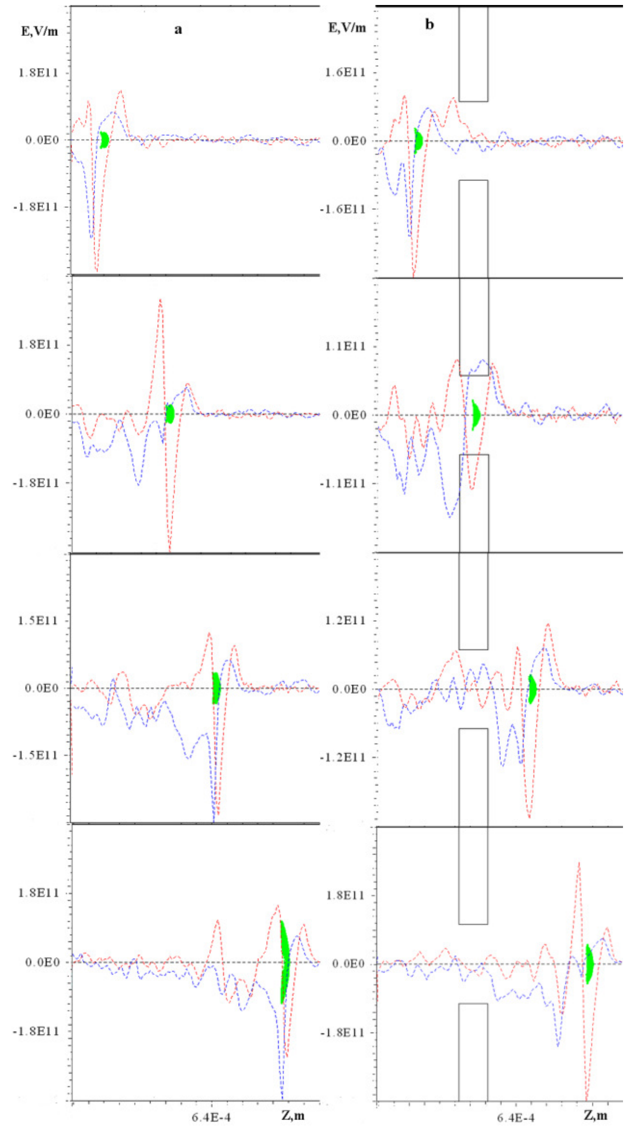

Figure 2: Time depended (time step 400 fs) electron bunch (green dots), longitudinal (red dash line) and transverse (blue dash line) plasma wave electric field distribution in channel at the mean beam radius with (b) and without (a) iris.

as an immersion lens. More accurate analyzes of Fig. 2 shows that iris added leads to plasma wave slowdown and bunch slip from potential well edge to focusing fields. It deals not only with structure changes but and plasma density variation near the iris. Figure 5 shows plasmas electron component (green dots), longitudinal (red) and transverse (blue) plasma wave electric field distribution at the channel edge for the time moment corresponds to 1000 fs after laser pulse started. First transverse plasma wave electric field maximum and white spot on electron density distribution (electrons lack) on Fig. 5 corresponds to laser pulse location. The iris changes not only field but and plasma channel density distribution that conclude in

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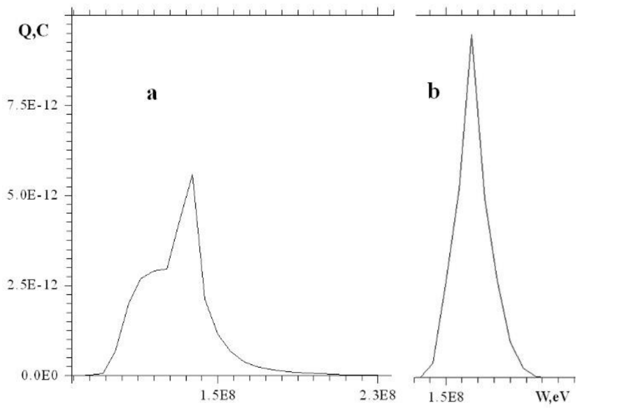

Figure 3: Electron bunch energy spectrum with (b) and without (a) iris.

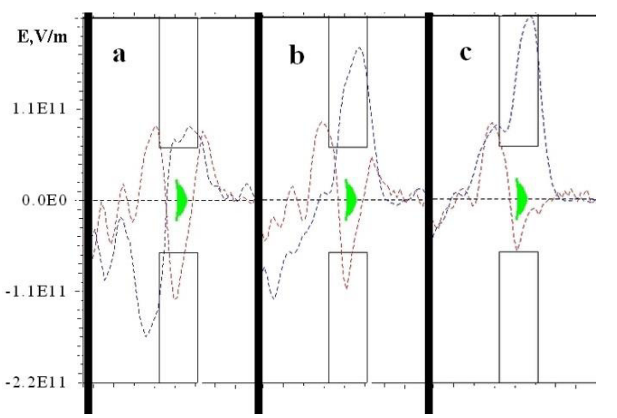

Figure 4: Longitudinal (red dash line) and transverse (blue dash line) plasma wave electric field distribution near the iris at radius 12 µm (a), 18 µm (b) and 24 µm (c).Iris radius 30 µm.

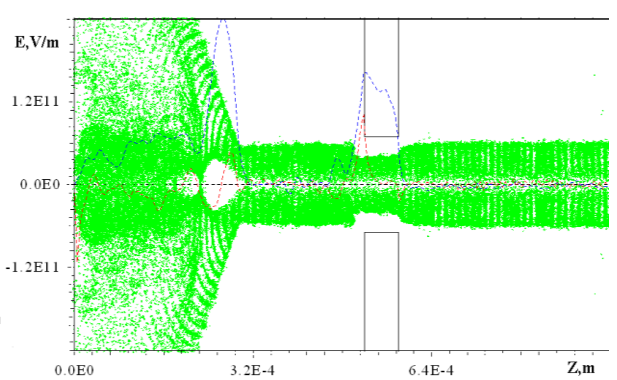

Figure 5: Plasmas electron component (green dots), llongitudinal (red dash line) and transverse (blue dash line) plasma wave electric field distribution at the channel edge. Time moment 1000 fs after laser pulse started.

injected electron bunch dynamic results. During laser pulse propagation, it is necessary to take into account not only electron but and ion plasma component movement either. Even for the rather short modeling time strong electromagnetic field induce to sensible changes of plasmas ion component distribution at the channel (Fig.6).

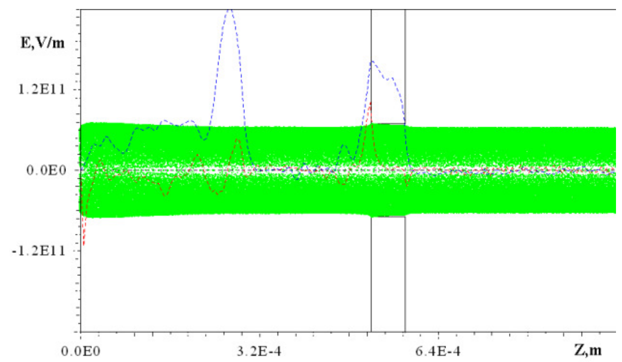

Figure 6: Plasmas ion component (green dots), llongitudinal (red dash line) and transverse (blue dash line) plasma wave electric field distribution at the channel edge. Time moment 1000 fs after laser pulse started.

CONCLUSION

The principal possibility to obtain radial focusing, improve injected electron bunch and accelerating plasma wave interaction with the help of capillary inhomogeneity is discussed. Considerable energy spectrum improvement is shown.

REFERENCES

[1] S.M. Polozov, “A possible scheme of electron beam bunching in laser plasma accelerators”, NIM A 729, 517 (2013).

[2] S.M. Polozov, “2D Beam Dynamics Simulation in Linear Mode LPWA Channel with Pre-modulation Stage”, Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations 6 (88), 29 (2013).

[3] S.M. Polozov, “Energy Spread Decreasing in Linear Mode Operating Laser Plasma Wakefield Accelerator”, Proc. of. PuPAC’12, 251 (2012).

[4] S.V. Bulanov et al., Phys. Plasmas, 15, 073111 (2008).

[5] A.J. Gonsalves et al., Nature Physics, 7, 862 (2011).

[6] D. Umstadter, J.K. Kim, E.Dodd, Phys. Rev. Lett., 76, 2073 (1996).

[7] E.Esarey et al., Phys. Rev. Lett., 79, 2682 (1997).

[8] V.I. Rashchikov, “Electromagnetic field calculation in complex geometry structures”, Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations, No. 10 (18), 50 -53 (1990).

[9] A.N. Didenko, V.I. Rashchikov, V.E. Fortov, ”Mechanism of generation of high intensity terahetrz radiation under the action of high power laser pulsed on a target”, Technical Physics, 56, No. 10, 1535–1538 (2011).

[10] S.M. Polozov, V.I. Rashchikov, “Electron Motion Simulation in laser-plasma channel for output energy spectrum minimization”, Proc. of 2015 International conference "Stability and control processes" in memory of V.I. Zubov (SCP), IEEE, 190-194 (2015).