

# LONGITUDINAL MOTION STABILITY OF ELECTRONS INSIDE THE PLASMA CHANNEL OF LPWA

**Sergey M. Polozov**

National Research Nuclear University  
Moscow Engineering Physics Institute  
and National Research Center  
Kurchatov Institute  
Russia  
SMPolozov@mephi.ru

**Vladimir I. Rashchikov**

National Research Nuclear University  
Moscow Engineering Physics Institute  
and National Research Center  
Kurchatov Institute  
Russia  
VIRashchikov@mephi.ru

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## Abstract

The acceleration of electrons in laser-plasma channels is one of the contemporary ideas on the energy frontier of accelerators. Demands of low energy spectrum and emittance are especially important for discussed colliders and light sources based on acceleration in plasma channels. The idea to use a laser-plasma accelerator as injector for these installations instead of traditional RF linacs looks like as a very perceptive way to replace the conventional RF linac-injector or linac-driver by a very compact system. Therefore, the new results of beam dynamics simulations in laser-plasma channel having pre-bunching stage are discussed in paper. Main simulations were focused on the study of the longitudinal electron motion stability inside of the plasma channel. It was shown that the form and the value of the plasma potential well are essentially depend on laser pulse amplitude, form and duration. The electron beam dynamics, in turn, is specified by plasma potential well parameters, which define the electrons capturing into acceleration and output parameters of the bunch. Electrons loosed from the synchronous motions in the plasma wave are defocusing soon after falling out from the potential well and are pushed to the plasma channel wall.

## Key words

Laser plasma wakefield acceleration, beam dynamics, longitudinal and transverse motion stability.

## 1 Introduction

A number of ideas to increase the rate of the energy gain have been discussed in the last few decades. This

rate is limited by discharge for conventional RF accelerators. The idea of electrons acceleration in a modulated plasma channel was proposed by Ya.B. Feinberg in the 1950's [Feinberg, 1959]. Possible schemes for the plasma wakefield acceleration (PWA) differing in ways of modulating the plasma channel were developed later. The first one uses a high energy (tens of GeV) beam of particles (both electrons and protons) to form a plasma wave and to accelerate a fraction of the injected particles or a probe beam [Muggli et al., 2008]. Another method is the laser plasma wakefield acceleration (LPWA) [Tajima and Dawson, 1979], in which a laser pulse is used to create a plasma wave. The problem of electron acceleration in plasma channel with varying density produced by power laser pulse or short electron bunch is under attentive consideration [Feinberg, 1959; Hogan et al., 2005]. The accelerating gradient in this channel is limited not by the discharge effects as in usual RF accelerating structures but the plasma density and laser-plasma transmission efficiency. Depending on laser intensity and plasma channel parameters there are linear and non-linear LPWA modes: in the underdense plasma, in which  $\pi^2 r_l^2 / \lambda_p^2 \gg a_0^2 / 2\gamma_l$  (quasi linear regime), and the non-linear regime with  $\pi^2 r_l^2 / \lambda_p^2 \ll a_0^2 / 2\gamma_l$ . Here  $r_l$  is the laser spot size,  $a_0 = eA / W_0$  normalized laser intensity,  $\gamma_l = (1 + a_0^2 / 2)^{1/2}$ . The electron beam dynamics is different in the two regimes. The theory of the laser and the plasma interaction and acceleration in the plasma channel are discussed in [Akhiezer and Polovin, 1956; Gorbunov and Kirsanov, 1987; Esarey, Schroeder, and Leemans, 2009].

Many simulations and experimental results were done for LPWA before now. All results show that two key problems are observed for LPWA: i) only low fraction (<5 %) of electrons is captured in the acceleration pro-

cess by the plasma wave and ii) accelerated electrons having very broad energy-spread ( 20-30 %). The impossibility of real accelerators construction based on lased plasma wake-field acceleration flows from this problem. This problems could be overcomes easily if we find the way, how to produce very short electron bunches with the length less than plasma wavelength. But the plasma wavelength is very short ( 1  $\mu m$ ) and it is impossible today to generate 0.1  $\mu m$  length bunches using contemporary technologies of photoguns construction and operation.

A few methods for improving the energy spread in the non-linear 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 [Bulanov et al., 2008]. The energy spectrum better than 3 % has been shown by numerical simulation for 1 GeV beam using this scheme. Later the same results were demonstrated experimentally [Gonsalves et al., 2011] with the similar plasma density profile. A ponderomotive injection scheme using two synchronized laser pulses was proposed in [Umstadter et al., 1996]. Two lasers can also excite a beat wave in the plasma, which is then used for capturing of the shot bunch [Esarey et al., 1997]. With a third laser pulse this method can produce cooled electron beams [Esarey and Lee-mans, 1999]. The method of controlled electron self-injection in wave breaking regime has been also proposed [Mangles et al., 2004], energy spread of 3 % has been demonstrated experimentally for this method.

All these methods improve the energy spread to about 3 % for a beam with energy 1 GeV. Still, this value is too high for many applications as injectors for storage rings or FEL's. The electron capturing efficiency also remains problematic. All methods described above apply to the non-linear or wave breaking regimes. However, the linear LPWA mode is also interesting for the 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.

## 2 Preliminary Beam Formation

Two ideas of the beam pre-bunching realization for linear mode were proposed [Polozov, 2012; Polozov, 2013a]. In the first the bunching scheme similar to waveguide buncher in conventional RF linac was studied. 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. The following assumptions were made: the beam is injected externally, the amplitude of the electric field does not vary on the scale of the time of bunch flight, the plasma is cold, linear and collisionless, and the space charge field of the in-

jected electrons is much lower than the plasma wave field. This scheme allowed to increase the capturing coefficient to  $K_t \simeq 40\%$ , but now sufficient energy spectrum dissipation of  $\delta W/W = 5 - 6\%$  is observed for electrons with energy of 200 MeV. This problem can be solved by using a number of short low density ( $10^{18} cm^{-3}$ ) plasma stages with gaps between of them [Polozov, 2013a]. This scheme is similar to the multi-gap klystron buncher of a conventional RF linac and is basing on a number of short plasma sub-stages (several laser wavelength  $\lambda_l$  long each) separated by drift gaps. At this case we obtained  $K_t$  more than 50 % and RMS energy spectrum reduction to 3 % for energy of 100 MeV [Polozov, 2013b].

These simulations were done using BEAMDULAC-LWA2D [Polozov, 2013a] code which was especially designed to study the beam dynamics in LPWA channel. One interesting result was observed during these simulations [Polozov, 2013b]. It was shown that externally injected electrons and not captured into LPWA acceleration (about 25-30 %) not only leave the bucket but also undergoes the intensive transverse defocusing (Fig. 1). Such electrons are going to the plasma channel boundary very fast (during a number of tens of  $\lambda_l$ ). The similar results were obtained in the following PIC modeling.

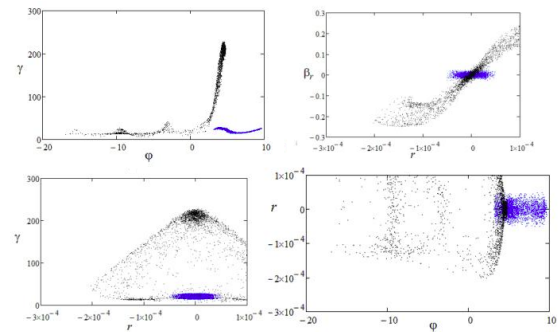


Figure 1. Results of 2D electrons dynamics simulation [Polozov, 2013b] for beam after pre-modulation for  $z = 1000\lambda_l$  (top to bottom): particles distribution in conventional longitudinal  $(\gamma, \varphi)$  and transverse  $(\beta_r, r[m])$  phase planes and in non-conventional  $(\gamma, r)$  and  $(r, \varphi)$  planes. Injection distributions after pre-modulation are plotted by blue points and output by black

## 3 PIC Laser-plasma Interaction Simulation and Longitudinally Stability of Bunch

The particle-in-cell code SUMA [Rashchikov, 1990] was used for electrons dynamics simulation in laser-plasma channel taking into account real field distribution in the channel. Simulations were performed to confirm previous results of theoretical investigation and

simulations. Mathematical model of SUMA code includes Maxwells equations, equation of the medium and equations of motion. Unperturbed plasma oscillations with different density values were simulated for the high accuracy code parameters tuning. Longitudinal oscillation frequencies in this case can be obtained analytically and they are in a good agreement with simulation results.

After SUMA code tuning for LPWA, computer simulation of waveguide-like buncher with  $200\lambda_l$  length, where  $\lambda_l = 1.06\mu m$ , was conducted. Let us consider the laser pulse passing through plasma filled channel and the plasma density wave formation. Plasma electrons distributions (black dots) changes in time during the laser pulse moving as shown at Fig. 2. Plasma ions distribution is assumed constant. The formation of the region without electrons behind the laser pulse is clearly seen in the Fig. 2. It is caused by the strong transverse force of the laser pulse. For the given plasma density and the laser pulse parameters, geometries of the capillarity and the plasma channel some electrons from the plasma may even leave the simulation region and get to the channel boundary (both for linear and nonlinear regimes). Behind the laser pulse near the channel axis, where electron density essentially less than that of the ion one, the depth and the longitudinal size of the potential well are strongly depend on laser pulse and plasma parameters. To obtain effective

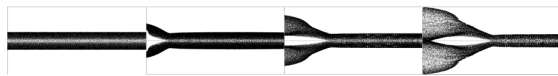


Figure 2. Time depended plasma electron density distribution inside the plasma channel

beam bunching we need to define the plasma and the laser pulse parameters which are coupled to each other. For example, optimal electron beam parameters after the buncher require electric field amplitude as less as possible but enough for space charge forces compensation. It leads to the plasma density reduction. However, the reduction of the plasma density leads to the electric field amplitude decreasing. As a result the mean velocity of the electron bunch will grow slower than the phase velocity of the wave.

Longitudinal (red dash line) and transverse (blue dash line) distributions of the plasma wave electric field in the buncher at the mean beam radius are shown in Fig. 3. The plasma density is equal to  $10^{18} cm^{-3}$ , the laser field is  $4 * 10^{11} V/m$ , duration of the laser pulse is 40 fs, the laser spot radius  $r = 30\mu m$ . The discharge was simulated inside of the capillary with the radius of  $120\mu m$ . The pulse duration of the electron current was chosen equal to 0.15 ps. The electron bunch (green dots) is injected after the laser pulse with delay equal

to 60 fs. The Figure 3a corresponds to the time of 300 fs after the laser pulse start. Electrons are injected close to zero of reducing longitudinal electric field of the plasma wave. The initial longitudinal size of the injected bunch is reduced twice during the bunching process. It is clear that electrons are at the focusing transverse electric field (Fig. 3a). The combined Figure 3b is divided in the horizontal direction. The upper part shows plasma self-field potentials distribution and charged particles distribution in the bottom. Black and red points correspond to plasma electrons and ions accordingly. Injected electrons are presented at the bottom part of the figure by blue points near the maximum of the potential. The potential well size is presented as the first longitudinal field oscillation. The form and the depth of the potential well depends on the plasma density and the laser pulse parameters that allows us to control the number of electrons which to be captured in acceleration. The initial energy of the injected electrons does not effect on the result in a sensible parameter range due to the essential depth of the potential well. The potential (the same parameters as in upper part of Fig. 3) and charged particles distributions (bottom part) in the channel with the constant plasma density of  $10^{18} cm^{-3}$  are shown in Fig. 4a with the time step of 100 fs. The electron bunch is squeezed in both

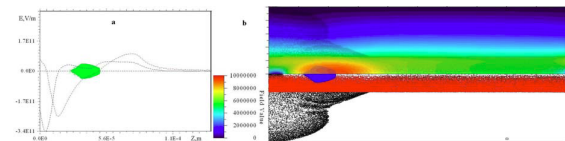


Figure 3. Plasma wave electric field (a), potential and charge particle (b) distribution in buncher

directions at the front of the potential well and then it gets to the end of the well where electrons are into the defocusing transverse electric field. Electrons fast get out off the axis due to this field. The longitudinal size of the electrons bunch starts to increase. Decreasing of the plasma density along the channel (see Fig. 5) is used to prevent the bunch delay behind of the potential. The correct choice of the plasma density gradient allows to keep electrons in the potential well and to exclude the defocusing as it is shown in Fig. 4b. The phase velocity of the plasma wave and the plasma density distribution should be analyzed more detail for the further bunching improvement. Another way to obtain similar result is to place the inhomogeneity inside the capillary near the plasma channel boundary. It might be an iris, which size and position should be chosen to achieve the effect we need. The evolution of the electron bunch (green dots) injected to the plasma channel is shown in Fig. 6. Red and blue dash lines, similar to Fig. 3, correspond to the distribution of longitudi-

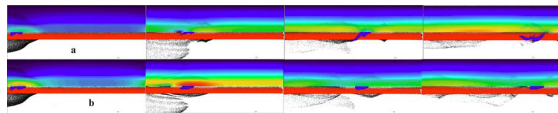


Figure 4. Time depended potential and charged particles distributions

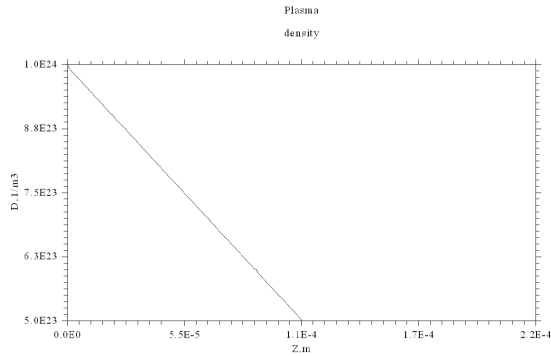


Figure 5. Plasma density distributions in the channel

nal and transverse electric fields in the plasma wave in channel with same plasma parameters at the mean beam radius. Using the iris we do not allow the electron bunch sizes to be increased in both directions that lead to improvement of its parameters. Energy spectrum considerably improves with iris installed inside of the capillary. Comparing the electron bunch evolution we can make the following conclusions. Passing through the iris, electrons are under influence of the focusing electric field of the plasma wave which amplitude increases with the radius. Therefore iris acts as an immersion lens. More accurate analyze of Fig. 6 shows that the iris installation leads to plasma wave slowdown and bunch slips from the potential edge to the focusing fields. This deals not only with structure changes but and with the plasma density variation near the iris.

#### 4 Conclusion

The principal possibility to obtain the narrow energy spectrum of injected electrons in the channel with comparatively low plasma density ( $< 10^{18} \text{ cm}^{-3}$ ) was shown. The correct choice of plasma density gradient in the buncher may considerably improve the capture rate and the energy spectrum. The improvement of the radial focusing of injected electron bunch and the efficiency of the accelerating plasma wave interaction with the help of the inhomogeneity placed inside of the capillary was discussed. It was shown that such inhomogeneity can improve both longitudinal and transverse bunch stability. These results give us to do one more step to the LPWA using for generation of high-quality and high-energy electron bunches which are necessary for future colliders and light sources.

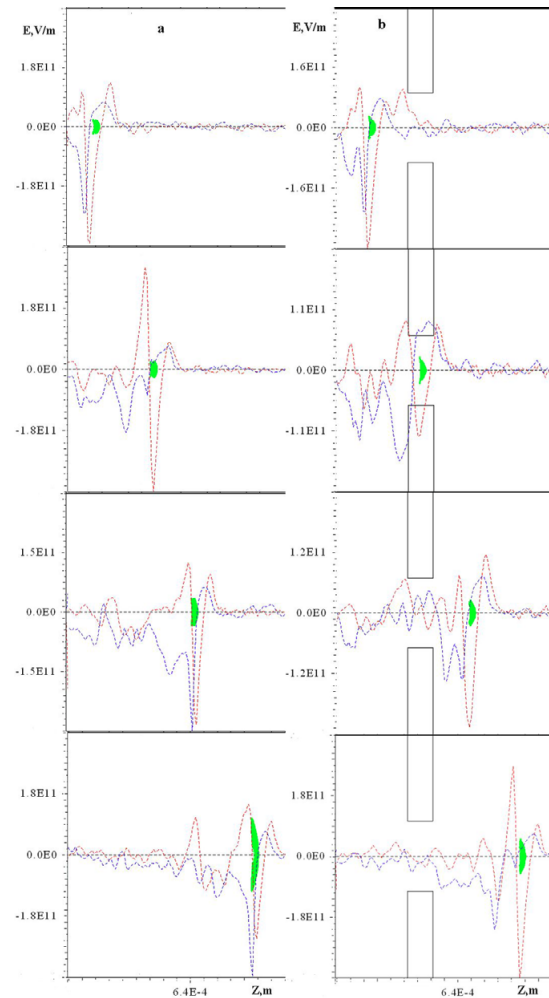


Figure 6. Time depended (time step 400 fs) electron bunch (green dots), longitudinal (red dash line) and transverse (blue dash line) plasma wave electric field distribution in channel at the mean beam radius with (b) and without (a) iris

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