Capturing coefficient increase and energy spread decrease in LPWA

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Abstract. The acceleration of electrons in laser plasma channels is one of the contemporary ideas on energy frontier of accelerators. Many simulations and experimental studies are now provided. But two main laser plasma acceleration problems are not solved until now: low fraction of particles is capturing into acceleration and accelerated electrons have very broad band. Special techniques should be proposed to preserve such negative effects. New results of beam dynamics simulations in laser plasma channel having pre-bunching stage are discussed in article. Results are obtained for two pre-bunching techniques which are analogous to waveguide and klystron type buncher used in RF accelerators.

1. Introduction
A number of ideas for increasing 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 [1]. 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 to form a plasma wave and accelerate a fraction of the injected particles or a probe beam [2]. Another method is the laser plasma wakefield acceleration (LPWA) [3], 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 [1, 4]. The accelerating gradient in this channel is limited not by the discharge effects as in usual accelerating structures but the plasma density and laser-plasma transmission efficiency. Depending of laser intensity and plasma channel parameters there are linear and non-linear LPWA modes: in the underdense plasma, in which \( \pi^2 r_l^2 / \lambda_p^2 \gg a_0^2 / 2 \gamma_t \), (quasi linear regime) and the non-linear regime with \( \pi^2 r_l^2 / \lambda_p^2 \ll a_0^2 / 2 \gamma_t \).

Here \( r_l \) is the laser spot size, \( a_0 = eA / W_0 \) normalized laser intensity, \( \gamma_t = (1 + a_0^2 / 2)^{1/2} \). The electron beam dynamics is different in the two regimes. The theory of the laser-plasma interaction and acceleration in the plasma channel are discussed in [5-7].

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 [8]. An energy spectrum better than 3 % for a 1 GeV beam has been numerically and in experiment has demonstrated a low energy spectrum...
< ±3 % [9] 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 [10]. Two lasers can also excite a beat wave in the plasma, which is then used for capturing of the shot bunch [11]. With a third laser pulse this method can produce “cooled” electron beams [12]. The method of controlled electron self-injection in wave breaking regime has been also proposed [13], and an energy spread of ±3 % has been demonstrated experimentally.

These methods improve the energy spread to about 3 % for a 1 GeV beam. Still, this number is too high for many applications. The electron capturing efficiency also remains problematic. All the methods described above apply to the non-linear or wave breaking regimes. However, 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.

2. Pre-bunching for linear mode LPWA

Two ideas of pre-bunching realisation for linear mode were proposed [14, 15]. In the first the bunching scheme similar to waveguide buncher in conventional RF linac was studied. The plasma channel is divided into two stages. 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 (figure 1a).

The following assumptions are made: the beam is injected externally, the amplitude of the electric field does not vary on the scale of the time of flight, the plasma is cold, linear and collisionless, and the space charge field of the injected electrons is much lower than the plasma. This scheme allowed to increase capture ratio to $K_t=40 \%$, but now sufficient energy spectrum dissipation $\delta W=5-6 \%$. This problem can be solved by using a number of short low density ($10^{18} \text{ cm}^{-3}$) plasma stages with gaps between of them (figure 1b). This scheme is similar to the multigap klystron buncher of conventional RF linac and based on a number of short plasma sub-stages (several $\lambda_j$ long each) separated by drift gaps. At this case we obtained $K_t$ more than 50 % and energy spectrum reduction to 3 % for energy of 100 MeV [16]. Simulations were done using new BEAMDULAC-LWA2D code version which was designed to study the beam dynamics in LPWA channel.

![Figure 1](image.png)

**Figure 1.** Two possible schemes of electrons pre-bunching for linear-mode LPWA.

3. Particle-in-cell simulations.

2.5D particle in cell code SUMA [17, 18] was used for electrons dynamics simulations in laser plasma channel taking into account real field distribution in the channel and to confirm previously results of theoretical investigation and simulations. The system of equations used in mathematical model
consists of the Maxwell equations, the equation of the medium, and the equation of motion. Unperturbed plasma oscillations with different density values were simulated for thin code parameters tuning. Longitudinal oscillation frequencies can be obtained analytically and are in a good agreement with simulation results. After that computer simulation of waveguide buncher with $200 \lambda_i$ length, where $\lambda_i = 1.06 \mu m$, was conducted. To obtain effective beam bunching we need to choose some plasma and laser pulse parameters, which are linked to each other. For example optimal electron beam characteristic after buncher requires electric field amplitude as less as possible but enough for space charge forces compensation. It leads to plasma density reduction. But plasma density reduction brings to electric field amplitude decreasing and as a result to not enough electron beam mean velocity accession rate with compare to wave phase velocity.

Figure 2a shows longitudinal (red dash line) and transverse (blue dash line) plasma wave electric field distribution in buncher at the mean beam radius. Plasma density is equal to $10^{24}$ m$^{-3}$, laser field $4 \times 10^{11}$ V/m, laser pulse duration 40 fs, laser spot radius $r = 30 \mu m$, capillary radius 120 $\mu m$. External electron current pulse duration is 0.15 ps. Electron bunch (green dots) is injected 60 fs after laser pulse. Figure 2a corresponds to time 300 fs after laser pulse start. Electrons are injected close to zero of reducing longitudinal electric field of plasma wave. For the time at Figure 2a initial longitudinal size of injected bunch is reduced twice during the bunching. As shown, electrons are at the focusing transverse electric field. Figure 2b shows the combine figure, which is divided in horizontal direction. The upper part shows plasma self field potentials distribution and lower - charge particles distribution. Black and red points correspond to plasma electrons and ions accordingly. Injected electrons are presented at the lower part of the figure by blue points near the potential maximum. The potential wall size is presented as the first longitudinal field osculation. The form and depth of the wall depends on the plasma density and laser pulse parameters that allows us to change the number of electrons to be captured in acceleration. Injected electron initial energy in a sensible range do not effect on the result due to essential potential wall depth.

**Figure 2.** Plasma wave electric field (a), potential and charge particle (b) distribution in buncher.

Figure 3a shows time depended (time step 100 fs) potential and charged particles distributions in the channel with constant plasma density $10^{24}$ m$^{-3}$. Electron bunch is tightened in both directions at the front and then get to the end of potential well where electrons are in the defocusing transverse electric field and get off the axis. Longitudinal size of the electron bunch starts to rise. Decreasing plasma density along the channel (see Figure 3b) is used to prevent bunch lag behind the well.

The correct chose of plasma density gradient allows to keep electrons in the potential well and to exclude the defocusing.
4. Conclusion
Principal possibility to obtain sufficient energy spectrum of injected electron beam at the channel with low plasma density (< 1018 cm3) was shown. The proper chose of plasma density gradient in the buncher may considerably improve capture rate and energy spectrum.

![Figure 3. Time depended potential and charged particles distributions](image)

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