

Laser wakefield acceleration of electron bunches in the mildly nonlinear regime

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Abstract

The possibility of accelerating electrons to the GeV level using a Petawatt laser focused in a uniform plasma is investigated. The proposed scheme relies on the wakefield acceleration of an electron bunch from a state-of-the-art radio frequency accelerator. Using an analytical model as well as numerical simulations performed with WAKE, an study of the injector parameters is carried out. In particular, it is found that the quality of the accelerated electron bunch -in terms of bunch length and energy spread- depends crucially on the injection energy. Injection energies of a few MeV lead to a GeV electron beam with sub-100 fs bunches and 10% energy spreads. Most of the features of the acceleration process can be explained with the analytical linear model, whom results are in good agreement with the numerical simulations.

During the last few years, both theoretical work and experiments have shown the feasibility of laser-plasma electron acceleration [1-4]. The interaction of a laser pulse with an underdense plasma produces a trail of oscillatory fluctuations of the electron density, e.g. a wakefield. The accelerating gradients in the wakefield can attain extremely high values (of the order of TeV/m), exceeding by four orders of magnitude the fields supported in conventional accelerators. Laser-plasma technology is currently considered for the construction of compact and economical accelerators [5]. Laser wakefield acceleration has permitted the production of high quality ultrashort electron beams of energies up to 170 MeV and charge of 0.5 nC [6].

The next generation of laser systems (with several Petawatt lasers currently under construction [7]), is expected to allow the production of GeV electron beams. Two scenarios are envisaged for reaching these energies. The first one consists of operating in the strongly nonlinear regime with high laser amplitudes ($a_0 \gg 1$) and small acceleration lengths (mm). Numerical simulations have shown that in this regime, near-GeV energies can be attained in a single stage device [8]. In the second scenario, an electron bunch of some MeVs created in a first

stage is injected into the wakefield of a moderate amplitude laser ($a_0 \simeq 1$) and accelerated over distances of some centimeters [9-11]. The weakly nonlinear nature of the interaction in this second scheme could permit to obtain stable operation conditions, avoiding wave breaking, strong self-focusing and the onset of microscopic instabilities. We study in this paper this second approach to get GeV electrons.

In the linear response approach, cold fluid equations, i.e. continuity equation, momentum equation and Poisson's equation, are solved to obtain the wake potential induced by the laser ponderomotive force. Assuming $\gamma_p \gg 1$ (with γ_p the relativistic factor corresponding to the wake velocity) and that the detuning length $L_d \approx \gamma_p^2 \lambda_p$ is much larger than the acceleration length $L_a = 2L_{Rayleigh}$, the maximum and minimum final energy for a bunch of length $L_b = \lambda_p$ are respectively given by[12]

$$\gamma_f^{max+} \approx \gamma_0 + (\pi/4)\delta_0 2\omega_p t_R \quad \text{and} \quad \gamma_f^{min} = (\pi/4)\delta \sqrt{2y - y^2} 2\omega_p t_R, \quad (1)$$

with

$$y = \frac{(\gamma_p - \gamma_0)^2}{\delta_0 \gamma_0 \gamma_p^2}, \quad \delta_0 = \sqrt{\pi} a_0^2 \frac{k_p L_0}{4} e^{-k_p^2 L_0^2 / 4},$$

γ_0 the injection relativistic factor and t_R the Rayleigh time. For a bunch of electrons uniformly distributed in a wake period $[0, 2\pi]$, the fraction of trapped particles $f_{trapped}$ and the final length L_f of the bunch are given by

$$f_{trapped} \approx \frac{2 \arccos(y)}{2\pi}, \quad k_p L_f \approx \arccos(-1 + y) - \frac{\pi}{2}. \quad (2)$$

In the weakly nonlinear regime ($a_0 < 1$), linear model predictions are in well agreement with nonlinear numerical results obtained with the code WAKE [13]. This can be seen in figure 1, that shows both the linear and nonlinear results for γ_f as a function of the injection γ . The laser amplitude is $a_0 = 0.85$. The laser wavelength is $\lambda_0 = 0.8 \mu\text{m}$, the pulse duration 30 fs, the laser energy and power 7.5 J and 0.25 PW respectively. The pulse focal spot is $w_0 = 100 \mu\text{m}$. Wide pulses are needed to get large acceleration length without guiding. Test electrons are injected at $z = -z_R$ and extracted at $z = z_R$ (acceleration length is $L_a = 2L_R \approx 8 \text{ cm}$). The relativistic factor of the laser pulse is $\gamma_p = \omega_0 / \omega_p = 125$.

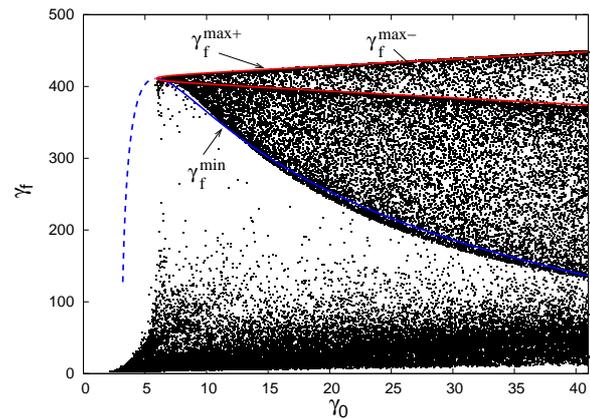


Figure 1: Nonlinear (dots) and linear (curves) results for the final γ vs. initial γ for $a_0 = 0.85$

Test electrons are uniformly distributed in the second wake period ($k_p L_b = 1$), with a bunch radius of $k_p \sigma_b = 2$. As can be seen in figure 1, electrons are trapped and accelerated by the wake electric field only for $\gamma_0 > 6$ (3 MeV). In the neighborhood of this value, the bandwidth is very small, while for larger injection energies the beam becomes less monoenergetic. Particles fill in the area between $\gamma_f^{\max+}$ and γ_f^{\min} , due to the finite initial bunch radius.

For higher laser amplitudes, nonlinear effects become significant. The main effect is the change in the wake velocity due to adiabatic shifting of the plasma frequency. For $a_0 = 1.72$, the effective relativistic factor at $t = -t_R$ is $\gamma_p^{\text{eff}} \approx 60$, well below the linear phase velocity $\gamma_p = 125$. As γ_p becomes smaller, the assumption $\gamma_p \gg 1$ becomes poorer. Figure 2 shows final γ vs. injection γ . Laser power and maximum intensity are 30 J and 1 PW respectively. As can be seen, minimal energy predicted by the linear model overestimates the numerical result. On the other hand, close to the minimum for trapping, energy spread of extracted bunches is small.

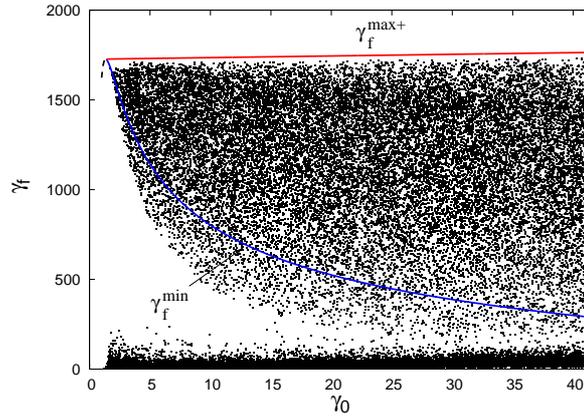


Figure 2: Nonlinear (dots) and linear (curves) results for final γ versus initial γ for $a_0 = 1.72$.

Analytical expressions and numerical calculations show that Petawatt lasers will permit the production of high quality GeV bunches in a two-stage device. The use of a homogeneous plasma rather than a plasma channel [10, 11] has the advantage of simplicity regarding the practical implementation of a two-stage scheme. In summary, best beam qualities, i.e. smallest bandwidths and emittances, are obtained with low injection energies, even when the initial bunch length is as large as the plasma wavelength. Hence, conventional RF injectors appears to be suited for the first stage of such an accelerator. On the other hand, in the present scheme, the bunch charge is limited by constraints on focusing. For charges of some tenths of nC, focusing of the low energy bunches to radii smaller than $w_0 = 100 \mu\text{m}$ is prevented by space charge effects. Production of GeV-nC bunches would require the use of higher injection energies (to avoid space charge effect in the focusing) and shorter bunches such as $\ll \lambda_p$, in order to keep the beam monoenergetic. Bunches with the required properties are currently produced by laser wakefield acceleration [6]. Therefore, the use of laser-plasma acceleration in the first stage appears to be beneficial to the production of highly charged bunches.

Simple estimations derived in the linear response framework are in good agreement with

nonlinear numerical simulations. The relativistic shift of the plasma frequency is the only nonlinear effect that plays a significant role in determining the properties of the extracted beam. Its main effect is to reduce the final beam energy and to increase the energy spread.

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