A New Scheme for High-Intensity Laser-Driven Electron Acceleration in a Plasma

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During the past few decades plasma accelerators have attracted increasing interest of scientists from all over the world due to its compactness, much cheaper construction costs compared to those for conventional one and various applications ranging from high energy physics to medical and industrial applications. An intense electromagnetic pulse can create a plasma wave through the stimulated scattering. Electrons trapped in the plasma wave can be accelerated to high energy.

The idea to accelerate the charged particles in a plasma medium using collective plasma wave fields generated by the high-energy electron beams belongs to the Soviet physicists G. I. Budker, V. I. Veksler and Ia. B. Fainberg [1] in 1956, whereas assumptions for generation of plasma Langmuir waves by nonrelativistic electron bunches propagating through plasma were first made earlier in 1949 [2, 3]. Contemporary research efforts revolve around the laser wakefield acceleration (LWFA) scheme of Tajima and Dawson [4] or electron-beam driven plasma wakefield (PWFA) scheme proposed by Chen et al. [5], both of which have seen tremendous progress in recent years. For a detailed review about the modern status of this research field we would like to refer a reader to [6, 7]. Early experiments of the 60s and 70s demonstrated that efficiency of acceleration using the high-energy beams is much less than the expected one and the generated field is much lower than a breakdown (overturn) electric field [8]:

$$E_{p_{max}} = 2\pi m V_p \omega_p / e. \tag{1}$$

where e- electron charge, m - its mass, V_p - plasma wave phase velocity, $V_p = \omega_p/k_p \simeq c$ where k_p - plasma wave vector, ω_p - plasma frequency, $\omega_p = \sqrt{4\pi e^2 n_e/m}$ with n_e being the electron density and m - its mass. The explanation for the experiments failure was given in the work [9] where it was shown that trapping of electrons in a generated by a beam plasma wave occurs and as a result growth of the field amplitude stops when the field amplitude is much less than that of the breakdown field [10].

With the apperance of the high-intensity lasers in the 80s, a new era of plasma acceleration has begun. The hopes were fed by possibility of the stimulated scattering of a laser pulse by plasma electrons in a rare plasma with the generation of high-intensity longitudinal plasma wave where the electron trapping does not occur and, as a result, high fields with respect to the breakdown field $E_{p_{max}}$ can be generated. However, there are still a lot of unsolved problems related to the development of instabilities hindering the laser-driven plasma-based acceleration [7].

A fundamental issue of parametrically driven plasma wave generation is the following: inspite of the fact that the instability induced by the backward (backwards the laser pulse) scattering generating a plasma wave or a wake has a maximum increment δ_1 compared to that generated by a forward (towards the injection of a laser pulse) one δ_2 by $\sim 2\omega_0/\omega_p$ times (ω_0 - laser pulse frequency) [10] (see Fig. 1), this acceleration scheme is not suitable for particle acceleration because such lasers have a very short laser pulse length. Since the wave vector of a plasma wave $\vec{k}_p$ is equal to the double magnitude of that of a laser pulse ($k_p \simeq 2\omega_0/c$), the phase velocity of a plasma wave is quite low. Due to this fact the wave leaves behind both the laser and the back scattered waves getting localized at the back to the front of the laser pulse (this is why it is called as a wake). As a result the plasma wave gets soon out of the acceleration phase with the laser wave and the electron beam injected into the plasma gets soon out of a phase with the plasma wave what halts the acceleration process. In the range of carried out experiments the acceleration effeciency estimates to not higher than 20-50 %. Recently, the SPARC_LAB facility of INFN-LNF in Frascati, Italy, reported the observation of electrons acceleration with an energy gain of 420 MeV (300 %) out of 150 MeV injected using a 250 TW laser system ($\lambda = 800$ nm, $\tau = 25$ fs, $E_M = 6$ J) [11] .

In this work, we are first to propose another acceleration scheme, namely: a stimulated forward-scattering based plasma acceleration. In addition, on a base of such model we would like to make some estimations for the experiment [11]. Due to the stimulated laser forward-scattering a plasma wave is generated as well. In this case, in comparison with a stimulated backward-scattering the plasma wave and laser wave can stay in acceleration resonance for a much longer time. Let the laser pulse with Langmuir frequency ω_0 be injected into the cold plasma at ${\omega_0}^2 >> {\omega_p}^2$. Consider the case when $Z||\vec{V}_0$, $\vec{V}_0$, $\vec{V}_1$ and $\vec{V}_p$ - phase velocities of laser, forward-scattered and plasma waves. Here, we employ the CGS system of units. The parametric resonance for the stimulated forward-scattering can be written as following:

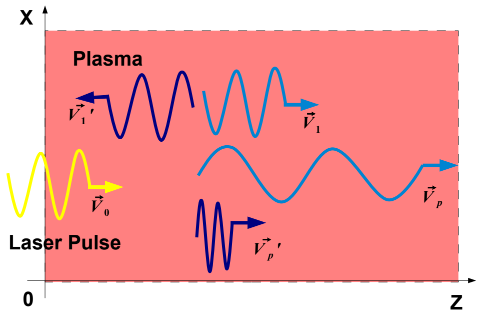

Figure 1: *Schematic 2D-illustration of interaction of the high-intensity laser pulse with plasma which generates a plasma wave and either forward- (light blue) or backward-scattered (blue) waves with velocities* $|\vec{V}_p| = |\vec{V}_0| = |\vec{V}_1|$, $k_0 \simeq k_1 > k_p$ *for a forward-scattering case,* V_1' *- phase velocity of a backward-scattered wave when* $|k_0| \simeq |-k_1'| < |k_p'|$, $k_p' \simeq 2\omega_0/c$.

$$\begin{aligned} \omega_0 &= \omega_1 + \omega_p \\ k_0 &= k_1 + k_p, \end{aligned} \tag{2}$$

where k_0, k_1 and k_p are the wave vectors of the incident laser pulse, forward-scattered wave and plasma wave respectively, ω_0, ω_1 - corresponding frequencies:

$$\begin{aligned} \omega_0 &= \sqrt{\omega_p^2 + k_0^2 c^2} \\ \omega_1 &= \sqrt{\omega_p^2 + k_1^2 c^2}, \end{aligned} \tag{3}$$

After having solved the system of Eqs. (2) and (3) one can find out that the phase velocities of three waves are equal

$$\left(V_0 = \frac{\omega_0}{k_0}\right) = \left(V_1 = \frac{\omega_1}{k_1}\right) = \left(V_p = \frac{\omega_p}{k_p}\right) = c\left(1 + \frac{\omega_p^2}{2\omega_0^2}\right), \tag{4}$$

where $\omega_p{}^2/\omega_0{}^2 << 1$. The condition for the resonance interaction (4) can be satisfied for a sufficiently long time until the amplitude of the plasma wave becomes higher than that of the laser incident wave and the reversed process of feeding back the incident wave starts. If the laser is powerful enough than the instability will keep growing until a breakdown (overturn) of the plasma wave occurs, i.e. when the magnitude of the saturation plasma wave amplitude becomes equal to $E_{p_{max}}$ (see Eq. 2). The acceleration constraint (1) enables us to controle the acceleration process. In order to determine the electron trapping condition for acceleration we need to estimate the duration of acceleration, i.e. the time interval during which the phase velocities of a plasma wave and that of an electron remain approximately equal to each other. This condition possibly was taken into account during the `SPARC_LAB` experiment in Frascatti with injected electron beam energies of 150 MeV. Taking into account this condition we can estimate the duration of acceleraion of an ultrarelativistic electron with an initial energy $\varepsilon = mc^2(\gamma-1)$, $\gamma = 1/\sqrt{1-u_0{}^2/c^2} >> 1$, u_0 is the speed of an electron beam. The speed of such an electron is the following:

$$\frac{u_0}{c} = 1 - \frac{1}{2\gamma^2} \tag{5}$$

Using the following estimation formula for acceleration time:

$$(V_p - u_0)\tau_f \approxeq c\pi/\omega_p. \tag{6}$$

and Eqs. (4) and (5) we can detemine the acceleration time :

$$\tau_f \approxeq \frac{\lambda_p \gamma^2 \gamma_p^2}{c(\gamma^2 + \gamma_p^2),} \tag{7}$$

where $\gamma_p = \omega_0/\omega_p$ and $\tau_f \approxeq \lambda_p \gamma_p^2/c$, $\lambda_p = 2\pi c/\omega_p$, at $\gamma >> \gamma_p$. Taking into account Eq. (1) and (7) the following momentum and energy growth can be obtained:

$$\Delta P \approx eE_{p_{max}}\tau_f, \quad \Delta\varepsilon \approx eE_{p_{max}}\tau_f c. \tag{8}$$

Let us make some estimations for a laser-driven plasma-based electron accelerator and compare with the results obtained at the `SPARC_LAB` facility of INFN-LNF in Frascati, Italy.

- **Estimated parameters**

- $\omega_0 = 2.35 \cdot 10^{15}$ s^{-1} ($\lambda = 800$ nm), $\omega_p = 1.8 \cdot 10^{13}$ s^{-1}, $n_e = 10^{17}$ cm^{-3}
- An electron with energy growth of 150 MeV ($\gamma = 297$) can gain the maximum energy $\Delta\varepsilon \simeq 0.3 \cdot 10^{12}$ eV in the saturation field of $E_{p_{max}} \simeq 1.9 \cdot 10^9$ V/cm during $\tau_f = 5 \cdot 10^{-9}$ s over the maximum acceleration length of $L \simeq 150$ cm. Provided that the length of a capillary could be of the same size: $L \simeq 150$ cm, the corresponding energy growth for the `SPARC_LAB` facility can be estimated to much higher energy growth of $\Delta\varepsilon \simeq 15 \cdot 10^9$ eV compared to the obtained one.

- The acceleration time in a frame of the stimulated backward-scattered model can be determined as $\tau_b = \pi/\omega_p$, $\tau_b \simeq 10^{-13}$ s which is much less than that for the forward-scattered case: $\tau_f \simeq 10^{-9}$ s by approx. γ^2 times (provided that $\gamma >> \omega_0/\omega_p$). The corresponding plasma wave lengths will be $\lambda_{p_b} = \pi c/\omega_0$, $\lambda_{p_b} \simeq 0.4\mu$m and $\lambda_{p_f} = 2\pi c/\omega_p$, $\lambda_f = 105\mu$m.

Results and Discussions

In the present work for the first time the analytical problem of interaction of a high-intensity laser pulse with plasmas in a frame of a stimulated forward-scattering model has been solved and a new approach to solution of the problem was proposed [12]. The acceleration scheme employing the stimulated backward-scattered wave for particle acceleration in a wakefield is not suitable for particle acceleration because high-intensity lasers have a very short laser pulse length leading to a very short interaction time between the injected electron beam and a plasma wave. Instead, our new approach employing the stimulated forward-scattering can provide more durable particle trapping time inside the field of a plasma wave of a much longer length compared to the backward-scattered model where electrons just slip off the wave. In Eq. for a breakdown electric field for illustration purpose we took a constant topf field because the exact electric field profile during the instability growth is not known. However, the time interval during which the breakdown field can be gained is much less than the acceleration time what justifies our choice of the field profile. To assess how an forward-scattering-based scheme compares quantitatively with the conventional laser wakefield acceleration scheme we are planning to run more extensive simulations of the considered phenomena using the **KARAT** code [13]. In order to acquire the maximum acceleration effeciency during experiment one would need to make the scattered at various angles radiation except the forward-scattered one be absorbed by plasma surrounding surfaces similar to the scheme employed for a SHF (superhigh frequency) plasma amplifier.

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