PROGRESS IN VACUUM LASER ACCELERATION

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Abstract

In a new vacuum laser acceleration scheme, relativistic electrons injected with small incident-angle relative to the laser propagation direction are not expelled by the laser beam as predicted by the ponderomotive potential model, but are captured and significantly accelerated in the strong laser field region and keep moving along the laser wave for a long time to get significant energy gain from the laser field. We call this new scheme CAS (capture and acceleration scenario).

The key points of CAS are as follows: It has been discovered that there exists lower wave phase velocity region (less than c) for any focused laser beam propagating in vacuum. It has been demonstrated for the first time that there exist acceleration channels for any focused laser beam propagating in vacuum, where the lower wave phase velocity combined with strong axial electric component make it like a wave guide tube of a conventional accelerator. The basic physics of CAS is that relativistic electrons injected into this acceleration channel can be trapped in the acceleration phase and remain in the phase with the laser field for sufficient long times, thereby receiving considerable energy from the field. The conditions for CAS to work are: the laser intensity should be strong enough (a_0 ≥4); the electron incident angle is sufficiently small ($\tan\vartheta \sim 0.12$); and the optimum incident electron momentum is sensitive to the laser beam width, and should be in the range of 5-15 MeV. One of the advantages of the CAS scheme is that: optics and medium placed near the laser focal region are not necessary, allowing use of high intensity laser and large energy gain. The energy gain can be 100MeV ($a_0 = 10$), 2GeV ($a_0 = 100$).

We have also investigated the detailed characteristics and output features of this acceleration scheme.

More than ten years of work in laser technology led to the development of the chirped-pulse amplification (CAP) [1]. To date, light intensity as high as $I\lambda^2 = 10^{20}\,\mathrm{W/cm^2}\cdot\mu\mathrm{m}^2$ (here I and λ are the laser intensity and wavelength in units of $\mathrm{W/cm^2}$ and $\mu\mathrm{m}$, respectively) has been achieved[2]. Consequently, there have emerged many new frontier research areas[3]. The development of laser-driven electron acceleration mechanisms is a fast advancing area of scientific research[4-6]. Compared with the 20MV/m acceleration gradient provided by contemporary linear accelerators, the $10^7\,\mathrm{MV/m}$ electric field gradients of the laser field have made the laser acceleration a very promising way to develop compact high-energy accelerators. Especially, the far-field free-electron laser acceleration in vacuum has received widely attention[7].

Recently a new scheme of the electron laser acceleration in vacuum has successfully been demonstrated with theoretical investigation and 3D test-particle simulations (numerical experiments).

Basically, there were two typical models that dominated the research field of VLA for past long time.

- Ponderomotive-potential model (PPM) [8]. In PPM, the averaged (over the fast-quavering) motion of an electron in the focus of a laser can be considered as a slow-drift moving in a conservative ponderomotive potential. The main feature of PPM is that the averaged electron motion is independent of the laser phase, as well as the laser polarization, and the electrons are expelled from the high-intensity regions. Now it is clear that the conventional PPM can exactly be applied only in the case $a_0 << 1$. As $a_0 > 1$ and with increasing a_0, the electron motion is getting deviated from the conventional PPM; sensitive to the laser phase, to the laser polarization, and is not always expelled from the laser high-intensity region.
- Lawson-Woodward Theorem (LWT) [9]. LWT was presented in different versions, however, the essential physics underlying LWT is that the phase velocity of a laser field near the focal region is assumed to be greater than c. Thus it was argued that the inevitable phase slippage would lead a relativistic electron to experience alternatively acceleration and deceleration phase regions as it traverses the laser field, which would result in the cancellation of the energy gain for an unlimited interaction length. It has now been proved that the basic assumption of LWT concerning the wave phase velocity is suitable for all cases no longer.

In our new VLA mechanism, electrons injected with low-energy and small incident-angle relative to the laser propagation direction are not expelled by the laser beam as predicted by the PPM model, but are captured and significantly accelerated in the strong laser field region and keep moving along the laser wave for a long time to get significant energy gain from the laser field. For convenience, we call this new VLA mechanism CAS (capture and acceleration scenario). The key points of CAS are as described as follows [10-12]:

- By theoretical investigation, for the first time, it has been verified that for a focused laser beam propagating in vacuum, there exists a region characterized by subluminous wave phase velocity $v_\varphi < c$. The phase velocity of a laser wave field can be calculated by the

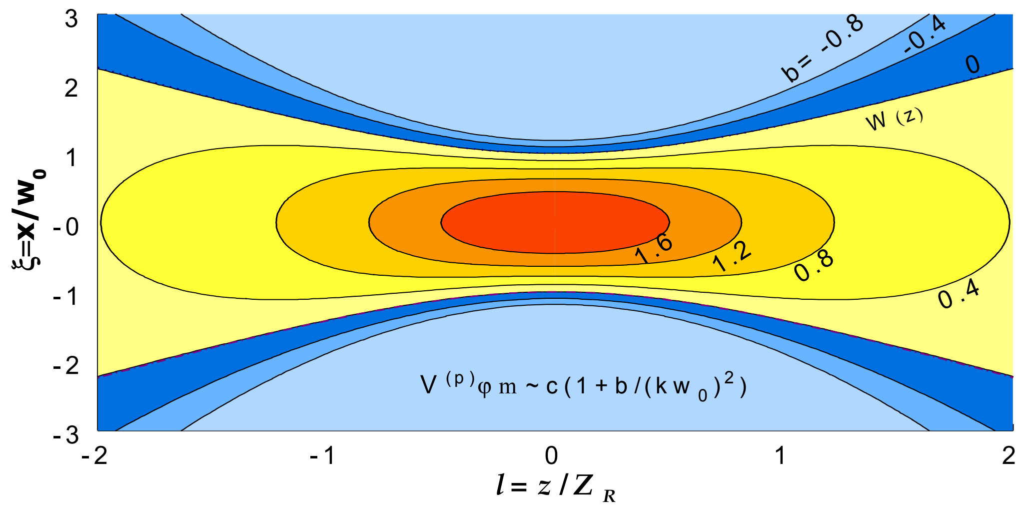

Figure 1: The distribution of the minimum phase velocity v_φ in the plane y=0.

equation: $\partial\varphi/\partial t + v_\varphi . \nabla\varphi = 0$, where φ is the phase field of the wave, $\nabla\varphi$ is the gradient of the phase. Take a laser beam of Hermite-Gaussian (0, 0) mode propagating along the z-axis as an example, $\varphi = kz - \omega t - \tan^{-1}\alpha + \dfrac{kr^2}{2z(1+1/\alpha^2)}$, where ω is the laser circular frequency, $k = \omega / c$, $\alpha = z/Z_R$, $Z_R = \frac{1}{2} k w_0^2$ the Rayleigh length, w_0 the beam width at the focus center, $r^2 = x^2 + y^2$, φ_0 the initial phase. Then the related phase velocity is

$$v_\varphi = \frac{\omega}{|\nabla\varphi|} = c\left(1 + s^2 \frac{4}{q^4}\left(\rho^2 - q^2 + s^2 f_p^2\right)\right)^{-1/2},$$

where $\rho = r/w_0$, $q = (1+\alpha^2)^{1/2}$, $f_p = 1 - \rho^2(1-\alpha^2)/(1+\alpha^2)$, and $s = 1/kw_0$.

Fig. 1 illustrates the two-dimensional contour of v_φ in the plane y=0. It can be seen that there exists a region where the phase velocity is less than c. This region emerges just beyond the beam width and extends along the diffraction angle $\theta_m \sim 1/kw_0$. The magnitude of the minimum phase velocity scales as $v_\varphi \sim c(1 + b/(kw_0)^2)$. To study the physical basis of this phenomenon, we note that the laser field concerned is not a plane wave, but a Gaussian beam field. The radius of the curvature firstly decreases from $z = 0$ to $z = Z_R$, and then increases from $z = Z_R$ to infinity due to the diffraction effect of the optical beam, which causes the subluminous phase velocity region to occur.

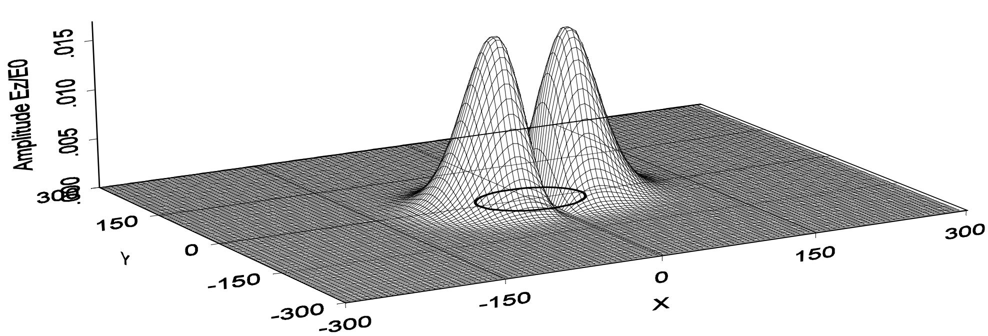

Figure 2: The distribution of the longitudinal electric field amplitude at the $z = 0$ plane for a linearly polarized laser beam of Hermite-Gaussian (0, 0) mode.

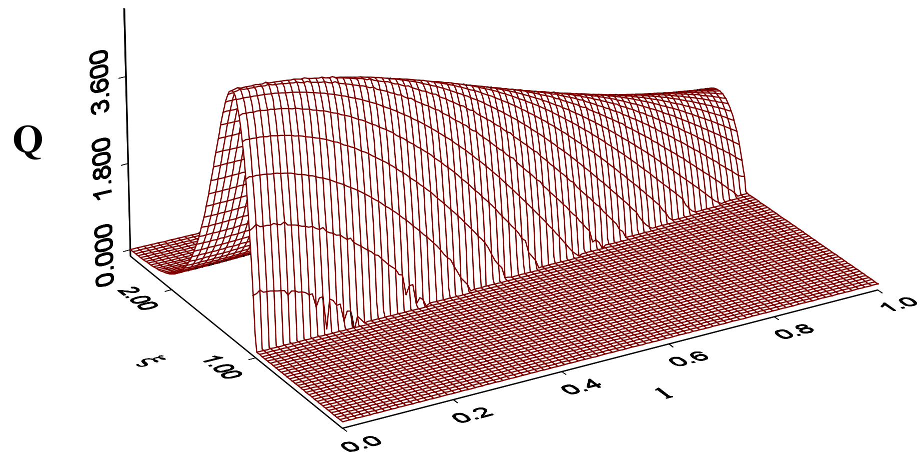

Figure 3: The distribution of the acceleration quality factor Q on the plane $y=0$. $\xi = x/w_0$, $\zeta = z/Z_R$.

- Taking into account of the distributions of the longitudinal electric field (see Fig.2) and the phase velocity (Fig.1) for a linearly polarized Gaussian beam, one can confirm that there exist acceleration channels for a focused laser beam propagating in vacuum, where the subluminous wave phase velocity combined with strong axial electric field make it as a wave guide tube of a conventional accelerator. We hereby introduce a quantity Q that combines these two factors together to represent the ability of the laser field to accelerate charged particles. We call it as acceleration quality factor, which is defined by $Q = Q_0(1-v_\varphi/c)[x/w(z)]\exp[-(x^2+y^2)/w(z)^2]$ for $v_\varphi \le c$, and $Q=0$ for $v_\varphi > c$. Here Q_0 is a normalized constant to make Q in the order of unit. In the expression of Q , $(1-v_\varphi/c)$ represents the contribution from the phase velocity, and the remaining factor is proportional to the amplitude of the

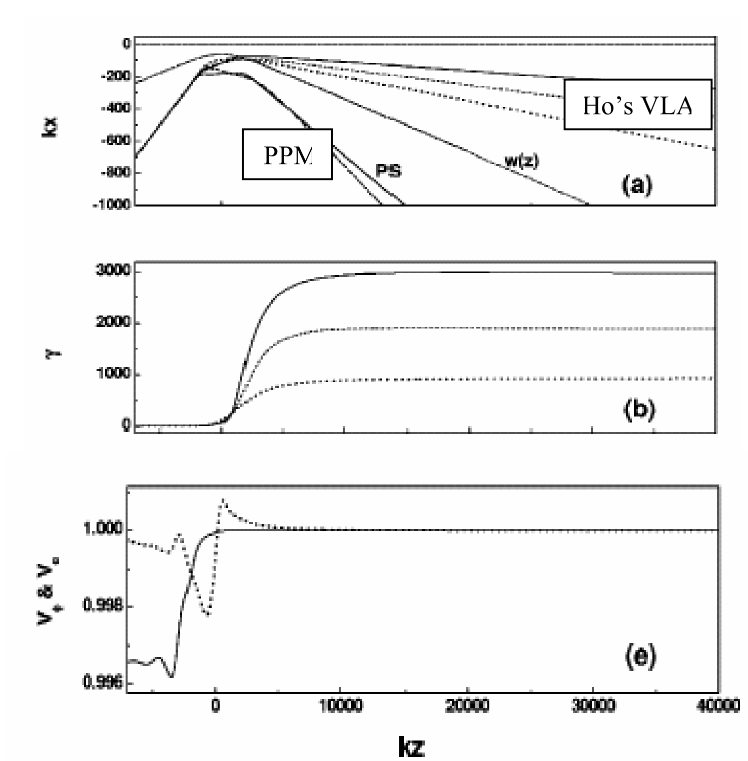

Figure 4: Output features of electrons at different laser intensity.

longitudinal electric field. Fig.3 presents the distribution of Q on the plane $y = 0$, which clearly demonstrates the existence of acceleration channels for a focused vacuum laser beam.

- The physical mechanism of the newly-proposed VLA scheme, CAS, is that relativistic electrons injected into this acceleration channel can be trapped in the acceleration phase and remain in the phase with the laser field for sufficient long times, thereby receiving considerable energy. The energy gain is primarily due to the axial electric field, and the maximum energy gain can be roughly estimated by: $\Delta E \approx 0.19 a_0 k w_0$ in unit of MeV. Furthermore, with 3-D simulations the conditions have been optimized for injecting electrons into the acceleration channel and making CAS scheme work. The laser intensity should be strong enough (a_0 ≥4), and the electron incident angle is sufficiently small ($\tan\vartheta \sim 0.1$). The optimum incident electron momentum is sensitive to the laser beam width, and should be in the range of 5-20 MeV. Typical simulation results are shown in Figure 4, where laser width kw0=60 and initial electron energy 6MeV are used. Figure 4-(a) is the dynamics trajectory at different laser intensity a_0 =100 (solid line), 60 (dashed line), and 30 (fine-dotted line); Figure 4-(b) is the energy gain; Figure 4-(c) shows the electron velocity and the phase velocity. It can be seen that the effective wave phase velocity along the CAS trajectories is less than c in the region near the beam waist, and it can even be less than the particle velocity, so that the energy gain can reach in order of GeV with a0=100. The Energy spectrum and angular spectrum of the output electrons at different laser intensities are shown in Figures 5 and 6, respectively. It is worthwhile to indicate that in Fig.5 the fraction of high-energy electrons is not exponentially decreased with energy as in many other laser-driven acceleration schemes.

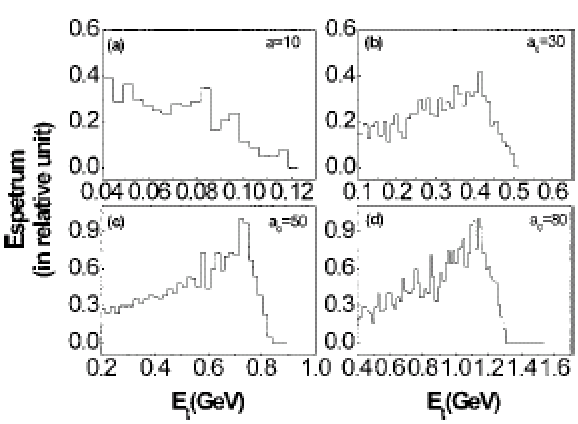

Figure 5: Energy spectrum of output electrons.

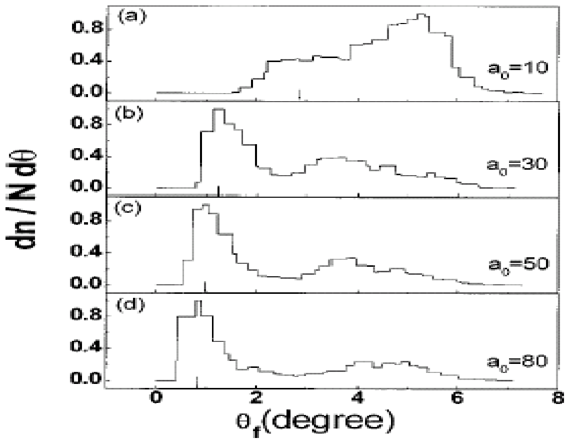

Figure 6: Angular spectrum of output electrons.

- One of the advantages of the CAS scheme is that optics and medium placed near the focal region are not essential, allowing use of high intensity laser and large energy gain.

Clearly, the newly proposed VLA scheme, CAS, is strongly supported with theoretical background. Provided this scheme could be confirmed experimentally, it would not only open a new approach to develop next generation of high-gradient and small-size laser accelerators, but be a significant progress in basic research as well.

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