High field gradient for electron acceleration and ultra-short electron pulse formation

A. E. Kaplan and A. L. Pokrovsky
Department of Electrical and Computer Engineering, Johns Hopkins University, Baltimore, Maryland 21218
sasha@striky.ece.jhu.edu

Abstract: We demonstrate possibility of multi-MeV electron acceleration and ultra-short electron bunch formation in the most basic "transverse" geometry of an electron beam and tightly focused laser beam whereby the beams propagate normally to each other.

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A universal way to attain high power with high efficiency within a broad spectrum is to use electron beams. Examples are free electron laser, its fore-runners, ondulator, powerful gyrotrons, Cherenkov radiation of relativistic electrons, the resonant transition radiation, etc. In most of these devices and effects, the electron (E) beam interacts with either the fabricated (periodic) structures *along* the axis of the periodicity or has to propagate inside a material, or through a large *dc* magnetic field. That means that the E-beam has to propagate almost parallel to the electromagntic (EM) wave propagation (and thus almost normally to the electric field of EM-wave), while the energy exchange is usually facilitated by a small electric field component, *parallel* to the E-beam. Such a "parallel-train" geometry is needed due to accumulative nature of the interaction: in the relatively weak EM-field the E-beam can pass only small part of its energy to a laser (L) beam within one wavelength, and thus, they have to propagate a long distance together, to be able to transfer significant energy from one to another.

We consider here a "perpendicular", or "transverse" geometry of the L- and E-beams, whereby they are propagating normally to each other. Two major factors allowing the E-beam to gain - and get accelerated (or lose - and radiate) large amount of energy within very few laser wavelengths are: (i) the large, relativistic intensities of tightly focused laser fields currently available ($\sim\ 10^{19} - 10^{20} W/cm^2$), that would allow electrons to gain energy beyond 10 MeV after passing the L-beam, which corresponds to near TeV/cm electron acceleration gradients (the highest gradient measured to date is 0.27 GeV/cm and it was generated by plasma-wakefield accelerator [1]); (ii) the large transverse gradients of the laser field, due to tight focusing, would allow electrons to run a very short distance to gain the energy, without having to return it back to the laser field.

To demonstrate the main effects we chose the most basic configuration of a laser standing wave formed by two counter-propagating (along y axis) linearly polarized L-beams with electric field parallel to the x axis, and an E-beam propagating parallel to the electric field polarization direction and passing through an anti-node plane of the standing wave where electric field has a spatial maximum and the magnetic field vanishes. The motion of the electron is then governed by the relativistic Lorenz equation for momentum of electron, p. By introducing normalized variables as: $\xi = kx$, $\tau = \omega t$, $\rho = p/mc$, $f(\xi) = eE(x)/mc\omega$, where $k = \omega/c$ is the wavenumber, and m is the rest mass of electron, $E(x)$ is the electric field profile in the anti-node plane of the L-beam ($E(x) \to 0$ when $|x| \to \infty$), we write it in general relativistic case as:

$$d\rho/d\tau = f(\xi)\sin(\tau + \phi); \quad d\xi/d\tau = \rho/\gamma, \text{ where } \gamma = \sqrt{1+\rho^2} \tag{1}$$

with γ being the relativistic factor. We neglected here the radiation ("friction") force on the electron; our estimates and simulations showed that it is negligible for the specific situation.

In general, Eq. (1) is not solved analytically, but it can be approximated in several practically important cases. The most common case of low gradient allows for adiabatic approximation by introducing a "slow" field-gradient (ponderomotive) force acting on a particle[2, 3]. In general, the result of the adiabatic approximation is that at the exit, (i) the particle output momentum and energy do not depend on the laser phase; (ii) it does not gain or lose energy (elastic scattering), and thus does not exchange energy with the EM-field.

To characterize adiabaticity and elasticity of electron scattering by the laser we introduce the following parameter $\mu \equiv 2\pi f_{mx}/(\xi_L\sqrt{\pi^2 + 4f_{mx}^2})$, where ξ_L is the scale of transverse field inhomogeneity, f_{mx} is the maximal amplitude of the profile. If $\mu \ll 1$, the exiting electron is expected to conserve its incident energy, while its original momentum is either conserved ("passing through" mode) or its sign is reversed ("reflection" mode). In an adia-

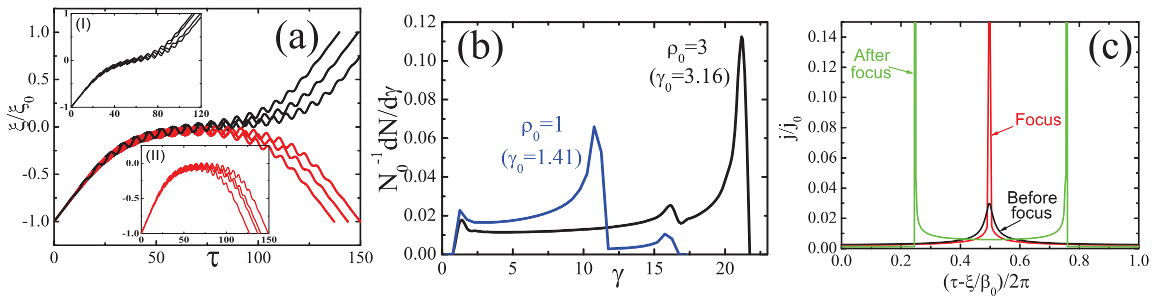

Fig. 1. a) Trajectories $\xi(\tau)$ of electrons scattered by a laser with 6 different phases equally spaced in the $[0; 2\pi]$ range. A near-Gaussian L-beam with $\xi_L = \pi$, $f_{mx} = 0.2$, and the incident momentum $\rho_0 = 0.1411 \approx \rho_{thr}$ for the main plot, $\rho_0 = 0.2 > \rho_{thr}$ for the inset (I) (transmission), and $\rho_0 = 0.1 < \rho_{thr}$ for the inset (II) (reflection). (b) Number of transmitted electrons (N) per energy for L-beam with $\xi_L = 2$, $f_{mx} = 12$. N_0 is the total number of incident electrons. (c) Focusing/bunching of electrons ($\rho_0 = 1$) by the L-beam ($\xi_L = \pi$, $f_{mx} = 0.04$). Temporal profile of the current density j before, at and after the focus.

batic situation, the output momentum and energy of an electron are incident-phase-independent, so that the slow (i. e. time-averaged for a single electron) momentum and energy coincide with the averaging over all possible phases - or ensemble of electrons (designated here by $\langle\,\rangle$), i. e. $\tilde{\rho} = \langle\rho\rangle$, and $\tilde{\gamma} = \langle\gamma\rangle$, and the system exhibits *ergodicity*.

Non-adiabatic, inelastic scattering occurs when the condition $\mu \ll 1$ is broken. It is easier to achieve $\mu \sim 1$ in relativistic field, $f_{mx} \gtrsim 1$, by having $\xi_L \lesssim \pi$ (L-beam diameter $\sim \lambda$ at focal point), than in nonrelativistic one by having $\xi_L \sim 2f_{mx} \ll 1$, which may be stringent, but not impossible to accomplish. The ultimate focusing of L-beam in vacuum is characterized by the spot size $\sim \lambda/2$ [4]; engineering of finer field distributions must include inhomogeneous (evanescent) wave components [5].

Manifestation of non-adiabatic, inelastic scattering is expected, for instance, when incident electron momentum, ρ_0 approaches the switching threshold. In this case one has a well pronounced "phase-dispersion" of the output electrons (Fig. 1a); the system ergodicity is not valid here anymore. Another typical example of inelastic electron scattering by strongly relativistic field, Fig. 1b, demonstrates a huge transfer of energy from the laser to E-beam. Because of the "phase-dispersion", there are, in general, transmitted and reflected from the L-beam electrons. For example, when the energy of incident electrons is 1.1 MeV ($\rho_0 = 3$), the transmitted spectrum is peaked at 10MeV with the width of about 0.6 MeV (FWHM). Remarkably, electrons acquired this energy over the distance of about one laser wavelength. This corresponds to a huge accelerating gradient ~ 0.1 TeV/cm. The reflected electrons acquire a similar energy gain and their spectrum has also a well pronounced peak.

The L-beam/E-beam "transverse" configuration under the study can also provide dramatic temporal klystron-like [6] focusing (E-bunch formation) of the E-beam after it passes through the L-beam. The system shows substantial momentum/speed modulation, so that the exiting E-beam bears the memory of the interaction within *each of laser cycles*. Beyond the exit, this may result in the shock-wave typical for a gas of non- or weakly-interacting particles, whereby the slower particles running in front of the group at some point (focus) are overrun by the faster particles coming from behind and creating for a moment infinite density at certain (focal) point. Similarly to the thin-lens approximation in optics, we construct "beyond the L-beam" electron trajectories by evaluating the time, τ_ξ, counted from e.g. beginning of the laser cycle, as laser phase ϕ plus the time lapsed from the moment an electron left that exit face, to the moment it reached distance ξ. The current density temporal profile, $j_\xi(\tau)$ (see Fig 1c), of E-beam at a distance ξ can in general be written as $j_\xi(\tau)/j_0 = [2\pi(d\tau/d\phi)]^{-1}$ (≥ 0), where $j_0 = j_{\xi=0}$. An estimate based on the spread of E-beam energy spectrum $\sim \Delta\gamma_{in} \sim 10^{-6}$ as in an electron microscope , $\xi_L = \pi$ and $f_{mx} \sim 0.04$, yields the electron bunch length $\Delta\tau_f \sim 1.5 \times 10^{-5}$, or $\Delta t_f \sim 45$ zs, which comes close to the quantum limit.

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