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Laser particle acceleration: beat-wave and wakefield experiments

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Abstract. In a plasma, some of the energy of a high-power laser beam can be transferred to a longitudinal plasma wave with a high phase velocity. This wave can in turn accelerate relativistic charged particles to very high energies. Several mechanisms have been proposed to generate these intense electric fields and some of them have already been tested experimentally. Using the beat wave method, electric fields of 1–10 GV m^{-1} have been produced and electrons have been accelerated with an energy gain from 1 MeV to more than 30 MeV. Some preliminary experiments have shown that electrons can be accelerated in plasma waves generated by the wakefield method. In the case of self-modulated wakefield, electric fields larger than 100 GV m^{-1} trap electrons and eject them from the plasma with an energy up to 100 MeV. The perspectives in the near future are the production of intense and short electron beams of a few MeV and the acceleration of electrons up to 1 GeV. To reach an energy of 1 TeV and get closer to the parameters required by the high-energy physicists, one will have to test some new methods to be able to guide the laser beam over large distances.

1. Introduction

In present day accelerators, the electric field is limited to less than 100 MV m^{-1} by breakdown problems in the metallic cavities. This leads to very long and very expensive structures; the best example is the LEP accelerator at CERN which is 27 km in circumference. To design smaller accelerators it is necessary to be able to generate much higher electric fields. A solution to this problem could be the use of lasers and plasmas. In high-power laser beams, the transverse electric field easily reaches 100 GV m^{-1}. Unfortunately these transverse fields cannot be used directly to efficiently accelerate particles to high energies. A plasma, however, is able to convert this transverse field in a longitudinal field suitable for the acceleration of relativistic particles (Schoessow 1995, Tajima and Dawson 1979).

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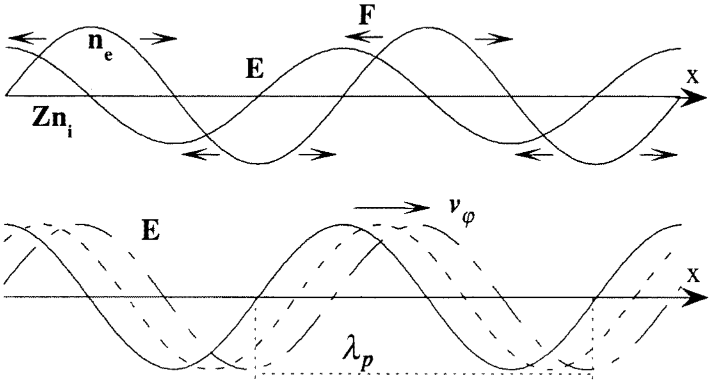

Figure 1. An electron plasma wave. Upper curves: representation of the electron density n_e, the ion density n_i, the electric field E and the restoring force F. Lower curves: the electric field at three successive times showing the propagation at the phase velocity v_φ. The space charge electric field E is responsible for the electron oscillation at the plasma frequency ω_p. Depending on the wavelength of the plasma wave, the phase velocity $v_\varphi = \omega_\mathrm{p}\lambda_\mathrm{p}/2\pi$ can be relativistic.

2. Principle of a plasma accelerator

In an electron plasma wave, the electric field due to the charge separation between electrons and ions can be very large. Moreover, if the wavelength of the wave is correctly chosen, the phase velocity is very close to the speed of light (cf figure 1). Thus a relativistic electron injected in the travelling wave will stay in phase with an accelerating field for a long distance (cf figure 2). For such a relativistic plasma wave, with a relative electron density perturbation δ ($n_\mathrm{e} = n_{\mathrm{e}0}[1 + \delta\cos(\omega_\mathrm{p}t - k_\mathrm{p}x]$), the electric field is given by

$$E_\mathrm{max} = mc\omega_\mathrm{p}\delta/e \qquad \text{i.e. } E_\mathrm{max}[\mathrm{GV\ m^{-1}}] = 30\delta\sqrt{n_{\mathrm{e}0}/10^{17}}$$

where $n_{\mathrm{e}0}$ is the equilibrium electron density in $\mathrm{cm^{-3}}$. In a plasma of density $10^{17}\mathrm{e}^-$ per $\mathrm{cm^3}$, corresponding to 2 mbar of fully ionized deuterium, and for a density perturbation close to 3%, the electric field is as high as 1 GV $\mathrm{m^{-1}}$.

The maximum energy gain is obtained on a distance l, over which the electron explores exactly half a plasma wavelength. In the case of an ultra relativistic electron, these quantities are given by

$$\Delta W_\mathrm{max} = eE_\mathrm{max}(2/\pi)l = 4\gamma^2mc^2\delta \approx 2\gamma^2\delta\ [\mathrm{MeV}] \qquad l = \gamma^2\lambda_\mathrm{p}$$

where γ is the relativistic factor associated with the phase velocity of the plasma wave. For a wave with $\gamma = 100$ and a wavelength $\lambda_\mathrm{p} = 100\ \mu\mathrm{m}$, the maximum energy gain is $\Delta W_\mathrm{max} = 20$ GeV over a distance $l = 1$ m.

3. The three possible schemes

Two mechanisms have been initially proposed to produce these relativistic waves: the beat wave and the wakefield. In both cases, the charge separation between electrons and ions in the plasma is due to the ponderomotive force which, in an inhomogeneous electromagnetic field, pushes the electrons out of the high-intensity zones while the ions stay almost immobile.

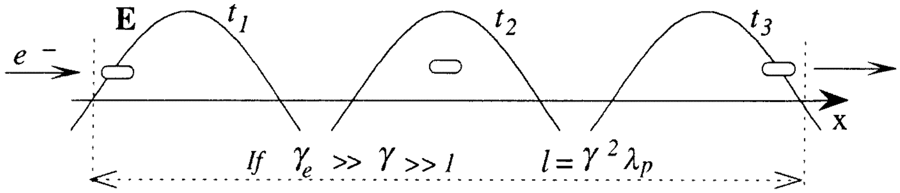

Figure 2. In the ideal case, an electron explores half a plasma wavelength before exiting the plasma. Entering the plasma at time t_1, an electron (relativistic factor γ_e), gains energy in a wave (relativistic factor γ) over a total length l.

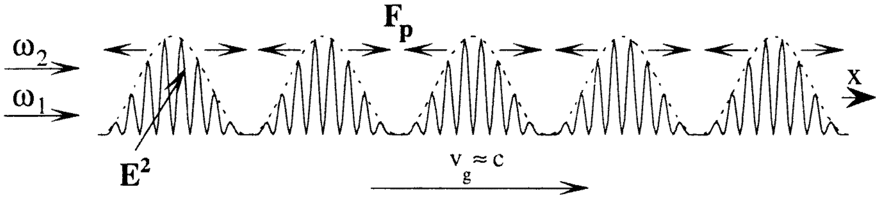

Figure 3. Beat wave. The beating between two beams with slightly different frequencies generates an inhomogeneous structure of the intensity E^2 and pushes the electrons out of the high-intensity zones. The whole picture moves at the group velocity of the incident electromagnetic waves.

In the case of a beat wave (figure 3), the inhomogeneity is obtained by superposition of two electromagnetic fields with slightly different frequencies ω_1 and ω_2. When the difference frequency $\delta\omega = \omega_1 - \omega_2$ is close to the natural oscillation frequency of the electrons in the plasma ω_p ($\omega_p^2 = n_{e0}e^2/m\epsilon_0$), an electron plasma wave is resonantly excited and the electric field reaches very high amplitudes. The phase velocity of the excited wave $(\omega_1 - \omega_2)/(k_1 - k_2)$ is equal to the group velocity of the electromagnetic waves which is very close to the speed of light c in a low-density plasma. The relativistic factor associated with the phase velocity v_φ is given by γ $(1/(1 - v_\varphi^2/c^2)^{1/2}) \approx \omega/\omega_p$, where ω is the mean laser wavelength.

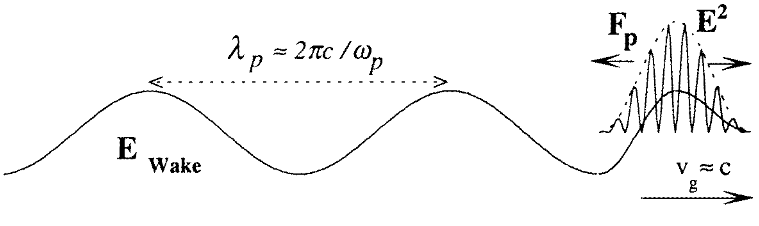

Figure 4. Wakefield. The envelope of the short laser pulse pushes the electrons forward and backward. A plasma wave is generated in the wake of the pulse.

In the case of a wakefield (figure 4), the ponderomotive force is related to the envelope of an ultrashort laser pulse: the rising front of the pulse pushes the electrons forward while the trailing edge pushes them backward. In the wake of the pulse the electrons then freely oscillate at the plasma frequency. The maximum efficiency is obtained when the pulse length τ is of the order of half the plasma period. This optimum pulse length is related to the electron density by $\tau[\mathrm{ps}] < 0.13/n_{17}^{1/2}$ (n_{17} is the electron density in $10^{17}\mathrm{e}^-$ per cm^3). For densities larger than $10^{17}\mathrm{e}^-$ per cm^3, this corresponds to subpicosecond pulses.

A third method has been recently proposed. In a plasma, an intense laser pulse excites Raman-type instabilities. The laser pulse propagates in the electron density perturbation generated by this instability and is spatially (or temporally) modulated with a wavelength (or period) exactly equal to the wavelength (or period) of a relativistic plasma wave (Antonsen and Mora 1992). The plasma then sees a series of ultrashort pulses perfectly matched for the production of very intense waves by the wakefield mechanism.

4. Experimental results and perspectives

4.1. Beat wave

The first acceleration experiments were based on the beat wave method (Martin *et al* 1987, Clayton *et al* 1993, Kitagawa *et al* 1992, Ebrahim 1994, Amiranoff *et al* 1995). As an example I will describe the experiment made at Ecole Polytechnique, France. A two-frequency laser beam ($\lambda = 1.053$ μm, 90 ps (FWHM), 10 J; $\lambda = 1.0642$ μm, 160 ps, 5 J) is focused in a vessel filled with deuterium at a pressure of approximately 2.2 mbar. The gas is fully ionized at the beginning of the pulse (Marquès *et al* 1993) thus generating a plasma with an electron density equal to the initial atomic density ($\approx 10^{17}$ cm^{-3}). The beating of the two wavelengths resonantly excites the accelerating plasma wave. A relativistic electron beam is injected and focused in the plasma and the spectrum of the accelerated electrons is measured by a magnetic spectrograph. In the case of Nd-glass lasers, at wavelengths close to 1 μm, we have shown that the growth of the plasma wave is limited by coupling with ion waves. In a few picoseconds, the coherent oscillation of the plasma electrons amplifies the ion density perturbations (Amiranoff *et al* 1992, Moulin *et al* 1994); the plasma becomes inhomogeneous and the laser excitation becomes out of phase with respect to the electron plasma oscillation. The electron density perturbation associated with the accelerating wave saturates at a level of a few percent and the maximum electric field is of the order of 1 GV m^{-1}.

The electron spectra after the plasma are shown in figure 5. The maximum energy gain is 1.4 MeV corresponding to a 0.7 GV m^{-1} electric field over a characteristic length of 2.8 mm. The second important effect that we have observed is the dephasing between the injected electrons and the phase velocity of the plasma wave. The electrons are always slower than the wave and successively explore accelerating and decelerating regions of the field. As shown in figure 5 this effect is more pronounced for slower electrons.

The situation is more favourable in the experiments realized with CO_2 lasers at wavelengths close to 10 μm (Clayton *et al* 1993, Kitagawa *et al* 1992, Ebrahim 1994). First, because of the much larger wavelength compared to the Nd case, the pump term, which is proportional to λ^2, is 100 times larger. Second, the density is close to $10^{16}\mathrm{e}^-$ per cm^3, i.e. 10 times lower; the typical ion period is 3 times longer. The dominant saturation mechanism is no longer the coupling with ion waves, but the relativistic dephasing which occurs when the oscillation velocity of the electrons in the plasma wave becomes relativistic: the plasma frequency is thus modified and the resonant condition is no longer fulfilled. The maximum density perturbation reaches 30%, the electric field is 3 GV m^{-1} and the maximum energy gain is close to 30 MeV (Clayton *et al* 1993, Ebrahim 1994).

To reach higher electric fields, it is important to generate the plasma wave before the ions have time to move significantly, i.e. in times shorter than a few ion plasma periods. In

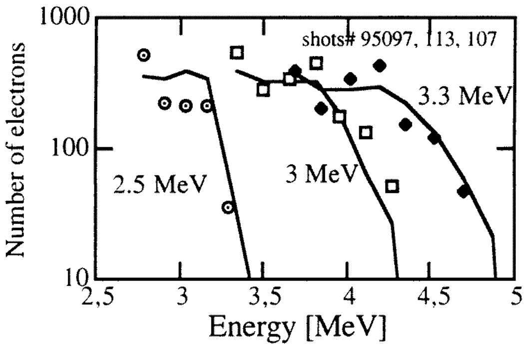

Figure 5. Electron spectra measured in Nd-glass beat wave experiments (Amiranoff *et al* 1995). The injection energies are 2.5, 3 and 3.3 MeV. The full arcs are the results of the theoretical model for the parameters $L = 2.8$ mm (typical acceleration length) and $\delta = 2.4\%$ ($E = 0.7$ GV m^{-1}, maximum accelerating field), and a plasma wave lifetime of 3 ps.

principle, an energy gain of 1 GeV can be obtained with Nd-glass lasers for pulse lengths of a few picoseconds and energies of 10–20 J. This type of experiment could be realized in the near future with techniques used to generate subpicosecond pulses (Joshi *et al* 1994).

4.2. Low-density wakefield

Intense and short pulse lasers have been available only recently and few experiments have been performed on this scheme. The first indirect measurement of the wakefield has been the detection of the electromagnetic emission of the electrons moving in the plasma wave (Hamster *et al* 1993). In another experiment realized with a Nd-glass laser, electrons have been accelerated from 1–13 MeV (Nakajima *et al* 1995). More recently the wakefield has been precisely measured by optical diagnostics in conditions where the density perturbation is mainly radial (Marquès *et al* 1996).

A clear and precise confirmation of the acceleration of electrons in the wake of a laser pulse is still to be done. It should be performed in the near future with Nd lasers, with a pulse duration of the order of 300 fs and power of a few terawatts. On a longer time scale, one could accelerate electrons up to 1 GeV with a laser energy of 25 J and 100 fs pulses.

4.3. Self-modulated wakefield

The most spectacular results have been obtained by focusing ultrashort laser beams in a gas jet at pressures of the order of 1 bar. The cumulative effects of self-focusing and modulation of the pulse generates a very intense wave in the wake of the laser pulse. This wave traps plasma electrons and accelerates them up to a maximum energy which mainly depends on the plasma density. The best results are a maximum energy of about 50 MeV and accelerating fields larger than 100 GV m^{-1} (Modena *et al* 1995, Umstadter 1995, Nakajima *et al* 1995).

Because of the high density which is necessary for this self-modulation to occur, the energy gain is limited to modest values. Nevertheless, this technique can be used to generate ultrashort electron pulses at energies of a few MeV (Umstadter *et al* 1996).

5. Conclusions

The first studies on the acceleration of charged particles by lasers in plasmas have given promising results. Electric fields of 1–100 GV m^{-1} have been produced and electrons have been accelerated up to a few tens of MeV. One can distinguish two different approaches. Working in high-density plasmas, one can generate short and intense electron beams at a few MeV. Synchronized with an ultrashort laser beam, these electron pulses can be used for fundamental studies where one needs an electron beam and a laser beam simultaneously. In low-density plasmas, the energy gain is no longer limited by the velocity of the wave itself but by the acceleration length. An important aspect of future studies will be the guiding of laser pulses over distances much longer than the Rayleigh length, the natural diffraction length of a beam in vacuum. Several schemes have been proposed as the generation of plasma guides comparable to classical optical fibres. The other important topic which has to be studied is the quality of the beams accelerated by the different techniques. The energy dispersion, the divergence and the maximum current of the beam are topics which will be addressed in the next few years.

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