IL NUOVO CIMENTO Vol. 34 C, N. 4 Luglio-Agosto 2011
DOI 10.1393/ncc/i2011-10915-9

Colloquia: Channeling 2010

The physics of the laser-plasma accelerators: Challenges and limits

D. Giulietti(*)
Dipartimento di Fisica and INFN, Sezione di Pisa - Pisa, Italy

(ricevuto il 22 Dicembre 2010; pubblicato online il 7 Luglio 2011)

Summary. — To meet the challenge of future accelerators based on the laser-plasma techniques new experimental schemes have to be investigated and a strategy on the laser technology to get ultra-high peak power as well as very high average power formulated. Top-level laser requirements for potential laser-based accelerator applications will be needed and the major limits to the electron energy gain have to be overcome, including laser pulse diffraction, electron dephasing and laser pulse energy depletion. A viable alternative to the multi-stage acceleration scheme could be a greater control of the laser pulse evolution in the underdense plasma that could inhibit filamentation and other detrimental instabilities as Raman and self-phase modulation enabling the full exploitation of the laser guiding over several Rayleigh lengths. A brief overview will be given of those aspects of laser plasma acceleration leading to a completely new generation of compact sources of energetic particles. In particular, a simplified introduction to the field of electron laser wakefield acceleration will be first given and some recent experiments reported.

PACS `52.38.-r` – Laser-plasma interactions.
PACS `52.38.Kd` – Laser-plasma acceleration of electrons and ions.

1. – Introduction

The story starts in the last 1970s when Tajima and Dawson [1] proposed an innovative particle acceleration scheme, the so-called *laser wakefield acceleration* (LWA) based on the laser pulse propagation in a plasma. The laser pulse, via the ponderomotive force (proportional to the gradient of the laser intensity) acting on the electron density, induces huge electric fields (100 GV/m and greater) up to 4 orders of magnitude greater than the ones set in the conventional accelerators. The availability of such enormous fields (consequence of the electrons-ions separation) is basically due to the matter being already ionized in a plasma, so that no limitation is needed on the field strength in order to avoid the material breakdown. The electrons expelled by the most intense laser pulse region

(*) E-mail: `danilo.giulietti@df.unipi.it`

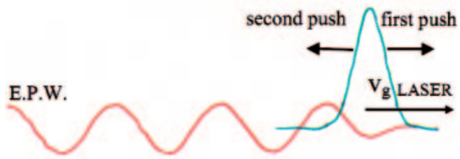

Fig. 1. – A schematic representation of a laser pulse inducing an electron plasma wave, via the ponderomotive force.

accumulate just behind the e.m. packet, thus producing an electron density perturbation in the wake of the laser pulse itself. Depending on the intensity and other laser pulse parameters (like the longitudinal and transversal dimensions) such a perturbation can assume different shapes and plasma waves in a non-linear regime can be excited.

The physical situation is very similar to that of a boat moving on the sea surface, the gravity playing the role of the ponderomotive force in the previous case. The water moves from the immersed volume of the boat towards the stern, where it accumulates in the first crest of a wave produced in the boat wake. The amplitude of this wave depends on the volume of the immersed part of the boat and other parameters like the shape and the velocity of the boat. However there is a major difference between the two cases, related to the nature of the two media in which such similar phenomena develop. While the water is a non-resonant medium, a plasma exhibits a resonant frequency, the so-called *plasma frequency* $\omega_p = \sqrt{4\pi n_e e^2/m_e}$, at which any electron density perturbation evolves in time. It follows that the excitation of the plasma wave is strongly enhanced when the laser pulse length fits in half of the plasma wavelength $\lambda_p \approx 2\pi c/\omega_p$ (*Langmuir length*). In this case the ponderomotive force associated to the laser pulse expels electrons from a region whose dimension matches the one of a density minimum region of a plasma wave. With this respect, this wakefield generation process can be considered as *quasi-resonant* (see fig. 1).

Once excited, the plasma wave has the right characteristics to accelerate electrons, which are injected in it, up to very high energy. Indeed, in the usual experimental conditions, the huge longitudinal electric field moves with a phase velocity, set by the laser pulse group velocity, very close to c. However, in order to gain as much energy as possible from the plasma wave, electrons need not only to be injected into the plasma wave with the suitable phase but also to experience an electric field of the same sign during the whole acceleration process. To be fulfilled, this condition requires, from the beginning of the process, relativistic electrons with an initial velocity close to c, which then increase their energy during the acceleration process. Once again this physical situation is very similar to another one that involves the sea waves and the surfers. Indeed, the surfer goes into the wave in a suitable phase of the wave and with an appropriate velocity. Only in this way he can acquire further velocity, while he is descending from the crest to the valley of the wave. After that he has to leave the wave, otherwise he is suddenly stopped.

2. – Laser-plasma acceleration: 1D model

The maximum energy gained by the electron in this acceleration process depends essentially upon the amplitude of the accelerating electric field, that is of the excited plasma wave, and the length of the path along which this acceleration occurs. Although a general approach to this issue is very complicated, in particular when non-linear processes have to be considered, a 1D model [2, 3] in the case of small-amplitude plasma waves can provide a satisfactory description, at least from a qualitative point of view, of the physical situation. In the frame of this model, if the velocity of the injected electron is already relativistic, the dephasing length comes out to be (see as an example [4] and references therein) $L_{\rm dph} \approx \gamma_p^2 \lambda_p$, where $\gamma_p = \omega_L/\omega_p$ is the Lorentz factor of the plasma wave (ω_L is the laser angular frequency). Moreover the maximum accelerating electric field scales as $n_e^{1/2}$ (as a consequence of the largest charge separation attainable in a plasma with a density n_e) and the dephasing length scales as $n_e^{-3/2}$ (as a consequence of the highest phase velocity of the plasma wave, imposed by the laser pulse group velocity). This leads to the maximum attainable energy scaling as $1/n_e$.

3. – Extending the acceleration length

From an experimental viewpoint, the situation is much more complicated. Indeed, when the plasma density is decreased so that the acceleration length can reach the cm scale, actually we face with the difficulty of creating so long and homogeneous laser plasmas. Moreover, in order to create and maintain high-amplitude plasma waves over such long distances, the laser intensity, on which the ponderomotive force depends, needs also to be kept sufficiently high. This condition is very difficult to be fulfilled due to the fundamental laws governing the focusing of an e.m. beam. As is well known, in the case of a Gaussian beam propagating in vacuum the longitudinal extent of the most intense region of the beam is quadratically related to the transversal one, as shown by the expression of the *Rayleigh length*, the distance, along the propagation direction, from the waist to the point where the intensity decreases by a factor 2: $z_R = \pi w_0^2/\lambda$, w_0 being the beam size in the waist. According to this formula, the intensities required for the wakefield acceleration scheme ($I_0 \approx 10^{19}\,\mathrm{W \cdot cm^{-2}}$) can be only maintained, with the laser pulse duration ($\tau \approx 20$–$30\,\mathrm{fs}$) and energies ($E_L \approx 5$–$10\,\mathrm{J}$) current available, on a mm scale ($L_{\rm acc} \approx 2E_L/(I_0 \tau \lambda) = 1$–$10\,\mathrm{mm}$). However, this length can be increased, *e.g.*, by suitably preforming a plasma channel and/or exploiting such phenomena as relativistic and ponderomotive self-focusing (see, for example, [5, 6]). Moreover, a very promising technique to overcome the above-mentioned difficulties is to let the laser pulse propagate in a suitable hollow optical fiber, in which a preformed plasma is created via electrical discharge [7].

4. – LPA experiments with ultra-short laser pulses

At this point a question might be arised: why we had to wait the advent of high-intensity, ultra-short laser pulses for developing the LWFA technique? The reasons are essentially two. The first and simpler one is that the high intensities required for the generation of electron plasma waves are easily achievable only with such lasers. However, the main reason is that, due to the "quasi- resonant" nature of the laser wakefield process, electron plasma waves at relatively high densities, required for obtaining an extremely high accelerating electric field (see above), can only be excited with sub 100 fs laser pulses.

After the first LPA experiments (*beat wave* and *self-modulated wakefield acceleration* schemes), in the mid-90s the overwhelming development of table-top multi TW, ultra-short pulse Ti:Sa lasers, based on the CPA technique, suddenly changed the scenario. Indeed, in laser-plasma experiments at high intensity, mainly conceived to investigate the physical mechanisms relevant for the Inertial Confinement Fusion (ICF), more and more energetic electrons were produced as the laser intensities increased and the pulse duration decreased. Reducing the laser pulse duration while still increasing its intensity led to the so-called *laser wakefield acceleration* (LWFA) scheme to be directly accessed with table-top laser systems. Within this scheme a short laser pulse directly creates a blowout region of depleted electron density due to the ponderomotive force $f_{\mathrm{pond}} = -(e^2/4m_e\omega^2)\nabla E_0^2$ (in the non-relativistic limit).

In one of the first LPA experiments carried out at the LOA facility in Palaiseau (France) [8], highly collimated bunches of high energy electrons were produced by focusing super-intense femtosecond laser pulses at an intensity of $8 \times 10^{19}\,\mathrm{W/cm^2}$ in sub-millimeter under-dense plasmas. In such experiment a thin plastic foil was exploded by the pedestal (lasting several ns) of the ultra-short pulse, thus producing a pre-plasma suitable for the quasi-resonance of a 35 fs main laser pulse with the electron plasma waves. The density of the plasma was mapped using Nomarski interferometry. The electron beam was fully characterized: up to 10^9 electrons per shot were accelerated, most of which along the laser axis in a beam of aperture $\approx 10^{-2}$ rad, with energies up to 40 MeV.

Although very stimulating for the groups active in the field of LPA, experiments performed using thin foils as targets were soon recognized as having a major drawback when high average flux particle (electrons or photons) sources have to be built. Indeed, solid targets are not suitable to fully exploit the 10 Hz repetition rate potential of most of the table-top joule class Ti:Sa laser systems available today, as the requirement for a fresh surface at each shot cannot be easily fulfilled. Thus, gas-jet targets are now mostly employed for laser-plasma electron acceleration experiments, which can in principle run at a few tens Hz.

In the last few years, a highly nonlinear regime of laser-plasma interaction was studied, which gives rise to a highly electron depleted, nearly spherical, region, called *bubble*, where self-injected electron bunches are subsequently accelerated up to very high energies and quasi-monochromatic electron beams (with energy spreads of the order of some %) can be obtained [9-11]. The electron trapping mechanism in this regime is somehow different from the LWFA one, due to just longitudinal or transverse wavebreaking. As clearly showed in the 3D PIC simulations reported in [9], the trajectories of the electrons, which experience both the ponderomotive force of the laser pulse and the Coulomb field due to the bubble, are such that electrons initially close to the propagation axis accumulates just at the rear of the bubble itself, thus getting trapped and being accelerated (see fig. 2).

This regime is particularly interesting, as it enables to foresee an actual chance of going in the near future from laser plasma acceleration experiments to real laser plasma based accelerators, with electron bunch parameters, such as energy spread and emittance, suitable for high-energy particle experiments.

From an experimental viewpoint, using simple gas-jet targets, electron beams with energy up to a few hundreds of MeV, accelerated over millimeter distances, have been produced so far, with energy spread of the order of 5–10% and total charge of some hundreds of pC [7,12,13]. In a recent experiment, the use of a capillary to guide the laser pulse over long distances at an intensity suitable for the excitation and the propagation of the plasma wave allowed to get a 1 GeV electron beam, with an acceleration length of 33 mm [14]. In that experiment, the laser pulse was successfully guided through a 400 μm diameter H_2-filled capillary discharge waveguide, made up of alumina. Parameters of the waveguide size, the gas pressure and the discharge current were previously optimized so as to have a good guiding of the main laser pulse, with very small losses.

Recently, a successful experiment [15] using a two-pulse scheme has been reported, designed in particular in order to have a better control of the electron injection into the plasma wave, thus improving the stability and the control of the electron bunch

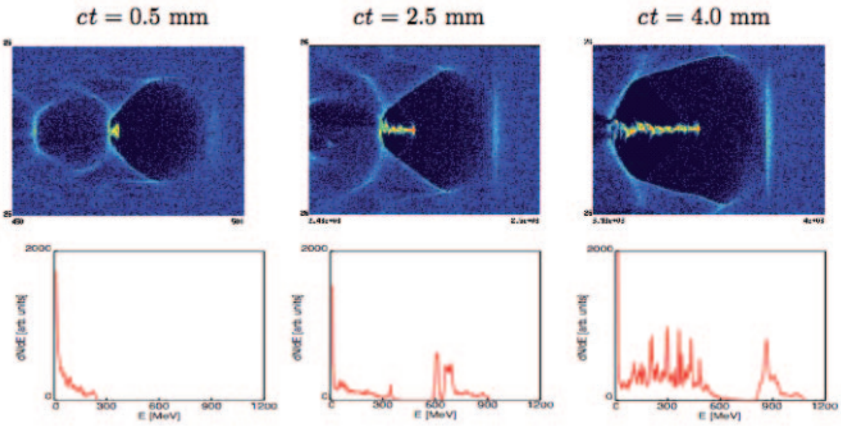

Fig. 2. – Particle In Cell (PIC) simulation of a 30 fs laser pulse propagating in a plasma ($n_e = 3 \times 10^{18}\,\text{cm}^{-3}$ electron density) at an intensity $I_0 = 5.2 \times 10^{19}\,\text{W}\,\text{cm}^{-2}$. In the top the electron plasma density distributions, while in the bottom the spectra of the accelerated electrons for three acceleration lengths. (Courtesy of Carlo Benedetti.)

parameters such as energy and energy spread. In detail, two counter-propagating laser pulses were used in the experiment: the main one, that is the one with the greater amplitude, creates a wakefield, whereas the second one was used for injecting electrons into the wakefield with the proper phase and in the proper place in the plasma. Indeed, in the region where the two beams cross each other a standing wave is created which, due to the radiation pressure, can inject very small bunches of electrons into the wake of the first pulse. The method, although leading to small total charge in the electron bunch (of some tens up to a few hundreds of pC) allows in principle a fine control of the electron energy and to very small values of the bunch duration (of the order of 10 fs) and of the energy spread, of the order of 1%, by properly tuning the plasma parameters and the time delay between the two pulses.

5. – Perspectives and conclusions

It should be noted here that the requirements for the free-electron-lasers and high-energy accelerators for particle physics experiments are still more stringent. As for the maximum energy, two-stage laser plasma accelerators have been considered so far. However, even if the most attractive answer to the requirements by high energy physicists seems to be the external injection of relativistic electron bunches from a LINAC into a plasma wave, no experiments have been carried out so far using a laser wakefield acceleration stage in order to accelerate electrons from a LINAC. Actually, this is a very challenging task: even from a simple argument one can realize that the injection of an electron bunch into plasma waves with wavelength smaller than $100\,\mu$m would require a laser and a LINAC synchronized with a jitter of the order of 10 fs!

In conclusion, we can say that the development of the ultra-short and ultra-intense laser systems based on the CPA technique enables to foresee a clear way to get miniaturized (table-top) particle accelerators and related sources of X/gamma-rays. Such a reduction in dimensions and costs has made the application of these innovative apparatuses to several fields, from medical diagnostics and therapy to material science and femtochemistry, realistic. Furthermore, particles accelerated by laser-plasma interaction can be used in the fast-ignition approach to ICF. For these reasons, national as well as international efforts are now in progress to fully investigate the new physics that the laser-matter interaction at such unprecedented intensities will open up.

REFERENCES

[1] Tajima T. and Dawson J. M., *Phys. Rev. Lett.*, **43** (1979) 267.
[2] Sprangle P., Esarey E. and Ting A., *Phys. Rev. A*, **41** (1990) 4463.
[3] Dawson J. M., *Phys. Rev.*, **113** (1959) 383.
[4] Esarey E., Sprangle P., Krall J. and Ting A., *IEEE Trans. Plasma Sci.*, **24** (1996) 252.
[5] Bonnaud G., Brandi H. S., Manus C., Mainfray G. and Lehner T., *Phys. Plasmas*, **1** (1994) 968.
[6] Esarey E., Sprangle P., Krall J. and Ting A., *IEEE J. Quantum Electron.*, **33** (1997) 1879.
[7] Geddes C. G. R., Toth Cs., van Tilborg J., Esarey E., Schroeder C. B., Bruhwiler D., Nieter C., Cary J. and Leemans W. P., *Nature*, **431** (2004) 538.
[8] Giulietti D., Galimberti M., Giulietti A., Gizzi L. A., Numico R., Tomassini P., Borghesi M., Malka V., Fritzler S., Pittman M., Ta Phouc K. and Pukhov A., *Phys. Plasmas*, **9** (2002) 3655.
[9] Pukhov A. and Meyer-ter-Vehn J., *Appl. Phys. B*, **74** (2002) 355.
[10] Kostyukov I., Pukhov A. and Kiselev S., *Phys. Plasmas*, **11** (2004) 5256.
[11] Pukhov A., Gordienko S., Kiselev S. and Kostyukov I., *Plasma Phys. Control. Fusion*, **46** (2004) B179.
[12] Mangles S. P. D., Murphy C. D., Najmudin Z., Thomas A. G. R., Collier J. L., Dangor A. E., Divall E. J., Foster P. S., Gallacher J. G., Hooker C. J., Jaroszinski D. A., Langley A. J., Mori W. B., Norreys P. A., Tsung F. S., Viskup R., Walton B. R. and Krushelnick K., *Nature*, **431** (2004) 535.
[13] Faure J., Glinec Y., Pukhov A., Kiselev S., Gordienko S., Lefebvre E., Rousseau J.-P., Burgy F. and Malka V., *Nature*, **431** (2004) 541.
[14] Leemans W. P., Nagler B., Gonsalves A. J., Toth Cs., Nakamura K., Geddes C. G. R., Esarey E., Schroede C. B. and Hooker S. M., *Nature Phys.*, **2** (2006) 696.
[15] Faure J., Rechatin C., Norlin A., Lifschitz A., Glinec Y. and Malka V., *Nature*, **444** (2006) 737.