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C. R. Physique 10 (2009) 106–115
Comptes Rendus Physique

Laser acceleration of particles in plasmas / Accélération laser de particules dans les plasmas

Principles of laser–plasma accelerators

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Available online 25 April 2009

Abstract

The continuing development of powerful laser systems has permitted to extend the interaction of laser beams with matter far into the relativistic domain in which extremely high electric and magnetic fields are generated. Thanks to these tremendous fields, that only plasma can support and sustain, new and compact approaches for producing energetic particle beams have been recently achieved. The incredible progress of these laser–plasma accelerators has allowed physicists to produce high quality beams of energetic radiation and particles. These beams have interesting properties such as shortness, brightness and spatial quality, and could lend themselves to applications in many fields, including medicine (radiotherapy, proton therapy, imaging), radiation biology (short-time-scale), chemistry (radiolysis), physics and material science (radiography, electron and photon diffraction), security (material inspection), and of course accelerator science. Stimulated by the advent of compact and powerful lasers, with moderate costs and high repetition rate, this research field has witnessed considerable growth in the past few years, and the promises of laser–plasma accelerators are in tremendous progress. The recent years in particular have seen spectacular progress in the acceleration of electrons and of ions, both in terms of energy and in terms of quality of the beams. ***To cite this article: V. Malka, P. Mora, C. R. Physique 10 (2009).***

Résumé

Les accélérateurs de particules laser–plasma. Le développement continu des lasers de puissance a permis d'étendre les régimes d'interaction laser–matière dans le domaine relativiste, dans lequel des champs électriques et magnétiques très élevés sont générés. Grâce à ces champs très élevés, que seul un plasma peut supporter et maintenir, de nouvelles approches pour la production de faisceaux de particules énergétiques ont été récemment réalisées. Les progrès de ces accélérateurs laser–plasma ont permis de produire des faisceaux de particules et de rayonnement énergétiques de grande qualité. Ces faisceaux ont des propriétés intéressantes comme la brièveté, la brillance et la qualité spatiale, et peuvent conduire à des applications dans de nombreux domaines, comme la médecine (radiothérapie, protonthérapie, imagerie), la biologie (radiographie à haute résolution temporelle), la chimie (radiolyse), la physique et la science des matériaux (radiographie, diffraction d'électrons et de photons), la sécurité (méthodes d'inspection), et évidemment la physique des accélérateurs. Stimulé par l'avènement de lasers compacts et puissants, de coûts modérés et de haut taux de répétition, ce champ de recherche a eu un essor considérable ces dernières années, et les potentiels des accélérateurs laser–plasma se sont considérablement accrus. Les années récentes ont vu en particulier des progrès spectaculaires dans l'accélération des électrons et des ions, à la fois en termes d'énergie et de qualité de faisceau. ***Pour citer cet article : V. Malka, P. Mora, C. R. Physique 10 (2009).***

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1631-0705/$ – see front matter
doi:10.1016/j.crhy.2009.03.008

Keywords: Plasma; Laser; Acceleration

Mots-clés : Plasma ; Laser ; Accélération

1. Introduction

The acceleration of electrons in the laser–plasma interaction has been observed since the 1970s, when it was initially considered as a deleterious effect, as, in the inertial fusion context, the so-called suprathermal electrons preheat the target. However, it has been quickly observed that a large benefit could be taken from these electrons. Two main directions are now followed. In the first direction, one tries to accelerate electrons to high energy, presently in the GeV range. The electrons may originate from a pre-accelerated beam, or directly from a gas target instantaneously transformed in a plasma by the ultra-intense laser pulse. In the second direction, one tries to transfer the energy of the electrons to fast ions, especially protons, presently in the few tens of MeV range. Thin targets are used for this transformation, the electrons being accelerated at the front of the target, while the ions may originate from the front part or the back part of the target, or from inside the target, depending on the parameters of the experiment. While the maximum energy was the initial goal of the pioneer experiments, there are now strong experimental efforts to improve the quality of the beams, in terms of luminosity, emittance, and energy spectrum. In the recent years, quasi-monoenergetic beams were obtained both for electrons and for ions.

2. Vacuum electron acceleration

A first question which arises is whether electrons (or ions) can be directly accelerated by the laser field in vacuum. Actually electrons were accelerated in the sub-MeV range with focused lasers of intensity in the $10^{19}\ \mathrm{W\,cm^{-2}}$ range [1]. A discussion of this experiment and a general theory was presented in Ref. [2]. It appeared that one can distinguish two regimes, depending on the initial velocity of the electron before its interaction with the laser field and the laser beam waist at focus. In the first regime (initial velocity not to close to the light velocity, i.e., $1 - v_z/c \gg 1/kw_0$, where v_z is the component of the electron velocity parallel to the laser propagation direction, c is the velocity of light, k is the laser wavevector, and w_0 is the beam waist at focus), the averaged particle motion does not depend on the polarization and on the phase of the laser field and can conveniently be described by the relativistic ponderomotive force. In the second regime the electron motion is more complicated, with a high sensitivity on the phase of the laser field and on the initial distance from the laser propagation axis. In addition, the net energy gain is rather modest, even for very intense laser fields. These results are not surprising as it is known that one obtains no final energy gain: (i) for a purely plane wave of arbitrary amplitude; and (ii) for electrons already in the ultra-relativistic regime [3].

3. Laser–plasma accelerator

The above conclusions are rather different in the laser–plasma accelerator case, as the plasma can act as a kind of transformer which changes the electromagnetic pulse, characterized by a high frequency transverse field, into a low frequency longitudinal wave, much more efficient in accelerating particles, as conventional accelerators do. The basic concept, initially presented by Tajima and Dawson [4], is rather simple. The ponderomotive force due to the front part of a short pulse pushes the plasma electrons in the forward direction, while the ponderomotive force due to the back part of the pulse pushes the electrons backward. If the pulse width at half maximum is approximately half the plasma period, then these two effects combine to launch a large amplitude plasma wave in the wake of the laser pulse. A characteristic of the plasma wave is that its phase velocity is equal to the group velocity of the laser pulse. In a low density plasma, where the plasma frequency ω_{pe} is much lower than the laser frequency ω_0, this velocity is quite close to the light velocity. As a result, electrons externally injected and trapped in the wake can gain a significant amount of energy until dephasing reverses the acceleration. The basic concept was later explicited and extended to a three-dimensional electromagnetic pulse by Gorbunov and Kirsanov [5].

When this concept was first presented, the duration of available laser pulses was not short enough to enable efficient acceleration in typical laboratory plasmas. On the other hand, an alternative concept, also proposed by Tajima and Dawson, was to use two laser pulses of frequencies ω_0 and ω_1 such that $\omega_0 - \omega_1 \approx \omega_{pe}$ to produce a beating at the plasma frequency, effectively dividing the long laser pulse in successive short pulses of duration $2\pi/\omega_{pe}$. This structure resonantly excites a plasma wave which amplitude saturates due to relativistic detuning [6] or modulational instability (via a coupling with the ions) [7]. Efficient acceleration was obtained in the 1–30 MeV range with CO_2 lasers or glass lasers [8].

The compression of amplified chirped optical pulses [9] opened a wide field of new research with subpicosecond ultra-intense pulses, and in particular enabled the first laser wakefield acceleration experiment in the original Tajima and Dawson regime at Palaiseau, where the acceleration of injected electrons of a few MeV was obtained, with a low density plasma ($n_e = 2.2 \times 10^{16}\ \mathrm{cm}^{-3}$) and a 400 fs, 1.057 μm, $4 \times 10^{17}\ \mathrm{W/cm^2}$ laser [10].

4. Self-modulated laser wakefield acceleration

Due to their large power, the subpicosecond ultra-intense pulses may be subject to a variety of nonlinear effects. The first identified nonlinear effect is the self-focusing of the laser pulse due to the relativistic variation of the plasma index of refraction along the pulse radius [11]. However it was soon recognized that a powerful pulse with a pulse duration τ verifying $\omega_{pe}\tau \geqslant 2$ is also subject to Raman-type instabilities which modulate its longitudinal profile [12] at a frequency close to the electron plasma frequency. As a result, a plasma wake can be resonantly excited, as in the beat wave case. It appeared that the plasma wave amplitude obtained in the corresponding experiment made by Modena et al. [13] at Rutherford Appleton Laboratory was of such amplitude that it eventually broke, with the production of electrons in the 50 MeV range or above. In this experiment, the plasma density was about $10^{19}\ \mathrm{cm}^{-3}$, and the characteristics of the laser were 800 fs, 1.054 μm, and $6 \times 10^{18}\ \mathrm{W/cm^2}$.

5. The bubble regime

In the previous sections all the electron beams that have been produced had a Maxwellian-like distribution. For beatwave and wakefield experiments, this was due to the duration of the injected electron beam, which was much longer that the plasma period. For the self modulated laser wakefield, this was due to heating mechanisms which occur during a period of time much longer that the plasma period. The appearance of a plateau in the electron distribution which extends up to 200 MeV and the improvement of the beam divergence have been obtained in the forced laser wakefield regime [14], at Laboratoire d'optique appliquée (LOA) with a 10 Hz, 30 TW laser. In this regime, the laser pulse duration, initially of the order of the plasma period, is strongly compressed down to 10 fs [15], and drives relativistic plasma waves to very high amplitudes, into the so-called nonlinear regime. Electrons rather than being injected in the tail of the laser pulse by heating processes are in this scheme injected behind the laser pulse. A further progress was obtained by Pukhov and Meyer-ter-Vehn [16] who explored a highly nonlinear regime where the wake of an ultra-short laser pulse takes the form of a bubble from which electrons are almost totally expelled by the ponderomotive force of the laser pulse. At the back of the bubble, electrons can be trapped and accelerated forming a quasi-mono-energetic beam. The formation of the bubble corresponds to an electron cavitation and to a radial wavebreaking of the electron density perturbations, as already observed in Refs. [17] and [18]. A continuous transition between the self-modulated laser wakefield, forced laser wakefield, and bubble regimes has been measured by changing the electron density, i.e., by changing the ratio pulse length/plasma wavelength [19]. Fig. 1 shows a scheme of the principle of the bubble regime.

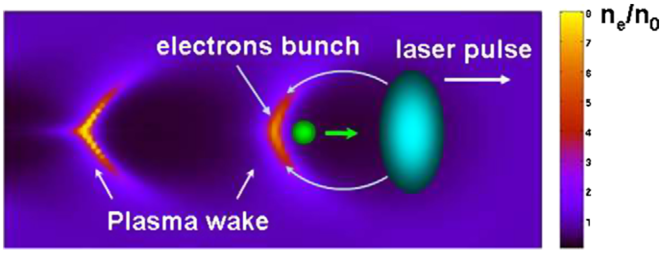

Fig. 1. The bubble regime: the laser creates a cavitated region followed by a wake field, electrons circulate around the bubble, and are injected behind the laser pulse.

The simulations have shown that the injection process stopped when the charge of the electron bunch increased up to a density close to electron background density. This injection feature limited in time and space explains why a quasi-monoenergetic beams of electrons may emerge from the wave-breaking mechanism [16,20].

The experimental observation of monoenergetic electrons was a major result of the recent years [21]. The characteristics of the electron beams are: (i) energy at the GeV level; (ii) energy spread of a few percent; (iii) normalized transverse emittance of the order of π mm mrad; and (iv) bunch duration below 10 fs. The main issues are now to gain in stability [22,23], energy, luminosity, and beam divergence. Of particular interest is the possibility to guide the laser pulse and to maintain its large intensity over long distances to increase the efficient acceleration length, such as in a recent Berkeley experiment [24], where a gas-filled capillary discharge waveguide was used.

6. Colliding laser pulses scheme

The control of the parameters of the electron beam (such as the charge, energy, and relative energy spread) is a crucial issue for many applications. In the colliding scheme successfully demonstrated at LOA, it has been shown that not only these issues were addressed but also that a high improvement of the stability was achieved. In this scheme, one laser beam is used to create the relativistic plasma wave, and a second laser pulse which when it collides with the main pulse, creates a standing wave which heats locally electrons of the plasma. The scheme of principle of the colliding laser pulses is shown in Fig. 2. The control of the heating level gives not only the number of electrons which will be trapped and accelerated but also the volume of phase space, or in other words, the energy spread of the injected electrons bunch. In the pioneer work of Esarey et al. [25], a fluid model was used to describe the evolution of the plasma wave whereas electrons were described as test particles. Electron trajectories in the beatwave as well as their energy gain were derived analytically from theory in the case of laser pulses with circular polarization. It has been shown that this approach fails to describe quantitatively the physics occurring at the pulse collision [26]. In the fluid approach, the electron beam charge has been found to be one order of magnitude greater than the one obtained in PIC simulations. For a correct description of injection, one has to describe properly: (i) the heating process, e.g. kinetic effects and their consequences on the dynamics of the plasma wave during the beating of the two laser pulses; (ii) the laser pulse evolution which governs the dynamics of the relativistic plasma waves [27]. New unexpected feature have shown that heating mechanism can be achieved when the two laser pulses are crossed polarized. The stochastic heating can be explained by the fact that for high laser intensities, the electron motion becomes relativistic

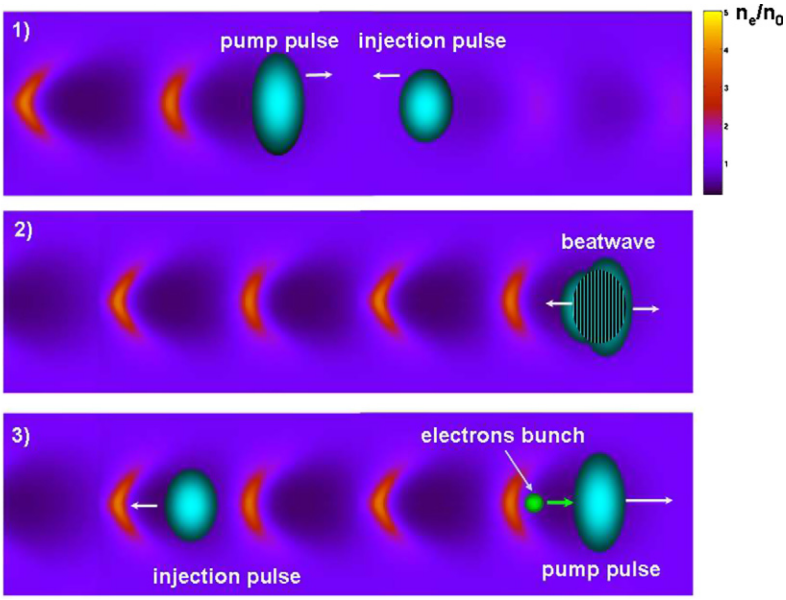

Fig. 2. Principle of injection in the counterpropagating colliding pulse scheme. (1) The two laser pulses have not collided yet; the pump pulse drives a plasma wake. (2) The pulses collide and their interference sets up a beatwave that preaccelerates electrons. (3) Preaccelerated electrons are trapped and further accelerated in the wake.

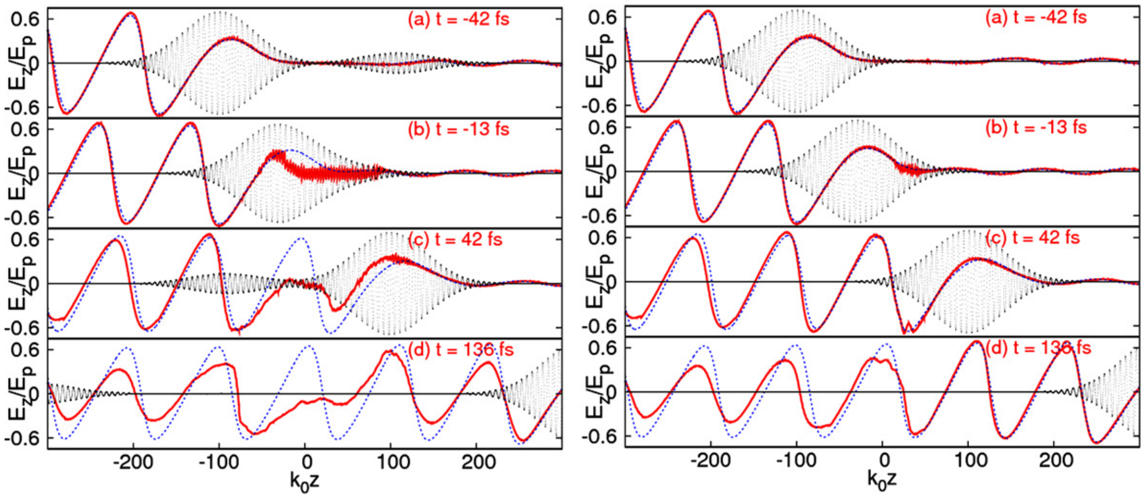

Fig. 3. Longitudinal electric field computed at different times in 1D PIC simulation (solid red line), and in fluid simulations (dotted blue line). The transverse electric field is also represented (thin dotted line). Parameters are $a_0 = 2$ and $a_1 = 0.4$, 30 fs duration at FWHM and wavelength $\lambda_0 = 0.8$ μm, electron plasma density 7×10^{18} cm^{-3}. Left: parallel polarization, right: crossed polarization.

which introduces a longitudinal component through the $\mathbf{v} \times \mathbf{B}$ force. This relativistic coupling makes it possible to heat electrons. Thus, the two perpendicular laser fields couple through the relativistic longitudinal motion of electrons. The heating level is modified by tuning the intensity of the injection laser beam or by changing the relative polarization of the two laser pulses. This consequently changes the volume in the phase space and therefore the charge and the energy spread of the electron beam. Fig. 3 shows at different times the longitudinal electric field, during and after collision for parallel and crossed polarization. The solid line corresponds to the PIC simulation results whereas the dotted line corresponds to the fluid calculation. The laser fields are also represented by the thin dotted line. When the pulses have the same polarization, electrons are trapped spatially in the beatwave and can not sustain the collective plasma oscillation inducing a strong inhibition of the plasma wave which persists after the collision. When the polarizations are crossed, the motion of electrons is only slightly disturbed compared to their fluid motion, and the plasma wave is almost unaffected during the collision, which tends to facilitate trapping. Importantly it has been shown that this approach allows a control of the electron beam energy which is done simply by changing the delay between the two laser pulses [22].

7. Ion acceleration

While electron acceleration in a plasma has been studied actively during the past 25 years, the emission of energetic ions from laser-produced plasmas has been a constant observation in laser–matter interactions since the early 1960s, as noticed more than 20 years ago by Gitomer et al. [28]. Ion acceleration in clusters were also widely studied in the 1990s [29]. In early experiments, the ions originated from the surface heated by the laser pulse and were directed toward the laser. By contrast, in the recent experiments using ultra-short pulses and thin foils [30], the ions are predominantly accelerated in the forward direction, apparently coming from the back side of the target. Much higher energies are obtained, with protons up to about 60 MeV and heavier ions up to about 5 MeV/nucleon.

Various mechanisms were proposed to explain the experimental observations, and the dominant mechanism may actually vary with laser intensity, target material and thickness. In any case the laser energy first couples to the electrons at the target front side. Roughly speaking, the electrons are accelerated by the electric field of the laser and pushed forward by the $\mathbf{v} \times \mathbf{B}$ force. The acceleration mechanism is dependent on the laser polarization (linear versus circular) as demonstrated by Macchi et al. [31].

Then the electron energy is transferred to the ions by at least two means. On one hand, ions initially located at the front surface can be dragged by the charge separation created at the front side of the target, and further accelerated inside the target by a shock propagating across the plasma [31,32]. On the other hand, atoms initially located at the back of the target can be ionized and accelerated by the charge separation created by the electrons emerging into vacuum [33]. Some experiments [34] and numerical simulations [35] were more specifically devoted to the identification of the dominant mechanism, the majority of which concluded in favor of the acceleration from the rear surface at current laser intensities. However, at ultra-high intensities, in the $10^{23}\ \mathrm{W\,cm^{-2}}$ range or above, new regimes appear, such as the laser breakout afterburner [36], when the laser penetrates to the rear of the target, or the laser piston regime [37], where the foil is accelerated as a whole.

The simplest model of ion expansion into a vacuum is the isothermal model [38], for which one can predict the ion front velocity as a function of time,

$$v_{front} \approx 2c_s \ln\left(\tau + \sqrt{\tau^2 + 1}\right) \tag{1}$$

where $\tau = \omega_{pi} t/\sqrt{2e}$. Here ω_{pi} is the ion plasma frequency of the unperturbed plasma, t is the expansion time, and $e = 2.71828\ldots$.

Of crucial importance is the energy spectrum of the ions deduced from the model. The self-similar model predicts a number of ions per unit energy and unit surface given by

$$\mathrm{d}N/\mathrm{d}\mathcal{E} = (n_{i0} c_s t/\sqrt{2\mathcal{E}\mathcal{E}_0}) \exp(-\sqrt{2\mathcal{E}/\mathcal{E}_0}) \tag{2}$$

where $\mathcal{E}_0 = Z k_B T_e$.

The ion front velocity in (1) diverges logarithmically with time, while the total energy in the fast ions diverges linearly, so that to be able to apply the model to the interpretation of experiments, one has to determine the relevant time t at which the acceleration is stopped. A natural choice for t is the laser pulse duration t_l [39], possibly within a numerical factor of order unity [40], and the corresponding comparison of Eq. (1) with a number of experimental results has been rather successful.

However, one might argue that, in the experiment, the acceleration does not stop suddenly, and that it goes on even for $t > t_l$. Moreover, the isothermal model assumes a constant electron temperature, which can be a reasonable assumption during the laser pulse, but is certainly violated for late times, as the electrons progressively give their energy to the ions [41] and cool down in the expansion.

An alternative is to use an adiabatic model [42,43], where the electron temperature decrease is determined by the energy gained by the ions and the energy lost by the electrostatic field. The most salient results of this adiabatic model are the prediction of a double layer structure of the ion front, significantly more pronounced than in the isothermal case, and the prediction of the maximum ion velocity as a function of the foil thickness.

Fig. 4 shows the electric field E as a function of x for a foil of width $L = 20\lambda_{D0}$, at time $\omega_{pi} t = 50$, as predicted by the model of Ref. [42]. The ion front is characterized by a peak of the electric field. Recent experimental results of probing of high-energy protons accelerating fields in short-pulse laser solid interaction have evidenced the existence of such a peak [44].

Other effects should also be taken into account, such as the fact that the electron distribution function is in general a non-Maxwellian distribution (possibly a two-temperature distribution [45], or a truncated distribution [46]), the fact

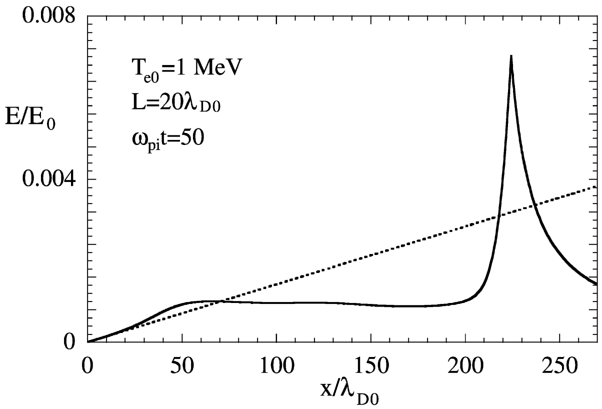

Fig. 4. Electric field as a function of x for a foil of width $L = 20\lambda_{D0}$, at time $\omega_{pi} t = 50$. E is normalized to $E_0 = (n_{e0} k_B T_{e0}/\epsilon_0)^{1/2}$. The dotted line is the electric field predicted for the expansion of a Gaussian plasma in the quasineutral approximation.

that two-dimensional and three-dimensional effects obviously limit the ion acceleration [43], the possibility of a finite initial density gradient at the back of the foil [47], the case of multispecies foils, etc.

8. Multispecies foils and quasi-monoenergetic ions

For a foil corresponding to one ion species, the width of the ion velocity spectrum is of the same order as the maximum velocity of the ions. To reduce the width of the ion spectrum, various methods were proposed, always combining light ions and heavier ions.

The first and simpler idea is to coat the back part of a target by an ultra-thin layer of light ions (corresponding to a higher value of Z/m) [48]. Obviously the thickness of the light ions layer has to be much smaller than the characteristic variation length of the initial accelerating field, which can be in the nanometer range. In this configuration, the light ions behave as test particles experiencing the field imposed by the expansion of the heavier ions.

The second possibility is to have a target composed by a mixture of light and heavy ions. The expansion leads to the formation of an electrostatic shock and a significant part of the light ions present a quasi-monoenergetic peak in the velocity (or energy) spectrum [49] at intermediate velocities.

A third solution, which is somehow a combination of the first two is to have a thin layer of low density light ions embedded in a heavy ions foil [50]. One may understand the mechanism of formation of the quasi-monoenergetic ions by first considering a thin foil of heavy ions with an arbitrary small density of light ions embedded in the target. In this case the expansion is only governed by the heavy ions, while light ions are simply treated as test particles in the resultant accelerating field. The result is illustrated in Fig. 5(a) where a numerical code similar to the one described in Ref. [42] was used. It is seen that fastest light ions are not the ions which were initially exactly at the back of the foil, but rather ions which were approximately two Debye length inside the target: during the expansion, they cross the heavy ion front, optimizing the time integral of the electric field, while light ions initially situated exactly at the back surface immediately reach the vacuum part of the expansion, where the electric field decreases as a function of space as well as a function of time. Fig. 5(b) shows the same phase space in the case where light ions impurities have a finite density. All the light ions occupied initially the layer $-2 < x/\lambda_{D0} < -0.3$ with a charge density of 1.1% of the total ion charge density. In this optimized mixture, the inner light ions, which in the previous case were progressively overtaking the outer ions, are now slightly slowed down by the Coulomb repulsion of outer ions. As a result, at the time where the picture is taken, the light ions have an almost perfectly monoenergetic spectrum. Later in time, the spectrum will only slightly broaden.

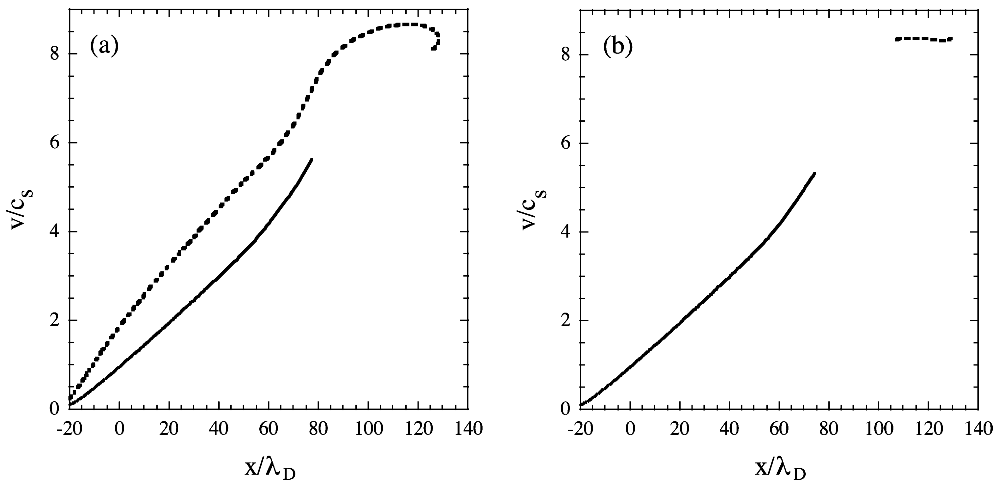

Fig. 5. (a) Phase space for the isothermal expansion of a plasma with light ions impurities with arbitrarily small density. All the normalizations correspond to the heavy ions. The light ions have a value of Z/m three times larger than the heavy ions (for instance heavy ions are four times ionized carbon and light ions are protons). The solid line corresponds to the heavy ions, the dotted line to the light ions. Time corresponds to $\omega_{pi}t = 20$. (b) Same as (a) except that light ions impurities have now a finite density. All the light ions occupied initially the layer $-2 < x/\lambda_{D0} < -0.3$ with a charge density of 1.1% of the total ion charge density.

The existence of quasi-monoenergetic ions have been evidenced in recent experiments [51]. Note also that the energy selection of ions can alternatively be obtained by a time dependent focusing as demonstrated in Ref. [52].

9. Summary and future challenges

Conventional accelerator technology has progressed through a long road paved by scientific challenges. A recent example is the development of superconductivity for high current acceleration in RF cavity, which has required tens of years of theoretical investigations and experimentations to understand the physical processes involved in those media and finally to control the technology which has been successfully used in accelerators such as LEP/LHC (CERN), or HERA (DESY-Hamburg). Laser–plasma accelerator research is following the same road paved with many successful (and unsuccessful) experiments. Thanks to this pioneering works and judging from the incredible results achieved over the last three years, the time has come where a technological approach has to be considered. Two stages laser–plasma accelerators schemes should allow the development of few GeV electron beam with a small relative energy spread and emittance [53]. In parallel, fundamental and experimental research should of course be pursued to explore new regimes and to validate theories and numerical codes. The improvement of the laser–plasma interaction with the evolution of short-pulse laser technology, a field in rapid progress [54], will still improve this new and very promising approach which potential societal applications in material science, medicine, chemistry and radiobiology [55].

Acknowledgements

V. Malka acknowledges J. Faure, C. Rechatin, E. Lefebvre, X. Davoine, A. Lifschitz for fruitful discussions and the support of the European Community-Research Infrastructure Activity under the FP6 and of European Community "Structuring the European Research Area" program (CARE, contract number RII3-CT-2003-506395), the support of the European Community-New and Emerging Science and Technology Activity under the FP6 "Structuring the European Research Area" program (project EuroLEAP, contract number 028514), the support of the French national agency ANR-05-NT05-2-41699 "ACCEL1".

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