REVIEW OF LASER WAKEFIELD ACCELERATORS

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Abstract
This review article highlights the recent evolution of research on laser wakefield accelerators, which has, in record time, led to the production of high quality electron beams beyond the GeV level, using compact laser systems. As shown here, the most significant breakthroughs allow to produce stable, high peak current and high quality electron beams, with a fine control of the charge, of the relative energy spread and of the electron energy. The path that has been followed to explore different injection scenarii (bubble/blow-out, colliding laser pulses, injection in gradient, longitudinal and ionization injection) is presented here.

INTRODUCTION

Since Lawrence's cyclotron machine delivered its first 1 MeV ion beam, accelerator science and technology have made incredible progress, constantly gaining in efficiency and in performance. The performances of accelerators such as the LHC have enabled scientists to study the most basic constituents of matter, to understand their interactions and to test the Standard model. Accelerator technology has also been developed for the production of intense and ultra-short X-ray beams, using synchrotron or free electron laser machines. In fundamental research, such radiation beams have been used to study ultra fast phenomena, including for example the evolution of DNA structures in biology, or the evolution of molecules or crystal structures in material science. With a market of more than a few billion dollars per year, accelerators are used today in many fields such as cancer therapy, ion implantation, electron cutting and melting, and non-destructive inspection. However, in conventional accelerators, due to electrical breakdown of the radio-frequency cavities, the value of the electric field is limited to about 100 MV/m. To overcome this limitation, it has been proposed to use a plasma medium, which can support extremely high electric field values up to TV/m [1].

In order to efficiently accelerate electrons, a plasma medium must sustain a collective electron motion that propagates with a phase velocity close to speed of light, while the ions remain almost at rest. These collective motions are called relativistic plasma waves. They can be produced by an intense laser pulse, as it was originally proposed by Tajima and Dawson [2]. When the laser pulse propagates through the plasma, it creates a density perturbation due to its ponderomotive force. This density perturbation propagates with a phase velocity equal to the group velocity of laser, which, in a tenuous plasma, is close to speed of light.

In the first experiments, injected electrons of a few MeV have been accelerated by GV/m electric fields using either the beat wave [3,4] or the laser wakefield scheme [5]. In all these experiments, because the bunch length of the injected electrons was much longer than the plasma wavelength, only a very small fraction of the injected electrons were accelerated. This leads to a very poor electron beam quality. With the development of more powerful lasers, much higher electric fields were achieved, making it possible to efficiently accelerate electrons from the plasma itself to higher energies. A major breakthrough was attained in 1994 at Rutherford Appleton Laboratory, where the relativistic wave-breaking limit was reached, with a measured electric field of a few hundreds of GV/m [6].

In this regime, the amplitude of the plasma wave is so large that a copious number of electrons are trapped and accelerated in the direction of the laser, thus producing an energetic electron beam. The corresponding mechanism is called the Self Modulated Laser Wake Field (SMLWF) [7-9]. In those experiments, the electron beam had a Maxwellian-like distribution, as it is expected from random injection processes in the relativistic plasma waves.

The SMLWF was then demonstrated with the compact laser system of "Salle Jaune" working at 10 Hz. In this experiment, the fact that the electron peak energy increased with decreasing electron plasma density showed that the dominant acceleration mechanism was indeed related to the relativistic plasma waves [10]. In 2002, another breakthrough was obtained in the Forced Laser Wake Field where low divergence electron beams with energies up to 200 MeV were obtained with the 1J "Salle Jaune" [1]. In this highly non-linear regime, the quality of the electron beam was improved by noticeably reducing the interaction between the laser beam and the electron beam.

In order to improve the quality of the electron energy distribution, electron injection has to be reduced to a very small volume of the phase space. In general, this means that the length of the injected electron bunch must be shorter that the plasma wavelength, i.e., much shorter than a few microns.

HIGH QUALITY ELECTRON BEAMS

The different injection schemes that have been experimentally demonstrated have lead to a substantial improvement of the electron beam quality. They include the bubble/blow-out regime, density gradient injection, ionization injection, colliding laser pulses injection and more recently longitudinal injection.

 ISBN 978-3-95450-122-9

Bubble/Blow-Out Regime

In 2002, 3D Particle-In-Cell (PIC) simulations revealed the existence of a very promising acceleration regime, that was called the bubble regime [11] and leads to the production of a quasi-monoenergetic electron beam containing a copious amount of charge. At lower laser intensity, 3D PIC simulations also showed similar improvement of the electron beam quality in what is know as the blow-out regime [12]. In those two regimes, the laser energy is focused in a sphere of a radius shorter than the plasma wavelength. The ponderomotive force radially expels the electrons of the plasma, thus forming a positively charged cavity surrounded by a dense region of electrons, immediately behind the laser pulse. Since the injection is well localized, all the injected electrons have similar initial properties in phase space. When the charge of the electron beam becomes large enough, the trapping process stops, leading to the generation an electron beam with of a quasi-monoenergetic distribution, as experimentally observed in 2004 [13-15]. In the lower density case of this regime [15], electrons are trapped far behind the laser, where they do not interact anymore with the laser field. This contributes to the improvement of the electron beam quality. The scheme of principle of the bubble/blow- out regime is illustrated in Fig.1.

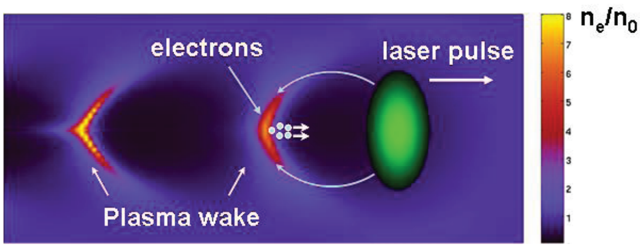

Figure 1: Scheme of principle of the bubble regime: The laser pulse that propagates from left to right, expels electrons on his path, forming a positively charged cavity. The radially expelled electrons flow along the cavity boundary and collide at the bubble base, before being accelerated behind the laser pulse.

Since 2004, several laboratories have obtained quasi-monoenergetic electron beams in the bubble/blow-out regime. Electrons at the GeV level were observed in this regime in a uniform plasma [16,17] or in a plasma discharge [18] i.e. a plasma with a parabolic density profile that allows the intense laser beam to propagate over a distance of a few centimeters. In all these experiments, the laser beam parameters did not fully satisfy all the bubble/blowout regime criteria. Nevertheless thanks to the self-focusing and self-shortening [19] effects, the non-linear evolution of the laser pulse allowed such transverse injection. Besides, some of these experiments were carried out in an intermediate regime in-between the forced laser wakefield and the bubble/ blowout regime.

In all the experiments performed so far, the laser plasma parameters were not sufficient to fully enter the bubble/ blowout regimes. Since self-injection occurs through transverse wave breaking, it is hardly appropriate for fine-tuning and control of the injected electron bunch.

Injection in a Density Gradient

One solution to control electron injection with current laser technology was proposed by Bulanov et al. [20]. It involves a downward density ramp, in which the length scale of the ramp is longer than the plasma wavelength. Injection in a downward density ramp relies on the slowing down of the plasma wave velocity in the density ramp. This decrease of the plasma wave phase velocity lowers the threshold above which plasma background electrons are trapped by the wave, and causes wave breaking of the wakefield in the density ramp. This method can therefore trigger wave breaking in a localized spatial region of the plasma. This scheme was demonstrated by focusing an intense laser pulse onto the downward density ramp at the exit of a gas jet [21], and produced stable electron beams at 0.4 MeV with high charge (> 300 pC). Although these results are very promising, the disadvantage of this scheme is that the low energy beam blows up very quickly once outside of the plasma, due to space charge effect.

To circumvent this issue, one should use a density gradient located early enough along the laser pulse propagation, so that electrons can be accelerated to relativistic energies. At LOA, a density gradient across a laser-created plasma channel was used to stabilize the injection [22]. The experiment was performed at an electron density close to the resonant density for the laser wakefield to guarantee an efficient post acceleration. High quality electron beams with narrow divergences (4 mrad), quasi-monoenergetic electron distributions (10% relative energy spread) and with 50 to 100 pC charge have been reported. The use of density gradients at the edges of a plasma channel have shown an improvement of the beam quality and of the reproducibility with respect to those produced in the bubble/blowout regime with the same laser system and with similar laser parameters. However, the electron energy distribution was still found to fluctuate from shot to shot.

By using the shock-front created by a knife-edge inserted in a gas jet [23,24] and by irradiating it with a multi-TW sub-10-fs laser system, that delivered pulses with 65 mJ energy on target and a duration of 8 fs FWHM for this experiment, stable and quasi-monenergetic electron beam were recorded. The comparison between the self-injection and density transition injection revealed a reduction of the relative energy spread and of the charge of a about a factor of 2.

At Lund Laser Center, a wire was introduced inside the flow of a supersonic gas jet, thereby creating shock waves and three regions of differing atomic density [25]. As a consequence of this structure, the laser plasma interaction went through three consecutive stages: laser self-compression, electron injection, and acceleration in the second plasma wave period. Experimental data have demonstrated that, compared to bubble injection in a constant density plasma, this scheme increases beam charge by up to 1 order of magnitude. Electron acceleration in the second plasma wave period reduces the electron beam divergence by 25%, and the localized injection at the density down ramps results in spectra with less than a few percent relative spread.

This scheme has also been used at LBNL, where electrons at 30 MeV were produced in a density ramp and accelerated up to 400 MeV in a second stage composed by a 4 cm parabolic plasma channel. Here also, the density gradient injection led to an improvement of the stability and quality of the electron beam [26].

The electron energy, divergence, charge, and relative energy spread were found to be, respectively, 400 MeV, 2 mrad, 10 pC, and 11%.

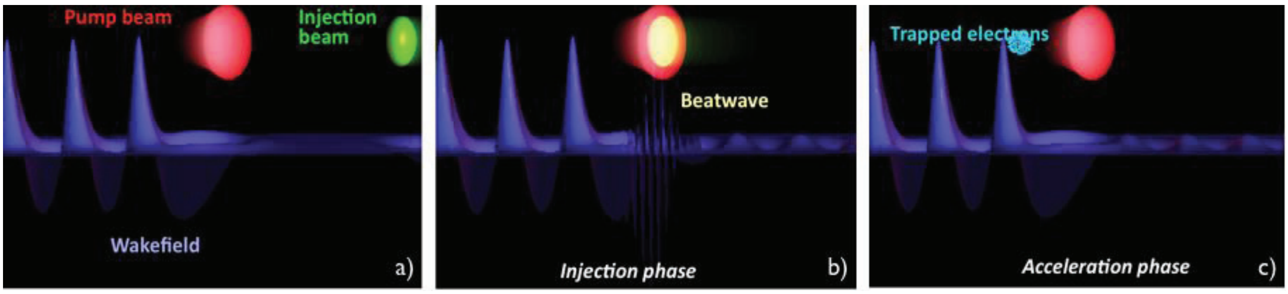

Figure 2: Scheme of principle of the injection with colliding laser pulses: (a) the two laser pulses propagate in opposite direction, (b) during the collision, some electrons get enough longitudinal momentum to be trapped by the relativistic plasma wave driven by the pump beam, and (c) trapped electrons are then accelerated in the wake of the pump laser pulse.

Injection with Colliding Laser Pulses

In 2006, stable and tunable quasimonoenergetic electron beams were measured by using two counterpropagating laser beams [27] in the colliding scheme [28]. The first laser pulse, the pump pulse, is used to excite the wakefield while the second pulse, the injection pulse, is used to heat electrons during its collision with the pump pulse. After the collision has occurred, electrons are trapped and further accelerated in the wakefield, as shown in Fig. 2.

To trap electrons in a regime where self-trapping does not occur, one has to either inject electrons with energies greater that the trapping energy or to dephase electrons with respect to the plasma wave. This can be achieved using an additional laser pulse whose only purpose is to locally trigger electron injection, through a heating process that results from the beating of this low-intensity laser pulse with the intense pump laser pulse. The interference of the two laser beams creates a beatwave pattern, with zero phase velocity, that heats some electrons from the plasma background. The force associated with this ponderomotive beatwave is proportional here to the laser frequency and therefore many times greater than the ponderomotive force associated with the pump laser (that is inversely proportional to the pulse duration at resonance). As a result, the mechanism is still efficient even for modest laser intensities. Upon interacting with this field pattern, some background electrons gain enough momentum to be trapped in the main plasma wave and then accelerated to high energies. As the overlapping of the lasers is short in time, the electrons are injected in a very short distance and can be accelerated to an almost mono-energetic.

The charge of the electron beam is controlled by tuning the heating level, which can be done by changing the intensity of the injection laser pulse [29-31], its polarization [32] or the plasma electronic density [33]. This consequently changes the volume of the injected electrons in phase space and therefore the charge and the energy spread of the electron beam.

Importantly, it was shown that the colliding pulse approach allows to control the electron beam energy which is done simply by changing the delay between the two laser pulses [34]. The robustness of this scheme also permitted to carry out very accurate studies of the dynamics of the electric field in the presence of a high current electron beam.

This effect, called the beam loading effect, was used to reduce the relative energy spread of the electron beam. It was demonstrated that there is an optimal load, which flattens the electric field, leading to the acceleration of all the electrons with the same value of the field and consequently producing an electron beam with a very small (1%) relative energy spread [33]. The robustness of this scheme was also used in demonstrating the production of electron bunches having durations as low as 1.5 fs [35].

Injection Triggered by Ionization

Another recently proposed scheme aims to control the injection by using a high Z gas and/or a high Z-low Z gas mixture. Thanks to the large differences in ionization potentials between the successive ionization states of the atoms, the leading edge of the laser pulse only ionizes the low energy level electrons, with which it then drives relativistic plasma waves. On the other hand, the inner level electrons are only ionized later, once the peak of the laser pulse reaches them, and this causes them to be trapped and accelerated in the plasma waves.

ISBN 978-3-95450-122-9

This ionization trapping mechanism was first demonstrated in a plasma wave driven by an electron beam, on the Stanford Linear Collider [36]. Electron trapping by ionization of high Z ions coming from the capillary walls was also inferred in experiments of laser wakefield acceleration [37]. In the case of self-guided laser driven wakefield, a mixture of helium and of trace amounts of different gases was used [38,39]. Because of relativistic self-focusing and self-steepening effects, the peak intensity of the laser changes along its propagation, and this can trigger ionization injection, albeit over a long distance and in an inhomogeneous way. As a consequence, the delivered electron beam has a large relative energy spread. Importantly, the energy required to trap electrons is reduced, making this approach of great interest to produce electron beams with a large charge at moderate laser energy.

To reduce the distance over which electrons are injected, experiments using two gas cells were performed at LLNL [40]. By restricting electron injection to a small region, in a first short cell filled with a gas mixture (the injector stage), energetic electron beams (of the order of 100 MeV) with a relatively large energy spread were generated. Some of these electrons were then further accelerated in a second, larger accelerator stage, consisting of a long cell filled with low-Z gas, which increased their energy up to 0.5 GeV while reducing the relative energy spread to < 5% FWHM.

Longitudinal Injection

Because of its simplicity, self-injection is the most commonly used method for trapping electrons into a plasma wave. This process can, in fact, be separated in two distinct physical mechanisms: longitudinal and transverse self-injection [41]. In longitudinal self-injection, the trajectory of injected electrons is mainly longitudinal, with a negligible transverse motion. As shown in Fig.3, injected electrons go through the laser pulse and gain energy while crossing the plasma wave. When they reach the rear of the first plasma period, their velocity exceeds the wake phase velocity and they are eventually injected. The only electrons that are trapped are those that were initially close to the laser propagation axis where the laser intensity and the wakefield amplitude are the highest and where the ponderomotive force is small. The longitudinal self-injection mechanism is analogous to one-dimensional longitudinal wave breaking [42].

Conversely, transverse self-injection, which occurs in the Bubble/Blow-out regime, is very sensitive to very small changes in the focal spot. Such fluctuations of the focal spot result in significant variations of the transverse electron distribution and in intrinsically unstable electron beams. On the contrary, the electrons in the first bunch come from regions close to the axis, and their distribution is symmetric. When these electrons are injected, the laser spot radius is large, and the radial ponderomotive force close to the axis is small. Electrons are thus weakly radially pushed when crossing the laser, and remain around the laser axis, where the accelerating field is largest. This behaviour is typical of longitudinal self-injection. Longitudinal injection has proved to produce stable electron beams of a few pC charge at few hundred of MeV.

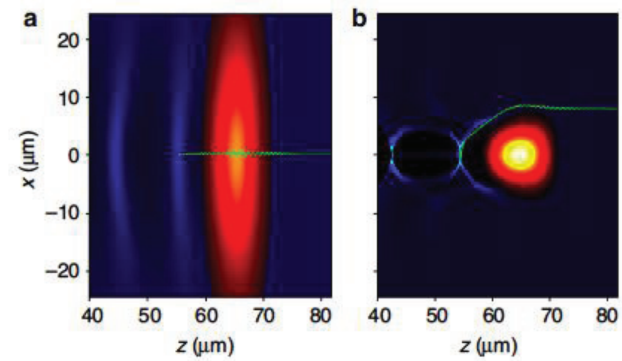

Figure 3 : Schematic for longitudinal and transverse self-injections. (a) Typical trajectory of an injected electron in the longitudinal self-injection mechanism. (b) Typical trajectory of an injected electron in the transverse self-injection mechanism. The blue colour scale represents the electron density. The red to yellow colour scale indicates the laser intensity. The green lines represent electron trajectories.

CONCLUSION

The parameters of the electron beams produced today with available laser technology have a real potential of applications [43] in material science for example for high-resolution gamma radiography [44,45], in medicine for cancer treatment [46-48], in chemistry [49-51] and in radiobiology [52]. Laser plasma accelerators are also very promising for the production of ultra-short X ray beams, e.g. through the Compton [53], betatron [54], or Bremsstralhung mechanism [55].

Due to the high quality and high current of its electron beams, laser plasma acceleration is a very pertinent approach for a compact FEL machines that could deliver a bright and energetic radiation beam within the next 5 years. Manipulation of electron beam with a % relative energy spread seems to be one of the key issues for demonstrating such compact FEL machine [56,57].

Several new ideas, to further improve the quality of the electron beam [58,59], have been proposed on the basis of theoretical works or simulations that need to be demonstrated experimentally. For the longer term future, the ultimate goal which is of major interest for high energy physics will require very high luminosity electron and positron beams having TeV energies. Reaching these parameters with laser plasma accelerators will take at least 5 decades and further significant works are required in order to develop this technology. For this purpose, a number of challenges have to be overcome: production of electron and positron beams, fair improvement of the laser plug-in efficiency, beam transport between the successive laser plasma accelerators stages without dramatic energy loses, guiding over long distances and improvement of the stability of the whole processes at each stages, etc [60,61].

Nevertheless, before reaching an objective and more accurate conclusion on the relevance of the laser plasma approach for high energy physics, it will be necessary to design a prototype machine (including several plasma accelerating stages) in coordination with accelerator physicists. An estimation of the cost and an identification of all the technical problems that are to be solved will permit to evaluate the risk with respect to other approaches (particle beam interaction in plasma medium, hot or cold technology, or others).

In conclusion, while a significant amount of work remains to be done in order to deliver beams of interest for high energy physics, a fine control of the electron beam parameters is now possible and many of the promised applications become reality.

ACKNOWLEDGMENTS

This work was supported by the European Research Council (PARIS ERC, contract number 226424) and EuCARD/ANAC, EC FP7 (contract number 227579).

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ISBN 978-3-95450-122-9