In this paper we will present some numerical simulations of the laser plasma acceleration, mainly focused to electrons. The simulations have been performed to find the best working point for some of the regimes that will be investigated by the INFN-CNR PLASMON-X project. FLAME (Frascati Laser for Acceleration and Multidisciplinary Experiments), a 300TW Ti:Sa laser, is being installed and commissioned at LNF (Laboratori Nazionali di Frascati) Frascati. The first pilot experiment (SITE, Self-Injection-Test-Experiment) is planned for the next year (2010). The simulations have been run using a fully self-consistent Particle-In-Cell (PIC) code ALaDyn (Acceleration by LAser and DYNamics of charged particles), the code is developed and maintained at the departement of Physics at the University of Bologna within the PLASMON-X project.

**Keywords:** laser-plasma interaction; electron acceleration; PIC simulations;

**PACS:** 52.38.-r; 41.75.Jv; 52.65.Rr

1. Introduction

Laser-Plasma acceleration, first proposed by Tajima and Dowson (1), is now considered a promising technique for particle acceleration, in 2004 three different groups independently had been able to produce quasi-monoenergetic electron bunches up to energies in the 100 MeV regime (2–4) and recently energies in the GeV range have been achieved by different groups (1–3). Though some characteristics still need further improvement (shock to shoot stability, monochromaticity, etc.), the road is promising and several effort have already being made. For example much is being done to control the injection of the electron bunch in the plasma wave using different techniques, a second counterpropagating laser beam wich stimulate the injection can give high control in terms of stabily (5) or the use of a plasma with a density gradients can result in electron bunches with low momentum spread (4).

PLASMONX (6) is a join project of INFN and CNR, will investigate the laser plasma acceleration and rely on the synergy between the 300 TW, 25 fs, Ti:Sa laser system FLAME and the 10 Hz, 150 MeV SPARC (Sorgente Pulsata Auto-amplificata di Radiazione Coerente) linear accelerator. The aim is to explore laser-driven particle acceleration with both self (from the plasma itself) and externally (from the linac for example) injected electron bunches, in view of realizing a (compact) optical accelerator. To accomplish this goal a strict control on the properties
2. SITE experiment: parameter study

2.1. Bubble regime

The laser wakefield acceleration (LWFA) exploits the longitudinal electric field of electron plasma waves that can be excited by laser pulse. LWFA is achieved, for example, by firing a very short and intense laser pulse on a gas jet and working in the so called “bubble regime”. The gas is ionized by the very first part of the pulse and then the interaction of the main part of the pulse happens with the just formed plasma. It is also possible to pre-create a plasma with different characteristic (i.e. transverse non-uniform profile) using other techniques. In all this cases a laser-plasma interaction can be considered.

The bubble regime is achieved when a short ($c\tau < \lambda_p$, where $\tau$ is the FWHM length of the laser pulse, $\lambda_p = 2\pi c/\omega_p$ and $\omega_p$ is the plasma frequency) and intense ($a_0 > 2$, where $a_0 \equiv eA_{\text{laser}}/mc^2 = 8.5 \cdot 10^{-10}\sqrt{I[W/cm^2]/(\lambda_0[\mu m])^2}$ is the normalized vector potential of the laser) laser pulse moves in a plasma. The intensity gradients of the laser fields expels the electrons outward creating a nearly bare ion column in the near trail of the pulse. The blown-out electrons form a narrow sheath outside this ion channel and the space charge generated by the charge separation pulls the electrons back creating a bubble-like wake. See fig. 1.

When the laser intensity is sufficiently high ($a_0 > 4$) the bubble wave is so intense that some of the electrons, when reaching the back of it can be injected and remain
trapped inside this cavity. The electric field experienced by these electrons has ideal accelerating properties. Being the cavity positively charged, the electron are attracted to the center of it and being the electron injected at the rear are infact accelerated towards the center being focused at the same time. This bubble follows the laser pulse at the same, nearly \( c \), speed while the electrons are trapped allowing acceleration on rather long scales (up to cm), when the pulse reaches the end of the plasma the electron are free and expelled at high energy.

In order for the laser to create efficiently the bubble is essential a short duration of the pulse, without it a nonlinear pulse modulation occurs and after a significant time a bubble can be created. An essential condition for the injection is the intensity to be high enough, in some of the first experiments this was reached after several micron of propagation due to self-focusing of the pulse in the plasma, “waisting” useful micron of possible acceleration length. The FLAME laser meets both the two conditions of short pulse length and high intensity, in this case when the laser pulse impinges into the gas-jet promptly excites a bubble wake where electrons are readily injected. All this happens without significant pulse evolution during the early stages of the interaction so the entire gas-jet length can be exploited for the acceleration process provided that the bubble wake remains stable.

2.2. Design of the test experiment

Having a prompt wake generation together with an efficient injections is not enough to get an efficient acceleration process. Different parameter of both the plasma and the laser pulse has to be put to a matching condition. In (9) a phenomenological theory is described and some conditions on the parameters are explained in order to have a “controlled” acceleration process. The condition for a “matched” (i.e. slightly oscillating) bubble requires \( k_p R_{bub} \approx k_p w_0 \approx 2\sqrt{\omega_0} \), where \( k_p = \omega_p / c \), \( R_{bub} \) is the radius of the bubble and \( w_0 \) is the laser waist (1/e^2 radius of the laser intensity profile). The energy gain of the electrons accelerated can then be evaluated by considering the deplation-length and the dephasing length. These two legth come from two phenomena. As explained earlier the bubble, whose field accelerate the electrons, moves following the laser pulse at the same speed. The group velocity of the electromagnetic waves in a plasma depends on the plasma density, namely the electron density, and is always less than \( c \). This means that the bubble will be slower than the accelerated bunch of electrons (\( E_K \gg 0.5 \text{MeV} \)) and soon or later, depending on some parameters, the electrons will reach the center of the bubble starting to experience a decelerating field so that the so-called dephas- ing is reached. The second phenomenon to be considered is called pumb deplations and is due to the fact that the laser pulse while propagating in the plasma is erosed by it, in particular the front of the pulse. This results in having a front of the pulse, responsible for creating the bubble wave, that is traveling slower than the expected group velocity giving rise to another source of dephasing. The dephasing length is given by \( L_d \approx (2\omega_0^3/3\omega_p^2) R_{bub} \) while the pump deplation length which is the distance on which the laser will be completely erosed by the plasma is \( L_{pd} \approx (\omega_0^3/\omega_p^2) c\tau \). If we then want that injected particles reach the dephasing before laser pump depletes, nearly disappering, the inequality \( L_{pd} > L_d \) must hold.

Following (9), we have that the maximum energy gain (at dephasing) can be cast in the form \( \Delta W [\text{GeV}] \approx 1.7 \times (P[\text{TW}]/100)^{1/3} (10^{18}/n_p[\text{cm}^{-3}])^{2/3} \) and the injected charge is \( Q[nC] \approx 0.4 \times (P[\text{TW}]/100)^{1/2} \).

Keeping in mind the previous consideration we can apply them to the characteristic of the laser pulse of FLAME \((P = 200 \text{ TW}, \tau = 30 \text{ fs})\), taking into account the matched bubble condition and choosing the laser waist \( w_0 \) as a free pa-
After we get the following expressions for the plasma density, the dephasing/pump-depletion lengths, the maximum energy and the injected charge:

\[ n_p \ [\text{cm}^{-3}] \approx 8.7 \times 10^{21} / (w_0 [\mu \text{m}])^3, \]
\[ L_d [\mu \text{m}] \approx 0.133 \times (w_0 [\mu \text{m}])^4, \]
\[ L_{pd} [\mu \text{m}] \approx 1.8 \times (w_0 [\mu \text{m}])^3, \]
\[ \Delta W [\text{MeV}] \approx 5.26 \times (w_0 [\mu \text{m}])^2 \]
\[ Q \approx 0.6 \text{nC}. \]

Setting for instance \( L_{acc} = L_d = 4 \text{ mm} \), \( L_{acc} \) being the acceleration length, a possible working point (WP) could be \( w_0 = 13 \mu \text{m} \), yielding \( a_0 = 5.8 \) (which corresponds to a peak intensity of \( 7.3 \times 10^{19} \text{ W/cm}^2 \)), \( n_p = 3.8 \times 10^{18} \text{ cm}^{-3} \). In this case the theoretical energy gain would be \( \Delta W \approx 0.9 \text{ GeV} \) but we find that the pump depletion length is \( L_{pd} \approx 4 \text{ mm} \) and is comparable with the acceleration length. In figure 2 we plot the accelerating field on a leading particle within the bubble (e.g. a particle which is injected in the early stages of the laser-plasma interaction) as a function of the time for the WP we are considering. The solid/red line is theoretical estimation from (9), the dashed/pink line is the actual value obtained from a 2D PIC simulation performed with the PIC code ALaDyn (10, 11). We see that the useful accelerating field for a leading particle goes to zero after \( \sim 2.8 \text{ mm} \) instead of 4 mm as expected theoretically. This is due to a modification in the structure of the wakefield which occurs when we consider the evolution of the laser pulse on a time scale which is comparable with the pump depletion time (12).

Being the dephasing faster than expected results not only in a lower energy gain of the electrons (0.6/0.7 GeV instead of 0.9 GeV in this case) but also in much poorer monochromaticity of the bunch. After this preliminary simulation a correction has been done and the working point changed decreasing the density to \( n_p^* = 3.0 \times 10^{18} \text{ cm}^{-3} \), in order to increase the pump depletion time, and increasing the laser waist to \( w_0^* = 15.5 \mu \text{m} \) (\( a_0^* = 4.9 \), corresponding to a peak intensity of \( 5.3 \times 10^{19} \text{ W/cm}^2 \)), in order to enlarge the bubble size (\( R_{bub} \approx w_0 \)). The solid/blue line in figure 2 is the useful accelerating field obtained with 2D PIC simulation for the corrected WP. The energy gain in this case is again \( \Delta W \approx 0.9 \text{ GeV} \) but now the dephasing length matches the total acceleration length. After this first simulations a fully selfconsistent 3D PIC simulation has been performed to test this corrected WP.

3. Simulation with ALaDyn

Simulation results are summarized in figure 3 where we present the evolution of the electron density, showing the formation of the bubble and the accelerated bunch, and the energy spectrum as a function of the time. The colored image are represent a 2D slice of the full 3D simulation and give a good idea of the acceleration
mechanism. At the end of the simulation several electron bunches are formed with the most energetic one having an energy of 0.9 GeV, a momentum spread (rms) of 3.3% and a charge of 0.6 nC. The results are in good agreement with the estimates discussed in the previous section. This is, more or less, what can be achieved in a bubble regime without considering more advanced techniques, and can be considered as good result.

Despite the high value of the energy and the slice current, which can be as high as 80-100 kA, the brightness/brilliance of this kind of bunches must be improved before considering successful applications to the radiation production (FEL or Thomson scattering). The use of “optically generated” electron bunches for radiation production needs further improvements and one possible framework could be the post-acceleration in laser-induced plasma waves of an externally injected bunch obtained with a conventional low-energy accelerator, such as SPARC, and characterized by low momentum spread and emittance. Several studies are already ongoing in this respect (13). Other possible solutions are under investigation for example considering the use of gasjets that gives a longitudinal density profile with two plateau at different values.

4. Conclusions

We presented some analytical considerations and numerical simulations devoted to the design of the PLASMON-X test experiment SITE that is going to be run during the commissioning of the laser FLAME. The work has been focused on the bubble regime that can be easily be achieved focusing the FLAME pulse on a gas jet exploiting some of the key features of the laser system. Our study showed how tuning some parameters energies of about 1GeV can be achieved with a 4mm gas jet.
Acknowledgements

We acknowledge the support of the CINECA Computing Center (grant: “Simulazioni PIC 3D per l’accelerazione laser-plasma”). We also want to thank the PPLA organizing committee for inviting us to the conference.

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