

## RESEARCH ARTICLE

### Simulation of the laser-plasma acceleration for the PLASMON-X project with the PIC code ALaDyn

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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 department of Physics at the University of Bologna within the PLAMSON-X project.

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## 1. Introduction

Laser-Plasma acceleration, first proposed by Tajima and Dawson (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 (shoot 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 eletron bunch in the plasma wave using different techniques, a second counterpropagating laser beam wich stimulate the injection can give high control in terms of stabiliy (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

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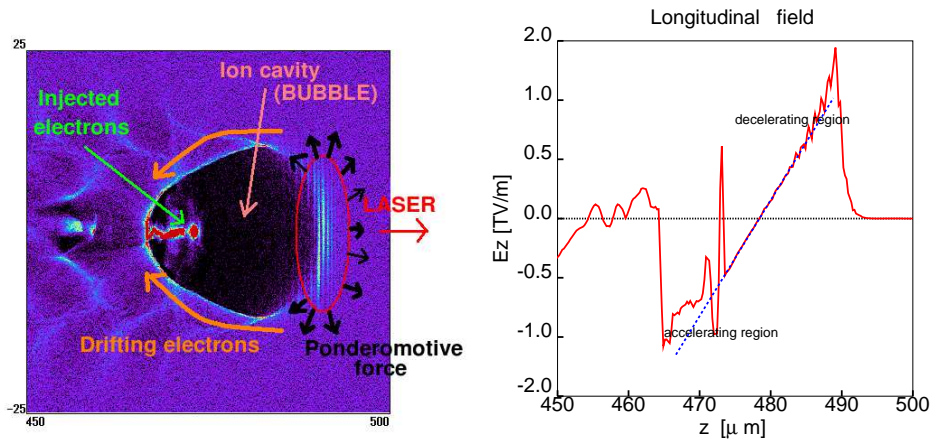


Figure 1. Bubble regime. Left: electron density in trail of the laser pulse (black=low density, red=high density). Right: the longitudinal electric field on the axis.

of the accelerated bunch (energy, final momentum spread, emittance, bunch length and charge) is needed. PlasmonX will also investigate the production of X ray radiation via Thomson scattering or the FEL mechanism. Some of the possible future steps in the use of the laser FLAME would be represented by ion acceleration experiments as well.

One of the main part of the commissioning of the laser system, scheduled for 2010, and part of the tests of FLAME performances will be a self injection experiment (SITE) The aim of the SITE is the production of GeV-class electron bunches from laser-plasma interaction using a gas-jet of few millimeters without external guiding for the laser, working directly in the so called bubble regime(7, 8).

Some numerical studies aimed to find good working point for SITE will be presented together with some analytical consideration.

## 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  $a_0 \equiv eA_{laser}/mc^2 = 8.5 \cdot 10^{-10} \sqrt{I[\text{W}/\text{cm}^2](\lambda_0[\mu\text{m}])^2}$  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 in fact 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  $k_p R_{bub} \simeq k_p w_0 \simeq 2\sqrt{a_0}$ , 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 depletion-length and the dephasing length. These two length 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 dephasing is reached. The second phenomenon to be considered is called pump depletions and is due to the fact that the laser pulse while propagating in the plasma is eroded 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  $L_d \simeq (2\omega_0^2/3\omega_p^2) R_{bub}$  while the pump depletion length which is the distance on which the laser will be completely eroded by the plasma is  $L_{pd} \simeq (\omega_0^2/\omega_p^2) c\tau$ . If we then want that injected particles reach the dephasing before laser pump depletes, nearly disappearing, 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  $\Delta W[\text{GeV}] \simeq 1.7 \times (P[\text{TW}]/100)^{1/3} (10^{18}/n_p[\text{cm}^{-3}])^{2/3}$  and the injected charge is  $Q[\text{nC}] \simeq 0.4 \times (P[\text{TW}]/100)^{1/2}$ .

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 param-

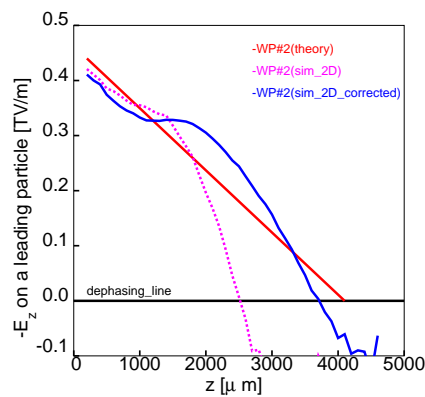


Figure 2. Useful accelerating field on a leading particle within the bubble as a function of the time. See the text for details.

ter we get the following expressions for the plasma density, the dephasing/pump-depletion lengths, the maximum energy and the injected charge:  $n_p [\text{cm}^{-3}] \simeq 8.7 \cdot 10^{21} / (w_0[\mu\text{m}])^3$ ,  $L_d[\mu\text{m}] \simeq 0.133 \times (w_0[\mu\text{m}])^4$ ,  $L_{pd}[\mu\text{m}] \simeq 1.8 \times (w_0[\mu\text{m}])^3$ ,  $\Delta W[\text{MeV}] \simeq 5.26 \times (w_0[\mu\text{m}])^2$  and  $Q \simeq 0.6 \text{ nC}$ . 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  $7.3 \cdot 10^{19} \text{ W/cm}^2$ ),  $n_p = 3.8 \cdot 10^{18} \text{ cm}^{-3}$ . In this case the theoretical energy gain would be  $\Delta W \simeq 0.9 \text{ GeV}$  but we find that the pump depletion length is  $L_{pd} \simeq 4 \text{ mm}$  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  $4 \text{ mm}$  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 ( $0.6/0.7 \text{ GeV}$  instead of  $0.9 \text{ GeV}$  in this case) but also in much poorer monochromaticity of the bunch. After this preliminar simulation a correction has been done and the working point changed decreasing the density to  $n_p^* = 3 \cdot 10^{18} \text{ cm}^{-3}$ , 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  $5.3 \cdot 10^{19} \text{ W/cm}^2$ ), in order to enlarge the bubble size ( $R_{bub} \simeq w_0$ ). 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  $\Delta W \simeq 0.9 \text{ GeV}$  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 images represent a 2D slice of the full 3D simulation and give a good idea of the acceleration

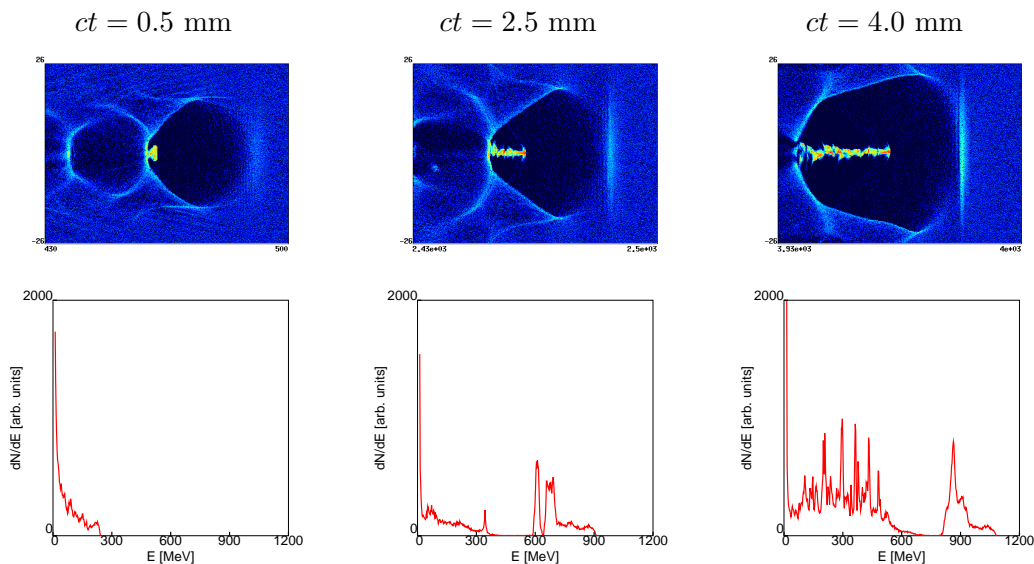


Figure 3. Electron density (top line) and energy spectrum (bottom line) at different times in the 3D PIC simulation for the SITE. The rms bunch length (the most energetic one) is  $1.8 \mu\text{m}$  or 6 fs, so the average current is 45 kA. The transverse size of the bunch is  $0.5 \mu\text{m}$ , the normalized emittance is 2.8 mm mrad and the corresponding beam divergence is 2.9 mrad. The bunch seems to be characterized by an overall high value of the emittance/momentum spread. In fact, even performing a slice analysis taking  $L_{\text{slice}} = 0.1 \mu\text{m}$ , the slice emittance values are always larger than  $(1.5 \div 2)$  mm mrad, while the slice momentum spread is in the range 2% - 4%.

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.

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