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# Improving the quality of enegetic electron beams produced by Laser Wake Field Acceleration

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Laser Wake Field Acceleration (LWFA) of relativistic electron bunches is a promising method to produce a large amount of energetic particles with a table-top equipment. To date, the quality of the electron beams produced with the widely used scheme employing a gas-jet system and a single femtoscond laser pulse is very poor, the energy spread being of the order of 100% and the angular divergence usually exceeding several degrees. The Intense Laser Irradiation Laboratory (ILIL, IPCF-CNR) in Pisa, Italy, is currently deeply involved, both on the experimental and theoretical sides, in studies devoted to increase the beam quality of the LWFA produced electron beams. Here we report on the two parallel activities of ILIL in this field. The first achieved its main results started with an experiment held at the LOA facility, based on LWFA in preformed plasmas obtained with the exploding foils technique and demonstrating the production of a relativistic electron bunch with a record value of angular divergence (less than one degree) but still with a large energy spread. The second activity is presently at the theoretical/numerical stage and is aimed to produce electron bunches with both small transverse and longitudinal emittances by taking advantage of the partial nonlinear, longitudinal wave-breaking of the Langmuir wave behind the pulse crossing a sharp density downramp. In this way a large amount of electrons can be injected in a controlled way in the accelerating region of the wake. PIC simulations (3D in the fields and 2D in the coordinates) demonstrate that, once concurring trapping phenomena are inhibited, extremely low values of the beam energy spread and divergence can be obtained.

Short scale-length prefomed plasmas (SSPP) are currently easily produced with the exploding-foils technique [2] in which a foil target of thickness ranging from a fraction of micrometer to few micrometers is exploded by an heating pulse before the arrival of the intense femtosecond pulse, thus producing a fully ionized hot plasma. The use of SSPP as a medium for LWFA experiments has several advantages among the classical scheme gas-jet + laser-pulse, the most relevant being the possibility to study the interaction of a laser pulse with a plasma having scale-lengths comparable with the Langmuir wavelength $l_p$. Futhermore, the pulse interacts with an already fully ionized medium, whose electron density map can be accurately estimated [3,4,5]. Finally, diffraction effects on the pulse can be neglected since the longitudinal size of the plasma is usually lower than the focused pulse Reyleigh length. Drawbacks are, however, the intrinsic difficulty of making high repetition-rate experiments, the reproducibility of the single shots results and, of course, the small extension of the acceleration length which limits the energy of the produced bunches to tens of MeV's.

In the above mentioned experiment at the Laboratoire d'Optique Appliquee (LOA) near Paris, France, the SSPP was produced using the nanosecond Amplified Spontaneous Emission (ASE) associated to the 35*fs*, 1*J* Ti:Sa laser pulse, which was focused in a 6_ *m* spot on the target foil [1]. A detailed mapping of the 3*D* preformed plasma density profile was obtained by using both a Nomarski interferometer and advanced numerical analysis methods [3,4,5]. The produced electron bunch was characterized by using either a standard magnetic spectrometer or the novel spectrometer SHEEBA [6,7], having also an angular resolution. The SHEEBA spectrometer consisting of a stack of radiochromic films, which change their optical density according to energy locally released by the beam. With the help of an Monte Carlo based analysis code, an accurate angular and spectral distribution of the single-shot produced electron bunches was obtained. The results show that, with a suitable set of the foil and pulse parameters, energetic bunches composed by an ultrarelativistic and collimated component (energy up to 40*MeV* and divergence less than one degree) and a less energetic ring-like component, are produced by means of the LWFA process.

We stress, however, that even if the produced electron bunches have a very low angular divergence (to our knowledge, the lowest obtained so far), the energy spectral width is of the order of 100%, i.e. as large as that usually gas-jet systems.

To reach the goal of the production of highly collimated and monochromatic electron beams, an efficient method to control the self-injection of the electrons in the accelerating region is needed. Several mechanisms have been proposed and are currently subject of active studies [8,9,10,11,12]. Among these, controlled injection with partial longitudinal breaking of the Langmuir wave after a density downramp [11,12], is the mechanism which uses only one laser pulse.

A joint research programme involving the ILIL group, the Physics Department of the University of Pisa, I.N.F.N and I.N.F.M has been recently started, aiming the optimization of the controlled injection by a sharp density downramp method. The first step of the programme was devoted to extend the original results of S. Bulanov et al. [11] in a multidimensional geometry, seeking the occurrence of competitive trapping processes which could degrade the final electron beam quality. The first numerical results of such a collaborations are encouraging [13,14,15]: in an 'ideal' plasma profile consisting of two perfectly flat plateaux, we found a regime in which all the trapping mechanisms except the nonlinear wavebreaking at the transition are inhibited, with the final production of a 10*MeV* bunch with about 5% energy spread and angular divergence about five degrees. The preformed plasma density profile is chosen in order to enable the partial breaking of the wake behind the laser pulse, with a scalelength of the density transition $L$ much smaller than the Langmuir wave number $l_p$ (sharp density transition). We used a fully relativistic PIC code developed by H. Ruhl [18], which runs on a *SP*4 system at CINECA, Italy [19]. Fig 1 shows the main results of the simulation. The laser pulse propagates along the $z$ direction and it is polarized along $y$, has a wavelength $l_l$=1m*m*, a duration $t_{FWHM}$=17*fs* full width at half maximum and a waist $w_0$=20m*m*. The preformed plasma has longitudinal density profile presenting two contiguous plateaux with a transition having scalelength $L$=2_ *m* located at $z$=50_ *m*. The electronic density of the first plateau (region I), where a regular wake develops, and the second plateau (region II) where the trapped particles are accelerated are $n_e^I$=2.1◊$10^{19}$$cm^{-3}$ and $n_e^{II}$=1.1◊$10^{19}$$cm^{-3}$, respectively. The laser pulse peak intensity was $I$=2.5◊$10^{18}$$W/cm^2$, corresponding to a normalized pulse amplitude $a_0 \cong 1.3$. The value of the peak intensity was chosen in order to suppress the trasverse wave breaking process, which can be responsible for the uncontrolled injection of particles and the degradation of the wake field quality. At the final simulation time the wake is still regular far beyond the pulse, even if an inverted curvature of the constant-phase lines due to beam loading developed (Fig. 1-a and c). The trapped bunch is well localized in the phase-space plot, both longitudinally and transversally and the final energy spectrum consists of a narrow peak with energy spread $\Delta E / E \approx 5\%$ full width at half maximum and a background containing a second bunch with a lower energy and beam quality, which can be easily separated from the first one.

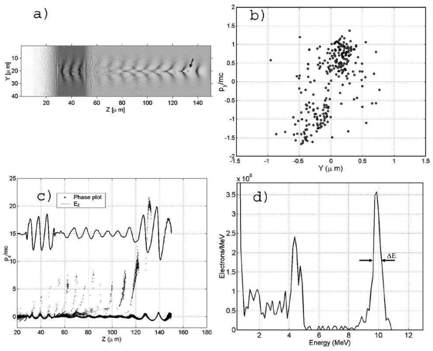


Figure 1: Final simulation time. a) Electron density. The arrow indicates the electron bunch. b) Transverse ($y$-$p_y$) phase-space plot of the bunch. c) Line-out on axis of the Longitudinal phase-space plot (single points) and line-out of the longitudinal electric field. Almost all the particles of the bunch are in a region in which the accelerating force is maximum. d) Energy spectrum of the particles accelerated with energy $E$>0.5$MeV$.

We stress that remarkable low values of both the normalized *rms* transverse $\varepsilon_n^{\perp} \cong 0.1 mm \cdot mrad$ and longitudinal $\varepsilon_n^{\parallel} \cong 2 mm \cdot keV$ beam emittances can be obtained.

The generation of a plasma with the required tailored plasma density profile is, to date, a challenge. Recently, Hosokai *et al.* [16] have employed a gas-jet system and produced a density transition by inducing in the plasma a shock wave produced by the laser pulse ASE. They demonstrated the trapping and acceleration of electron bunches with low angular divergence, but still having a large energy spread. Another possible method to produce a plasma with an electronic density presenting a sharp downramp employes a couple of plastic thin foils, which are exploded by the irradiation with a heating laser pulse before the arrival of the femtosecond main pulse. In order to test this last scheme with 2D hydrodynamical simulations, we considered an heating pulse of duration 3*ns*, peak intensity 1◊$10^{14}$*W/cm*$^2$, wavelength 0.8_ *m* and focal spot of about 10_ *m*, counter-propagating with respect to the main pulse. The two parallel plastic foils are placed about 200_ *m* far away and have different thickness (0.1_ *m* and 0.2_ *m*). The simulation of the foils irradiation and plasma formation has been performed with the hydrodynamic eulerian code POLLUX [17] in 2D with azimuthal symmetry. 1.5*ns* after the arrival of the heating peak pulse, the plasma electron density shows two plateaux separated by a very short scalelength transition (*L*_5_*m*), which is probably the effect of a shock caused by the collision between the expanding plasma regions of the rear side of the first foil and the front side of the second foil. The radial density profile is flat within a radius exceeding 30_ *m*. As a result, a long acceleration region (about 500_ *m*) with a good flatness of the electron density, as well a density transition with a short scalelength, are obtained. The value of the electron density in the accelerating region is optimum for a laser pulse of a duration not exceeding $\tau \cong \lambda_p / c \cong 35 fs$, being *c*=0.3_ *m*/*fs* the light speed.

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