OBSERVATION OF LASER WAKEFIELD ACCELERATION OF ELECTRONS

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Abstract

The acceleration of electrons injected in a plasma wave generated by the laser wakefield mechanism has been measured at Ecole Polytechnique. We have also observed a background noise faking high energy electrons, due to particles deflected in the plasma, in correlation with the electron plasma wave. A maximum energy gain of 1.6 MeV has been measured. The maximum longitudinal electric field is estimated to be 1.5 GV/m. The experimental data agree well with theoretical predictions when 3D effects are taken into account, with a plasma duration of 1 ps.

1 INTRODUCTION

The generation of large amplitude electric fields in plasmas by high-power lasers has been studied for several years in the context of high-field particle acceleration [1].

In the Laser Beat Wave Acceleration (LBWA) approach, the beating of two frequency lasers creates a modulation of its intensity. LBWA has been extensively studied during the 90's with 1 μm [2] and 10 μm [3-5].

In the "standard" Laser Wake Field Acceleration (LWFA) approach, a single short laser pulse excites the EPW [6]. As the ponderomotive force associated with the longitudinal gradient of the laser pulse exerts two successive pushes in opposite directions on the plasma electrons, the excitation of the EPW is maximum when the laser pulse duration is of the order of ω_p^{-1}.

At high electron density, and high laser intensity - with respect to ω_p^{-1} - laser pulse breaks into short pulselets at ω_p^{-1}. In this self-modulated mode (SMLWFA), the very high longitudinal electric field of the EPW traps plasma electrons and accelerates them to high energies [7-9]. However, SMLWFA is not suited for high energy accelerators, in particular because the EPW grows from an instability and also because of the low the Lorentz factor of the phase velocity of the EPW at high electron density.

Standard LWFA is particularly suited for particle acceleration. It is not affected by saturation (e.g. relativistic detuning [4] or modulational instability [2]) as is LBWA, and operates at low density, where γ_p can be quite high. The excitation of radial EPW by laser wake field has already been observed by two-pulse frequency-domain interferometry [10-12].

We present here the first observation of LWFA of injected electrons. A particular emphasis has been given to the separation of the signal from the background (BG) noise in the design of the experimental apparatus and in the analysis of the data. In the case of LBWA experiments, We infer that deflected electrons can scatter on the walls of the vacuum chamber and fake a signal, as is possibly the case in [14] and in the surprising result of [15].

2 WAKEFIELD ACCELERATION

The transverse and longitudinal components of a linear EPW created by laser wakefield, for a laser beam with a gaussian profile and a gaussian time distribution, can be expressed as: $E_r = (4r/w^2)Asin(\omega_p t - k_p z)$ and $E_z = k_p Acos(\omega_p t - k_p z)$, with :

$$A = \sqrt{\pi}\omega_p \tau_0 exp(-\frac{\omega_p^2 \tau_0^2}{4})\frac{I_{max} e}{2\epsilon_0 mc\omega^2} exp(-\frac{2r^2}{w^2}), \quad (1)$$

where the time variation of the laser intensity is described by $exp(-(t/\tau_0)^2)$, I_{max} is the maximum intensity, w the $1/e^2$ radius in intensity, and $k_p = \omega_p/c$. At a given value of τ_0, E_z varies like $(\omega_p\tau_0)^2 exp(-(\omega_p\tau_0)^2/4)$. This gives a broad maximum close to $\omega_p\tau_0 = 2$, i.e. $\omega_p\tau = 4\sqrt{ln2}$, where τ is the pulse duration at FWHM. With $\tau = 400$ fs, this corresponds to an electron density $n = 2.2 \times 10^{16}$ cm^{-3}, an EPW wavelength $\lambda_p = 226\mu$m, and an EPW Lorentz factor $\gamma_p = 214$. The corresponding helium pressure is 0.4 mbar for a fully ionized plasma. Finally, the maximum electric field at resonance is E_z(GV/m)$= 1.35 \times 10^{-18} I_{max}$ (W/cm^2)$\lambda^2(\mu$m)/τ(ps). The relative longitudinal perturbation of the electron density is $\lambda_{\|} = E_z/E_0$, where $E_0 = mc\omega_p/e$.

The ratio of the transverse to the longidudinal electric field, at $r \approx w_0/\sqrt{2}$ is $E_r/E_z = \sqrt{2}\lambda_p/\pi w_0$, here equal to 4. We obtain the value of the relative transverse perturbation of the electron density by $\delta_\perp/\delta_\| = (E_r/E_z)^2$, here equal to 16. The EPW is excited in the radial regime : the transverse electric field is stronger than the longitudinal one. Particle simulations [16] show that with these parameters, E_z actually reaches a saturation value when $\delta_\perp \approx 2$, corresponding here to $\delta_\| \approx 10\%$.

3 EXPERIMENTAL RESULTS

The experimental apparatus is based on the existing facility already used for the study of LBWA [2, 17]. A sketch of the experiment as in 1994 can be found in Fig. 1 of ref. [17]. We use the 400 fs 1.057 μm chirped pulse amplified laser at LULI. After transport to the experimental room, the 80 mm diameter beam is injected into a pulse compressor, and focused in a gas filled chamber by a 1.4 m focal length 30^0 off-axis parabola. A fraction of the compressed beam is collected before focusing and sent to a single-shot second-order autocorrelator for pulse duration measurement. A low intensity fraction of the beam is collected after the plasma and sent to a focal spot monitor. The continuous electron beam from a Van de Graaff is injected into the plasma at the total energy of 3 MeV. The accelerated electrons are measured by a magnetic spectrograph. The number of channels of the detector has been extended to 17, allowing the measurement of electrons from 3.3 to 5.9 MeV total energy in a single shot. The ADC's are located as close as possible to the photomultipliers. The duration of their gate was set to 20 ns. The voltage of the PM's was tuned so that the calibration factor, detemined by cosmic rays, was equal to 2.5 ADC counts per electron. The duration of the gate was set to 20 ns.

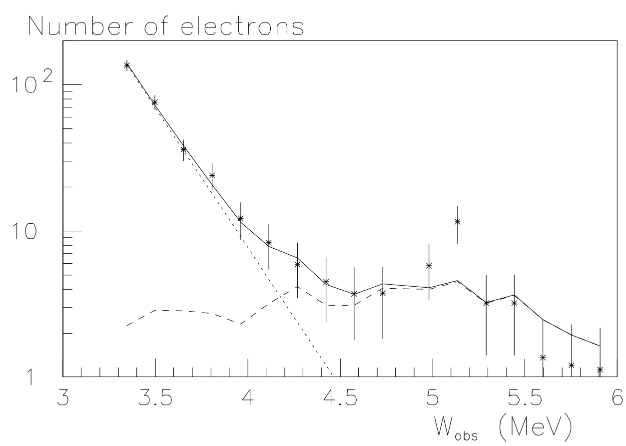

Figure 1: Spectrum of a typical shot (dots). The continuous line shows the sum of the two contributions to the fit.

A series of 250 shots has been performed, most of them with a laser energy in the range 4-9 J. On average, 20 % of this energy was focused to a spot with typical size $w_{0,H} = 30$ μm (horizontal waist) and $w_{0,V} = 19$ μm (vertical waist), with Rayleigh length of $z_{0,H} = 2.3$ mm and $z_{0,V} = 2.0$ mm. With a central spot energy of 1.5 J, the values of the maximum power, intensity, electric field, EPW amplitude, and of the expected linear energy gain are $P_{max} = 3.5$ TW, $I_{max} = 4 \times 10^{17}$ W/cm^2, $E_z = 1.5$ GV/m, $\delta_{\|} = 10\%$, $\Delta W = \pi e z_0 E_z = 10$ MeV. The main source of fluctuation is due to the laser pulse duration. For shots for which the quantities $\tau, E, w_{0,H,V}$ could be measured, the amplitude varies in the range $\delta_{\|} = 1 - 15\%$. Electron acceleration was observed in all of these shots.
A typical spectrum is presented in Fig. 1 (dots). It shows a peak at low electron energy, which can be fitted by a decreasing exponential (dotted line) and a high energy tail (dashed line) that has the same shape as the BG noise spectrum.

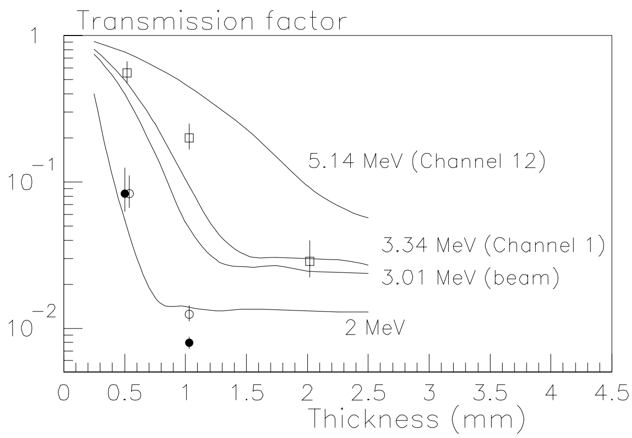

Figure 2: Transmission factors with stainless steel filters as a function of their thickness; channel 1 : $\sqcap$ (laser shots); channel 12 : $\circ$ (laser shots), $\bullet$ (gas BG noise runs). The error bars indicate the dispersion on several shots or runs. Continuous lines : simulation with EGS4.

To check the energy of the electrons impinging on a given channel, we have inserted stainless steel filters with various thicknesses in front of the scintillators. The signal of the corresponding channel is reduced by a factor which depends on the mean electron energy. The transmission factor for laser shots and BG noise runs is compared to the result of an EGS4 simulation [18] at the electron energy corresponding to the channel (Fig. 2). Taking for example channel 12, corresponding to nominal electron energy of 5.14 MeV, we infer from the low transmission factor that the high energy tail is actually due to electrons with an average energy of 2 MeV.

4 DISCUSSION

The BG noise due to Coulomb scattering of the beam electrons in the gas, has been substracted in Fig. 1. This noise has been studied in dedicated runs, without the laser, in which 200 acquisitions were taken. For each channel, the average value scales with pressure with a typical proportionnality factor of 8 e$^-$/mbar. This factor does not decrease with the channel number. This "gas" BG is due to electrons deflected at low angle in the gas, that impact on the flange of the bottle neck of the dump. Part of these are back-scattred, re-enter the magnetic field of the spectrograph, and may fly back into the detector. A numerical estimate of the amplitude of this noise was given in Ref. [17] and found to be in agreement with measurements.
The tail in Fig. 1 is due to an excess of BG noise. It is observed only for shots with accelerated electrons, i.e. *in correlation with the EPW*. We call it "EPW" BG noise. The deflection of beam electrons in the plasma occurs close to the electron focus, while Coulomb scattering can occur along the whole path of the electrons, with a different geometry. To simulate the former, we have introduced a 11 μm Al foil at focus, in vacuum. The obtained noise spectrum has

a shape similar to the shape of the gas spectrum. The electrons scattered at large angle in the foil are blocked by a collimator [17]. Few of them are re-scattered at the edge of the collimator. As the latter is not at focus, some of them impact on the flange of the dump. This explains the similar shape of the two distributions.
The signals of three channels was also recorded on a storage oscilloscope for each shot. A peak, about 10 ns in duration at 10%, is observed in correlation with the ADC recording, with the same proportionnality factor for channel 1 (signal), 8 and 12 (EPW BG noise). Therefore both the EPW BG noise and the signal are shorter than 10 ns, while the gas BG noise is obviously continuous. The EPW BG noise level is too high to be due only to the electrons deflected by the transverse electric field of the EPW, because of its short (ps) life-time, and because of the high rejection power of the collimation system [17], as shown by the low noise level induced by the foil. A long term (ns) effect like the Weibel instability already observed in Ref. [13] is a good candidate to explain this BG.

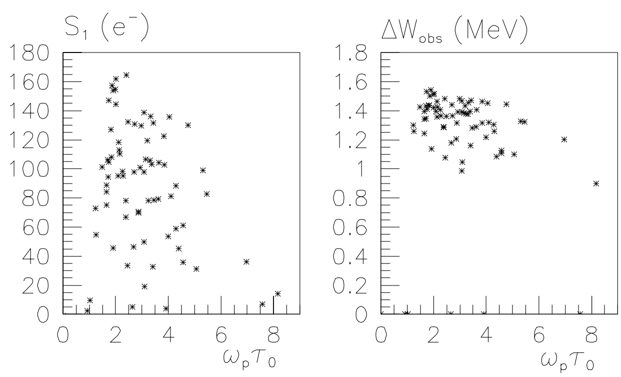

Figure 3: Variations of S_1 (left) and of ΔW_{obs} (right) with $\omega_p\tau_0$. The fitting procedure ($S_1 > 10e^-$) introduces a cut off at $\Delta W_{obs} = 0.85$ MeV.

The signal is separated from the EPW BG noise by the process of the simultaneous fit of the exponential peak and of the tail (Fig. 1). We define the end point W_{obs} of the spectrum of the signal as the energy for which the exponential peak decreases to one electron. In the shots where enough channels have a signal enabling to make a fit, the slope α is found equal to $\alpha_0 = -4.4 \pm 1.1$ MeV^{-1}, a number that does not depend on the parameters of the laser pulse or of the plasma. As the value of the observed energy gain ΔW_{obs}, is extremely sensitive to the value of α, we have used $\alpha = \alpha_0$ to compute ΔW_{obs}.
Figure 3 presents the variation of the signal S_1 in channel 1 with $\omega_p\tau_0$ (left). The data shows a maximum close to $\omega_p\tau_0 = 2$. The spectrum of ΔW_{obs}, is much broader (right), as ΔW_{obs} varies like logS_1 in the exponential peak. Here, $\delta_{\|}$ is low, and the length of the high gradient region, of the order of $2z_0$, is smaller than the dephasing length of the electrons with respect to the EPW, equal to 8 mm. Therefore, ΔW_{obs} should have the same resonant dependance with $\omega_p\tau_0$ as A (Eq. 1). Note also that the maximum value of ΔW_{obs}, close to 1.6 Mev, is smaller than the value obtained from the linear approximation with 1D geometry, close to 10MeV.
In a more detailed simulation, using 3D Monte Carlo [19], the effect of the transverse electric field is taken into account. A good agreement is found with our experimental data, the spectrum in the first 10 channels shows an exponential peak with a slope of -6.1 MeV^{-1} [20]. As the electron flow delivered by the Van de Graaff is constant during the life-time T of the EPW, we infer an estimate of T from a comparison of the normalisations of the observed and simulated spectra. The obtained value is about 1 ps, in agreement with particle simulations [16].

5 CONCLUSION

We have observed the acceleration of electrons in an EPW generated by laser wakefield, with a maximum energy gain of 1.6 MeV. The corresponding longitudinal electric field is of the order of 1.5 GV/m. The resonance dependance is as predicted.
We also observed a tail in the high energy channels. Our cross-check using stainless steel filters proves that this tail is actually due to low energy deflected electrons. This BG, clearly correlated with the plasma wave, can fake accelerated electrons in this kind of experiments.
The experimental data agree with theoretical predictions when 3D effects are taken into account, the duration of the plasma wave being of the order of 1 ps.

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