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Laser electron acceleration with TW-to-PW pulses

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Abstract. We present here 3D-PIC simulation with the code ILLUMINATION for the interaction of a short (sub-10fs) high power (Terawatt to Petawatt) Laser pulse with underdense plasmas. This range covers the parameter regime of the new Light wave synthesizer (LWS) currently under construction at MPQ. Further the advantages of sub-10fs pules compared to longer pulses will be studied.

1. INTRODUCTION

The quality of laser produced electron beams has been dramatically improved during the last year [1–3] which opens the way for a compact electron source delivering quasi monoenergetic, high density, multi-MeV, sub-50fs bunches. These high quality beams where predicted theoretically a few years ago [4] where simulations showed, that a high power, ultra short laser pulse can form a electron free cavitation behind the laser pulse. This bubble can capture electrons and accelerate them to a well defined energy. We will present here 3D-PIC simulation for the interaction of a short (sub-10fs) high power (Terawatt to Petawatt) Laser pulse with underdense plasmas. This range covers the parameter regime of the new Light wave synthesizer (LWS) currently under construction at MPQ. Operation will start with 10TW (LWS-10) at the end of 2005, and finally reach the PW regime (LWS-1000) within the next years. We will show that in contrast to present laser systems, the LWS has the necessary properties to enter the bubble acceleration regime right from the start of the plasma interaction. Hence the LWS will provide a considerabe more stable source for well defined electron bunches.

2. BUBBLE ACCELERATION WITH SUB-10FS PULSES

Previous simulations indicate that the bubble regime calls for ultrashort laser pulses [4]. In general two limits must be satisfied to drive a stable bubble: (1) the laser pulse must be shorter than the plasma wavelength and (2) the intensity of the laser must be high enough to drive the plasma wave above the wave-breaking limit. Here a systematic study in terms of plasma density, pulse duration and peak intensity was done for sub-10fs pulses to clarify the influence on the bubble electron properties. Figure 1 shows two simulations for a plasma wavelength of $\lambda_p = 8\mu m$ for two different laser amplitudes. The upper pictures correspond to $a_0 = 3$ ($a_0 = eE_0/\omega_0 m_e c_0$) whereas the lower ones represent $a_0 = 5$. The other laser parameters are for both cases: $\lambda_0 = 800\,\text{nm}$, a gaussian pulse shape both in time and space with $\tau_{FWHM} = 5\,fs$ and a beam waist of $w_0 = 5\mu m$. Both pulses fulfill the first condition but only for $a_0 = 5$ the field is high enough to break the plasma wave, which can be clearly seen in the density plots on the left side of fig.1. Whereas for $a_0 = 3$ a curved but still regular wakefield is present, the plasma wave breaks for $a_0 = 5$ down into a single electron free cavitation with the high density quasi-monoenergetic electron bunch inside the bubble. The corresponding spectra are given in the right plot also highlight the differences. The well pronounced peak at $75 \pm 10 MeV$ contains almost 15% of the initial laser energy. For longer propagation distances the laser looses substantially intensity leading to the collapse of the bubble after another $\approx 200\mu m$ and finally to the disappearance for the peak in the electron spectrum.

Figure 2 shows the dependence of the electron peak as the initial laser field increases from $a_0 = 3$ to $a_0 = 30$. It can be seen that the electron energy increases sub linear with the field amplitude. The energy

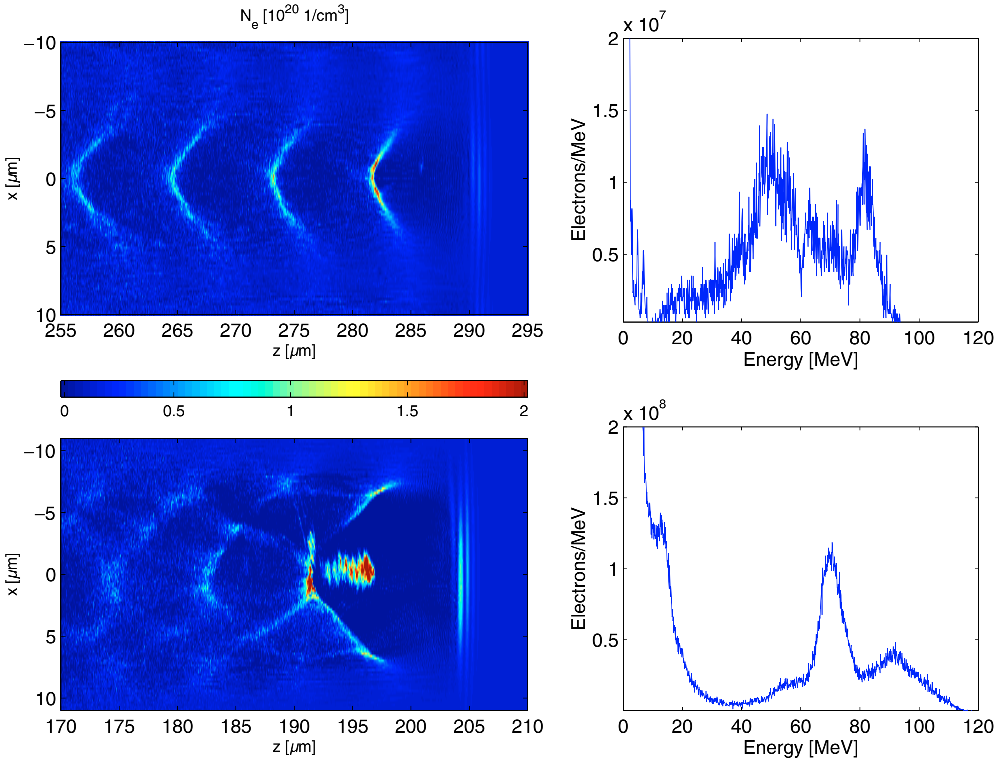

Figure 1. Electron density and spectrum for two different laser amplitudes: top $a_0 = 3$ (below the bubble limit) and down $a_0 = 5$ (over the bubble limit).

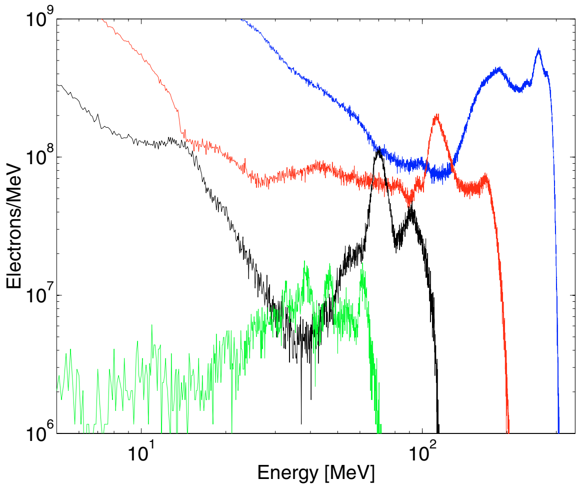

Figure 2. Spectra of accelerated electrons for different Laser amplitudes: green: $a_0 = 3$, black: $a_0 = 5$, red: $a_0 = 10$, blue: $a_0 = 30$.

gain for the electrons inside the bubble is proportional to the longitudinal acceleration field E_z and the acceleration length l_z, which is limited by the distance over which the laser sustains the bubble and is here in the range of $200 - 400\mu m$. E_z represents the remaining positive charge inside the bubble and hence depends on its size, which turns out to increase only like $a_0^{0.25}$.

The consequences of the simulations for sub-10fs are that (1) precise control over the plasma interaction length is crucial to maximize the energy in the electron bunch and (2) it is not likely to produce GeV electrons inside only one bubble acceleration stage with sub-10fs laser systems in the near future.

3. BUBBLE ACCELERATION WITH CURRENT LASER PULSES

The recent reported quasi-monoenergetic electrons where produced with 30-80 fs laser pulse. These parameters are on the edge or even far below the necessary bubble parameters so the questions arises, if sub-10fs laser pulses are necessary for bubble acceleration. To answer this a number of experiments where simulated. Figure 3 shows the laser intensity as a typical pulse used at IOQ Jena ($80fs, a_0 = 3, I = 2 \cdot 10^{19} W/cm^2, w_0 = 5\mu m, 700mJ$) propagates through a gaussian shaped plasma with peak density of $4 \cdot 10^{19} 1/cm^3$ and width of $\approx 350\mu m$. Initially the laser pulse forms an electron free channel comparable to the laser pulse dimensions. During the propagation the laser pulse breaks up and only the part of the laser which is within the first plasma waves survives. The part on the laser pulse inside this first cavitation propagates through a low density plasma whereas the leading edge propagates through the higher dense background plasma. This difference in the density leads to self phasemodulation which broadens the laser spectrum. Since the trailing edge of the pulse propagates nearly in vacuum it is faster than the leading edge and the pulse ends up as a sub-10fs laser pulse $\approx 200\mu m$ after the peak in the plasma density (see last snapshot in figure 3). The corresponding plasma density and electron spectrum for this snapshot are given in Figure 4. Varying the peak density between $4 - 16 \cdot 10^{19} 1/cm^3$ results in similar behavior but the spectral position of the electron peak changes between 10-30MeV which is within the experimental observed range. For $n_e \geq 1.6 \cdot 10^{20} 1/cm^3$ no bubble formation was found.

Additionally we simulated experiments which where done with the ASTRA Laser at RAL previous to the experiment reported in [2] and the LOA experiment reported in [1]. For the ASTRA experiment we took a 40fs, 390mJ laser with $w_0 = 21.25\mu$m propagating through a plasma with $n_e = 2 \cdot 10^{19} 1/cm^3$, whereas for the LOA experiment we simulated a 33fs, 1J, $w_0 = 24\mu$m pulse with a plasma density of $n_e = 6 \cdot 10^{18} 1/cm^3$. Here, in contrast to the longer Jena Pulse, both lasers are approximately as long as the plasma wavelength but have an initially lower intensity due to the wide focusing. So in both cases relativistic self focusing is the first nonlinear effect leading to an increased peak intensity, then self-phase modulations shortens the pulse below 10fs which finally drives a bubble and results in quasi-

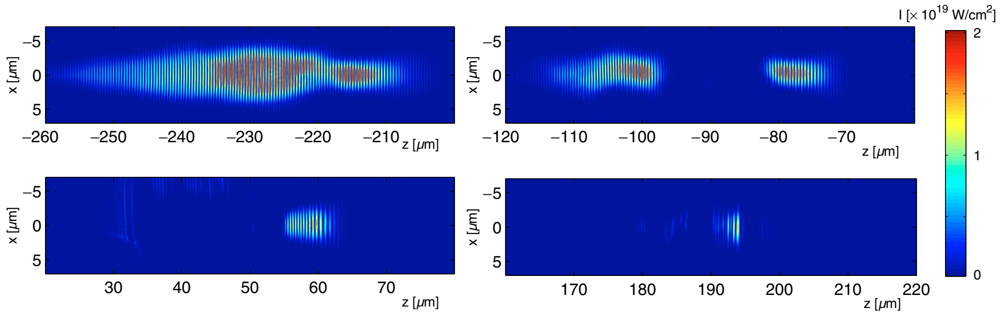

Figure 3. Snapshots of the laser intensity obtained on the focal plane as an initially 80fs laser pulse propagates through a gauss-shapes plasma profile with 1/e-width of $350\mu m$ centered at $z = 0\mu m$ The snapshots are separated by $45fs$.

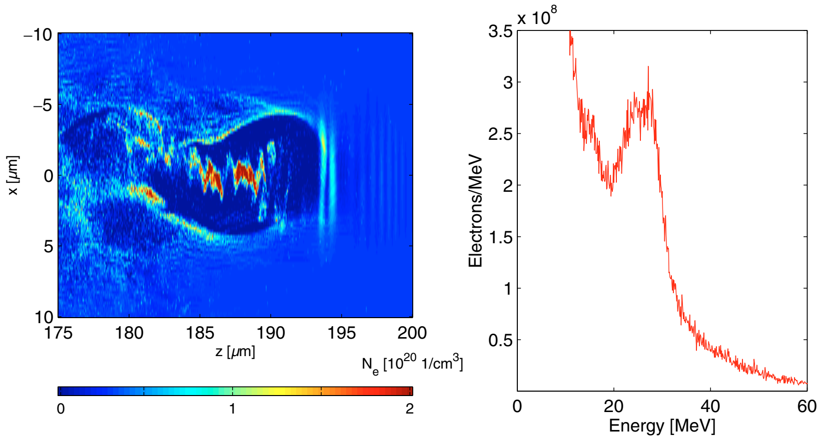

Figure 4. Electron density and spectrum for the last snapshot of fig.3.

monoenergetic electrons. Although these lasers start with different initial conditions and end all up as sub-10fs pulses the efficiencies are substantially different. Only $\approx$5% of the laser energy is converted into the sub-10fs pulse for the Jena pulse whereas almost 90% of the LOA Pulse can be used for bubble acceleration. This due to the fact that only the laser energy within the first plasmawave can be further compressed and used to drive a bubble.

4. CONCLUSIONS

We presented here simulations of bubble acceleration for the upcoming LWS Laser system at MPQ which is capable the accelerate electron bunches with sub-10fs duration to an energy range between 50-250 MeV in a single stage. Precise control over the laser and plasma parameter should provide a stable electron source since nonlinear propagation effects are minimized for ultrashort laser pulses. Further simulating recent experiments clearly show that all reported quasi-monoenergetic electron spectra result from the bubble acceleration mechanism after the laser pulse undergoes strong nonlinear modification and ends up as a sub-10fs pulse. Hence, this should allow a better control over the experiment, when the acceleration set in right from the start of the laser plasma interaction, which can be done in a very efficient way by using sub-10fs laser pulses.

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