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RELATIVISTIC ELECTRON WAKEFIELD ACCELERATION

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The propagation of high-intensity laser pulses in underdense plasmas is a highly complex nonlinear process. Apart form fundamental physical questions, there exists considerable technological interest in the study of relativistic laser plasma interaction. Some possible applications are x-ray lasers, fast-ignitor fusion mechanisms, and electron acceleration. Recent experiments performed with sub-50fs laser pulses showed the generation of electron beams in the MeV range [1,2], opening the way for the realization of electron pulses with unique temporal and spatial properties. The mechanism for electron acceleration is so far not fully clarified. Acceleration of electrons by a wakefield was proposed over 20 years ago [3], but experimental evidence of this process is still missing. Instead Direct Laser Acceleration seems to dominate the electron acceleration for laser pulse durations longer than 100fs [2,4].

We present here 3-dimenisonal particle-in-cell (PIC) simulations, which show that the efficiency of the above mentioned electron acceleration mechanisms sensitively depends on the laser pulse duration. Furthermore it is shown, that 3D propagation effects play a dominant role for the acceleration process.

To clarify the necessity of 3D simulations the maximum electron energy as a function of the propagation distance was investigated for a 5fs (FWHM), λ_0=0.8µm laser pulse with peak intensity of $5\cdot10^{18}$W/cm² propagating in a preionized cold plasma with wavelength of λ_p=8µm. The maximum energy obtain from linear theory [3] is for this parameter set ≈100MeV, which is reproduced in good agreement by 1D simulations. In contrast the energy gain saturates at 20MeV for the full 3D simulation. This behavior was reproduced for different intensities, pulse durations and plasma densities. The reason for the difference is that three-dimensional effects lead to wave breaking of the plasma wakefield and ultimately limits the acceleration process. Hence the question arises for which laser parameter electron acceleration is optimized.

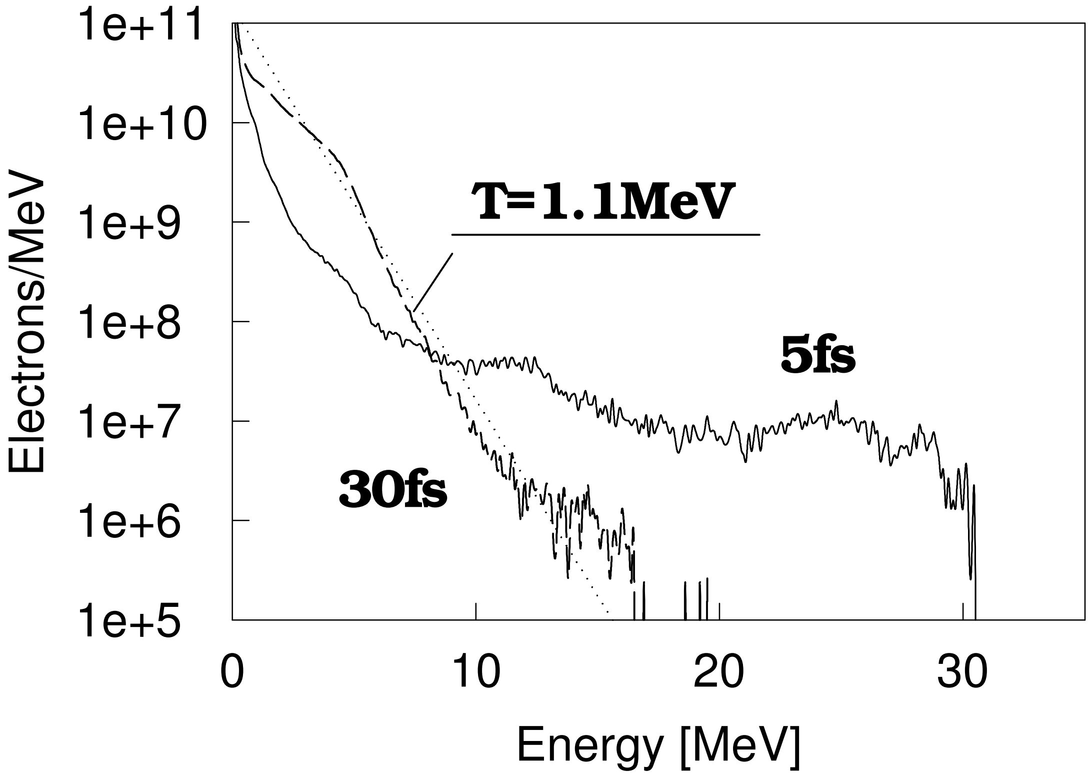

Figure 1: Spectrum of the electron after 100μm propagation, the 30 fs case represents experimental data from ref. [1]. The dotted line depicts the maxwellian temperature of the fast electrons measured in [1]. For detailed parameter see text.

The simulation indicate that the acceleration becomes increasingly efficient with the use of shorter pulse durations. Figure 1 depicts the electron spectrum for different pulse durations, the other parameter are: laser peak intensity of $5\cdot10^{18}$W/cm² at λ_0=0.8μm and the plasma wavelength λ_p = 5.648 μm. The dashed line represents a 30fs pulse reproducing the experimental results of reference [1] whereas the full line depicts a spectrum obtained with a 5fs pulse. The dotted line depicts the maxwellian temperature of the fast electrons measured in [1], underlining the capability of the PIC-Code to reproduce experimental results. The propagation distance is 90μm, further propagation does not change the spectral properties. The benefit of the few-cycle pulse is obvious because the cutoff energy and the number of the cutoff electrons are improved by a factor of two and ten, respectively. The temporal characteristic is also improved for the shorter pulse. Whereas in the 30fs case the fastest electron represent a 60fs pulse in a cone with opening angle of 40°, the 5fs

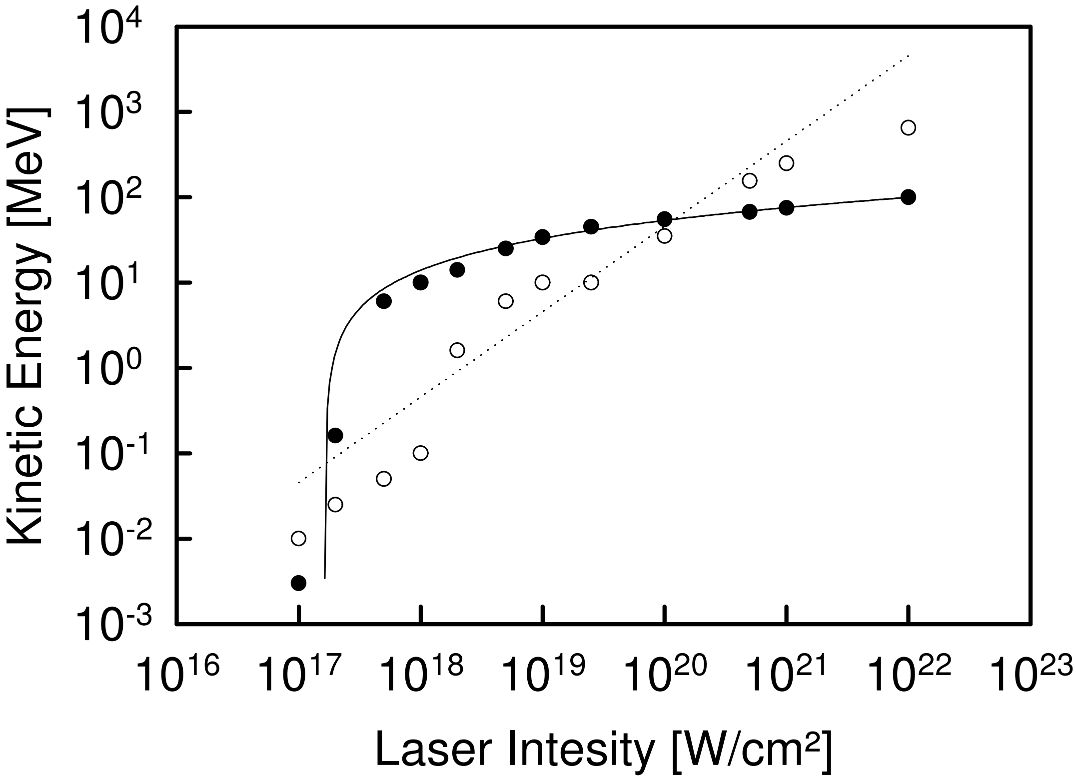

Figure 2: Kinetic energy as a function of the laser intensity for a 5 fs laser pulse. The full dots represent wakefield accelerated electrons, whereas the open dots depict electrons under the laser envelope. The full line is a fit, the dotted line depicts the kinetic energy resulting from wiggling inside the laserfield. For detailed parameter see text.

interaction produces a 6fs pulse with opening angle of 11°. The reason for the 5fs advantage is that in this case the condition $c \cdot \tau/\lambda_P \approx 0.25$, τ is the laser pulse duration, to efficiently excite a plasma wave is fulfilled, whereas a wakefield is missing for the too long 30fs pulse. A modification of λ_P to match the condition in the 30fs case leads to a wakefield but nevertheless direct laser acceleration dominates still, because the amplitude of the wakefield is much lower compared to the amplitude for the 5fs pulse.

In the 5fs case and also in the 30fs case both acceleration mechanisms are present but with different efficiencies. Figure 2 shows the maximum kinetic energy of the electrons for different laser intensity for a 5fs laser pulse with λ_0=0.8µm and a plasma wavelength of λ_p=8µm.. The full dots represent electrons accelerated by the wakefield behind the laser pulse, whereas the open dots show electrons accelerated by the laser. The doted line represents a theoretical estimation of the kinetic energy resulting from wiggling inside the laser field. This energy will eventually disappear as the electrons leave the laser pulse. It becomes clear that DLA only works around 10^{19} W/cm² but wakefield acceleration is always dominant in this parameter regime. The full line is a least square fit indicating that the maximal achievable energy with wakefield acceleration scales as $E_{Kin} \sim I^{0.0333}$

Concluding, our numerical analyses reveals that wakefield acceleration is dominant for laser pulses in the sub-20fs range, whereas direct laser acceleration dominates for longer pulses. Further we find that wakefield acceleration with sub-20fs pulses is superior to direct laser acceleration in several respects giving the possibility to produce unique sub-10fs multi-MeV electron bursts with low energy dispersion and low divergence angle.

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