ACCELERATION OF CHARGED PARTICLES BY HIGH INTENSITY FEW-CYCLE LASER PULSES *

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Abstract

Only recently a breakthrough in laser plasma acceleration has been achieved with the observation of intense (nC) mono-energetic (10 % relative width) electron beams in the 100 MeV energy range [1]. Above the wave-breaking threshold the electrons are trapped and accelerated in a single wake of the laser pulse, called bubble, according to PIC simulations [2]. At the MPQ Garching we plan to investigate the acceleration of electrons in this bubble regime by the use of 10 TW few-cycle laser pulse. As the pulse length of the few-cycle pulse of 5-10 fs remains below the plasma period also at comparatively high plasma densities, we expect the scheme to become more stable and efficient.

INTRODUCTION - LASER ELECTRON ACCELERATION

With the advent of short-pulse lasers in the power range of multi-TW to PW focal intensities above 10^{21} W/cm^2 can be realized. These correspond to electric fields of 10^{14} V/m, exceeding conventional acceleration gradients by orders of magnitude. Different methods have been discussed for the 'rectification' of these oscillating transverse fields and thus for the efficient acceleration of electrons into the MeV to GeV range: ponderomotive effects, longitudinal laser-driven plasma waves (laser wake-field acceleration, LWFA) [3], self-modulated LWFA [4], direct acceleration (DLA) [5], or the quasi-static charge separation at boundaries leading to ion acceleration [6]. SM-LWFA allows for the acceleration of rather intense electron pulses (nC) [4], occurring when the pulse duration is long compared to the plasma wavelength. It refers to the modulation instability which drives plasma waves to high amplitudes and finally to wave-breaking. Electrons get trapped and are accelerated to high energies. The mechanism becomes important when relativistic self-focusing sets in and propagation channels are formed [7]. However, wave breaking destroys the plasma wave in the channel and then direct laser acceleration (DLA) dominates [5]. The DLA mechanism is based on a resonant energy exchange between the laser pulse and co-moving relativistic electrons similar to the process in free electron lasers. Though leading to high-current beams, a disadvantage of this acceleration mode is that the energy spectrum shows an exponential distribution.

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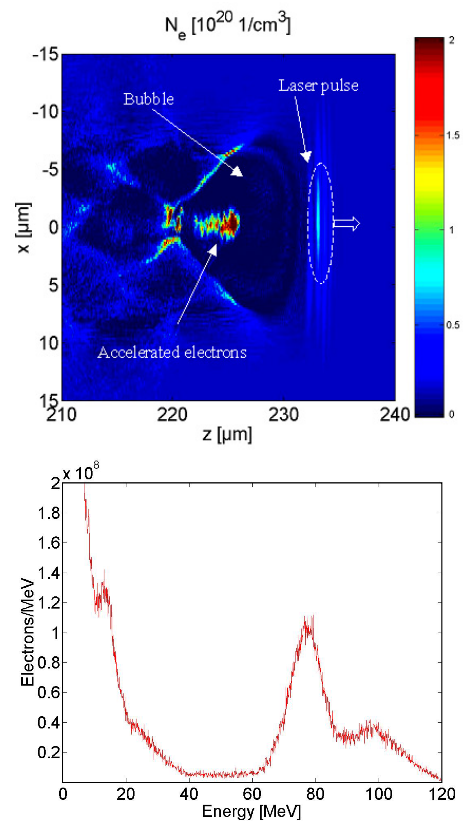

Figure 1: 3D PIC Simulation [code ILLUMINATION by M. Geissler] of the laser bubble acceleration mechanism for LWS 10 conditions and electron density $n_e = 0.01\, n_c$ of the critical density. The upper frame illustrates the bubble displaying the spatial electron density distribution, the lower a snapshot of the resulting electron spectrum.

'BUBBLE' ACCELERATION

The bubble acceleration regime depicts a novel regime of laser plasma wake-field acceleration where this drawback can be overcome [2]. It occurs when the laser pulse duration is shorter than the plasma period and the intensity exceeds the wave-breaking threshold. Electrons are radially expelled by the ponderomotive force of the relativistic laser pulse, forming a near spherical void of positive charge, the bubble, co-propagating with the short laser pulse. One plasma period later the electrons return attracted by the positively charged bubble and some of them are trapped to form an intense energetic stem at the bub-

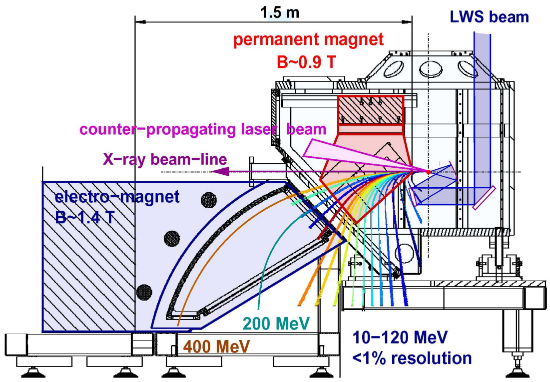

Figure 2: Schematic drawing of a target chamber comprising a hybrid magnet spectrometer for the online analysis of the electron spectra as well as for the investigation of the conversion into X-rays.

ble rear side. This situation is illustrated by Fig. 1, where the electron density is displayed in the plane of the laser polarization and the propagation direction.

However, the requirements for reaching this broken-wave regime are rather stringent. The pulse must fit into one plasma wave and the laser intensity must be sufficient for reaching the wave-breaking threshold. Thus, for shorter pulses a higher plasma density can be chosen. Higher densities are favorable as the plasma tends to break more easily and a larger number of electrons can be accelerated. Present laser systems were observed to not fully match these conditions, yet, relativistic pulse shortening recently allowed the first observation of the bubble regime [1]. At MPQ, relativistic intensities will soon be available for pulse durations of ~ 5 fs. These few-cycle pulses provide ideal conditions for directly entering the bubble regime, so that a high degree of reproducibility for further applications can be anticipated.

Simulations indicate that about one nC of charge can be trapped and accelerated in a micro-meter scale volume, yielding a bunch density exceeding that of conventional accelerators by about six orders of magnitude. For the case of the LWS-10 laser, under construction at MPQ and aiming for 10-20 TW in 5 fs pulses, the 3D PIC simulations suggest the attainment of near mono-energetic electron pulses between 50-100 MeV energy, about 10 % energy spread (see Fig. 1), a divergence in the range of mrad and a source diameter of 3 μm at 10-20 fs pulse length. For the systematic investigation of the quality and stability of these pulses, a target chamber (Fig. 2) is presently installed that enables the online spectrometry using a hybrid magnet spectrometer. It will consist of a focusing permanent dipole magnet (gap 5 cm, B-field $\sim$ 0.9 T) positioned inside the chamber followed by a larger conventional magnet. This construction provides good energy resolution, accessibility of the target region for further laser beams and facilitates radiation protection by bending the electron beams into the basement.

APPLICATIONS

Regarding, on the one hand, the exceptional density of the electron bunches, the ultra-short time structure, and the high conversion efficiency, and, on the other hand, the still rather broad electron energy spectrum, one rewarding application of such pulses will be the conversion of the electron energy into intense X-ray pulses in the fs-regime. Different schemes are planned to be tested, ranging from Thomson backscattering to undulator radiation. From colliding laser beams even photon-photon collision experiments might become realizable.

For the (linear) Thomson-scattering of light from relativistic electrons [8] the cross-section is of the order of the square of the classical electron radius ($\sim$ 670 mbarn) so that in the backscattering geometry with $\omega_{back} \sim (2\gamma_e)^2\,\omega_{in}$ about 10^{10} incoherent X-ray photons at an energy of $\sim$ 12 keV can be expected from an electron bunch containing 10^9 electrons at 50 MeV ($\gamma_e = 100$). Alternatively, the incoming second laser pulse can be regarded as a modulator (like an undulator or wiggler) at a μm scale wavelength thus explaining the comparatively high X-ray energy at comparatively low electron energy.

For undulator radiation from a magnetic undulator much higher electron energies are required as the modulation period can hardly be constructed to be below few mm. For the anticipated beam energy of $\gamma_e \sim 100$ this period would translate into a wavelength of the spontaneous undulator radiation in the far UV of $\sim$ 100 nm. However, in a bubble driven free-electron-laser (FEL) this radiation could be amplified and high brilliance could be reached. Such a scenario might in the future – once electron energies of $\gamma_e \sim 1000$ can be reached – lead to the realization of a table-top electron accelerator combined with a brilliant table-top coherent X-ray source (XFEL).

REFERENCES

[1] S.P.D. Mangles, et al., Nature **431** (2004) 353; C.G.R. Geddes, et al, in ibid, 538; J. Faure, et al., in ibid, 541

[2] J. Meyer-ter-Vehn, A. Pukhov, Appl. Phys. **B74** (2002) 355

[3] E. Esarey, et al., IEEE Trans. Plasma Sci. **24** (1996) 252 F. Amiranoff, et al., Nucl. Instr. Meth. **A 410** (1998) 364

[4] A. Modena, et al., Nature, **337** (1995) 606

[5] C. Gahn, et al., Phys. Rev. Lett., **83** (1999) 4772

[6] J. Schreiber et al., Appl. Phys. **B 79** (2004) 1041 and refs. therein

[7] A. Pukhov, et al., Phys. Plasmas **6** (1999) 2847

[8] E. Esarey, et al., Phys. Rev. **E48** (1993) 3003

[9] P. Elleaume, et al., Nuc. Instr. Meth. **A 455** (2000) 503