Multi-MeV Electron Beam Generation by Direct Laser Acceleration in High-density Plasma Channels

C. Gahn [a], G. D. Tsakiris [a], A. Pukhov [a], J. Meyer-ter-Vehn [a], G. Pretzler [a], P. G. Thirolf, K. J. Witte [a], and D. Habs
[a] Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany

State-of-the-art high power laser systems as the ATLAS laser at Max-Planck-Institut für Quantenoptik (MPQ) reach focused intensities exceeding $10^{18}\,\mathrm{W/cm^2}$. Interacting with an underdense plasma, the laser pulses undergo self-focusing and channel formation. Electrons are pushed out of the channel by the laser ponderomotive force and a static radial electric field is built up. Furthermore, a strong electron current driven in forward direction gives rise to a ~100 MG azimuthal magnetic field. In such a channel, some electrons are accelerated up to multi-MeV energies. These electrons play an important role in the fast ignitor concept for inertial confinement fusion and in laser induced nuclear reactions. The aim of this work was to characterize the electron beam and to identify the underlying accelerating mechanism.

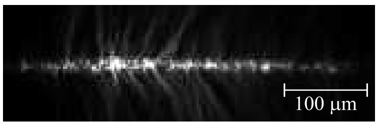

Fig. 1: Channel image taken by a side-scattering imaging system.

In order to create a channel, the laser pulse was focused into a helium gas jet of $10^{20}\,\mathrm{cm^{-3}}$ atomic density. (for details see [1,2]). The leading edge of the laser pulse completely ionized the gas and a channel was formed as shown in fig.1. The electron energy distribution was measured simultaneously utilizing a novel 45-channel electron-spectrometer that was designed for the special needs of laser-plasma experiments [3]. A typical energy spectrum of the electron beam is shown in fig.2. The angular distribution of electrons with a certain energy is given in fig.3.

Both figures depict the predictions of three dimensional particle-in-cell (3D PIC) simulations using the code Virtual Laser Plasma Lab at MPQ. These simulations take into account the real experimental setup and the laser pulse profile. The good agreement in forms and absolute electron numbers between PIC predictions and experiment prompted a closer look into the electron acceleration mechanism based on the simulation results [2].

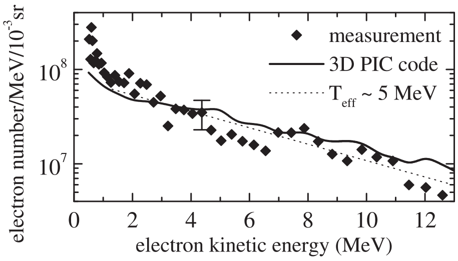

Fig. 2: Electron energy spectrum measured in laser beam direction (diamonds), exponential fit (dotted line), and prediction of the 3D PIC simulation (solid line).

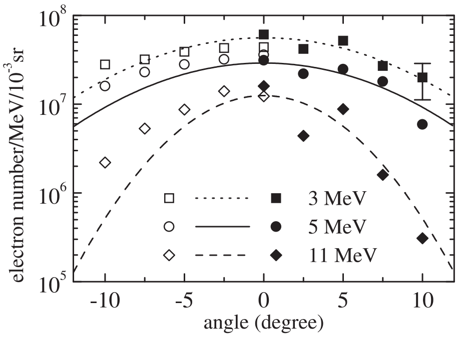

Fig. 3: Angular dependence of electrons with different energies (0° is the laser beam direction). Solid symbols are experimental results, hollow symbols show the predictions of the PIC simulation.

Basically, two candidates came into question: wakefield and/or direct laser acceleration. In the former process the electrons are trapped and accelerated in the longitudinal electric fields of plasma waves in the wake of the laser pulse. In the latter the electrons are accelerated resonantly by the electric laser field while they oscillate transversely in the static fields that accompany channel formation. In principle, this process is similar to the inverse free electron laser. The energy gain for each electron integrated over its whole trajectory is plotted into the histogram of fig.4. It can be seen that most of the electrons experienced a transverse overall acceleration (represented by $\Gamma_\perp$) rather than a longitudinal one (Γ_z).

Hence, the dominant accelerating mechanism is the direct laser acceleration. During this transverse acceleration the electron momentum gain is converted into forward direction via the Lorentz $\vec{v} \times \vec{B}$-force exerted by the magnetic laser field. Finally all the accelerated electrons form a multi-MeV beam propagating in the channel direction.

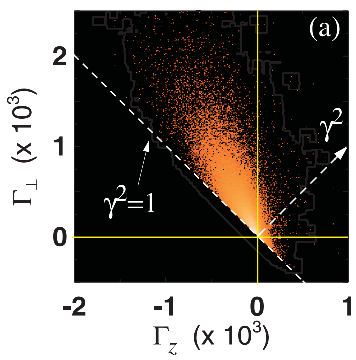

Fig. 4: Breakdown of electron spectrum with respect to the major acceleration mechanism where $\gamma^2 = 1 + \Gamma_z + \Gamma_\perp$.

References

[1] C. Gahn *et al.*, Jahresbericht 1998, p. 54
[2] C. Gahn *et al.*, Phys. Rev. Lett. **83** (1999) 4772
[3] C. Gahn *et al.*, accepted for publication in Rev. Sci. Instrum. (2000)