Electron acceleration using high power lasers

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The usage of laser-plasma interaction to accelerate particles has become a promising way of research in accelerator physics. The main advantage of plasma sources compared to conventional linear accelerators is the ability to accelerate particles on much shorter distances. This can result in better availability of such facilities for industry, medicine, or research and immensely boost progress in mentioned areas.

One way of accelerating electrons using laser-plasma sources is by the mechanism called Direct laser acceleration (DLA). Intense laser pulse propagates through low-density plasma and accelerates electrons by a resonant process to energies up to hundreds of MeV. The high charge provided by this process compared to other plasma sources is suitable for creating good quality radiation sources or possibly for testing fundamental phenomena of quantum electrodynamics.

It is almost impossible to treat a huge variety of nonlinear phenomena present during the interaction purely analytically. Because of the high complexity of the given setup, computationally demanding particle-in-cell (PIC) simulations are necessary. The code solves the motion of particles under the action of self-consistently developing electromagnetic fields present in plasma. The algorithm of the PIC code consists of integrating equations of motion, whilst electromagnetic fields are subsequently developed according to the motion of particles in the previous step. Since in real systems, the number of particles present is extremely large, they are represented in the simulation as a set of macroparticles instead. This makes the system computationally affordable but still very demanding even on current HPC machines.

The DLA mechanism is well known for more than twenty years. However, the experimental investigation of setup with varying density profiles was performed recently[1]. It was shown, that under certain conditions electrons can experience optimal acceleration resulting in unusually high energies and charge of the accelerated electron beam.

The aim of our work is to understand conditions, under which the varying density profile is favorable for the acceleration. This would allow us to construct optimal laser-plasma accelerators, maximizing energy gain for the given laser beam. To understand this, we performed quasi-3D PIC simulations using code Osiris[2] of a laser pulse propagating through the plasma with a Gaussian density profile. We observed that varying density profile increases the effect of self-focusing. This results in higher electromagnetic field amplitude acting on accelerated electrons. Furthermore, self-focusing causes curvature of wavefronts which brings the longitudinal electric field into the interaction. This may be favorable for the resonance condition. On top of those observations, we identified phenomena favorable for the acceleration in the presented regime and developed an analytical model consistent with simulation results.

[1] Hussein E. A et al., (2021) New Journal of Physics 23, 023031
[2] Fonseca R, et al., (2013) Plasma Phys. Control. Fusion 55, 124011