Study of electron acceleration dynamics by modifying a gas target with a shock wave

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***Abstract*— We present a method for studying the dynamics of electron acceleration, based on interrupting the acceleration process by the shock wave front created by an additional nanosecond laser pulse. Experimentally obtained electron spectra at various stages of acceleration are provided, as well as confirming results from PIC modeling.**

Keywords*— *laser acceleration of electrons, relativistic femtosecond radiation, PIC simulations

I. Introduction

Laser-plasma accelerators are developing both towards obtaining energies in GeV, and towards creating systems with energies of a few to tens of MeV and a high repetition rate. The latter uses laser pulses with energies limited to tens of mJ. Effective excitation of electron-accelerating plasma waves at such energies is always associated with self-focusing. The critical power is achieved at sufficiently high electron density (0.05 n_c for 1 TW laser pulse. n_c – critical density). The acceleration length at such density does not exceed several hundred micrometers. To create diagnostics with sufficient resolution, it is necessary to be able to modify the plasma on a scale of several tens of micrometers. This is difficult to achieve with a hydrodynamic shock, which is usually obtained by introducing an obstacle into a gas flow. However, shock waves created by a nanosecond laser pulse have very sharp fronts with a length of tens of micrometers in the first few nanoseconds and are suitable for the task at hand.

II. Experimental setup end simulation parmeters.

The main femtosecond (fs) laser pulse is generated by a Ti:sapphire crystal system. The duration of the laser pulse is about 50 fs, and the energy on the target reaches 50 mJ. The central wavelength is 800 nm. The radiation is focused using an off-axis parabolic mirror (F/D=7) into a spot with a diameter of 3.2 μm. The calculated peak intensity reaches 5-7 × 10^{18} W/cm^2. To create a shock wave, an additional pulse from a Nd:YAG laser with a duration of about 10 ns at a wavelength of 1064 nm (ns pulse) was used. It was focused by a lens with a focal length of 15 cm to a peak intensity of 10^{12} W/cm^2. A conical nozzle with a hole diameter of 400 μm was used as a gas (nitrogen) target. The gas from the nozzle scattered into a vacuum and at the height of the laser pulse waist the density profile can be described by a Gaussian function with a half-width of 270 μm. The maximum electron density in the center of the profile after ionization was 0.04 n_c. The nozzle holder and the steering mirrors of the laser pulses were motorized, allowing for spatial positioning of the gas jet and the shock waves during the experiment. By placing a nanosecond pulse waist in different areas of the gas jet, one can control the position of the density jump by the shock wave. The density jump caused by the shock resulted in a fivefold increase in density at the wave front, while inside the region bounded by the shock fronts, the concentration dropped practically to zero. The width of the jump was 15 μm. The electron beam, propagating in the direction of the passing femtosecond pulse, was directed to a magnetic spectrometer with a LANEX detector.

In addition to experimental methods, SMILEI PIC simulation was used in pseudo-3D mode with azimuthal symmetry. To conserve computational resources, a moving window was employed. The computational domain, with a radius of 30λ and a length of 60λ, moved at a speed of 0.98c. The longitudinal resolution was taken as λ/32, the transverse resolution as λ/8, and the time step as λ/48c. The duration, focusing diameter, and field amplitude of the laser pulse were taken from the experiment (τ=50 fs FWHM, d=3.2 μm FWHM, a_0=1.7). Profiles of neutral atom density (nitrogen) were taken from interferometry data, modified by hydrodynamic calculation to include shock waves.

III. Discussion and Conclusion

By truncating the plasma channel with a shock front, electron spectra at various stages of acceleration were obtained in both the experiment and the PIC simulation. Good agreement was found between the experimental data and the simulation results. The duration of the laser pulse exceeded the optimal one; therefore, acceleration occurred according to the SMLWFA mechanism. The acceleration length from the beginning of injection to the onset of defocusing was 80 μm. The injection occurred on a slowly decreasing plasma profile after the pulse passed through the maximum concentration in the center of the nozzle. Let us denote the injection point as 0 μm. In the initial stages (0-40 μm), the electron spectrum is exponential due to ongoing injection. Injection ceases at the point of 40 μm. Electron energies increase to a maximum of 12 MeV at the point of 60 μm, at which the spectrum becomes quasi-monochromatic (9-12 MeV). Subsequently, defocusing is observed at the point of 80 μm, leading to a decrease in electrons energy. By placing the shock front at the point of 60 μm, defocusing can be avoided, yielding a collimated beam with a charge of 3 pC, a divergence of 25 mrad, and a quasi-monochromatic spectrum with electron energies ranging from 8 to 11 MeV.

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