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Stable electron beams from laser wakefield acceleration with few-terawatt driver using a supersonic air jet

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ABSTRACT

The generation of stable electron beams produced by the laser wakefield acceleration mechanism with a few-terawatt laser system (600 mJ, 50 fs) in a supersonic synthetic air jet is reported and the requirements necessary to build such a stable electron source are experimentally investigated in conditions near the bubble regime threshold. The resulting electron beams have stable energies of (17.4 ± 1.1) MeV and an energy spread of (13.5 ± 1.5) MeV (FWHM), which has been achieved by optimizing the properties of the supersonic gas jet target for the given laser system. Due to the availability of few-terawatt laser systems in many laboratories around the world these stable electron beams open possibilities for applications of this type of particle source.

1. Introduction

The interaction of a femtosecond laser with underdense plasma has been successfully used for electron acceleration with energies of up to a few GeV [1]. This kind of accelerator can, generally, be used for various applications such as high energy physics and table top high brightness photon sources [2–4]. In addition, there are applications for devices providing stable electron bunches at lower energies. Electrons in the range of tens of MeV can be well utilized, for example, in a source of ultra-short X-ray pulses based on inverse Compton scattering [5], as well as in radiotherapy [6], and electron radiography and the measurement of electric and magnetic fields [7–9].

The quality of generated electron bunches and the stability of the laser-plasma accelerator depend on the driving laser, on the processes within the plasma, and principally on the injection of electrons into the acceleration stage. Conditions necessary to build an electron accelerator with the purpose of energy stability are investigated with a few-terawatt laser pulse in a plasma of higher density in conditions near the bubble regime threshold (i.e. when the laser strength parameter $a_0 < 2$). Various gas types, such as H_2, He, N_2, or Ar, were already tested to improve the electron source properties [10–12]. Here we examine whether a supersonic jet of synthetic air (i.e. a mixture of nitrogen and oxygen without the presence of other gases) can be effectively used in this type of laser-plasma accelerator. Synthetic air allows high plasma densities to be reached without the necessity of high backing pressure (it would require almost four times higher backing pressure to reach the same density if helium target was used). A high backing pressure not only has stricter requirements on the gas pipes but also increases demands on the gas valve and reduces its lifetime. The denser plasma, which is obtained when synthetic air is used, contributes to stronger laser self-focusing due to reasons described below.

This is especially important, because there are, in principle, two possible injection mechanisms when using a synthetic air target: self-injection due to plasma wave breaking [13] and ionization injection [14]. In the case of a few-terawatt laser system, the typical vacuum intensity of laser pulse is in the order of magnitude of 10^{18} W/cm^2, and thus it does not allow complete ionization of nitrogen and oxygen atoms (the required laser intensity to ionize K-shells of these elements is more than 10^{19} W/cm^2), while electrons from L-shells are fully depleted by the rising edge of the pulse. Nevertheless, the K-shell electrons can be ionized when an intensity $>10^{19}$ W/cm^2 is achieved due to relativistic self-focusing of the laser beam in plasma. When this happens, electrons can be trapped in the acceleration phase due to the ionization injection mechanism.

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The self-focusing in a plasma occurs for a laser power P exceeding the critical power P_{crit} which can be calculated for a collimated Gaussian beam as [15,16]

$$P_{\mathrm{crit}}\,[\mathrm{GW}] = 16.2\left(\frac{\omega_L}{\omega_p}\right)^2 = 16.2\frac{n_{\mathrm{crit}}}{n_e} \tag{1}$$

where ω_L and ω_p are the laser and plasma frequencies respectively, n_{crit} is the critical plasma density and n_e is the electron plasma density. Eq. (1) shows that the critical power P_{crit} can be effectively lowered by increasing the plasma density n_e, which results in stronger self-focusing. The laser pulse reaches a higher normalized vector potential due to self-focusing given by [17]

$$a_{\mathrm{SF}} = 2\left(\frac{P}{P_{\mathrm{crit}}}\right)^{1/3} \tag{2}$$

with the focal spot radius

$$R_{\mathrm{SF}} = \frac{\lambda_L}{\pi}\left(a_{\mathrm{SF}}\frac{n_{\mathrm{crit}}}{n_e}\right)^{1/2}, \tag{3}$$

where λ_L is the laser wavelength. Therefore, by setting the plasma density accordingly, the focal spot size in self-focusing can be tailored to reach the laser intensity required for complete ionization of the target atoms within a relatively small region of space.

The additional ionization injection is, of course, also possible in commonly used helium targets with the admixture of heavier atoms, e.g. argon. The disadvantage of using argon is obvious when laser intensity necessary for emission of electrons from atoms is considered again. The laser pulse intensity necessary for ionization of the L-shell of argon ranges from 1.5×10^{18} W/cm^2 to 1×10^{19} W/cm^2. This results in the gradual injection of electrons along the laser propagation in the plasma as the intensity of a self-channeling few-terawatt laser pulse fluctuates between these values. Thus the energy spread of accelerated electron bunch is broadened as a consequence of unequal acceleration lengths. This may be avoided when the synthetic air target is used, and consequently electron bunches with a stable peak energy and energy spread can be obtained. The expected energy of accelerated electrons is lower when compared to an ideal bubble regime with an ion cavity which is completely void of electrons. This is due to the irregular shape of the created ion cavity in our conditions and the fact that this region propagating behind the driving laser pulse is not completely free of electrons, thus the accelerating electric field is lower than in the ideal bubble regime. The accelerating conditions can, however, be estimated from particle-in-cell simulations (as described in Section 4).

2. Experimental setup

The Ti:sapphire laser system at the PALS laboratory [18] provides laser pulses with a duration of 40 fs, maximum power of 25 TW, a central wavelength of 808 nm and can be operated at a maximum repetition rate of 10 Hz. However, during this experiment, it was operated in the single shot regime with an energy of 600 mJ after compression (i.e. on target) and a pulse duration of 50 fs. The laser beam was linearly polarized at an angle of about 20° with respect to the horizontal plane to investigate whether the electron pointing direction has a direct relation to the laser polarization. The main focusing element in the experimental setup (depicted in Fig. 1) is an off-axis parabolic (OAP) mirror with an effective focal length of 326 mm corresponding to $f/6.5$. The target is represented by a gas jet produced from a supersonic de Laval nozzle, and compressed synthetic air is used as the gaseous medium.

During the experiment, fundamental plasma parameters as well as parameters of the resultant electron beams are monitored in order to achieve stable accelerating conditions. The focal spot is one of these main parameters for the laser wakefield acceleration (LWFA). For this reason, offline diagnostics of the focal spot is used, which consists of a 10× zoom microscopic lens mounted on a CCD camera and allows the focal spot size and its shape to be optimized.

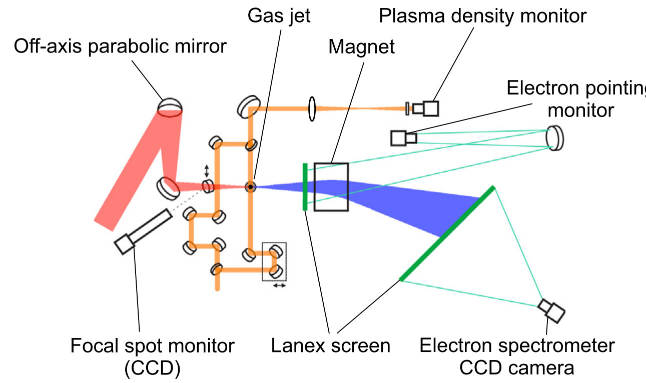

Fig. 1. The experimental setup of the laser-driven electron accelerator and the diagnostics used. The femtosecond laser pulse (red) is focused onto the gas jet target. The camera for an offline focal spot diagnostics is present. Plasma created in the target area is probed by the auxiliary pulse of the Mach–Zehnder interferometer (orange). Accelerated electrons (blue) are diagnosed by the magnetic spectrometer and the pointing stability is measured before electrons enter the magnetic field of the spectrometer dipole. Electrons are detected by scintillating Lanex screens (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Another key parameter that needs to be monitored is the plasma density. For this purpose, a probe laser beam, which is split from the main beam in the compressor [18], is used in the Mach–Zehnder interferometer. Images from the interferometer are used to determine the plasma density from the fringe shift and to optimize the conditions for self-focusing of the plasma channel. The phase shift caused by the neutral gas could be, in general, subtracted using a reference shot without the driving laser pulse. This shift is, however, significantly smaller than that caused by the plasma, and changes on much larger spatial scales. Considering the Abel inversion, this can be neglected.

In addition to the parameters of the accelerator, the electron beam parameters, such as pointing stability, energy and energy spread, were also monitored. The electron pointing stability measurement is composed of a small scintillating Lanex screen placed between the target and the front of the dipole magnet of the electron spectrometer (as shown in Fig. 1), where the magnetic field of the dipole is negligible and thus it does not affect the electron trajectory. This Lanex screen is imaged from the back side by a CCD camera. In order to prevent the camera being hit by generated X-rays, the imaging is performed via reflection from a mirror.

The diagnostics also allows the measurement of the shot-to-shot stability of the electron beam. Measurements of the pointing stability and electron spectrum are performed simultaneously. While the multiple scattering of electrons on the front Lanex screen can be effectively unfolded [19], the screen is in our case eventually removed when the stable generation of electron beams is achieved in order to improve the signal on the electron spectrometer. In addition, the information on electron pointing stability improves the energy determination from the spectrometer.

The magnetic electron spectrometer setup contains the dipole magnet with a length of 70 mm and gap of 10 mm, which creates a uniform magnetic field of 0.27 T in the gap between the poles. Fig. 1 shows the setup of the spectrometer which can measure energies in the range from 8 to 120 MeV (without the pointing stability correction which can further change this range for any given shot).

For the purpose of particle detection, a large scintillating Lanex screen is imaged from behind with the aid of an calibrated camera. The screen is placed at a distance of 298 mm from the back of the magnet at an angle of 42 degrees with respect to the transverse direction. This setup allows a simple charge measurement as reported in [20].