Nuclear Instruments and Methods in Physics Research A 740 (2014) 54–59

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Reproducibility of electron beams from laser wakefield acceleration in capillary tubes

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ARTICLE INFO

Keywords:
Laser wakefield
Laser plasma accelerator
Electron acceleration
Capillary tube
Electron beam stability

ABSTRACT

The stability of accelerated electron beams produced by self-injection of plasma electrons into the wakefield driven by a laser pulse guided inside capillary tubes is analyzed statistically in relation to laser and plasma parameters, and compared to results obtained in a gas jet. The analysis shows that reproducible electron beams are achieved with a charge of 66 pC ±11%, a FWHM beam divergence of 9 mrad ±14%, a maximum energy of 120 MeV ±10% and pointing fluctuations of 2.3 mrad using 10 mm long, 178 μm diameter capillary tubes at an electron density of $(10.0 \pm 1.5) \times 10^{18}\,\text{cm}^{-3}$. Active stabilization of the laser pointing was used and laser parameters were recorded on each shot. Although the shot-to-shot laser energy fluctuations can account for a fraction of the electrons fluctuations, gas density fluctuations are suspected to be a more important source of instability.

1. Introduction

The development of conventional, linear electron accelerators composed of evacuated radio-frequency cavities has reached a technological limit with accelerating gradients of the order of 50 MV/m. Alternative ways of accelerating electrons in plasmas are being investigated since the proposition of laser plasma wakefield acceleration (LPA) [1]. The plasma wave created in the wake of an intense and short laser pulse is associated with large amplitude electric fields, typically in the range 10–100 GV/m with state-of-the-art laser systems. For high enough intensity (typically above $10^{18}\,\text{W/cm}^2$), plasma electrons are blown out from the high intensity region close to the laser axis, and a moving cavity, or bubble, is created behind the driving pulse. A fraction of the plasma electrons can become self-trapped in this ion cavity and be accelerated to high energies. This mechanism provides with relative ease a source of accelerated electrons, with properties that depend on several laser and plasma parameters and competing nonlinear mechanisms. Electron acceleration has been observed experimentally by numerous groups (see for example Esarey et al. for a review [2]) in various plasma targets such as gas jets, gas cells, capillary discharge waveguides and dielectric capillary tubes [3].

The produced electron beams, with an energy ranging from 50 MeV to a few GeV with the most powerful laser drivers [4,5], have an interest for various applications, including the generation of radiation [6] in the X-ray range in the plasma, as drivers for free electron lasers, or the development of injectors for multi-stage laser plasma accelerators [7].

Development of these novel sources of electrons will depend on their reliability and the stability of their properties. In order to get some insight on the performance of an electron source produced by self-injection of plasma electrons, we have studied the stability of electron parameters against laser and plasma parameters.

The properties of electron beams reported in this paper were achieved in capillary tubes and gas jet targets with plasma densities suitable for a comparison of results. Previous studies [8,3] have shown, for example, that similar electron energy and charge can be achieved with these two types of targets for specific plasma densities.

The paper is organized as follows: the experimental setup is presented in Section 2; the properties of electron beams generated inside capillary tubes are shown in Section 3; the effect of the gas distribution on electron properties is reported in Section 4; and finally, in Section 5, a conclusion is given.

2. Experimental setup

The reproducibility of electron beams from laser wakefield acceleration in capillary tubes has been studied at the Lund Laser Centre (LLC) in Sweden with a multi-terawatt laser. The laser is a

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http://dx.doi.org/10.1016/j.nima.2013.10.062

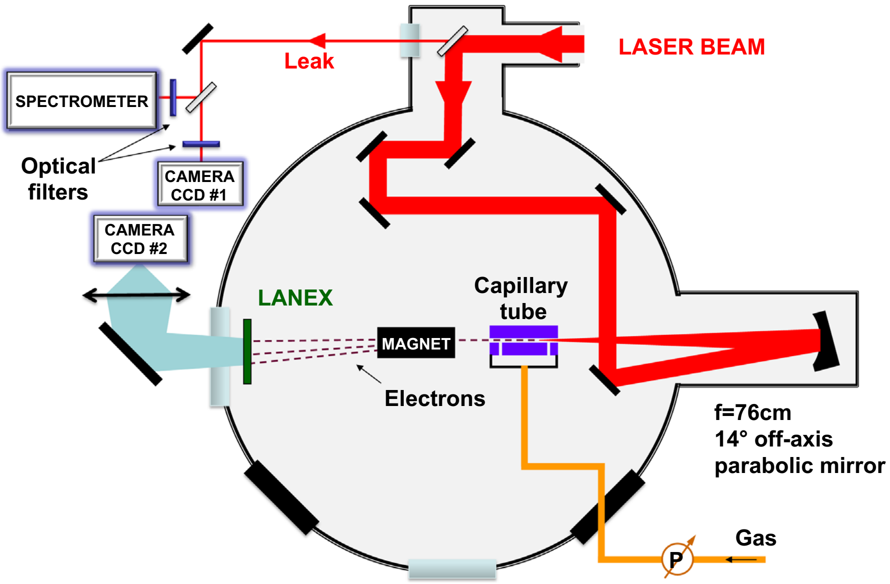

Fig. 1. Schematic diagram of the experimental setup.

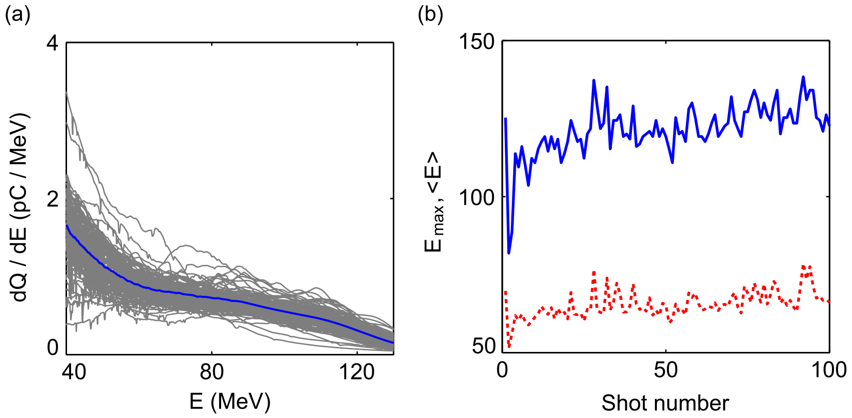

Fig. 2. Data from a series of 100 shots in a 10 mm long, 178 μm diameter capillary tube containing H_2 at an electronic density of $(10.0 \pm 1.5) \times 10^{18}$ cm^{-3}: (a) electron spectra (gray lines) and the corresponding mean curve (blue line) and (b) average energy (red dashed line) and maximum energy (blue solid line) of the electron spectra shown in (a); the mean values of $\langle E \rangle$ and E_{max} are 65 and 120 MeV with a standard deviation of 9 and 10%, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

titanium-doped sapphire (Ti:Sa) laser using chirped pulse amplification (CPA), and delivers pulses with FWHM duration of 40 fs and a wavelength of 800 nm. The experimental setup is schematically shown in Fig. 1.

The laser beam with an energy on target of (800 ± 20) mJ was focused using a $f = 76$ cm off-axis parabola. The laser spot on target inside the chamber was optimized by tuning a deformable mirror. A Gaussian waist of 17 μm (radius at e^{-2}) was computed by fitting the laser radial profile with a Gaussian function. 88% of the laser energy was contained within a circle having a radius equal to 17 μm. The laser peak intensity is thus estimated to be $I_0 \approx 3.6 \times 10^{18}$ W/cm^2 and the normalized laser vector potential $a_0 \approx 1.3$. An active system for stabilizing the laser pointing developed at LLC [9] was used in this experimental campaign, giving a standard deviation of the laser pointing of ≈ 4 μrad and improving the electron properties as well as extending the lifetime of capillary tubes [10]. Input laser parameters were recorded on every shot using a small fraction of the incident laser beam leaking through a dielectric mirror. This fraction was further divided and sent to a fiber spectrometer and focused on a charge-coupled device (CCD) camera. The relative shot-to-shot fluctuations of the laser energy were computed from the signal recorded by this camera. The relative fluctuations of laser pulse duration were approximately estimated by applying an inverse Fourier transform on the laser spectra, assuming a flat phase.

Capillary tubes were mounted, one at a time, in a motorized holder allowing the capillary tubes to be accurately aligned on the laser axis. The capillary tubes could be removed from the laser axis and a 3 mm nozzle of a gas jet inserted instead. Therefore, it was possible to switch from one gas target to the other without opening the vacuum chamber, thus avoiding significant drifts of laser parameters. Capillary tubes with inner diameter of 178 μm and a length varying from 8 mm to 20 mm were used for the data presented here. They are made of glass and are optically smooth at the laser wavelength. Gas was let in through two slits cut in the capillary wall, providing a spatially uniform gas density profile between the two slits. The molecular density inside the capillary tubes was adjusted by a gas regulator controlling the upstream reservoir pressure. The resulting molecular density for different reservoir pressure had been characterized by interferometric studies [11]. The gas density was shown to fluctuate about 15% in space and in time due to the propagation of sound waves in the gas plateau during the gas filling process. The laser pulses were focused 1 mm inside the capillary tubes.