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Electron injector for compact staged high energy accelerator

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ABSTRACT

An electron injector for multi-stage laser wakefield experiments is presented. It consists of a variable length gas cell of small longitudinal dimension (⩽10 mm). The gas filling process in this cell was characterized both experimentally and with fluid simulation. Electron acceleration experiments were performed at two different laser facilities. Results show low divergence and low pointing fluctuation electron bunches suitable for transport to a second stage, and a peaked energy distribution suitable for injection into the second stage wakefield accelerator.

1. Introduction

In laser wakefield experiments, the laser beam needs to interact with a plasma of controlled density value and distribution. The plasma can be created by discharge [1] or directly by laser ionization of gas [2] provided by a gas jet or confined in a material structure such as a capillary tube [3,4] or a gas cell [5].

The choice of confinement structure is linked to experimental requirements in terms of plasma density, length, homogeneity, stability and reproducibility. To accelerate electron bunches to the GeV level, the interaction length has to be of the order of a few cm; in that case a guiding structure, such as a dielectric capillary with or without discharge, is needed to guide the laser along the plasma and prevent laser diffraction. To achieve lower energy electron bunches, the plasma length can be reduced to mm scale, and a gas cell is an appropriate confinement structure. Indeed, the use of gas cells to confine the gas has been shown to contribute to the stability of the generated electron bunches [6–8] as the gas is relatively homogeneous in comparison with a supersonic gas jet.

In the frame of CILEX [9], multi-stage laser plasma acceleration experiments will be implemented at the APOLLON facility, and the main components are designed and tested using existing facilities. A prototype of the electron injector, called ELISA for ELectron Injector for compact Staged high energy Accelerator, has been built. Electron bunches with a divergence lower than 10 mrad are required in order to be transported to the second stage and with an energy spread of ~1% to be efficiently accelerated in the wakefield of the second stage. The energy range targeted for the injector is 50–200 MeV, as these relativistic energies can be achieved at various facilities and the transport beam line size is manageable. The stability of the electron bunch pointing is also a key parameter as the electron bunch injected into the second stage accelerator needs to be positioned precisely at the center of the focal volume, in order to avoid phase slippage or transverse fields effects. In addition, the injector has to provide electron bunches with the highest possible charge. These considerations have led to the choice of a gas cell for the stability, with short length (≤10 mm) for low energy. The use of ionization-induced injection [10–12] is also investigated to produce low energy spread and low divergence electron bunches with high charge.

The remaining of the paper is organized as follows: Section 2 presents the gas cell design and its characterization and Section 3 shows some examples of electron properties measured during acceleration experiments at two different laser facilities.

2. Gas cell design and characterization

2.1. Cell description

A gas cell with variable length was used to confine hydrogen gas (H_2), with the addition of a small fraction of N_2 for the ionization-induced injection scheme. The gas cell and the motorized positioning holder are shown in Fig. 1(a)and a schematic drawing of a section of the gas cell is presented in Fig. 1(b). The main part of the cell is a 20 mm diameter cylinder with a 3 mm

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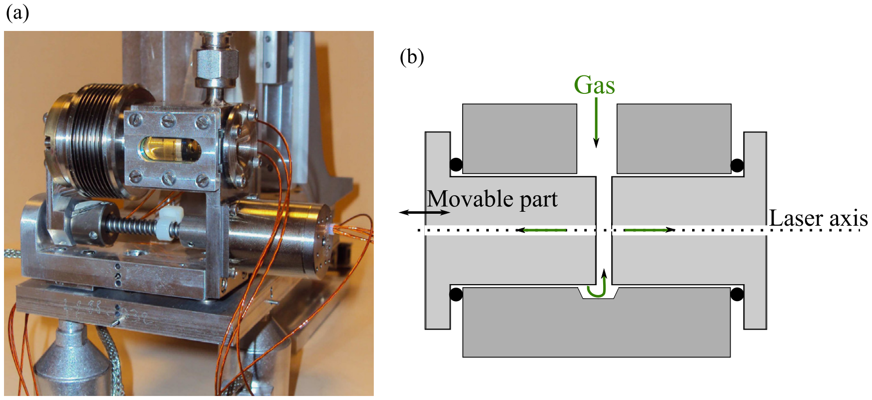

Fig. 1. (a) Picture of ELISA gas cell. (b) Schematic drawing of a section of the gas cell showing the gas inlet (top) and groove (opposite bottom).

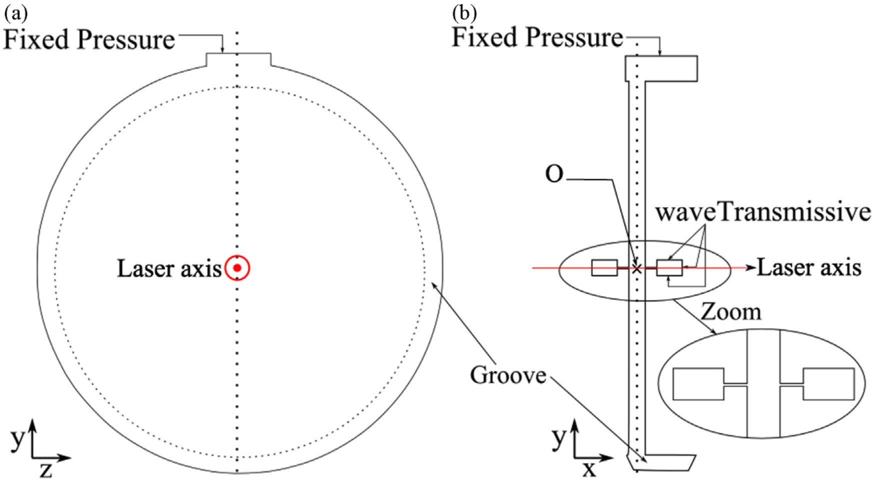

Fig. 2. Simulation geometry and boundary conditions. (a) Transverse cross section. (b) Longitudinal section with zoom on central part. Dotted lines on each figure indicate the position of the other figure plane.

diameter gas inlet at the top. Optical quality windows are present on each side for optical diagnostics transverse to the laser propagation axis. The cell inner length can be varied from 0 to 10 mm. Replaceable entrance and exit plates made of 500 μm thick steel, drilled with 200 μm diameter holes, are mounted to the cell with indium seals. The gas is injected in the cell by the opening of an electrovalve allowing the gas to flow from a reservoir into the cell volume. As the gas will then leak through the entrance and exit holes into the vacuum chamber, it is crucial to know the dynamics of the gas flow in order to control the value of the density with which the laser pulse interacts and minimize density fluctuations.

2.2. Fluid simulations

Fluid simulations are an efficient tool to determine the dynamics of the gas flow with good precision. It gives access to the gas distribution on the whole geometry which can be difficult to measure experimentally due to the low densities and short lengths, or due to the presence of walls preventing optical probing.

3D simulations were performed using openFOAM [13] and the turbulent, transient solver sonicFoam with sonic flow capabilities. SonicFoam is particularly suitable for this case because of the high initial ratio between the inlet pressure and the pressure inside the cell, and between the pressure inside the cell and the pressure in the vacuum boxes when the cell is filled. The gas used in the simulation is H_2 and the geometry is schematically presented in Fig. 2. The transverse section is represented in Fig. 2(a). The gas inlet is located at the top where the pressure is fixed at 500 mbar, representing the end of the pipe connecting the reservoir to the gas cell. The longitudinal section drawn in Fig. 2(b) shows two vacuum boxes connected to the inner part of the cell by 200 μm wide, 500 μm long pipes representing the entrance and exit plates. A groove located all around the inner part of the cell and aligned with the gas inlet is used to improve the homogeneity of the filling process (also visible in Fig. 1(b)). It allows the gas to flow around the central part of the gas cell when the cell length is smaller than the gas pipe diameter (3 mm) in a cylindrical manner. The boundary condition applied to the 3 outer boundaries of each vacuum box allows the gas to go through and exit the simulation box (labeled as waveTransmissive in Fig. 2). Thanks to this transmissive boundary condition, vacuum boxes can be reduced to a small volume to reduce computation time without over filling them and avoid modifying the flow of gas by its accumulation inside the vacuum boxes. This boundary condition is realistic, as in practice the vacuum chamber surrounding the cell is very large compared to the characteristic length of the cell (ratio of ~ 1 m/1 mm) so that the pressure inside the vacuum chamber is always low compared to the pressure inside the cell.

Electronic density at the center of the cell (point O in Fig. 2(b)), calculated from simulated gas density assuming complete ionization, is plotted as a function of time in Fig. 3(a). We can see a slow increase at the beginning and until $t_1 = 28$ μs as gas is mainly flowing along the groove surrounding the inside of cell as seen in Fig. 4(a) where the density of hydrogen ρ_{H_2} is represented on the

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