Plasma density profile measurements for ultra-short high power laser beam guiding experiments at SPARC LAB

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Abstract. External injection is a promising method to achieve high accelerating gradients and to control the beam properties. The energy gain of an electron via the wakefield is proportional to the product of the accelerating field multiplied by the effective propagation distance of the laser. Therefore, in order to bring the electron energy in the order of the GeV, a longer propagation length is required, which can be obtained by guiding the laser pulse in a wave-guide. In the case of SPARC LAB, a 500 µm diameter hydrogen-filled capillary discharge is used; to guide the laser beam it is necessary to act on the refractive index of the plasma, depending on its density. In this work measurements of the trend over time of the longitudinal profile of the plasma density within the capillary are presented, along with openFOAM simulations of the gas profile distribution. Preliminary test of laser guiding are also shown, detecting the behaviour of the laser beam at the exit of the capillary with respect to the discharge current value.

1. Introduction

Nowadays the new frontier of particle accelerators is the compactness of the accelerating structures, to allow their use in places beyond research facilities such as hospitals and industry. The goal is therefore the generation of beams of charged particles, stable and repeatable to be accessible to public and private institutions for different applications [1]. Plasma acceleration makes it possible to generate high accelerating gradients in an extremely small space [2]. The maximum plasma accelerating field scales as \( E_0[V/m] \approx 96\sqrt{n_0}[cm^{-3}] \), where \( n_0 \) is the electron plasma density. Accelerating gradients up to \( TV/m \) are therefore in principle achievable [3].

Using a high-intensity laser, for example, it is easy to accelerate electrons by ionising a gas, creating an accelerating field, and generating high-energy electron beams at the same time, by means of the so-called self-injection mechanism [4][5]. However, the self-injection method usually has a big limit due to the poor quality of the accelerated beams: unless specific injection configurations are used [6], the electrons are injected in the accelerating field region at different times and therefore they are subject to different accelerating fields. The beams produced have
for this reason high energy spread and divergence, and this makes them difficult to be used for a large number of applications [7][8]. A solution to this problem is represented by the external-injection scheme, consisting in the acceleration of a pre-existing electron bunch coming from a RF Linac, by exploiting the plasma wakefield stimulated by an intense laser in a plasma [3][9]. In this way it is in principle possible to obtain a high energy boost at the exit of the plasma channel, keeping the initial electron beam quality. The main advantage of this scheme, since the bunch generation is decoupled by the acceleration process, is that it might be possible to have more control on the injection of the electron bunches into the accelerating field [3][10].

1.1. Laser guiding process and motivations

In the case of external injection, it is however necessary to solve several constraints of laser wakefield acceleration, such as the laser energy depletion and the limitation of the accelerating distance due to the laser diffraction.

The depletion length is the distance over which a laser pulse that propagates in the plasma loses energy due to the absorption of the plasma itself. This limit can be overcome using a preformed plasma channel, so that the laser energy is not used for the gas ionisation, but it is entirely available for being transferred to the accelerating field.

A Gaussian beam has a limit in its natural diffraction, tending to diverge after a Rayleigh length. If the laser pulse is very intense, this can be compensated by a lens effect called self-focusing, by which the laser focuses the pulse. [11].

The electron energy gain from the wakefield is proportional to the product of the accelerating field for the effective propagation distance of the laser. This distance is about $\pi Z_R$, with $Z_R$ the diffraction length of the laser pulse (Rayleigh length). Thus, to accelerate particles to the GeV level, a longer propagation length is required [12][13]. Nonetheless, one way to overcome the laser diffraction is to achieve optical guiding of the pulse in the plasma [14][15]. A possible way to do that is to use a preformed plasma channel, for example by means of a gas-filled capillary discharge. The use of this type of device contrasts both the depletion length limit, as mentioned above, and the laser pulse diffraction limit. In this case, the plasma channel is formed by the temperature profile during the discharge: due to an initially higher temperature on axis, after a certain time depending on the initial conditions, plasma electrons are forced radially. This results in a parabolic radial plasma density profile, with lower density on the axis [16]. Given a laser pulse of intensity $I = I_0 \exp(-2r^2/r_i^2)$ and a parabolic density distribution of the plasma channel $n(r) = n_0 + (r/r_m)^2 n_d$, where $r \leq r_m$, this hollow profile can be used to guide the laser pulse if the laser waist radius is equal to a match spot between the pulse and the guide. The match spot is defined as $r_m = (\pi r_e n_d)^{-1/2}$, with $r_i$ radius at waist, $n_0$ plasma density on the axis, $n_d$ edge-axis density difference, and $r_e$ electron radius [17]. It is therefore necessary to operate on the refractive index of the plasma to guide the beam, and since the refractive index depends on plasma density [18], this makes plasma density measurements of key importance for such a type of plasma acceleration experiments.

2. Experimental set-up and measurements

The study of the best coupling condition between the ultra-short high-power FLAME laser pulse [19] and the SPARC high-brightness electron beam is essential for the future external-injection experiments at SPARC_LAB (INFN Frascati) [20]. In this scheme, the wakefield will be created by the FLAME laser pulse, propagating in a hydrogen gas-filled capillary discharge [21]. This wakefield will be used to accelerate the electron bunches produced by the SPARC photo-injector [9]. The goal of this experiment is to demonstrate that a high-brightness electron beam can be accelerated by a plasma wave without any significant degradation of its quality [10][22].

In order to study the laser guiding process, an experimental test station for the different capillaries and for the relative guiding process of a test laser beam was built. Discharge circuits
have been built, capable of providing a pulsed potential difference at the ends of the capillary (few centimetres long), greater than the discharge voltage of the gas used (H) according to Paschen’s law, therefore of the order of tens of kV [23][24]. This high voltage is applied by means of electrodes at the two terminals of the capillary.

2.1. Plasma density measurement system
Plasma density measurements have been carried out, exploiting the Stark effect. The presence of electrons and ions and, therefore, of their electric field, generates a spectral enlargement \( dL \simeq \alpha n_0^{2/3} \), where \( \alpha \) is a function of electron density and temperature [25][26]. For these Stark broadening measurements, a spectrometer with a resolution of a few angstroms was used, to be able to resolve the chosen emission line (\( H_\alpha = 656 \text{ nm} \) or \( H_\beta = 486 \text{ nm} \) line). The rest of the setup was as follows: a first lens reproduces the longitudinal profile of the capillary, the light emitted is transported by an optical system on the slit of the spectrometer, then on its diffractive grating; a second lens conveys the light on a CCD, which must be equipped with an intensifier to increase the signal/noise ratio, with active time of the order of tens of ns. In this way it is possible to make a measurement resolved in time of the electronic density profile present inside the capillary.

Using this method, the measurements presented in this work refer to a 3D printed transparent plastic capillary with a length of 3 cm and a diameter of 500 \( \mu \text{m} \). By means of a mechanical solenoid valve it is possible to inject the gas inside the capillary using a system of two inlets positioned at 1/3 and 2/3 of the capillary length (see Fig. 2): this expedient is used to improve the uniformity of the hydrogen distribution inside the channel, which is necessary to guarantee a longitudinal uniformity of the plasma. The hydrogen pressure has been set so as to obtain about 200 mbar at the entrance of the experimental chamber, so an initial pressure of tens of mbar is estimated inside the capillary before the discharge. The solenoid valve was opened for 3 ms and after its complete closure the discharge was carried through a discharge circuit: a voltage of 18 kV was applied to the electrodes, producing a current curve over time with a peak of 270 A. With these parameters, summarised in table 1, the data collected by the spectroscopic method described above are shown in Fig. 3 - 4: the emission line used here is the \( H_\beta \). The spectral enlargement was calculated as follows: for each ICCD image, the widths of all transverse profiles for each pixel were calculated, assuming a dominant Lorentzian trend and using the FWHM of the fits. The plasma density \( n_0 \) was estimated using the previously given relation, by means of the parameters tabulated in [26]. In detail, \( \alpha = 9.77 \times 10^{-2} \) has been used, since the expected
order of magnitude for plasma density is $10^{18} \text{ cm}^{-3}$ and the estimated temperature is greater than 3 $eV$. This estimation was made using the simple model of plasma equilibrium inside a capillary channel described in [16], adapted to the geometry and to the initial conditions used.

The average maximum plasma density found is of $2.5 \times 10^{18} \text{ cm}^{-3}$. The sample data analysis shown in Fig. 4 is a statistical analysis averaged over one hundred images: the statistical error estimated for the central part of the capillary (more stable part of about 2 cm) is 5%. Outside of this central zone the error increases by a few percentage points, due to density ramp fluctuations. This trend is related to the fact that the plasma flows out of the capillary and is therefore affected by the pumping system that maintains the vacuum in the experimental chamber.

| Parameter                      | Value    |
|-------------------------------|----------|
| Capillary length              | 3 cm     |
| Capillary diameter            | 500 µm   |
| H pressure                    | 200 mbar |
| Discharge voltage             | 18 kV    |
| Discharge peak current        | 270 A    |

**Table 1.** Density measurements set-up and parameters.

2.2. Laser guiding preliminary tests

Preliminary guiding tests have been carried out: first of all a low power, high repetition rate (about 80 MHz) laser beam has been used. This beam is specifically the laser pulse coming from the oscillator of the high power Flame laser. It is focused at the capillary entrance, by means of a lens with a short focal length (i.e. 500 mm, see Fig. 5), which allows a transmission inside the empty capillary of about 50% of the pulse. Once the plasma is generated by the discharge,
Table 2. Lasers parameters.

| Parameter                  | Value      |
|----------------------------|------------|
| Oscillator rate            | 79.667 MHz |
| Probe energy               | 10 mJ      |
| Probe temporal length      | 40 fs      |
| Probe spot@focus           | 50 µm      |

the high repetition rate of the pulse used allows for an instantaneous scan of the variation in the intensity of the laser pulse during the whole discharge time. The laser’s arrival is detected by a photo-diode placed at the exit of the capillary, and this signal is temporally overlapped with that of the discharge signal.

Figure 5. Laser guiding test set-up: the laser is focused with a 50 cm lens at the entrance of the capillary. The imaging system is composed of two lens, joined to a CCD with a microscopic objective.

The suitable time window for the pulse guiding has been identified in Fig. 6: the discharge starts around time $t = 0$, so before this time the laser propagates inside the capillary without plasma with a transmission of about 50% with respect to the beam intensity entering the capillary, due to the diffraction through the capillary. There is a sharp increase in laser intensity (left $y$–axis) in a time window immediately after the peak of the discharge (defined by the grey lines). In this time window a transmission (green lines) of the beam up to 80% is achieved, with respect to the beam intensity entering the capillary. After the guiding window, the intensity of the laser signal is quickly attenuated, i.e. the pulse is absorbed by the plasma itself. After the end of the discharge, the laser intensity then returns to the initial transmission value through the capillary.

This desired effect has been then reproduced using a beam with a low repetition rate of 1 Hz, which is the possible frequency for the external injection experiment at SPARC_LAB. In particular, the Flame laser probe beam has been used: a compressed Gaussian beam of 10 mJ and 40 fs, with a waist spot (i.e. a transverse size) of about 50 µm. The transverse and longitudinal dimensions of this beam are almost the same as the high repetition rate beam: this allows the use of the same optical system. The transverse profile of the pulse at the exit of the capillary is detected by an imaging system with a CCD. The set-up for these measurements is shown in Fig. 5, while the lasers parameters are summarised in the table 2.

By synchronising the arrival of this laser beam in the guiding window inside the discharge, a profile of the output laser similar to the pulse waist profile, i.e. a comparable transverse
Figure 6. Guiding results of the Flame oscillator pulse: the red curve is the discharge with respect to the time, while the blue curve is the 80 MHz oscillator pulse. At the beginning of the discharge both signals are disturbed by electronic noise and the intensity of the laser has a false peak. The background noise that appears on the laser signal is due to the signal-to-noise ratio, which is limited by the low intensity of the laser beam available. The delimited guiding window clearly shows an increase in laser signal intensity.

Dimension, has been detected (Fig. 7). This means that the probe pulse is guided in the same guiding window previously found by means of the high repetition rate pulse. Vice versa, by synchronising the pulse at the beginning or at the end of the discharge, the results obtained show that the transverse profile of the laser is dominated by diffraction (Fig. 8). These trends of the laser pulses, oscillator and probe, have been obtained for the capillary with diameter of 500 µm, while instead using a capillary with a diameter of 1 mm (lower plasma density [27]) no effects of pulse guiding have been found.

Figure 7. Imaging of the probe laser spot coming out of the capillary, inside the temporal guiding window found by the oscillator pulse.

Figure 8. Imaging of the probe laser spot coming out of the capillary, outside the temporal guiding window found by the oscillator pulse.
3. OpenFOAM simulations
To obtain a plasma hollow profile with a H-prefilled capillary discharge, a neutral gas profile as uniform as possible in the longitudinal and transverse directions of the capillary is required [21]. The gas flow reaches a steady state in which the pressure in the section of the capillary between the injection points is axially uniform, while between each injection point and the capillary exit the pressure drops to the background pressure of the vacuum chamber. Therefore if the initial hydrogen density is uniform between the gas injection points, the plasma waveguide can also have a uniform guiding profile in its central section.

For this reason, starting from the CAD models of the capillary, fluid dynamics simulations in OpenFOAM have been built, with the aim of obtaining the distribution of the density of gas inside the capillary before the discharge. In the simulated geometry of the capillary there is an inlet that replicates the electro-valve opened, on which the gas pressure is applied. There are also two outlet zones that simulate the two vacuum zones close to the exits on both sides of the capillary. Using the simulated gas pressure, temperature and velocity variables, it is possible to calculate the gas density for each point at each moment of the simulation. In Fig. 9 the result at the final time (3 ms) of the OpenFOAM simulation for the capillary used in the experiments is shown.

![3D OpenFOAM simulation showing the H-density distribution inside the capillary, evolved for 3 ms. Like in the real guiding device, in the simulation the gas flows through an inlet, which is then divided into two secondary inlets. There are also two outlet zones (some cm³) at the extremes of the capillary ends, so as to detect the flow of gas in the vacuum zone just outside of the capillary.](image)

4. Further outlook
In this study spectroscopic measurements of the plasma longitudinal profile inside a plasma capillary discharge were presented, as well as first guiding tests of two different types of lasers inside it. Simulations of neutral gas density before the discharge, which confirm that the system initial conditions are suitable to obtain a plasma density profile suitable to guide a laser beam, were presented.

In the near future spectroscopic measurements of the transverse profile of the capillary will be performed, together with new guiding tests, using the high power laser Flame.

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