PLASMA DENSITY PROFILE CHARACTERIZATION FOR RESONANT PLASMA WAKEFIELD ACCELERATION EXPERIMENT AT SPARC_LAB

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Abstract

New generation of particle accelerators is based on the excitation of large amplitude plasma waves driven by either electron or laser beams, named as Plasma Wakefield Accelerator (PWFA) and Laser Wakefield Accelerator (LWFA), respectively. Future experiments scheduled at the SPARC_LAB test facility aim to demonstrate the acceleration of externally injected high brightness electron beams through both schemes. In particular, in the so-called resonant PWFA a train of more than two driver electron bunches generated with the laser comb technique resonantly excites wakefields into the plasma, the last bunch (witness) is injected at the proper accelerating phase gaining energy from the wake. The quality of the accelerated beam depends strongly on plasma density and its distribution along the acceleration length. The desired density can be achieved with a correct shaping of the capillary in which plasma is formed. The measurements of plasma density, as well as other plasma characteristics, can be performed with spectroscopic measurements of the plasma self emitted light. The measurement of density distribution for hydrogen filled capillaries is here reported.

INTRODUCTION

Plasma-based acceleration techniques have proved the ability to accelerate electron beams at high energies over short distances due to the high acceleration gradient that plasma can sustain. Recent works [1, 2] have increased the interest in these techniques although the accelerated beams have showed a considerably high energy spread. In order to reduce the deterioration of the beam quality, at the SPARC_LAB facility [3] we aim to externally inject a high brightness beam produced by a RF based linac into a plasma wakefield previously excited by either electron or laser beams [4]. The amplitude of the wakefields, their spatial dimensions and the consequent accelerating gradient depends on the electron plasma density and its variation along the longitudinal dimension of the capillary [5]. Moreover, the current flow caused by the ionization discharge is an important parameter that acts on the propagation of the beams inside the capillary. It is straightforward that a deep knowledge of the plasma density and its evolution, as well of the current flow needed to ionize the gas, is mandatory for a correct control of the accelerated beam.

EXPERIMENTAL SETUP

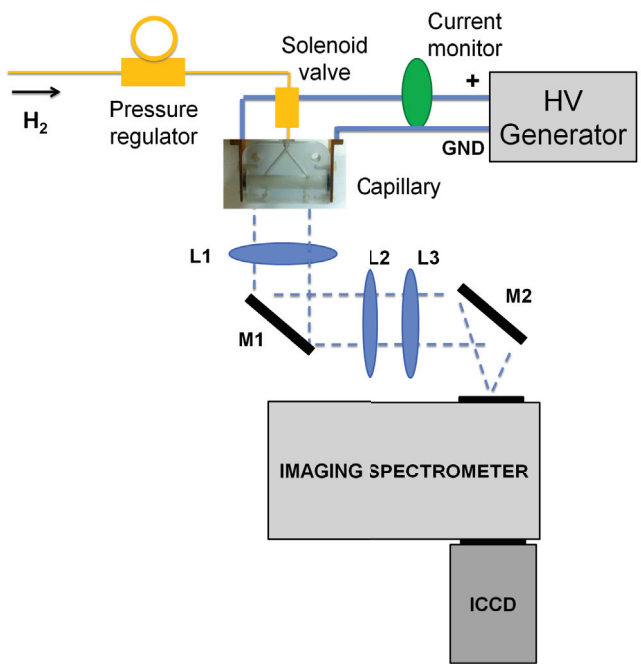

Figure 1: Experimental setup for the measurements of the main characteristics of the hydrogen filled capillary plasma source.

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The experimental layout for the spectroscopic analysis is shown in Fig. 1. A sapphire capillary of circular cross section of 1 mm diameter is fed by two gas inlets of 0.5 mm diameter placed at 7.5 mm from the respective end. For our experiments we decided to use hydrogen gas produced by electrolysis in a NM Plus Hydrogen Generator (Linde). The pressure of the gas can be varied with a pressure regulator placed more than 1 m far from the aperture valve. For the measurements shown in this article, the pressure was set to 250 mbar on the pressure regulator. A high speed solenoid valve lets the gas flow inside the capillary. The valve is set to be opened for 3 ms before the discharge. This time is dictated by the constrain to keep the pressure inside the test chamber below $1 \cdot 10^{-7}$ mbar before every shot. A voltage of 20 kV is applied between the two ends of the capillary by a capacitor of 2 nF charged by a discharge circuit. The current of the discharge can be monitored by a Pearson current monitor placed around one of the two wires that feeds the capillary electrodes. The light emitted by the plasma is collected by a system of lenses that produce an image of the capillary onto the entrance slit of an imaging spectrometer (SP 275 of the ARC Corporation). The spectrometer has an aperture ratio of f/3.8, focal length of 275 mm, and it is equipped with a grating with groove density of 2400 g/mm. This method of diagnosis has already been used in our laboratory for the measurement of plasma density in laser trigger ablative capillaries [6]. A fast-gated intensified camera (Andor iSTAR 320) is used as the detector for the spectrometer.

EXPERIMENTAL RESULTS

A profile of the discharge current has been acquired after every shot. Its temporal profile depends on the ionization process and on the discharge circuit that has been set up [7]. An example of current profile with 20 kV of voltage applied to the discharge circuit is shown in Fig.2. The same profile has been observed for many shots under the same experimental conditions showing a very good reproducibility. The peak current of the discharge can be varied by varying the voltage applied to the discharge circuit, as shown in Fig.3. Both the reliability and the reproducibility of the discharge parameters allow a good control of the ionization process and the current evolution during the discharge.

The light emitted by the hydrogen is collected and sent to the spectrometer by an imaging system composed by three lenses and two mirrors. The capillary is imaged on the entrance slit of the imaging spectrometer, then with the gated camera it is possible to analyze the image of the capillary spectrally dispersed by the spectrometer. The analysis of the Stark effect on the Balmer beta line can lead to plasma density information around the emitting atoms [8]. By triggering the intensified camera with different delays it was possible to scan the temporal evolution of the plasma density along the entire longitudinal dimension of the capillary. The results of this analysis are shown in Fig.4. To help the reconstruction of the spatial dimension of the spectroscopic

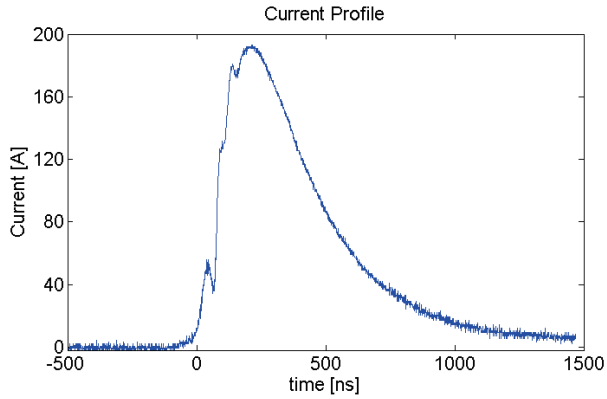

Figure 2: Discharge current profile when a voltage of 20 kV is applied to the discharge circuit.

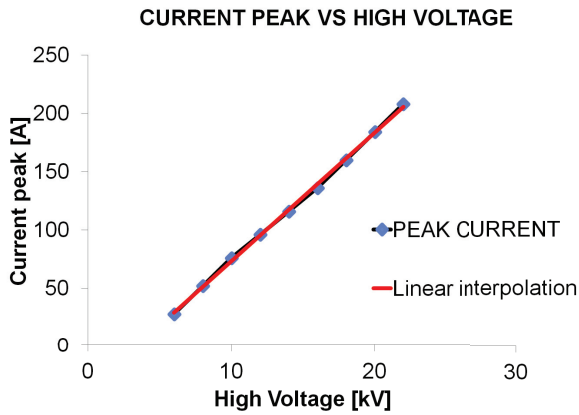

Figure 3: Maximum current peak value measured by varying the voltage applied to the electrodes.

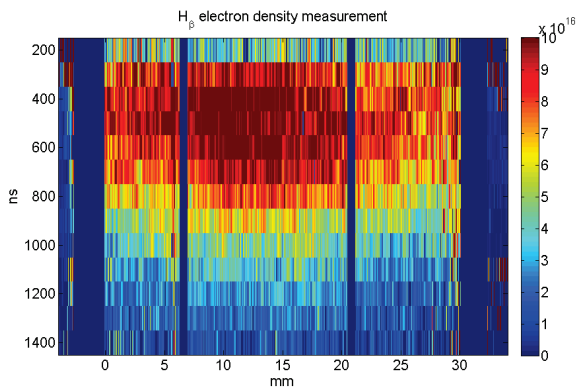

Figure 4: Plasma density evolution along the longitudinal capillary dimension. Every measurement has been acquired with 100 ns of time gating, varying the trigger of 100 ns after every shot. The dark shadows on the image are the shadows of electrodes (thicker) and reference wires (thiner) used to spatially calibrate the spectrograms.

images two wires of 0.45 mm diameter were tied on the capillary. The shadows of these wires, together with the shadows of the electrodes, allows to reconstruct the longitudinal dimension of the spectroscopic image. The spectrograms with

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the plasma density informations are acquired every 100 ns after the discharge trigger for a gate opening time of 100 ns. In every acquisition, the plasma shows the maximum density in the middle of the capillary, then it decreases closer to the electrodes to almost the 65% of its maximum value. After 1500 ns from the discharge trigger the signal is too weak to be analyzed and the gate time of the intensified camera must be modified.

We have analyzed the temporal density evolution by averaging the density in the middle of the capillary. The average values of the density between the 14th and the 16th millimeter of the capillary are shown in Fig.5. The plasma density reaches its maximum around 400 ns after the discharge trigger, some tens of nanoseconds after the maximum of the current profile. Before its maximum, the density increase sharply, then it decrease. We fit the decreasing data with an exponential curve starting when the discharge has reached one third of its peak amplitude. The fit gave a time constant of the density decay of 479.95 ns.

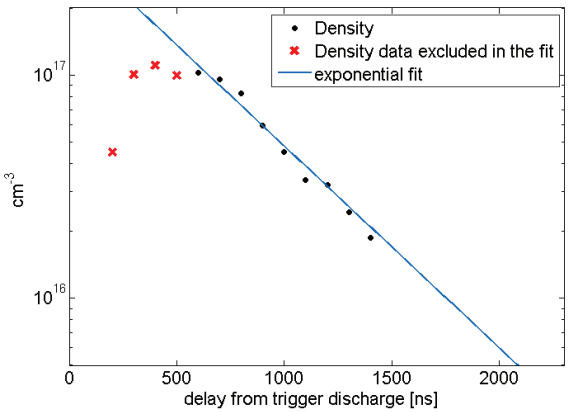

Figure 5: Temporal density evolution averaged between 14 and 16 mm inside the capillary in logarithmic scale. The plasma density reaches its maximum around 400 ns after the trigger discharge. The decrease of density starting from 600 ns after the trigger has been fitted with an exponential curve.

CONCLUSION

We have shown the measurements of the plasma density and current profile of an hydrogen filled capillary for resonant PWFA experiment. The analysis of the discharge current flow has shown a good shot to shot reproducibility of the discharge current profile, and the possibility to control its maximum peak value by varying the applied voltage with excellent reliability. The density measurements performed with our setup allow to detect the plasma density variation along the longitudinal dimension of the capillary and its temporal evolution with steps of 100 ns and with a gate time of 100 ns. The maximum density inside the cylindrical capillary is in the center and the density decreases to the 65% of its value close to the electrodes. Analyzing the temporal evolution of the plasma density it has been possible to measure the maximum around 400 ns after the discharge trigger, some tens of nanoseconds after the peak of the current discharge.

Further analysis has been planned to better characterize the plasma density online during the experiment.

ACKNOWLEDGEMENT

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