GAS-FILLED CAPILLARIES FOR PLASMA-BASED ACCELERATORS

F. Filippi*, M.P. Anania, E. Brentegani, A. Biagioni, E.Chiadroni, M. Ferrario, R. Pompili, S. Romeo
Laboratori Nazionali di Frascati, INFN, Frascati, Italia
A. Cianchi, Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italia
A. Zigler, Hebrew University of Jerusalem, Jerusalem, Israel

Abstract

Plasma Wakefield Accelerators are based on the excitation of large amplitude plasma waves excited by either a laser or a particle driver beam. The amplitude of the waves, as well as their spatial dimensions and the consequent accelerating gradient depend strongly on the background electron density along the path of the accelerated particles. The process needs stable and reliable plasma sources, whose density profile must be controlled and properly engineered to ensure the appropriate accelerating mechanism. Plasma confinement inside gas filled capillaries have been studied in the past since this technique allows to control the evolution of the plasma, ensuring a stable and repeatable plasma density distribution during the interaction with the drivers. Moreover, in a gas filled capillary plasma can be pre-ionized by a current discharge to avoid ionization losses. Different capillary geometries have been studied to allow the proper temporal and spatial evolution of the plasma along the acceleration length. Results of this analysis obtained by varying the length and the number of gas inlets will be presented.

INTRODUCTION

Modern high energy particle accelerators require several hundreds of meter to transfer energy from an electromagnetic field to particles. The easiest way to reduce their dimensions (and cost) is to increase the acceleration gradient, nevertheless its peak value is limited by the wall breakdown that rules the maximum accelerating field that can be sent into a radio-frequency cavity. On the opposite, plasma does not suffer of breakdown and at the same time shows collective effects which are used in plasma-based acceleration techniques to transfer energy to an accelerating particle [1,2]. In these techniques one or more driver beams, either a laser or particle bunch(es), excite large amplitude plasma waves able to cede energy to a bunch of accelerating particles which may be extracted by the plasma itself (self-injection) or generated by an external source and then injected into the plasma (external injection) [3].

The quality of the accelerated beam depends strongly on the properties of the plasma, especially on its local density, defined as the number of free plasma electrons contained in a cube centimeter (cm^{-3}). Indeed, the amplitude of plasma waves, as well as their spatial dimensions and the consequent accelerating gradient felt by particles, depend on the background electron density. Variation in plasma density along the interaction length results in a variation of the accelerating structures, then it must be controlled and properly tailored to preserve the quality of the accelerated beam. Gas-filled capillaries are well-suited devices to control plasma density up to centimeter scale length. This technique has been studied in the past [4,5] since it allows to control the evolution of the plasma, ensuring a stable and repeatable plasma density distribution during the interaction with the drivers. Moreover, in a gas filled capillary plasma is pre-ionized avoiding ionization losses, crucial for low energy drivers [6,7].
Here, we will show the temporal evolution of the longitudinal plasma density measured in two different capillaries filled with 300 mbar hydrogen and ionized by a current discharge of few hundreds of amperes. The first one is a 3 cm long capillary with circular cross section of 1 mm diameter fed by two gas inlets of 0.5 mm diameter placed at 7.5 mm from each edge of the capillary [8]. The other one is a 1 cm long capillary with 1 mm diameter fed by a single inlet of 0.5 mm diameter placed at the half of the capillary length.

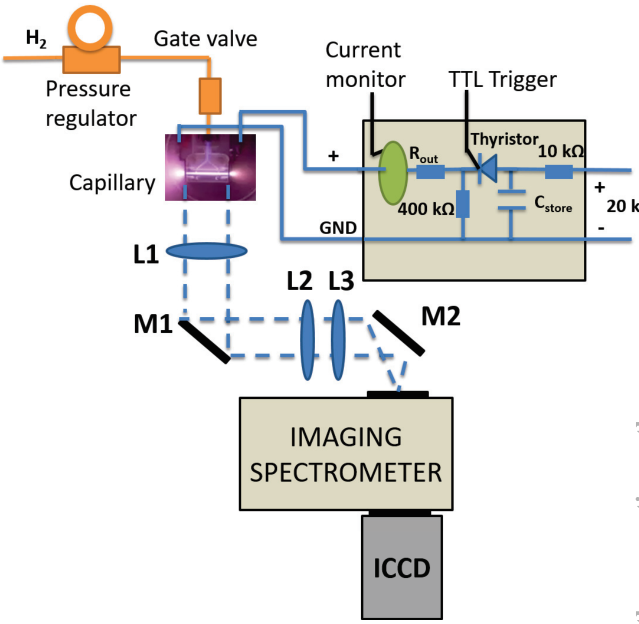

Figure 1: Experimental setup.

The measurements have been performed by using the Stark broadening analysis of the self-emitted Balmer beta line of the hydrogen, as described in our previous works [9, 10]. The setup of the experiment is schematically shown in Fig. 1. The hydrogen backing pressure set at the regulator is of 300 mbar, a fast gate valve let it flows into the capillary for 3 ms then a discharge circuit let a current flowing into the capillary ionizing the gas. The plasma density along the

---

* francesco.filippi@lnf.infn.it

capillary length has been measured every 100 ns from the discharge trigger with a temporal resolution given by the gate time of the ICCD camera of 100 ns.

DOUBLE-INLETS CAPILLARY

To let the driver(s) interact with the desired plasma density it is possible to wait after the discharge until the expected plasma profile is reached.

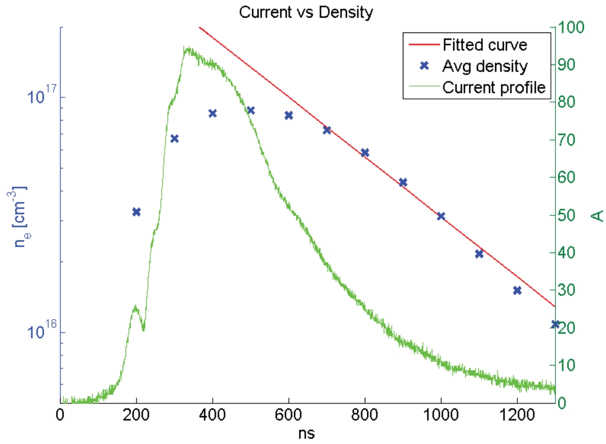

Figure 2: Comparison between profile of the current discharge and the average plasma density along the capillary. The density data have been fitted with an exponential curve (red line).

A typical trend of the averaged density compared with the discharge evolution in the 3 cm capillary is shown in Fig. 2. The experimental data (cross) have been obtained by averaging the measured plasma density along the entire capillary length. As can be seen, the highest density is reached around 500 ns after the discharge trigger, then it decays. The density shows an exponential decay from its maximum to the complete recombination, as expected by the theoretical models [4]. The decay constant is defined as the time needed by the plasma density to reach its maximum value multiplied by e^{-1}. It can be measured by an exponential fit of the data. The fit sowed in Fig. 2 presents a decay constant of 340 ns. To examine more in detail the plasma distribution along the interaction length, we have also measured the local density with a spatial resolution of 0.125 mm. The density profile along the entire capillary length is shown in Fig. 3. The spatial distribution of the plasma density shows a local maximum that decreases close to the electrodes. In the early instants of the discharge the density appears to be not exactly symmetric probably due to an uneven background density of the gas caused by some geometrical differences between the inlets. These differences have been probably introduced during the manufacturing of the capillary. This unwanted inhomogeneity can be problematic for the propagation of the beam during the acceleration process which may be dephased respect to the accelerating structure. Nevertheless, after few hundreds of nanoseconds the plasma density decreases flattening its profile. At 1000 ns after the discharge, the density is almost flat along the entire capillary.

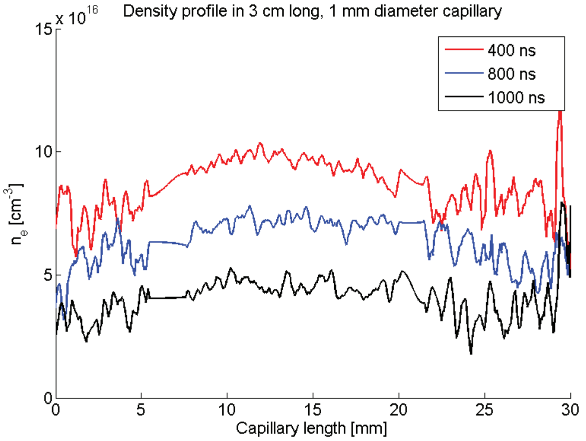

Figure 3: Longitudinal density distribution along a 3 cm capillary with 20 kV of applied voltage.

SINGLE-INLET CAPILLARY

To experimentally test the effect of a different inlet configuration we have used a 1 cm long capillary fed by a single inlet placed in the middle of the capillary. In this configuration the gas filling is symmetric. The shortest length of the capillary is dictated by the fact that a single inlet can hardly filled homogeneously bigger volumes. For these measurements we also increased the current up to 230 A in order to completely ionize the gas contained into the capillary. The decay constant of the plasma is weakly affected by these variations since it was 380 ns as measured with the same technique exposed before.

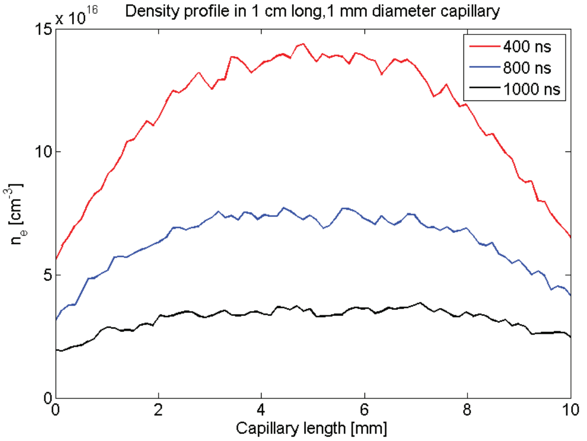

Figure 4: Longitudinal density distribution along a 1 cm capillary with 20 kV of applied voltage.

As expected, the symmetric feeding of the single inlet ensures a more symmetric, then predictable, density, which is evident in Fig. 4. The density overcome the value of $1 \cdot 10^{17}$ cm^{-3} at 400 ns after the discharge trigger, then it decreases being flatter with almost the same density shown in previous capillary configuration at 1000 ns after the discharge when the density is almost flat. The good homogeneity of the plasma profile in the latter moments of the discharge is particularly suitable for most of the acceleration process which requires centimeter scale constant plasma density.

CONCLUSION

We have shown the different plasma density distribution achieved by two different capillary geometries, one fed by two inlets placed at 7.5 mm from each edge of the capillary and the other one fed by a single inlet injecting gas in the middle of a 1 cm long capillary. Multiple inlets presented an unexpected density distribution probably caused by small differences between the inlets due to the manufacturing process. This induced to an unwanted density variation along the acceleration length. Nevertheless after some hundreds of nanoseconds after the discharge the density tends to become homogeneous and almost flat. On the contrary, the single-inlet capillary showed a remarkably symmetric plasma distribution and its homogeneity after 1000 ns from the trigger discharge is comparable with what obtained with the longer capillary. The homogeneous plasma distribution reached with these devices is well suitable for most of the acceleration schemes which requires centimeter scale homogeneous density profile. Further measurements will investigate the possibility to modify the capillary geometry in order to taper the plasma density along the interaction path.

ACKNOWLEDGEMENT

This work has been supported by the EU Commission in the Seventh Framework Program, Grant Agreement 312453-EuCARD-2, H2020 research and innovation program under grant agreement n. 653782, and the Italian Minister of Research in the framework of FIRB – Fondo per gli Investimenti della Ricerca di Base, Project n. RBFR12NK5K.

REFERENCES

[1] T. Tajima, and J. Dawson, “Laser electron accelerator,” *Phys. Rev. Lett.*, 43.4, (1979): 267.

[2] E. Esarey, C. Schroeder and W. P. Leemans, “Physics of laser-driven plasma-based electron accelerators,” *Rev. Mod. Phys*, vol. 81, no. 3, pp. 1229–1285, Aug. 2009.

[3] M. Ferrario *et al.*,, “SPARC_LAB present and future,” *Rev. Mod. Phys*, 309, pp. 183–188, 2013.

[4] N. A. Bobrova *et al.*, “Simulations of a hydrogen-filled capillary discharge waveguide,” *Rev. Rev. E*, 65.1: 016407.

[5] D. Spence and S. Hooker, “Investigation of a hydrogen plasma waveguide,” *Rev. Rev. E*, 63, 15401 (2000).

[6] E. Kallos, “Plasma wakefield accelerators using multiple electron bunches,” Ph.D. thesis, Electrical Engineering Dept., University of Southern California, USA, 2008.

[7] A. Butler, D. Spence, and S. Hooker, “Guiding of High-Intensity Laser Pulses with a Hydrogen-Filled Capillary Discharge Waveguide,” *Phys. Rev. Lett.*, 89, 185003 (2002).

[8] R. Pompili, *et al.*, “Experimental characterization of active plasma lensing for electron beams,” *Applied Physics Letters*, 110.10 (2017): 104101.

[9] F. Filippi *et al.*, in *Proc. IPAC’16*, pp. 2554–2556.

[10] F. Filippi *et al.*, “Spectroscopic measurements of plasma emission light for plasma-based acceleration experiments,” *Journal of Instrumentation*, 11.09 (2016): C09015.