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3D CHARACTERIZATION OF PLASMA DENSITY IN CAPILLARY DISCHARGES FOR PLASMA-BASED ACCELERATORS*

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Abstract

Accurate characterization of plasma density profiles is vital for optimizing plasma-based accelerators, as density directly affects beam acceleration and quality. Plasma capillaries also serve as lenses and for beam guiding, highlighting their role in advanced accelerators. This study measures longitudinal and transverse density profiles of plasma capillaries, achieving 3D characterization using Stark broadening techniques. Two optical lines capture emitted plasma light. Parameters include gas flow rate, operating mode (pulsed/continuous), voltage, capillary type and geometry, gas type, and repetition rate, allowing evaluation of operational impacts on plasma density. Results show consistent density measurements across various positions, indicating the method's capability to capture spatial variations in plasma density. Understanding these profiles is crucial for developing and optimizing laser-driven and beam-driven plasma accelerators, as well as enhancing plasma lenses and beam guiding, enabling fine-tuning of parameters to maximize acceleration efficiency and control beam quality.

INTRODUCTION

Gas-filled discharge capillaries have demonstrated their suitability in the context of the future facility EuPRAXIA@SPARC_LAB [1–3]. In order to match the lifetime and repeatability of the future accelerator, the use of ceramics for capillaries has been proposed [4]. With such opaque material, spectroscopic measurements of plasma parameters are now feasible by only taking the light emitted at the outlets of the plasma channel. We present the results of the so-called "transverse plasma density measurements" by Stark Broadening technique, comparing them to known longitudinal profiles, enabling a three-dimensional characterization of the plasma density. Beyond enabling longitudinal reconstruction, transverse diagnostics are crucial for assessing the radial density profile, which plays a key role in laser guiding efficiency and beam focusing [5, 6]. While the transverse plasma density directly affects laser guiding performance, which is central to laser-driven stages planned for the second EuPRAXIA site, it is also relevant in the beam-driven context of EuPRAXIA@SPARC_LAB. In particular, for characterazing plasma sources to optimize the interaction with particle beams.

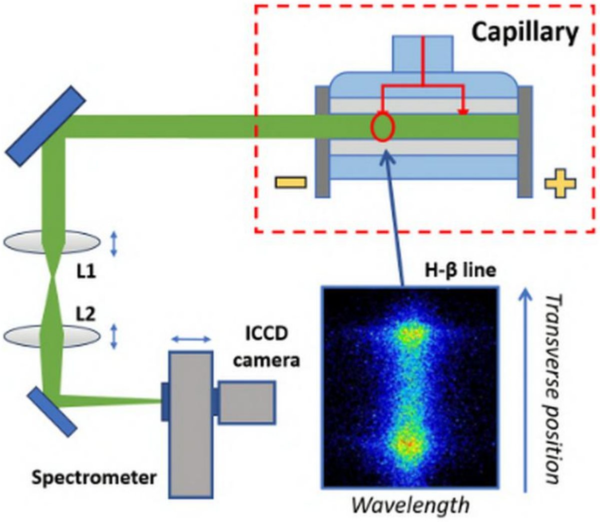

Figure 1: Schematic layout of the experimental setup for capillary discharge transverse spectroscopy.

EXPERIMENTAL SETUP

Transverse diagnostics provide local plasma density measurements at selected positions along the capillary. By comparing these values to the corresponding points on the longitudinal profile, we evaluate the ability to reconstruct the full longitudinal density from a series of transverse slices. To measure different slices of plasma (red circle in Fig. 1), we used a telescopic system to collect the light and send it to an acquiring system composed of a spectomer and an ICCD camera. The whole setup is mounted on a translation stage, allowing precise selection of each slice.

The capillary is 3D-plastic printed with a 10 cm long, 2 mm wide plasma channel, installed in a vacuum chamber able to reach 10^{-7} mbar. Hydrogen gas is injected through the plasma formation channel via two inlets, filled with gas by an external electro-valve and a pressure regulator. High-voltage pulses are applied to a couple of electrodes attached at the end of the capillary. The current waveform is acquired by an oscilloscope connected to the HV (High Voltage) system. A delay generator is synchronizing the discharge, the gas injection and the spectroscopic measurements at diverse delays. A picture of the experimental installation for the measurements is presented in Fig. 2.

EXPERIMENTAL RESULTS

To assess the relevance of transverse measurements as a diagnostic tool, we present in this paper a first comparison

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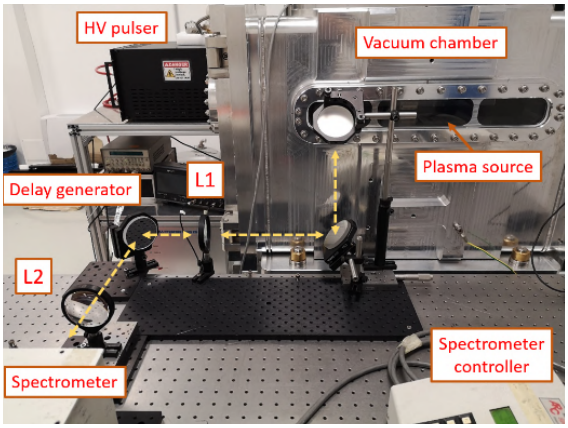

Figure 2: Experimental system.

with the standard longitudinal plasma density profile measurement. Due to the symmetric geometry of the plasma channel, measurements were performed over half of the capillary, from the left outlet to its center. A voltage of 13 kV was applied to the electrodes, generating a peak current of 890 A shot-to-shot. The duration time of the HV pulse is around 1.5-2μs. Spectroscopic images were acquired at various delays after the discharge, ranging from 800 ns to 4000 ns in steps of 400 ns, to acquire both formation and recombination phase of the plasma. We present in Fig. 3 different plasma longitudinal density profile taken at multiple delays. We acquire 4.5 cm of the capillary and 0.5 cm of the outlet region to characterize with precision the ramp region of the capillary.

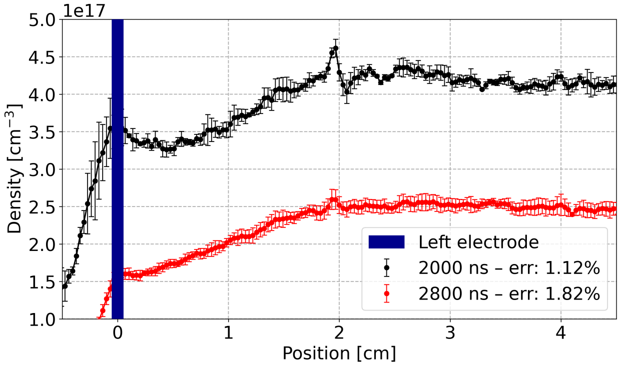

Figure 3: Longitudinal plasma density profile measurements after peak discharge

In Fig. 4 we show the evolution of the mean plasma density in the capillary over time, with classical behavior of such plasma discharge system [7].

With the experimental setup presented in Fig. 1 we select slices of plasma to observe at 1 cm inside the capillary (ramp region) and 3 cm inside (plateau region). The measurements were taken at same delay time and same HV pulse.

In Fig. 5 we show the so-called transverse plasma density measurements. The blue regions represent the capillary walls, and the density is measured across the section of the plasma channel. For each delay, 50 images were acquired and individual plasma density profiles were extracted. The final result is the average profile, with error bars corresponding to the standard deviation across the 50 shots, restricted to the capillary region.

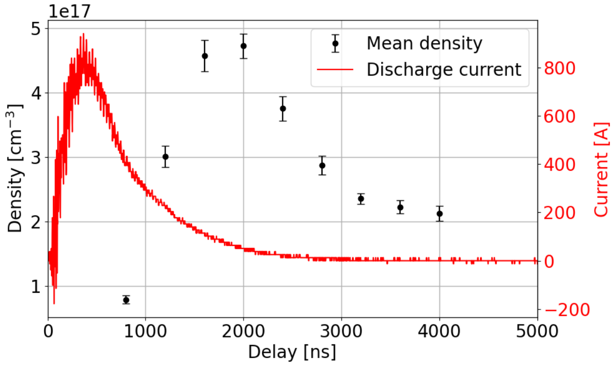

Figure 4: Plasma density over time

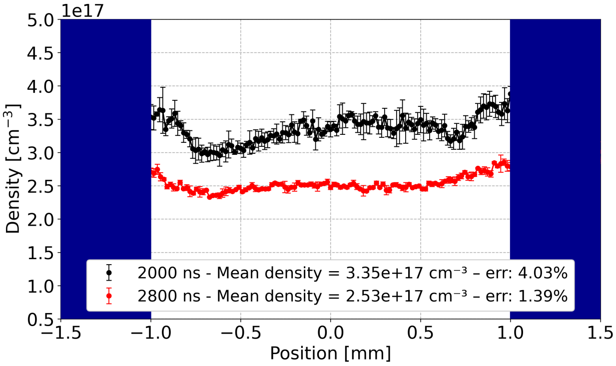

Figure 5: Transverse plasma density at 1 cm inside

To compare the results obtained from transverse and longitudinal measurements, we compared the mean density obtained for each slice of plasma observed with the transverse setup to the corresponding longitudinal profile at the same location and delay.

A quantitative comparison was performed at two representative delays: 2000 ns and 2800 ns. At 2000 ns, the transverse and longitudinal profiles showed relative differences of 6.2% at 1 cm and 9.6% at 3 cm, with a root-mean-square deviation of 3.3×10^{16} cm^{-3}.

At 2800 ns, the agreement was even better, with only 3.2% difference at 1 cm and 0.15% at 3 cm, and a corresponding RMS error of 4.6×10^{15} cm^{-3}. These results confirm the accuracy and reproducibility of the transverse diagnostic across different plasma conditions.

To further illustrate the compatibility of the two diagnostics, Fig. 6 shows a direct comparison between the longitudinal and transverse plasma density profiles measured independently at the same position inside the capillary. Despite differences in data acquisition and analysis paths, the two profiles show excellent agreement in both shape and peak value, confirming the reliability of the transverse diagnostic as a quantitative tool.

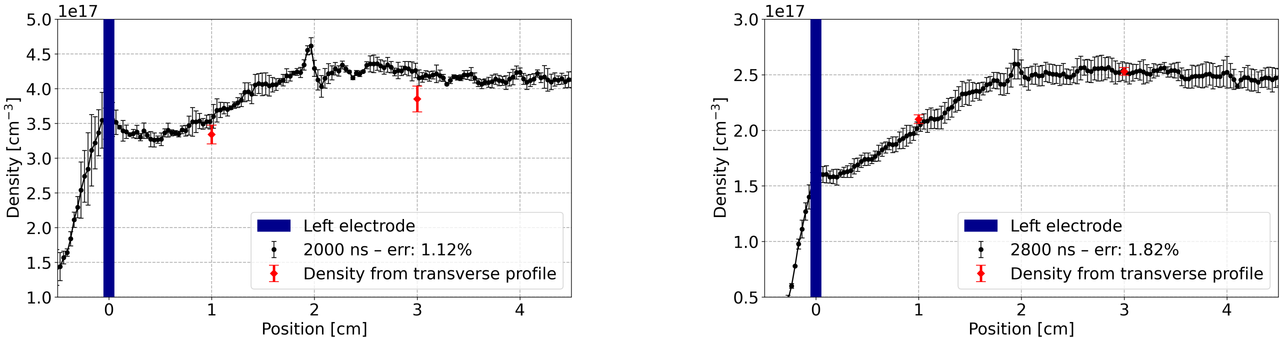

Figure 6: Comparison between longitudinal and transverse plasma density profiles measured at the same delay

These results validate the possibility of reconstructing spatial plasma density maps by combining transverse measurements taken at multiple positions along the capillary.

DISCUSSION

The consistency between the transverse and longitudinal measurements demonstrates the reliability of our method for spatially resolving plasma density in capillary discharges. This validates the use of transverse diagnostics as a standalone tool for partial characterization, particularly useful when access to the full longitudinal profile is limited.

Moreover, the transverse profiles offer direct access to the radial density distribution, which governs the refractive index gradient in the plasma. This transverse diagnostic is very important for the laser driven case, which need a hollow transverse density profile.

In future work, transverse profiles will be measured at multiple positions along the capillary and compared with simulations to build a more complete three-dimensional map of the plasma. Additional attention will be paid to the dynamics of the outflow region, which although not considered in the present study, could influence beam propagation downstream of the plasma channel.

A natural extension of this work will consist in performing a full scan of the capillary at multiple axial positions, combining transverse measurements taken every centimeter. This would allow us to reconstruct a quasi-continuous 3D plasma density map, which is essential not only for beam guiding simulations but also for benchmarking fluid and kinetic plasma models.

Furthermore, the robustness of the transverse diagnostic across various operating conditions—such as different capillary geometries, repetition rates, and gas species—will be explored. These future developments will contribute to establishing a compact, non-invasive, and high-throughput diagnostic system for next-generation plasma-based accelerator facilities.

CONCLUSION

We have presented a method to characterize the plasma density in capillary discharges using transverse spectroscopic measurements, validated against standard longitudinal diagnostics. This approach provides access to the radial density distribution, a key parameter for beam focusing and laser guiding in plasma-based accelerators.

The agreement between transverse and longitudinal profiles confirms the reliability of the method and supports its use for partial or full 3D plasma mapping. These results represent an essential step toward developing robust and compact diagnostics for the high-repetition-rate operation required by future facilities such as EuPRAXIA@SPARC_LAB and its laser-driven counterpart.

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