Experimental and theoretical characterization of very long plasma source for plasma-based particle accelerators

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Summary

We accomplished the experimental and theoretical testing of a 40 cm long plasma-discharge capillary, designed to be the first plasma source for the **EuPRAXIA@SPARC_LAB** project.

Theoretical analysis allowed to characterize the neutral gas dynamics inside the capillary, from the injection to the high voltage ionization.

Experimental testing of the device demonstrated an excellent uniformity of plasma density profiles along the main capillary channel, with measured average values of $\mathbf{0.8 \div 1.1 \times 10^{17} cm^{-3}}$, consistent results compared to simulated neutral gas density of $\mathbf{1 \div 3.5 \times 10^{17} cm^{-3}}$.

Plasma_Lab test facility at Sparc_Lab

- The gas injection system generates hydrogen gas and injects it inside plasma-discharge capillaries through the activation of an electro-mechanical valve.
- The high voltage electrical circuit delivers **kV-range short voltage pulses** for gas ionization.
- The diagnostic system is constituted by an optical line, a spectrometer and an ICCD camera for the analysis of gas emission spectrum.

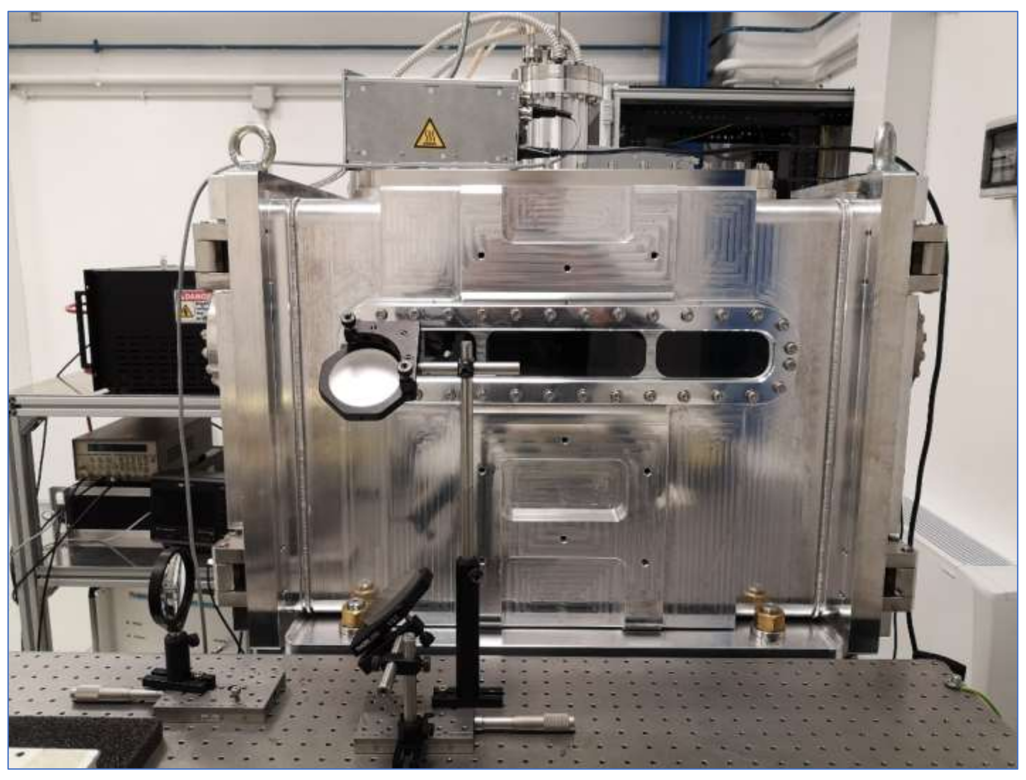

Fig. 1 Plasma_Lab experimental setup

Experimental testing

The tested plasma source consists in a **40*cm*-long 2*mm*-diameter 6-inlets plastic hydrogen-filled capillary**.

Plasma density measurements were performed by means of the spectroscopic technique based on the Stark broadening[1], with the following experimental settings:

- **Gas injection pressure** $\mathbf{p = 10 \div 30\ mbar}$
- Electro-mechanical valve activation at **1 *Hz*** for a time interval of **5 *ms***
- **10 *kV*** voltage pulses applied to copper electrodes at the capillary extremities **1.4 *ms*** after the valve closure, resulting in the onset of a **380 *A*** plasma current pulse

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Data acquisition and analysis

Spectral images were acquired by the ICCD camera at **delay times** ranging between **3200÷4200 *ns***, with **50 images** per each delay time for giving statistically reliable results.

Measured plasma density profiles show a **50% uniformity** from center to electrode, excellent result considering the exceptional device length.

Plasma density averaged over the longitudinal axis manifests a gradual decrease from **1.1** to $\mathbf{0.8 \times 10^{17} cm^{-3}}$ in the considered time interval.

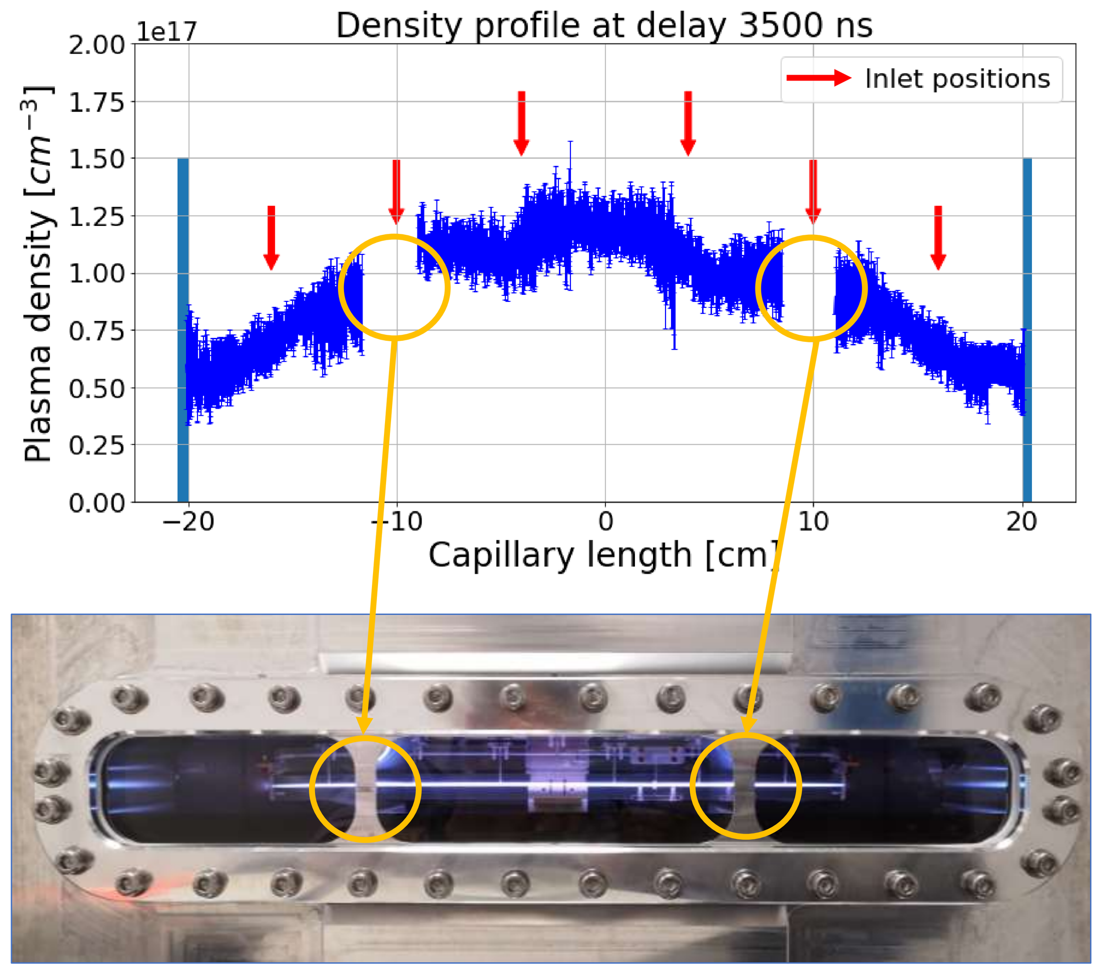

Fig. 2 (Top) Plasma density profile at 3500 *ns*. (Bottom) Tested 40 cm-long capillary

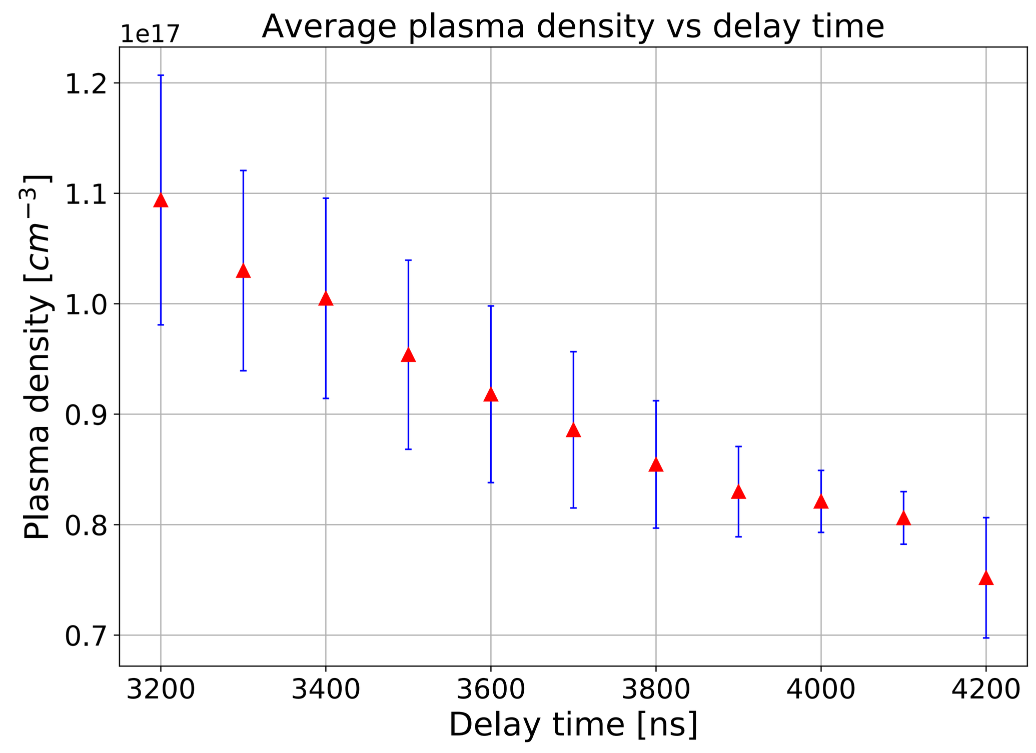

Fig. 3 Plasma density averaged over the longitudinal capillary axis against delay time

Theoretical characterization

CFD software **OpenFoam**[2] was employed to simulate the neutral gas dynamics inside the 40 *cm* long capillary. The solver **SonicFoamART40** allowed to simulate the gas propagation in subsonic motion regime.

The mesh grid is composed by:

- Hexahedral cells with dimensions **1*mm*** × **1*mm*** ×**1*mm***
- Two refinement levels inside the regions close to the capillary surface

Main numerical parameters set for the simulation were:

- Maximum CFL parameter $\mathbf{C_{max} = 0.3}$
- Maximum time step $\mathbf{\Delta t_{max} = 1\ \mu s}$
- Injection pressure of **10, 20 and 30 *mbar***

Simulation results

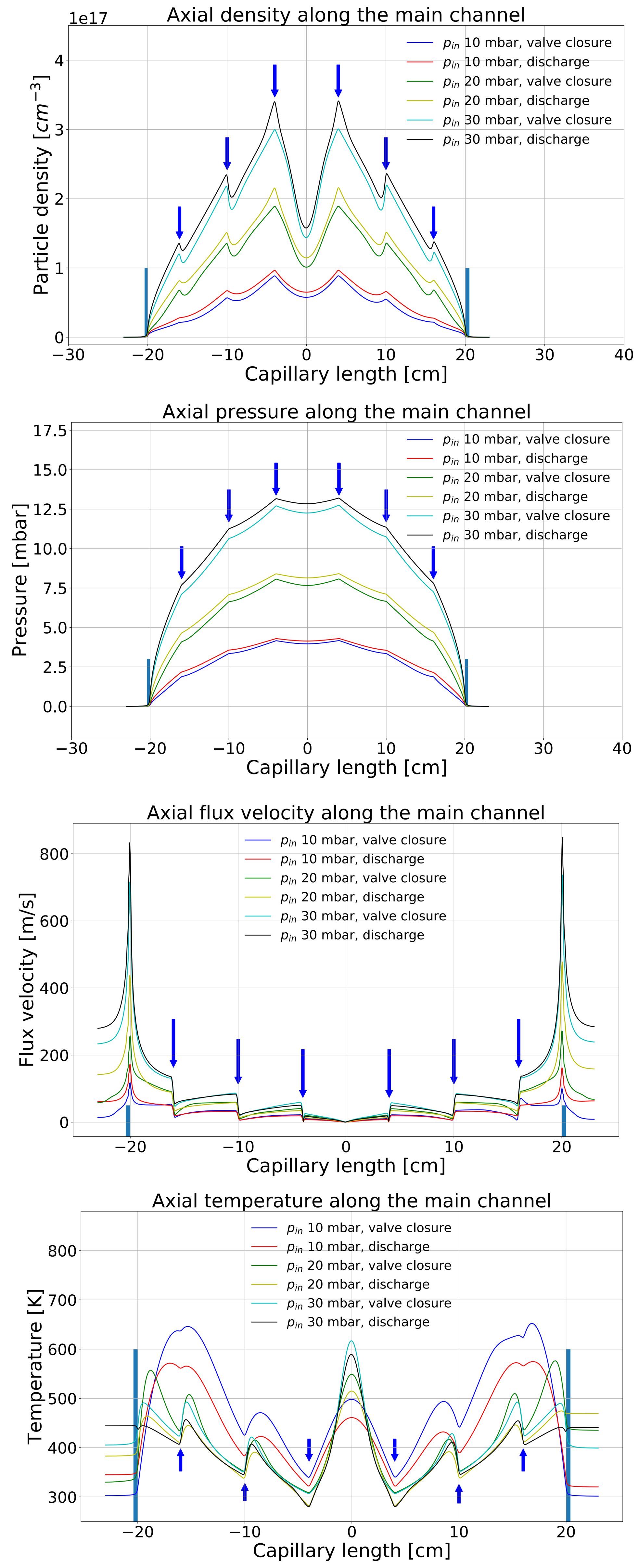

Fig. 4 Longitudinal profiles of main gas parameters: particle density, pressure, temperature and flux velocity. Arrows indicate inlets positions.

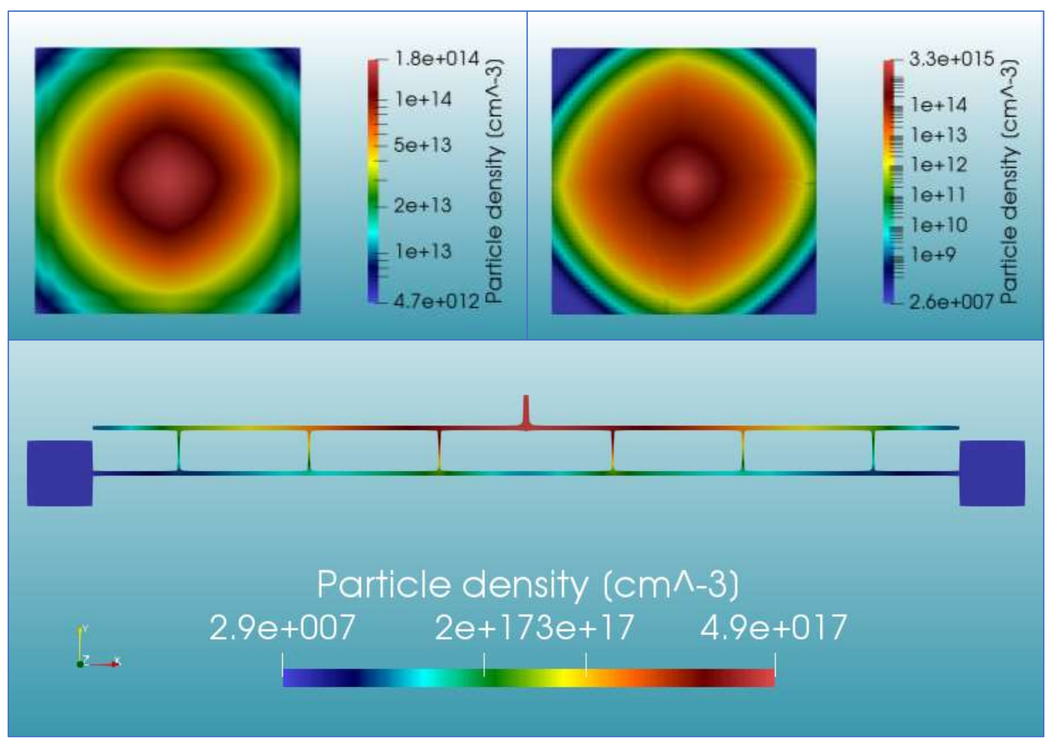

Fig. 5 Density distributions at the ionization instant with injection pressure of 20 mbar. (Top) Transverse density distribution outside the capillary at a distance of 1 cm (left) and 1 mm (right) from the electrodes. (Bottom) Gas density distribution along the capillary

List of references

[1] H. R. Griem, "Spectral Line Broadening by Plasmas", Department of Physics and Astronomy, University of Maryland, College Park, Maryland.
[2] H. G. Weller, G. Tabor, H. Jasak, C. Fureby, "A tensorial approach to computational continuum mechanics using object-oriented techniques", COMPUTERS IN PHYSICS, VOL. 12, NO. 6, NOV/DEC 1998.