Study of Electron Density in Capillary Discharge Plasma for Laser Plasma Accelerator

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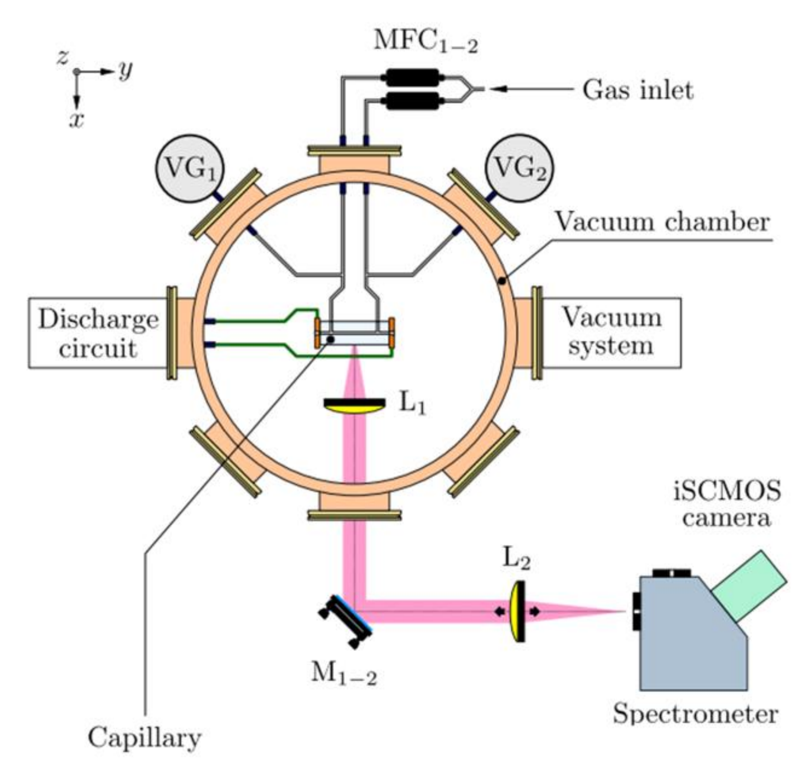
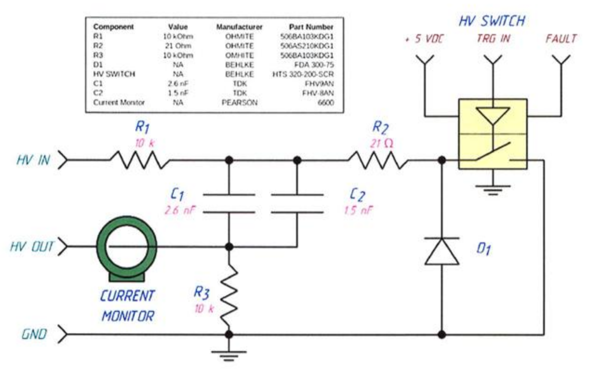
Abstract

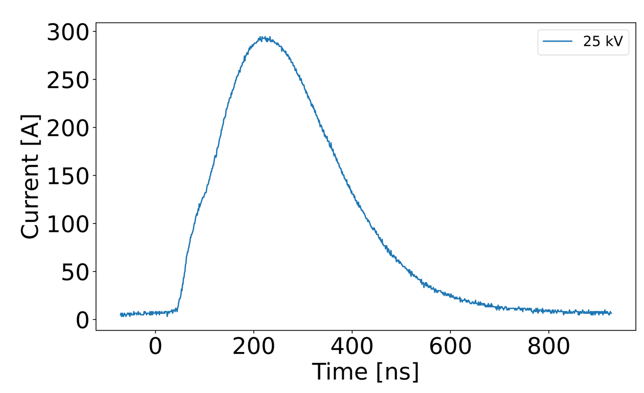
Gas-filled capillary discharge has emerged as a promising source in plasma-based accelerators. Pre-formed plasma channels enhance stability in Laser-Wakefield Accelerators by overcoming diffraction effects and maintaining laser focus over longer distances, thereby increasing energy transfer efficiency. Also, due to their limited gas consumption, they are well-suited for high repetition rate applications. Using Stark broadening, we measured profiles under varying conditions, achieving densities of (2–3) × 10^{18} cm^{-3}. Moreover, we present three-dimensional (3D) Particle-In-Cell (PIC) simulations incorporating experimentally measured plasma density profiles. The simulation results reveal electron injection and acceleration, with electrons attaining a mean energy of 0.5 GeV using a laser pulse of 2.0 J energy. This type of plasma source is a crucial technology for the 100 Hz plasma accelerator-based Free Electron Laser (FEL) being developed at ELI-ERIC and for the EuPRAXIA project.

Experimental setup

The plasma source characterised in this study is a 15 mm long sapphire capillary with a square cross-section of 300 x 300 µm, filled with hydrogen. The hydrogen is supplied continuously from an electrolytic generator and introduced into the capillary via two inlets, with the flow regulated by two independent mass flow controllers.
Plasma is generated by applying a high-voltage electrical discharge, with a duration of approximately 300 ns (full width at half maximum (FWHM)), across two electrodes placed at each end of the capillary. This discharge provides a current of about 300 A at 25 kV.

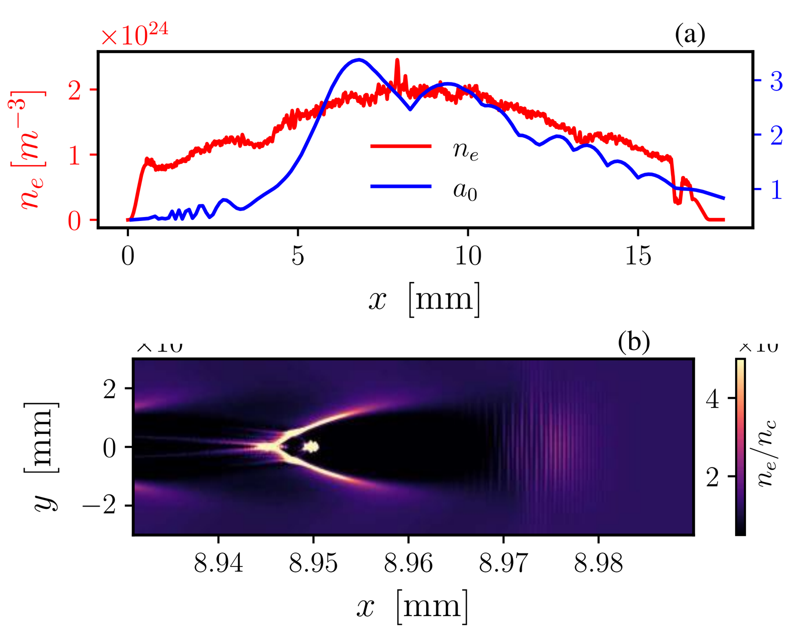






3D PIC simulations

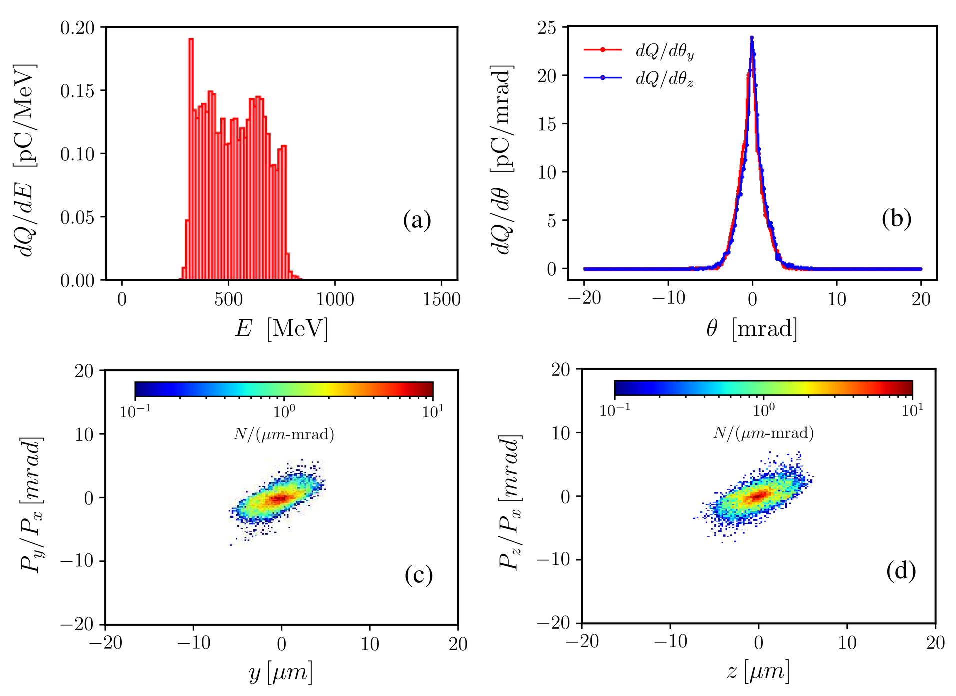
Particle-in-cell (PIC) simulations were performed using *SMILEI* code. The driver laser is considered a Gaussian pulse, linearly polarized along the y-direction and propagating in the x-direction. The laser parameters used in the simulation are the following: 820 nm wavelength, 2 J energy, 30 fs pulse duration (FWHM), and 20 µm beam waist. The laser was initially focused at a position x = 8.0 mm. The experimentally measured plasma density profile was used as input for the simulation. In the transverse direction, a parabolic density profile of the form $n_e(r) = n_e(0)[1 + 0.33(r^2/R_0^2)]$, where R_0 = 300 µm is the capillary radius, was assumed.



Simulation results show laser self-focusing in the 6–11 mm plasma plateau region, where laser power exceeds the critical threshold by a factor of 5. This increases a_0 beyond its vacuum focus value (~2.3), maintaining it through the density plateau.

Electrons are injected and trapped in the first bubble. The net injected charge in the first bubble is approximately 60 pC.

The accelerated electron beam, measured after exiting the plasma at x = 17.5 mm, has a charge of 60 pC, mean energy of 525 MeV, ~25% RMS energy spread, and RMS divergence of 1.3 mrad (horizontal) and 1.4 mrad (vertical). The corresponding RMS normalized emittances are 1.8 mm·mrad and 2.2 mm·mrad.



Stark broadening method

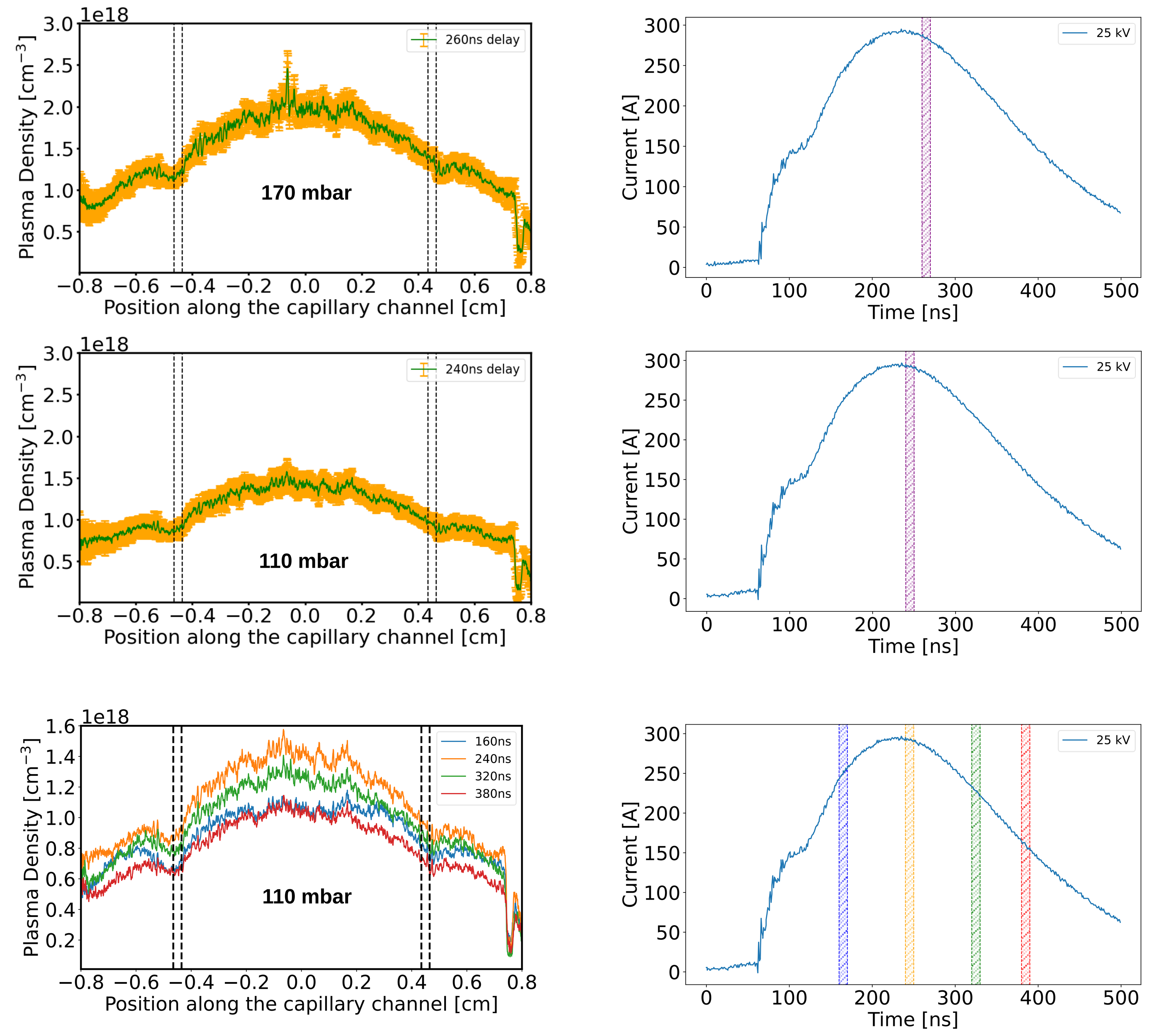
The application of a high-voltage electrical discharge to the electrodes induces rapid electron temperature elevation, driving gas ionisation through collisional processes [1]. This results in a plasma that is either fully or partially ionised, depending on discharge parameters.
The Stark broadening method exploits spectral line broadening caused primarily by microscopic electric field fluctuations within the plasma [2]. Plasma electron density n_e is determined from the spectral line width using the relation [3]:

$$n_e[cm^{-3}] = 8.02 \times 10^{12} \left(\frac{\Delta\lambda_{FWHM}}{\alpha_{H_\alpha}}\right)^{\frac{3}{2}},$$

where $\Delta\lambda_{FWHM}$ represents the FWHM of the Stark-broadened spectral line in angstroms, and the constant $\alpha_{H_\alpha} = 0.0214$ denotes the fractional intensity width of the H_α line at 656.3 nm, derived from electron temperature and density dependencies [4].

Plasma density measurements

Longitudinal electron density profiles, measured by varying camera delay and gas flow rates, show peak densities of 2.4 $\times 10^{18}$ cm^{-3} and 1.3 $\times 10^{18}$ cm^{-3} at flow rates of 0.150 mg/s and 0.075 mg/s per inlet, respectively.
These values fall within the plasma waveguiding requirements ($10^{17} - 10^{18}$ cm^{-3}), while optimal LWFA acceleration (scaling as $E \propto \sqrt{n_e}$) necessitates the 10^{18} cm^{-3} regime. This density regime is confined between gas inlets, limiting effective acceleration to ~60% of the capillary length.
The higher flow regime shows increased instabilities, likely due to incomplete ionisation within the channel. As the discharge current rises, it may remain insufficient to fully ionise the bulk gas before thermal equilibrium is achieved [5].



Conclusion

In this poster, we have presented the characterisation of the longitudinal plasma density profile for a 15 mm long sapphire capillary, achieving a peak density of 2.4 × 10^{18} cm^{-3} under the discharge conditions of 25 kV and 0.150 mg/s per gas inlet. The results reveal a stable high-density region over 10^{18} cm^{-3} covering 60% of the capillary length. This finding motivates further studies with extended capillaries to fully exploit the accelerating potential over longer interaction lengths.
3D PIC simulations utilizing the experimentally measured density profile demonstrated an effective acceleration of electron beams along the plasma channel, achieving a mean energy of 0.5 GeV. Although the transverse properties of the accelerated electron beams are reasonably good, the energy spread remains high and is therefore incompatible with the requirements for FEL. By optimizing capillary geometries and adjusting gas parameters, such as pressure gradients and gas mixtures, it would be possible to refine the density profiles and produce electron beams that meet FEL specifications.

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