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Spectral line shape for plasma electron density characterization in capillary tubes

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Abstract. We report the experimental activity on the plasma-discharge capillary tubes suitable for plasma-based accelerators (PBAs) carried out at the SPARC_LAB (sources for plasma accelerators and compton with laser and beam) test-facility. A high-voltage discharge is produced inside a Hydrogen-filled capillary tube. Through spectroscopic techniques, the density of the plasma thus produced is monitored either spatially or temporally through the line Stark broadening profiles.

1. Introduction

Nowadays, in the particle accelerator field, plasma-based accelerators are highly demanded to reduce the barriers of the conventional accelerator structures [1, 2]. In fact, one of the essential characteristics of plasma-based accelerators is their compactness due to small-scale (mm to cm) plasma modules, providing extremely high accelerating gradients up to hundreds of GV/m. A plasma, produced by high-voltage electric discharge in a 3 cm/long-1 mm/diameter capillary tube, is targeted [3]. The experiment has been carried out at the SPARC_LAB test-facility [4] within the EuPRAXIA framework [5]. The principal target of this innovative technique is to monitor and characterize the produced plasma from which, depending on the qualities of the particle bunches, must be accelerated via the propagation in the plasma of an intense and ultra-short laser pulse (LWFA) [6, 7] or an energetic electron bunch (PWFA) [8, 9].

2. Experiment Setup

Figure 1 shows the employed experimental setup to produce and confine the plasma in a capillary tube. The capillary is located in a vacuum chamber at 10 $^{-8}$ mbar. Two gas inlets inject Hydrogen into the capillary tube. An external high-voltage source provides the power (12 kV) and is applied to the Copper electrodes, which are connected at the capillary extremities to ionize the gas through a resistor-capacitor circuit (300 A). Two mechanical valves set the gas injection time (3 ms) and injection frequency (1 Hz). A pressure regulator sets the pressure (10-50 mbar) inside the channel to obtain the required plasma electron density of $\approx 10^{17}$ cm^{-3}. The plasma emission light is dispersed by the spectrometer (SpectraPro 275) and recorded by an ICCD

(Andor iSTAR 20). Eventually, a delay generator (Stanford Research DG535) synchronizes all the described individual events.

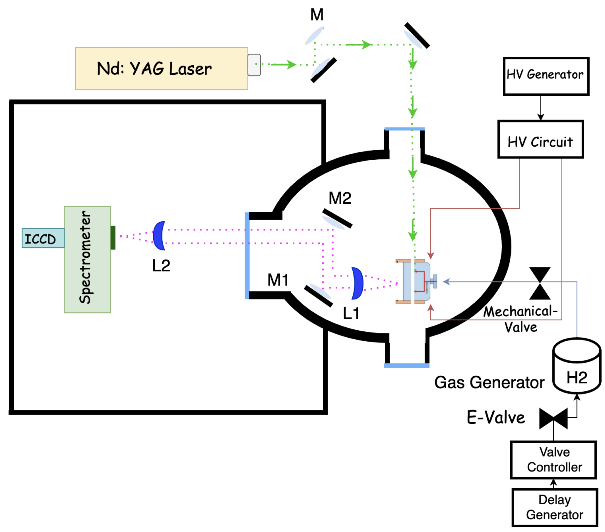

Figure 1. The employed experimental set-up to produce and characterize plasma in a Hydrogen-filled capillary tube. A second harmonic Nd: YAG laser probe at 532 nm is used for the optical alignment.

3. Spectroscopic Technique

The spectral line broadening can be produced in plasmas by different causes, while two of them are the most relevant: the Stark effect, due to the electric field produced by the charged particles inside the plasma (related to the plasma density), and the Doppler effect, due to the thermal motion of the particles (related to the plasma temperature). Under our experimental conditions, densities of the order of 10^{17-18} cm^{-3} and temperatures of the order of a few eV, the dominant line broadening is the Stark effect (up to 23 nm as a function of plasma recombination time for H_β). We have fitted the spectral lines with the Gaussian, Lorentzian, and Voigt profiles [11]. As shown in Figure 2, the best fit with the Lorentzian profile is obtained, which confirms what we have assumed; namely, the dominant broadening effect is the Stark one.

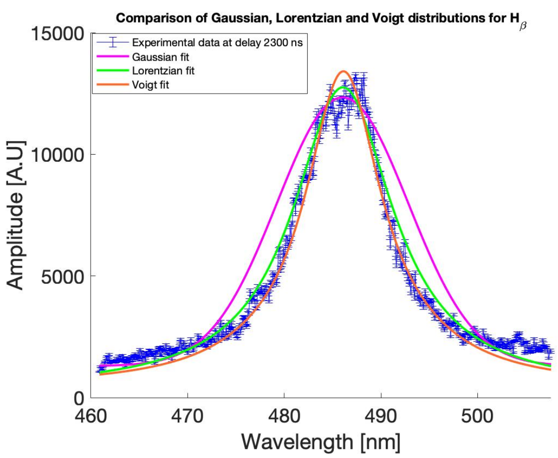

Figure 2. Comparison of line shapes (Gaussian, Lorentzian and Voigt) in a 3 cm/long-1 mm/diameter Hydrogen-filled capillary tube for H_β line.

Finally, from the measurement of the line width (FWHM), we have deduced the value of the electron density of the plasma [10], $n_e\ [\mathrm{cm}^{-3}] = 8.02 \times 10^{12} \left(\frac{\Delta\lambda_{\frac{1}{2}}}{\alpha_{\frac{1}{2}}}\right)^{\frac{3}{2}}$, where $\Delta\lambda_{\frac{1}{2}}$ is the full width at half maximum (FWHM) of the Stark-broadened spectral line in angstroms, and $\alpha_{\frac{1}{2}}$ values in angstrom units have tabulated by Griem [12].

4. Plasma Electron Density: temporal evolution

By changing the time interval between the arrival time of the discharge current pulse and the beginning of the data acquisition, the temporal evolution of the plasma density is attained as a function of plasma recombination time. We have investigated the time dependence of the shot-to-shot variation of the plasma density at the different delays from the start of the discharge. The mean density profile (12 kV-300 A) for each delay time averaged over 50 shots is space integrated along the 3 cm/long capillary tube. The measurements refer to the H_β line for the delays ranging from 1000 to 2600 ns after the gas breakdown. Figure 3 shows as the electron density has a maximum value of about $5.3\times\ 10^{17}\ cm^{-3}$ and decreases gradually over time. Since plasma evolution occurs through different phases [13], this behavior is due to the increase in ionization rate at the beginning of the first phase. The plasma density behavior as a function of time conveys that at the shorter delay times after triggering the discharge as 1000 ns, the system is hot enough to produce quite hot plasma and distribute the maximum plasma density. Thus, as time passes by increasing the delay time and approaching 2000 ns, the system cools down, and the plasma electron density decreases.

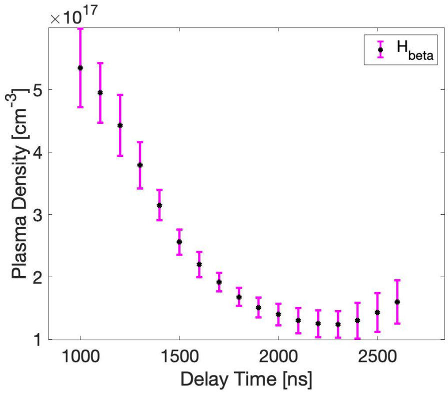

Figure 3. Space integrated plasma electron density versus time, averaged over 50 shots.

This behavior is easily understood, considering the effects that the temporal evolution of the electric discharge produces on the plasma temperature and consequently on the electron-ion cross-section and the relative collision frequency [14]. In conclusion, one can say that the plasma produced by an electric discharge and confined in a capillary tube has promising characteristics as a medium to develop plasma acceleration induced both by ultra-short laser pulses and relativistic electron bunches from a small LINAC [15]. The characteristics of the plasma desired for acceleration for quite a long time (several tens of ns) are maintained, making them compatible with the times during which the acceleration process must develop (a few 0.1 ns).

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