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Electron density measurement in gas discharge plasmas by optical and acoustic methods

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Abstract: Plasma density represents a very important parameter for both laser wakefield and plasma wakefield acceleration, which use a gas-filled capillary plasma source. Several techniques can be used to measure the plasma density within a capillary discharge, which are mainly based on optical diagnostic methods, as for example the well-known spectroscopic method using the Stark broadening effect. In this work, we introduce a preliminary study on an alternative way to detect the plasma density, based on the shock waves produced by gas discharge in a capillary. Firstly, the measurements of the acoustic spectral content relative to the laser-induced plasmas by a solid target allowed us to understand the main properties of the acoustic waves produced during this kind of plasma generation; afterwards, we have extended such acoustic technique to the capillary plasma source in order to calibrate it by comparison with the stark broadening method.

Keywords: Plasma diagnostics - interferometry, spectroscopy and imaging; Plasma generation (laser-produced, RF, x ray-produced)

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Contents

1 Introduction

Plasma wakefield acceleration (PWFA) represents one of the most promising techniques to achieve higher acceleration energies up to GeV level in a very short accelerating distance (GV/m range accelerating field) [1]. For the PWFA experiments foreseen at the SPARC_LAB test facility we are going to use a gas-filled capillary plasma source, whose plasma density measurement is required. There are several techniques employed for the determination of electron density which includes, plasma spectroscopy, probe-based diagnostics, laser interferometry and Thomson scattering. Between all the spectroscopic techniques available to analyze plasmas, the Stark broadening [2] is a very attractive method because it is very simple to implement with respect to the other ones, especially by working with a simple gas like hydrogen in the electron density range less than 10^{18} cm^{-3}. Besides the Stark broadening method, we present here a very innovative technique that can be used to detect the plasma density within a gas-filled capillary plasma, which is based on the acoustic wave generated during the electrical discharge; it does not have any limit about the electron density range and it is very easy to implement. The gas discharge, produced by two electrodes placed at the ends of the capillary, causes a very fast ionization of the gas inside it, which in turn is followed by a shock wave generation, traveling at variable velocity which is related to the own plasma formation mechanism [3, 4]. Consequently, the frequency response and the amplitude level of such acoustic wave are related to the properties of the ionized gas. The plasma density can be measured by analyzing the shock wave properties, given by a microphone mounted on the capillary's wall that returns the acoustic energy produced during the electrical discharge. The correlation among the plasma properties (essentially its electron density) and the acoustic signals can be obtained by calibrating it with the Stark broadening measurements. Once the calibration is achieved it could be possible to measure the plasma properties by the acoustic waves in a very simple way, without any other optical device.

In this paper, we report the measurement results concerning the shock wave generation during the plasma creation by a solid target, for which we have measured, at the same time, the electron density througt the Stark effect and the acoustic waves. A direct comparison between two techniques is also reported.

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2 Materials and methods

The plasma was produced by a solid target using a laser-induced plasma generation, which is, in general, employed to analyze several matter properties; this method of investigation is well-known as laser-induced breakdown spectroscopy (LIBS). In this process, the laser beam hits the sample's surface and ionizes some molecules; consequently, the free electrons will be accelerated by the laser field and then collide with the neighbouring molecules in air, creating a typical plasma plume through an avalanche ionization mechanism that depends on the laser beam, surrounding gas and matter properties [5]. In these conditions, the plasma spectroscopy will allow us to investigate the physical characteristics of the matter.

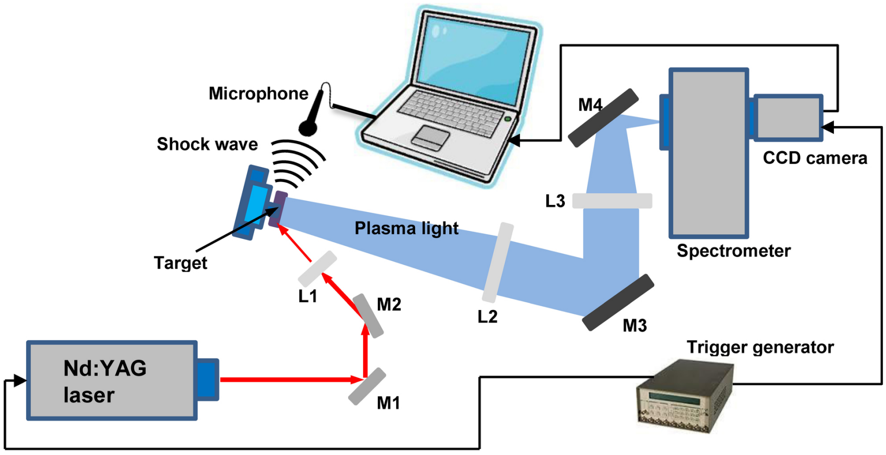

Figure 1. Experimental apparatus to detect the plasma density using the acoustic technique and the Stark effect method.

Figure 1 shows the experimental setup that has been used to detect the plasma electron density, n_e. There are two different measurement systems: the first one is based on the Stark effect, that uses several lenses, a spectrometer and a CCD camera; the second one is based on an acoustic technique and uses only a microphone to acquire the shock waves produced during the plasma creation. As you can see, the laser radiation has been generated by a pulsed Nd:YAG laser (Lotis Tii LS2131, 11 ns pulse, $\lambda = 1064$ nm, 1–10 Hz frequency and 110 mJ laser energy) that has been focused by an $f = 3$ cm lens (L1) on the target: a piece of ABS (Acrylonitrile butadiene styrene, $(C_8H_8{\cdot}C_4H_6{\cdot}C_3H_3N)_n$) plastic placed in air. Also, two mirrors (M1 and M2) have been used to transport the laser beam to the target. These radiation conditions have allowed to reach an optical intensity on the target up about 10^9 W/cm^2, which represents the minimum intensity to produce plasma from solid targets [6]. With regards to the spectroscopic technique, the emitted light by the plasma has been collected through other two lenses (L2 and L3), which have both 7.5 cm diameter but different focal length ($f = 15$ cm and $f = 20$ cm), and two metal mirrors (M3 and M4) that have both 7.5 cm diameter. In this way, the plasma light is transported into the entrance slit of the spectrometer (ARC SpectraPro-275) and then the hydrogen Balmer lines have been acquired by a CCD camera that is mounted at the output of the spectrometer. Finally, a delay generator (SRS DG535) has been used to syncronize the laser Q-switch and the CCD camera acquisition start. The acoustic measurement setup is very simple to implement, it is composed of a microphone placed at 5 cm from the acoustic source, laterally with respect to the plasma plume; also, in order to acquire the shock waves produced during the gas ionization, we have used an acoustic acquisition software.

In order to understand how a shock wave is generated during the plasma plume formation, we have firstly to take into account that the laser energy produces a very fast growth of the surface temperature. Afterwards, the ionized matter will compress the surrounding air in a very short time range and this process represents a shock wave expansion that is associated to the plasma plume propagation. Depending on the distance from the sample surface, that depends on the propagation time of the pressure wave, it is possible to identify three different propagation ways [7]: in the first one, within a distance that is similar to the irradiated spot diameter, the evaporated particles will propagate towards the air molecules and the shock wave pressure will be much higher than the air pressure; in the second one, the shock wave overpressure becames close to the surrounding gas pressure and, finally, during the last propagation way, the shock wave will undergo a transition towards an acoustic wave.

In this experiment, the goal is to compare the Stark broadening measurement with the acoustic one. Therefore, the proper observation distance (about 5 cm) is chosen on the basis of a compromise between the amplitude of the shock waves and the damages the microphone might undergo. The measurements have been taken by varying the laser energy, considering that the observation distance does not affect the relationship between the acoustic pressure and the electron density of the plasma but it only produces an attenuation of the shock wave amplitude over the whole spectrum. The relationship between the electrons originated from the target and the shock wave propagation can be analyzed starting from the acoustic wave equation, which can be written as [8]:

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) p\,(r,t) = -K\frac{\partial C\,(r,t)}{\partial t} \tag{2.1}$$

where c is the sound speed, $p(r,t)$ is the acoustic pressure, K is a parameter that represents the calorimeter constants and $C(r,t)$ is the source term that determines the shock wave generation. When the laser beam hits the target surface, hot electrons are released from it and collide with the neighbouring air molecules, creating an avalanche mechanism that moves these molecules and which produces a shock wave. The source term $C(r,t)$ represents the connection between the pressure of the shock wave and the plasma properties. Indeed, it describes how the acoustic wave is created when the laser beam hits the solid target and the electrons released from its surface ionize the surrounding air molecules. Therefore, $C(r,t)$ represents a heating function that takes into account the heat energy amount, released by the laser beam on the target surface, that is transformed into kinetic energy acquired by the air molecules. This function [8] depends on plasma parameters, laser beam properties and density as well as chemical composition of the ionized air molecules. In order to highlight the dependence on the electron density, the last two properties are inserted in a second function, called $h(r,t)$. Therefore, $C(r,t)$ can be defined as:

$$C\,(r,t) \propto \frac{1}{2}n_e m_e v_e^2 h\,(r,t) \tag{2.2}$$

where n_e, m_e and v_e are density, mass and speed of electrons, respectively. By inserting eq. (2.2) in eq. (2.1), it is possible to obtain the acoustic pressure of the shock wave produced during the gas

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ionization, according to the following formula:

$$p(r,t) \propto \frac{1}{2} n_e m_e v_e^2 g(r,t) \tag{2.3}$$

This formula describes the relationship between the shock wave due to the gas ionization and the resulting electron density. Therefore, eq. (2.3) shows that the measurement of the shock wave amplitude is equivalent to measure the electron density n_e of the plasma. The additional function $g(r,t)$ [9] includes the Green's function solution of the eq. (2.1) and the previously defined function $h(r,t)$. The complete expressions of both functions $h(r,t)$ and $g(r,t)$ do not depend on the plasma parameter n_e, therefore will be disregarded here. We would like to highlight that so far eq. (2.3) does not allow a direct measurement of the plasma density, however it is necessary to explain the dependence of acoustic measurements on the plasma density.

3 Results and discussion

Hydrogen atoms emit light with different wavelengths in the visible range when excited by an external source. The broadening of these lines, known as Balmer spectral lines, is due to several effects. Stark broadening is caused by an external electric field acting on the emitter, which is represented, in our case, by the solid target. The external electric field is due to the free electrons that the laser field extracts from the target surface. This effect has been modelled [11–13] and the plasma electron density can be measured.

Figure 2 shows the spectrum curves of the hydrogen Balmer alpha line, H_α (λ = 656.3 nm), that have been obtained through the Stark broadening measurements, using an ABS plastic target, when the laser energy has been scanned from 75 mJ to 110 mJ. By measuring the width of the Stark broadening H_α line [10, 11], it is possible to estimate the electron plasma density inside the plume.

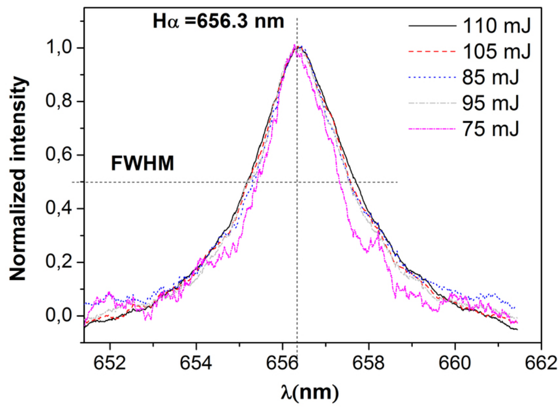

Figure 2. Hydrogen Balmer alpha lines that we have measured for a target composed of ABS plastic at different laser energy values.

The wider is the spectral line-width of H_α, the higher is the electron density of the plume and viceversa; the relation between electron density and H_α line-width is given by:

$$\Delta\lambda[\text{nm}] = \alpha(n_e, T) n_e [10^{18}\,\text{cm}^{-3}]^{3/2} \tag{3.1}$$

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where $\Delta\lambda$ represents the full width at half maximum (FWHM) of the spectral line and the $\alpha(n_e,T)$ is a function of the electron density and the plasma temperature [12]. In order to measure the plasma electron density by Stark effect, also other spectral Balmer lines can be used (i.e. H_β and H_γ); however, we have only focused, in this experiment, on H_α lines.

All curves in figure 2 are fitted with a Lorentz function [13] and their widths $\Delta\lambda$ are the FWHM calculated on the fitted curves and plasma density is retrieved from eq. (3.1). As we can see, line widths are very close each other but not completely overlapped, being the density different at a different laser energy and ranging from $2 \cdot 10^{18}$ to $3.4 \cdot 10^{18}$ cm^{-3}. By increasing the laser energy, we measured an increasing plasma density. The results of the measurements have been averaged over 6 shots and the error is a statistical error, which is always within the 10 %. There are other mechanisms of broadenings that can wide the hydrogen spectral lines in the density range from 10^{16} to 10^{18} cm^{-3} (that represents our measuring range), i.e. the natural and the Doppler broadening [13]. The thermal motion of the particles causes the Doppler broadening, which depends on plasma temperature. In our conditions, the plasma temperature is lower than 4 eV, therefore, the Doppler broadening contribution is lower than 0.1 nm, that can be neglected with respect to the Stark effect contribution. Natural broadening is a consequence of the Heisenberg uncertainty principle, according to the formula $\Delta E \Delta t > h/4\pi$. A short lifetime of an excited state corresponds to a large energy uncertainty ΔE, thus resulting in a larger broad emission. For optical spectroscopy, the natural broadening is about a tenth as much as the Doppler broadening, hence it can be neglected in our measurements.

In our experiments, we used a laser pulse duration of 11 ns, with 110 mJ maximum energy, at $\lambda = 1064$ nm. Since the plasma temperature is directly proportional to laser parameters, on the basis of the measurements reported in [14], the plasma temperature can be estimated to be of the order of 1 eV. Therefore, the Stark effect is dominant and we can neglect the temperature contribution. Moreover, we are interested in a plasma density range between 10^{16} and 10^{18} cm^{-3}, which allows us to assume the parameter $\alpha(n_e, T)$ independent from the temperature and the plasma density; hence, $\alpha(n_e, T)$ can be assumed constant. The $\alpha(n_e,T)$ value used for our measurements is 5.4 [15]. Since the laser energy range is rather small, as well as the plasma temperature range, also acoustic measurements have been assumed independent on the temperature.

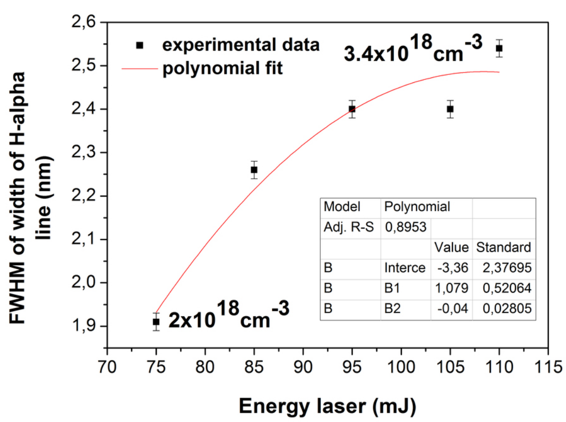

Figure 3. Width of hydrogen Balmer alpha line at FWHM as a function of the laser energy.

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Figure 3 reports the widths of the H_α line at FWHM as a function of the laser energy when the laser energy is changed from 75 mJ to 110 mJ; the width of the spectral line increases from 1.9 nm to 2.55 nm. These latter values correspond to a plasma electron density between $2 \cdot 10^{18}$ cm^{-3} and $3.4 \cdot 10^{18}$ cm^{-3}, respectively. The trend of figure 3 shows the nonlinear behaviour of the laser-induced plasma creation in air, caused by saturation limit of the air molecules placed close to the sample surface. Indeed, since the air density is around $5 \cdot 10^{18}$ cm^{-3}, as long as the laser energy is lower than 100 mJ, the electrons emitted by the sample surface have enough energy to ionize the air molecules but not enough to ionize the total amount of them: this condition allows a fast growth of the plasma density. On the other hand, if the laser energy becames higher than 100 mJ, the electrons ionize the total amount of the air molecules and so the plasma density will remain constant even if the laser energy will be increased.

The acoustic spectra reported in figure 4a represent the typical behaviour of a shock wave in air, which the spectrum belongs to the audible bandwidth that goes from 20 Hz to 20 KHz. These spectra have been acquired using a microphone that has the same bandwidth and a dynamic range equal to 60 dB, which means that the microphone can acquire acoustic signals from $2 \cdot 10^{-5}$ Pa (reference sound pressure for all microphones) to $2 \cdot 10^{-2}$ Pa. The spectra highlight that with increasing laser energy, the plasma density is higher, thus resulting in a larger measured acoustic pressure. Furthermore, such behaviour occurs for all resonance frequencies of shock wave generated during the plasma formation (5.6 kHz, 12 kHz, 17.5 kHz), as shown in figure 4b.

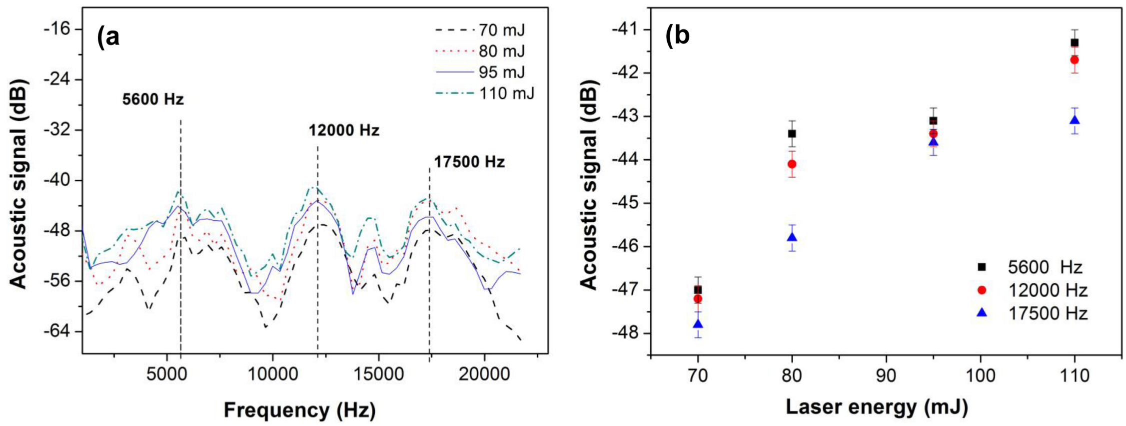

Figure 4. Acoustic measurements: a) Spectra of the acoustic signals as a function of the laser energy acquired during the plasma creation; b) Maximum values of the acoustic spectra for each resonance frequency.

In order to make a comparison between the acoustic method and the spectroscopic one, we have investigated how such resonance frequencies change their values changing the laser energy, as already done for the Stark broadening method.

For such reason, in figure 4b, only the amplitude values corresponding to each resonance frequency have been represented as a function of the laser energy. Also in these measurements, the amplitude profiles of the acoustic signals follow a nonlinear behaviour due to the totally ionization of the air molecules when the laser energy exceeds about 100 mJ, as it has already been shown with the spectroscopic measurements [6]. For each curve, when the laser energy is changed from 70 mJ to 110 mJ, the amplitude values measured by microphone goes from −48 to −42 dB respectively.

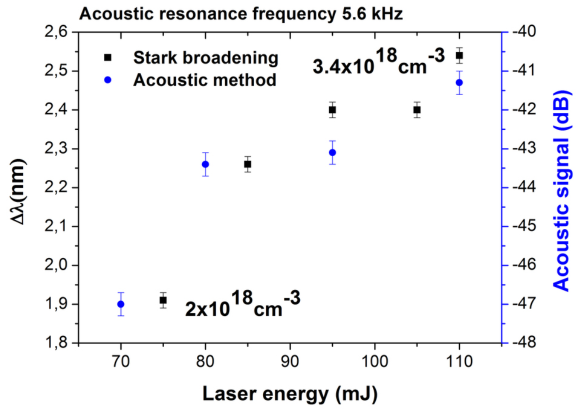

Figure 5. Comparison between the amplitude profiles of the acoustic signal (5.6 kHz) and the Stark broadening of the H_α line.

At this stage, a direct comparison between the amplitude profiles of the acoustic signal and the Stark broadening of the H_α line can give us the calibration factor of the acoustic technique through the spectroscopic one, as deduced from figure 5. The latter figure contains the amplitude profile of the acoustic signal relative to the lower resonance frequency at 5.6 kHz. Figure 5 shows that both measurement techniques highlight a saturation at a laser energy of about 100/110 mJ and are in decent accordance within the range of measurements.

The acoustic measurements for a laser-induced plasma in air described before will be used at the SPARC_LAB test facility for a gas-filled capillary. Figure 6 shows the capillary that will be used during the experiment and, in particular, figure 6b shows changes to the experimental setup needed to acquire the shock wave generated during the gas ionization. Figure 6a shows the side view of the plasma capillary: the two gas injectors with 300 μm radius and the plasma channel (3 cm long, with 500 μm radius). The two electrodes at the ends of the capillary provide the high voltage to the hydrogen gas.

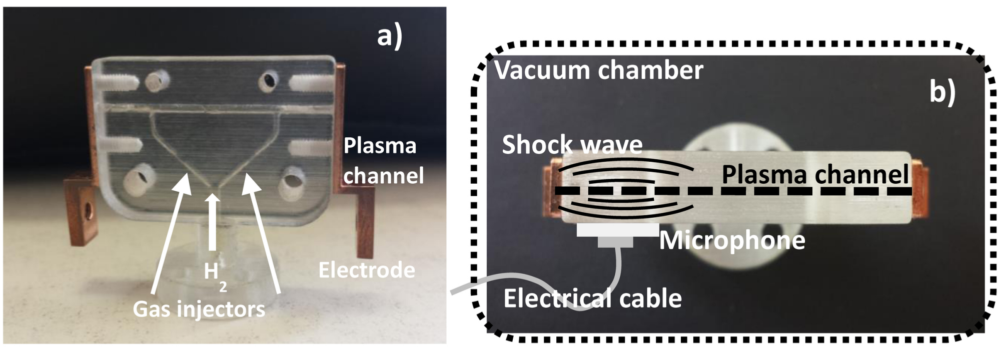

Figure 6. Picture of the gas-filled capillary plasma source used at the SPARC_LAB test facility: a) side view; b) top view.

As shown in figure 6b, the plasma channel (represented by a dashed line), as well as all the components of the capillary, is inserted in a backing of plastic holder, which is 8 mm wide. We are going to mount the microphone (which is about 5 mm wide) on the side wall of the capillary holder,

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around 3.5 mm from the plasma channel so that it can detect the shock waves produced during the discharge inside the plasma channel. Of course, such acoustic acquisition system will be placed within a vacuum chamber (represented by a dotted box in figure 6b) but the shock waves will never propagate into vacuum. In fact, while the gas discharge expands into vacuum of the plasma channel and creates the shock wave, the latter goes through the holder and reaches the microphone that converts the acoustic signal into an electric signal that will be took out from the vacuum chamber. The microphone can be mounted everywhere on the capillary, as long as it can receive the shock wave and it can be protected from the high voltage.

4 Conclusions

In this paper we have presented an innovative way to measure plasma density, showing that there is a close relationship among the amplitude of the acoustic signal, the plasma generation and the optical emission. We have shown that the Stark broadening technique can be used to calibrate the acoustic signal (shock wave) in order to determine the starting parameters of the plasma, essentially his electron density. Both methods describe the typical nonlinear behaviour of the laser-induced breakdown spectroscopy in air, for which the electron density will change his trend when the laser energy reaches 100 mJ, remaining constant after that value [6]. We have seen that acoustic measurements describe the laser-induced plasma formation, and the acoustic curves, for each resonance frequency, follow the same trend of the H_α line width due to Stark effect. The very good agreement between the two density measurement techniques can represents a good motivation for using the shock wave to detect the plasma density. The acoustic method described for a laser-induced plasma in air can be extend to a gas-filled capillary plasma source, since also in the latter a shock wave will be generated during the gas ionization. Such technique is also reliable and simple to implement: we need only a microphone attached on the wall of the capillary.

Acknowledgments

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