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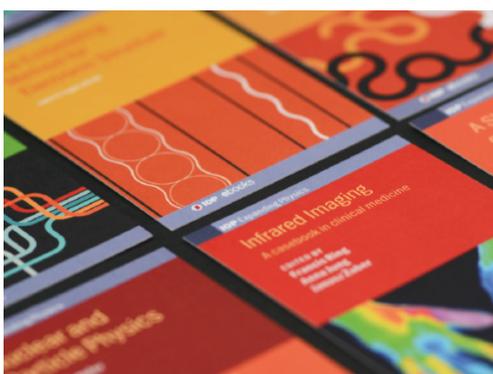
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Determination of electric field strength and kinetic temperature in the cathode fall region of a hollow cathode discharge

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Abstract. In this work, we demonstrate the high potential of two-photon excitation of the 1S - 2S transition of atomic hydrogen followed by optogalvanic detection, for measuring under identical experimental conditions, the kinetic temperature and the electric field strength in the cathode sheath region of a hollow cathode discharge. The first obtained results for both parameters are discussed in this paper.

1. Introduction

Experimental and theoretical investigations carried out for many years have provided a lot of information about low-pressure gases discharges. However, there is still a lack of knowledge concerning discharge dynamics; so that, new data are needed to complete the modelling of such complex phenomena, see e.g. [1-4], and the references therein.

For years our group has been involved in developing new experimental techniques for plasma diagnostic. In this work, we demonstrate the high potential of two-photon excitation of the 1S - 2S transition of atomic hydrogen followed by optogalvanic detection for measuring, under identical experimental conditions, the kinetic temperature (T_{kin}) and the electric field strength (E-field) in the cathode sheath region of a hollow cathode discharge (HCD).

In first measurements we applied the usual laser beam combination for this type of measurements: counter propagating beams for the Doppler-free measurements of the (E-field) and only one linearly polarized beam for measuring the Doppler broadened profile. The de-convolution of Doppler-free from the Doppler-broadened profiles results in the pure Doppler profile, hence the kinetic temperature. These first measurements of T_{kin} in the cathode fall revealed some curious results, i.e. temperature lower than room temperature. Analyzing the experimental conditions we came to the conclusion, that the Doppler-free profile corresponds to a local measurement given by the overlap volume of the two counter propagating beams, while the Doppler-broadened profile corresponds to an integrated measurement including the areas without E-field and cooler boundary layers of the plasma as well.

In order to overcome those limitations we remind, that the 1S - 2S transition is quite exceptional, because the conservation of the angular momentum is restricted to only $\Delta L = 0$, i.e. the two-photon excitation is only possible by two photons of opposite angular momentum (opposite circularly polarized laser beams). Using three appropriate circularly polarized laser beams, it is possible therefore to conduct four types of local measurements in exactly the same overlap volume which allow

us to measure: a) homogeneous broadening, i.e. the Stark splitting without any Doppler broadened background, b) usual absorption spectra composed by the convolution of homogeneous and inhomogeneous broadening, c) the composition of a) and b), and d) is a zero signal control measurement.

2. Experimental arrangement and measurements

The experimental set-up is shown in figure 1. We used our advanced UV laser spectrometer, specially developed for plasma diagnostic. It provides tuneable 243 nm radiation needed for two-photon excitation of the 1S - 2S hydrogen transition: up to 10 mJ pulse energy in 2.5 ns with nearly Fourier-transform limited bandwidth of 300 MHz. Measurements are performed in a low density HCD plasma with a diameter of 15 mm and 50 mm length. For mapping the E-field and T_{kin} distributions, the HCD is mounted on a vertical translator stage. High spatial resolution is needed because of the very small sheath thickness of the cathode fall region (about 2.5 mm, depending on the discharge parameters). The spatial resolution is given by the overlap volume of the laser beams. Taken into account divergence of the beams and their crossing angle, the overlap volume is about 30 mm long with a central diameter of 200 μm . A comprehensive explanation of the whole experimental arrangement, figure 1, can be found elsewhere [6]. Our experimental laser spectroscopic arrangement, see figure 1, is based on three nearly perfectly circularly polarized laser beams of 243 nm (beams 1, 2 and 3).

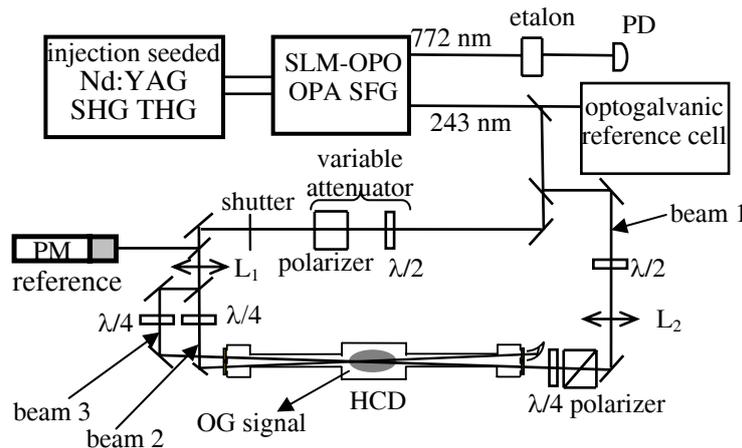


Figure 1. Experimental arrangement

Four different combinations of these three beams allow various types of measurements, see Table 1, which provide to measure the Doppler-free Stark splitting a), the inhomogeneous Doppler broadening b), the mixture of both c) as control for independent (linear) superposition of homogeneous and inhomogeneous broadening. Quite remarkable is the zero signal probe measurement d), because only two counter propagating beams with perfect opposite circular polarization should not give any signal at all, because the two photon absorption of the 1S - 2S transition is restricted to an angular momentum transfer of $\Delta L = 0$. In order to achieve nearly perfect circular polarization for all the beams; it is necessary to minimize any distortion of the linear and circular polarization states caused by other optical devices involved in the experiment. In addition, the temporal delay introduced between beams 2 and 3 must be as small as possible (in our case: less than 4 % of the laser pulse duration) in order to maintain the temporal overlap.

Figure 2 shows, as example, the four different spectra obtained by the four different laser beam configurations explained above, acquired for the following fixed discharge conditions of 400 Pa and 100 mA at a distance of 150 μm from the cathode surface.

Table 1. Characteristics and combination of the three laser beams which provide the four types of measurements and the corresponding spectra a) to d) shown in Figure 2

<i>Figure 2</i>	<i>Beam, propagation</i>	<i>Polarization, angular momentum transfer</i>	<i>Measurement</i>	<i>Broadening</i>
a	1 and 2, counter	opposite, $\Delta L = 0$	Doppler free	homogeneous
b	2 and 3, collinear	opposite, $\Delta L = 0$	Doppler broadened	inhomogeneous
c	1, 2 and 3, mixed	mixed, $\Delta L = 0$	mixed	mixed
d	1 and 3, counter	identical, $\Delta L = 2$	zero signal	-

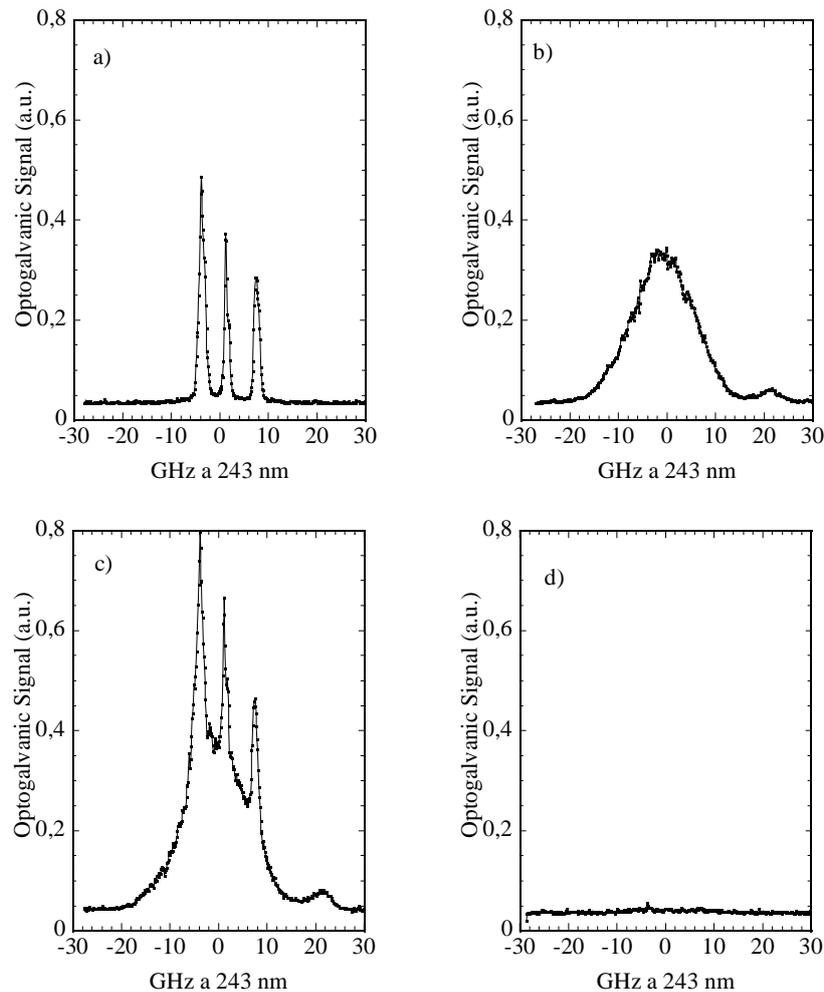


Figure 2. Four different spectra without any data evaluation, all obtained from the same measurement volume and fixed discharge conditions: 400 Pa, 100 mA, at 150 μm from the cathode surface

These spectra exhibit also very clearly the high polarization quality of the beams. Furthermore, the spectra c) is obviously sum of the spectra a) and b), hence the signals do not exhibit any saturation. Please note, that all the signals are only created where the laser beams overlap, this is the consequence of using the circularly polarized beams combined with the angular momentum transfer restricted to $\Delta L = 0$. For mapping the kinetic temperature (T_{kin}) and the electric field strength (E-field) we have measured in one measurement campaign the set of the four spectra at various distances from the cathode surface, starting at a minimum distance of about 150 μm in 8 steps of 250 μm .

3. Results

The Doppler-free profiles, figure 2 a), allow a reliable determination of the local E-field via the frequency shift of the red (blue) shifted $2P^{1/2}$ ($2P^{3/2}$) Stark components and the variation of the E-field in the cathode fall region [5-7].

The inhomogeneous broadening, i.e. the Doppler broadening, can be extracted by de-convolution [8] of the spectra a) from spectra b). This was done by calculating the inverse Fourier transform (FT) of the ratio of the FT of the Doppler broadened profile b) to the FT of the Doppler-free spectra a). As expected, the spectral profiles obtained after de-convolution exhibit very well Gaussian line shapes and provide therefore a T_{kin} , figure 3. However, the variation of T_{kin} with distance from the cathode surface is still a surprise and fairly the same for both discharge pressures investigated: 400 Pa and 900 Pa. Only for an E-field of about 1 kV/cm or lower, T_{kin} confirms the common understanding of low density discharges and reveals for both discharge pressures nearly the same reasonable value of about 375 K, i.e. somewhat larger than room temperature. However, with decreasing distance from the cathode surface (from 1.8 mm down to 0.15 mm for 400 Pa, and from 1.3 mm down to 0.15 mm for 900 Pa) and with the corresponding increasing field strength (up to 2.5 kV/cm for 400 Pa and 2.8 kV/cm for 900 Pa) T_{kin} decays more or less parabolic down to 140 K. We are convinced, that this reveals strong deviations from a homogeneous velocity distribution in the cathode fall region of the HCD. We have to remind, that the inhomogeneous broadening and the related T_{kin} which we can measure is only the projection of all atomic velocities present in the overlap volume onto the laser beam direction, while the projection of the atomic velocity distribution perpendicular to the laser beams, e.g. in the radial direction parallel to the local electric field is absolutely inaccessible. Our first interpretation of the “kinetic temperatures” determined in this study in the cathode fall region is quite simple therefore. The strong radial acceleration of the hydrogen ions towards the cathode and the large charge-transfer cross-section of hydrogen may be the reason for the pronounced discrepancy with respect to a homogeneous atomic velocity distribution. A more detailed analysis is demanded.

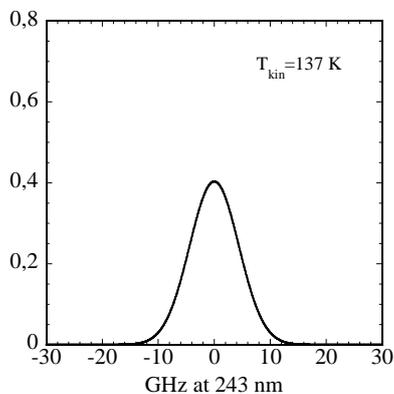


Figure 3. Gaussian profile obtained by de-convolution of the Doppler free profile from the Doppler-broadened spectra shown in figure 2. In order to avoid noise of the profile due to the de-convolution procedure, the noise of the measured spectra was eliminated first by usual fit procedures, The convolution of the Doppler-free spectra figure 2a) with the Gaussian profile obtained by de-convolution agrees perfectly with the Doppler broadened spectra figure 2b).

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