Analysis of the measured 1S-2S Stark spectra of hydrogen isotopes used for E-field strength determination in a hollow cathode discharge

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Analysis of the measured 1S-2S Stark spectra of hydrogen isotopes used for E-field strength determination in a hollow cathode discharge

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Abstract. This paper is dedicated to analyse in detail the Stark splitting spectra of the 1S - 2S transition of hydrogen isotopes, used to determine the local electric field strength in the cathode fall of a hollow cathode discharge, by measuring the Doppler free two-photon absorption via optogalvanic detection. The measured irradiance distribution in the overlap volume of the two laser beams is used to integrate the rate equations, which give the ion yield distribution with high spatial resolution. Inserting the local ion yield in the local electric field strength of the cathode fall allows reconstructing and analysing the Stark splitting spectra.

1. Introduction

In a hollow cathode discharge (HCD) the local electric field strength (E-field) is one of the most relevant discharge parameters directly connected with charged particle fluxes, their energy distribution functions and the charge densities [1-2]. In a HCD discharge, as it is well known, two regions can be distinguished: a small dark space closed to the cathode surface where the local E-field varies strongly because the potential applied between the electrodes mainly drops off in this region, while the negative glow plasma fills up most of the discharge volume. Thus, the E-field measurements, in this kind of discharges, demand for a well characterized spatial resolution parallel to the cathode surface.

In previous papers [3-5], we reported on the determination of the E-field in the cathode fall region of the HCD, operated either in hydrogen or deuterium, via the Stark splitting of the 1S - 2S transition. We used Doppler free two-photon excitation combined with optogalvanic detection to characterize the cathode fall voltage drop of the HCD in a wide range of discharge parameters. The comparison of the calculated and measured frequency shifts of the Stark components gives the E-field, which varies sharply over very short distance. However, the measured Stark components are found to be much broader than expected.

To exclude that this broadening is not caused by the spatial resolution provided by the overlap of the two counter-propagating laser beams, the excitation conditions in the measurement volume has to be characterized with high precision. In this paper we report on a straight forward approach, based on highly resolved spatial and temporal irradiance distribution of both laser beams, we integrate the rate equations, e.g. for two-photon resonant ionization (optogalvanic detection) and obtain the three

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dimensional Ion-yield with high spatial resolution. In a final step, the local Ion yield is inserted in the measured local E-field at different distances close to the cathode surface; hence we obtain the spectra of the Stark components accounting also for laser bandwidth.

2. Experimental details and results for the local electric field strength measurements

Measurements were performed in low density plasma generated in a home-made HCD, figure 1. The outer structure of the hollow cathode is a vacuum seal chamber made of brass which includes: electrical isolation, water cooling, gas in and outlet and electrical connections. Anodes and the cathode are made of stainless steel and inserted in the outer structure. The hollow cathode (10 mm inner diameter and 50 mm long) is placed in between two hollow anodes to allow end-on spectroscopy parallel to the hollow cathode axis close to the cathode surface. The discharge is operated at a constant gas flow of hydrogen or deuterium and a fixed pressure. The device provides stationary stable non-LTE plasma, characterized by low density and kinetic temperature of atoms and molecules. In this study we have generated plasma by currents from 50 to 200 mA and pressures from 270 to 1350 Pa. The entire HCD is mounted on two translator stages, which allow for precise horizontal (x) and vertical (y) displacements, see figure 2, while the laser spectroscopic setup is fixed. The counter-propagating laser beams are crossing in the horizontal plane; and the measurement volume, i.e. the beam overlap, is aligned parallel to the cathode surface and centred with respect to the cathode length. The vertical translator stage allows varying the distance of the measurement volume with respect to the cathode surface.

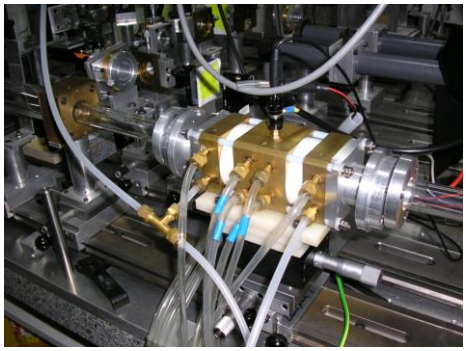

Figure 1. Image of the HCD in the laser spectroscopic setup.

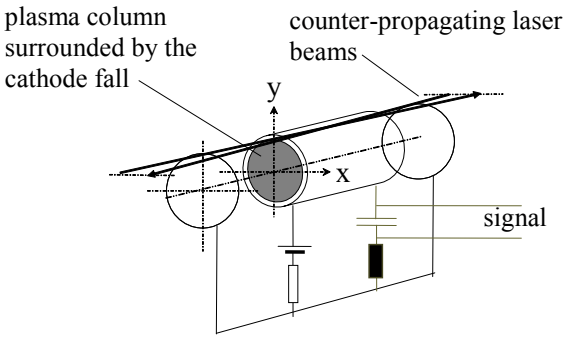

Figure 2. Two-photon absorption followed by photo-ionization generates additional electric charges in the overlap volume. The strong E-field in the cathode fall creates a charge avalanche detected by capacitive coupling.

The radiation needed for two-photon excitation of the 1S - 2S transition is generated by an advanced tuneable single longitudinal mode (SLM) UV-laser spectrometer, that provides up to 10 mJ pulse energy in 2.5 ns at 243 nm, with 300 MHz bandwidth. Each of the two counter-propagating laser beams is focused in the overlap volume by a 1m focus lens. They are opposite circularly polarized according to the angular momentum selection rules ($\Delta L = 0$). A complete description of the laser system and the whole experimental set-up used for E-field determination can be found in the references [3-5].

To determine the E-field, successive laser scans were taken at different distances from the cathode surface. The comparison of the measured and the theoretical frequency shifts of the Stark components give precise values of the E-field, because the spectra reveal very well defined frequency positions for the maximum of each Stark component. Figure 3 shows one example of some results of the E-field as

a function of the cathode distance for various experimental conditions. Obviously, the E-field varies very strongly over short distances in front of the cathode: in a sheath of about 2 mm the local electric field strength increases up to 4 kV/cm.

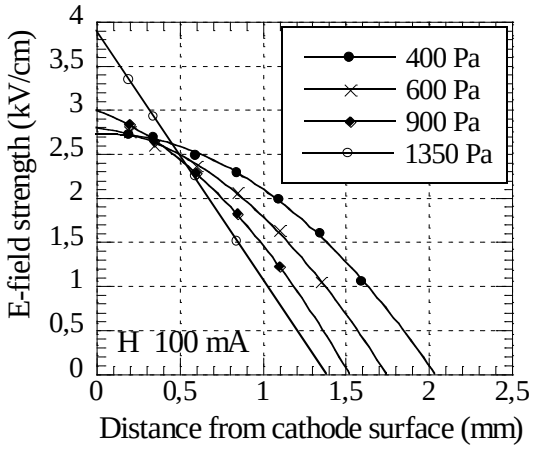

Figure 3. E-field vs distance from the cathode in the hollow cathode discharge for Hydrogen, 100 mA discharge current and various pressures.

However, the experimental profiles are broader than expected, see figure 4. To exclude that this broadening is a consequence of the spatial resolution, the measurement volume has to be determined with high precision.

3. Characterization of the spatial resolution based on the determination of the local Ion Yield

As already mentioned the spatial resolution is determined by the overlap volume of the two laser beams in the HCD. For its determination, MATLAB programs are used to incorporate the beam propagation and irradiance distributions necessary for calculating the excitation conditions in the overlap volume. This calculation implies the integration of the coupled rate equations suited for the two-photon excitation of the 1S - 2S transition of atomic hydrogen, which accounts for two-photon absorption, photo-ionization, collisions and fluorescence decay. The integration requires knowledge of the temporal and spatial irradiance distribution in both beam waists.

To acquire spatial beam profiles we employ a high resolution UV camera (LaserCam-HR-UV, Coherent, pixel size 6.7 µm x 6.7 µm), and a fast photodiode for the temporal pulse shape. Without getting in all details that can be found elsewhere [6], basically the calculation scheme is as follows: the experimental overlap volume due to a crossing angle of 1.53º is represented by slices of 500 µm length in the propagation direction. For each slice the equations are integrated in 50 ps steps, for a laser pulse of 2.5 ns FWHM and for volume elements of 6.7 µm x 6.7 µm x 500 µm. Spatial and temporal irradiance distributions of the two beams are defined by the pulse energy and the temporal pulse shape.

These calculations reveal with high spatial resolution the Ion yield distribution for various irradiances, and allow characterizing the spatial resolution, saturation effect due two depletion of the ground state density, and the influence of the spectral width of the two-photon absorption profile on Ion yield. It turns out that the optogalvanic detection has an exceptional high spatial resolution, because for up to 100 MW/cm^2 more than 75% of the optogalvanic signal is created in a tiny central area of the overlap volume of only 100 µm x 100 µm and a length of 10 mm. Finally, the obtained Ion yield distribution opens the possibility to achieve for the first time a reliable analysis and interpretation of the spectra.

4. Analysis of the spectra by combining local Ion Yield and local E-field strength distribution

Inserting the Ion yield distribution into the measured cathode voltage drop allows calculating the spectral shape of the Stark components, at any position of the cathode fall as a consequence of the spatial resolution. Spectral resolution of the laser is also included. In figure 4 one example of the reconstructed spectra (fine continuous lines) is compared with the measured spectra (dots), for a discharge pressure of 600 Pa, a current of 100 mA and 200 μm distance from the inner cathode surface. Obviously, the well separated Stark components of the reconstructed spectra exhibit significant less broadening than the measured ones. The double peak of each Stark component of the reconstructed spectra is due to the underlying hyper-fine structure (621 MHz) of the 1S-2S transition of hydrogen, which is easily resolved by 300 MHz laser bandwidth.

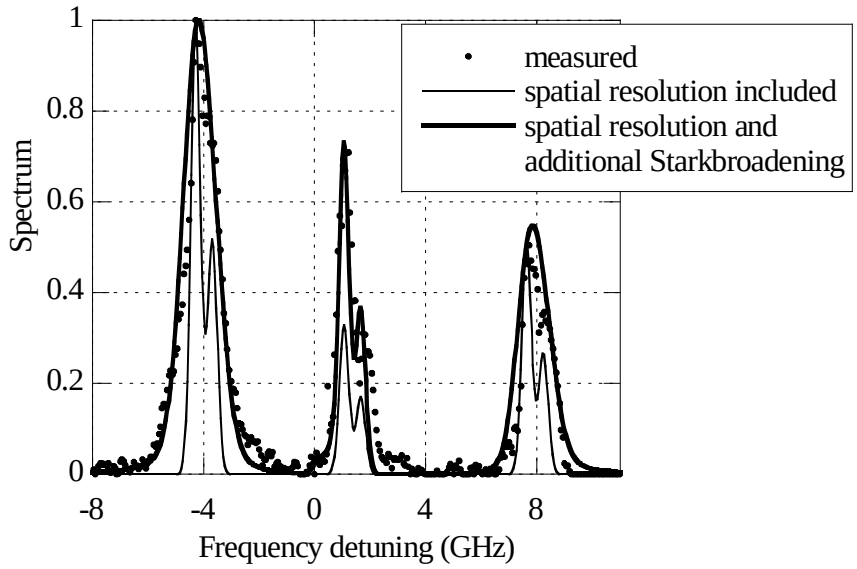

Figure 4. Measured and reconstructed spectra, for a discharge current of 100 mA and 600 Pa at a distance of 200 μm from the cathode surface.

Because of the discrepancy between measured and reconstructed spectra, we assume that the measured spectra reveal an additional homogeneous Stark broadening due to electron and ion collisions present in the cathode fall. In order to proof our presumption of an additional homogeneous Stark broadening acting with identical electric field distribution on all three Stark components, spectra were calculated which account for such an additional Stark broadening, arbitrarily chosen to fit the measured spectra. This leads indeed to much more broadened spectra (thick continuous line), which are fitting quite well with the measured ones. However, a convincing reconstruction of the spectra requires novel Stark broadening calculations, which might be essential for modeling and understanding of cathode fall dynamics.

5. References

[1] Donkó Z 2011 *Plasma Sources Sci. and Technol*. **20** 024001
[2] Bogaerts A, Neyts E, Gijbels R and van der Mullen J 2002 *Spectrochimica Acta Part B* **57** 609
[3] de la Rosa M I, Pérez C, Grützmacher K, Gonzalo A B and Steiger A 2006 *Plasma Sources Sci. Technol*. **15** 105
[4] de la Rosa M I, Pérez C, Grützmacher K and Fuentes L M 2009 *Plasma Sources Sci. and Technol.* **18** 015012

[5] Pérez C, de la Rosa M I and Grüztmacher K 2010 *Eur. Phys. J. D* **56** 369
[6] García-Lechuga M, Fuentes LM, Grützmacher K, Pérez C and de la Rosa M I *2013 Proc. SPIE 8785, 8th Iberoamerican Optics Meeting and 11th Latin American Meeting on Optics, Lasers, and Applications (Oporto),* 87854F

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