Spatially Resolved Experimental Investigation of Hydrogen Discharges Sustained by Propagating Surface Wave

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The study of Balmer line shapes is usually applied to detect the generation of fast-excited hydrogen atoms in various gas discharges. The Balmer line spectra emitted by different types of DC glow and radio frequency (RF) discharges have a typical multimode behaviour, with widely broadened "wings" ("fast" hydrogen) and a sharp top ("slow" hydrogen). This has currently been explained in terms of Doppler shift and broadening due to charge acceleration (atomic H^+ and molecular H_2^+ and H_3^+ ions) in the high DC electric fields present in the sheath regions of these discharges. Charge acceleration followed by neutralization and generation of fast excited H atoms at the wall is likely to be the origin of the "wings" in the observed spectra [1].

In this work, a classical surface wave (SW) sustained discharge has been used as a plasma source. The discharge is created using a surfatron-based set-up [2, 3]. The microwave power is provided by a HF generator (300 – 700 MHz), whose output power was varied from 40 to 250 W. The discharge takes place inside a Pyrex tube with internal and external radii of 2.25 and 2.5 cm, respectively. The background gas is injected into the discharge tube at flow rates from 0.4 to 20 sccm under laminar gas flow conditions. The pressure ranges from 0.01 to 0.3 mbar. The discharge is sustained by the electric field of a SW, which simultaneously propagates and creates its own propagation structure. The wave power is progressively dissipated by the plasma electrons along the wave path and the absorbed power per unit length, as well as the electron density, decrease gradually towards the plasma column end. Under the present conditions, this corresponds to a decrease in electron density from about 2×10^{10} cm^{-3} at the beginning of the plasma column to about $(1 – 2) \times N_{cr}$ ($N_{cr} \approx 7 \times 10^9$ cm^{-3}) at its end. The effective values of the microwave electric field intensity sustaining the discharge, as calculated in the framework of self-consistent model previously developed [4], are in the range 1 – 7 V/cm.

In order to obtain space resolution of the measurements an imaging optical system has been used. The imaging system is able to couple the plasma-emitted radiation into a SPEX 1250M spectrometer equipped with a nitrogen cooled CCD camera. The above system includes: i) an objective lens with a 3:1 ratio, which matches the plasma and the fibre sizes; ii) an imaging optical fibre, which rotates the image by 90 degrees; iii) a 1:1 inverse-telecentric lens, which effectively couples light into the input slit of the spectrometer, namely by ensuring the most possible uniform, spatial response. The optical system was designed using a high-resolution flexible Schott optical fibre, model IG-567-36, made of 10 μm individual fibres with an extended UV transmission. The cryogenic, back-illuminated, UV-sensitive CCD camera has a 2048 × 512 matrix, featuring a 13.5 μm pixel-size, which provides high spatial and spectral resolutions.

Abel inversion has been applied to derive radially resolved profiles of the Balmer emissions. The measured spectra exhibit a bi-Gaussian structure as seen in Fig. 1, where the H_δ line intensity is shown.

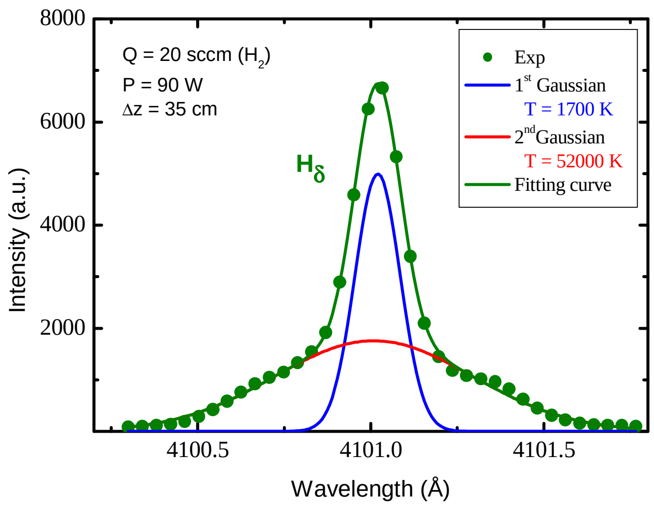

Fig. 1. Typical H_δ line profile.

This type of spectrum reveals the existence of two groups of atoms, i.e., a “hot” group, corresponding to the central peak, and a “super hot” (average energy ~ 7 eV) one, corresponding to the broadened part. The measured profiles change significantly along the radius, as seen in Figs. 2 (a, b) where the radial evolution of the line intensity is shown. The measurements have been performed at two different frequencies, i.e., 500 MHz and 350 MHz. The broader base expands towards the wall indicating that even hotter H atoms are present in that region. The effect is seen to be more pronounced at 350 MHz. When the pressure increases the profiles become single-Gaussian.

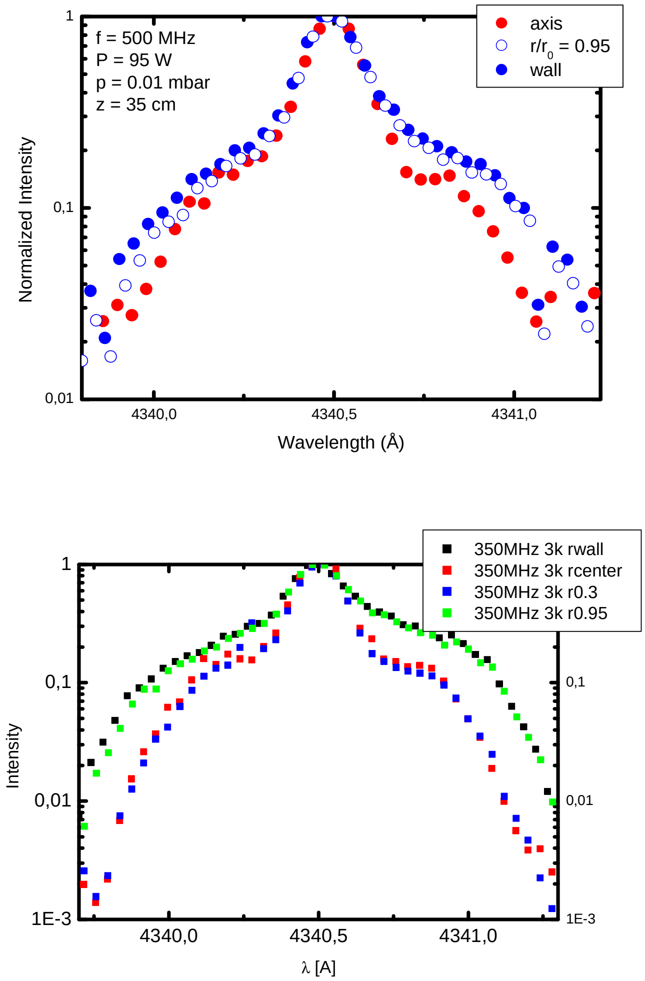

Fig. 2 (a, b). Radial evolution of the line intensity.

As is known, the sheath width and the corresponding DC electric field intensity increase when the frequency decreases. Thus, these results provide some confidence to the idea that "super hot" H atoms are generated near the wall in this type of discharge. What is the origin of "super hot" atoms H (n = 4 – 7)? Having in view their high kinetic energies, it appears that "super hot" atoms can only be originated from charge acceleration followed by neutralization. The acceleration of H^+ ions in the radial, DC space charge electric field followed by their recombination with electrons at the wall and subsequent emission of a fast excited atom back into the plasma may be a plausible explanation. At the lower pressures of this experiment, typical ion mean free paths λ_{ion} are larger than the tube radius (the mean free path for an H^+

ion with energy $\varepsilon_{ion} \geq 0.5$ eV at a 0.01 mbar pressure is about 3 cm), therefore H^+ ions fall freely on the wall and acquire a kinetic energy equal to the radial potential energy drop, which is of the order of KT_e (note that the electron temperature is in the range 4 – 6 eV). After wall recombination and as a result of elastic collisions with the wall, the excited atoms bounce back into the volume with approximately the same kinetic energy, ε, i.e., $\varepsilon \approx \varepsilon_{ion}$. Here, the wall acts like a third body in the recombination process. Similarly to classical three-body volume recombination, wall recombination generates "super hot" atoms excited in the upper levels. At higher pressures, when $\lambda_{ion} \sim R$ or $\lambda_{ion} < R$, the kinetic energy acquired by an ion as it falls to the wall is approximately $\varepsilon_{ion} \approx eE_{dc}\lambda_{ion}$, where E_{dc} is a mean dc electric field intensity. For typical radial field intensities of the order of a few V/cm, ions can still gain a few eV in kinetic energy as long as λ_{ion} remains comparable to the tube radius. However, as the pressure increases and λ_{ion} (~ 0.15 cm) becomes much smaller than R, ion transport to the wall becomes dominated by diffusion and the kinetic energy gained in the radial transport is much smaller.

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