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Balmer Line Broadening in Microwave Plasmas

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The Balmer line spectra emitted by different types of DC glow and RF discharges have typical multimode behaviour, with widely broadened "wings" ("fast" hydrogen) and a sharp top ("slow" hydrogen), while the spectra emitted by microwave discharges usually exhibit single mode behaviour. As is well known, these discharges are free from strong DC fields.

This report presents spectroscopic measurements of Balmer lines emitted by a microwave H_2 plasma at low pressures (p = 0.01 – 0.2 mbar). A classical surface wave sustained discharge has been used as a plasma source [1]. The microwave power is provided by a 500 MHz generator (P = 40 – 250 W). The discharge takes place inside a Pyrex tube with internal and external radii of 2.25 and 2.5 cm. Under the present conditions, the electron density decreases from about (1 – 1.5) × 10^{10} cm^{-3} at the beginning of the plasma column to about (2 – 3) × N_{cr} ($N_{cr} \approx 7 \times 10^9$ cm^{-3}) at the end. The effective value of the microwave electric field intensity sustaining the discharge ranges between 5 V/cm and 10 V/cm [2]. The optical system used consists of a 1.25 m focal length (visible light) Jobin-Yvon Spex 1250 spectrometer, with a holographic diffraction grating (2400 gmm^{-1}) equipped with a liquid-nitrogen cooled CCD camera. The light emitted by the plasma is collected perpendicularly to the discharge tube axis by a bundle optical fibre.

The measured profiles of the H_β, H_γ, H_δ, H_ε, lines (note that the H_α line is critical regarding self-absorption) are well fitted by either a single or two Gaussian profiles (much better than by a Voigt profile). Two different software tools, *viz.*, GRAMS/32® and MatLab based, have been used to this end. Under the present conditions, the experimental profiles are a convolution of Doppler profiles and the instrumental profile. In order to determine the "pure" Doppler broadening, the fine structure of the Balmer lines has also been taken into account.

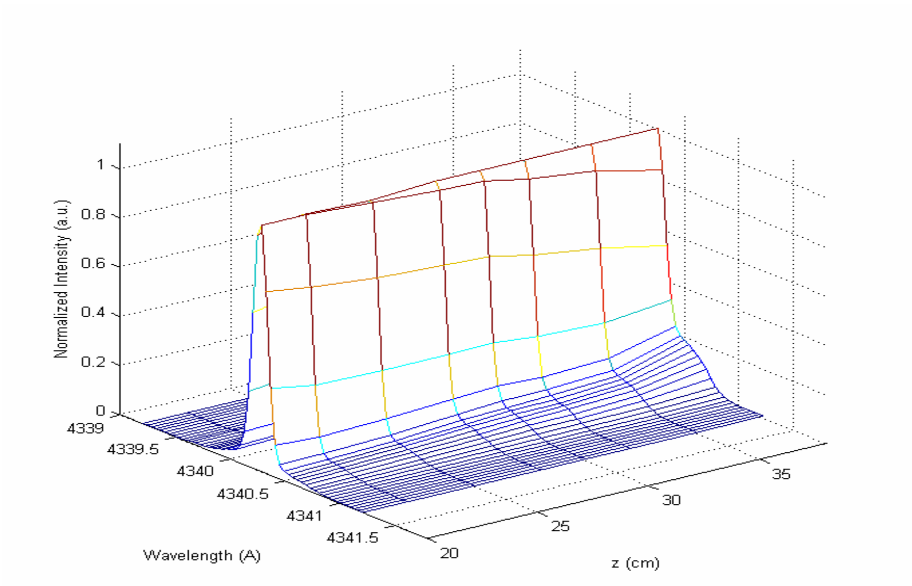

Fig. 1. Axial variation of H_γ line emission spectrum (p = 0.01 mbar; P = 90 W; L = 45 cm).

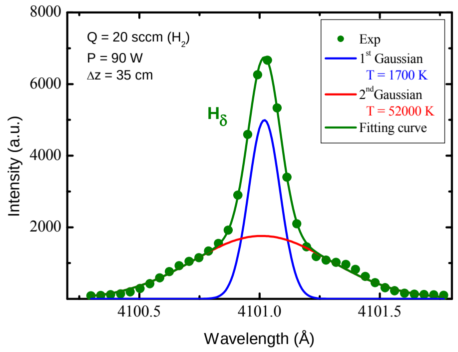

Fig. 2: Measured and synthetic H_δ line profiles.

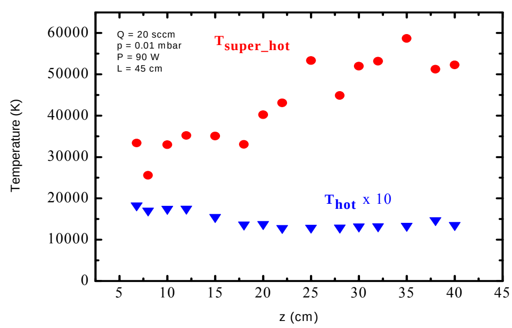

Fig. 3: Axial variation of temperatures of H atoms.

The evolution of the Hγ spectral line profiles along the discharge is shown in Fig. 1. The broader base starts to appear near the middle of the plasma column length and it expands towards the column end, where widely broadened "wings" are well established. As an example, the experimental and the synthetic H_δ line profiles at the axial distance Δz = 35 cm are shown in Fig. 2. The Doppler temperatures show significant axial variations. The mean energy corresponding to the "super hot" Gaussian part is about 4 eV up to 20 cm axial distance and then it sharply increases to 8 eV close to the end, at Δz = 40 cm. The Doppler temperature corresponding to the sharp Gaussian peak decreases from about 1,800 K to about 1,400 K close to the end. These temperatures are nearly three times higher than the rotational temperature, which decreases from 600 K to 400 K along the plasma column.

The structure of the observed line shapes result from a two-component velocity distribution arising from two different groups of processes. The central narrow Gaussian is a result of electron induced processes. "Hot" excited H atoms can be generated due to the dissociation processes involving electrons and vibrationally excited H_2 molecules, i.e.,

$$H_2(X, v=1\text{-}4) + e \rightarrow H_2^*(\varepsilon = 17\text{ -}19 \text{ eV}) + e \rightarrow H_{hot}(n=1) + H_{hot}(n=4\text{-}8) + e \qquad \text{(R1)}$$

Here, H_2^* are hydrogen molecules excited in weakly bound electronic terms, with energy ε = 17 – 19 eV > $E_n + D_{H2} + \Delta\varepsilon_k$, where E_n are the energies of the excited electronic states of H(n = 4-7) atoms, D_{H2} = 4.48 eV is the dissociation energy of hydrogen molecules and $\Delta\varepsilon_k$ = 0.1 – 1.8 eV is the range of kinetic energies of the two dissociated H atoms. These processes can be effective due to the high electron temperature (up to 6 eV) and the high vibrational temperature T_v of H_2(X) molecules typical of this type of discharge. The widely broadened line wings are caused by the presence of fast excited hydrogen atoms in the discharge. Fast excited H (n = 4-7) atoms may appear as a result of wall electron-ion recombination. Close to the wall, the positive H^+ ions are accelerated in the space charge sheath and then recombine with electrons at the wall to return back as hot excited atoms. The kinetic energy accumulated by the ion during its free fall to the wall is approximately $\varepsilon_{ion} \approx E_{dc}\lambda$, where λ is the mean free path and E_{dc} is a mean DC electric field intensity. The mean free path for an H^+ ion with energy $\varepsilon_{ion} \geq 0.5$ eV is about 3 cm. Thus, a radial electric field intensity of the order of $E_{dc} \approx$ 2 V/cm (note that the electron temperature is about 4 - 6 eV) is enough to create accelerated ions with energy $\varepsilon_{ion} \approx 6$ eV. Moreover, the fast H atoms bounced back into the plasma are predominantly excited at higher electronic levels as the obtained results demonstrate.

When the pressure increases up to 0.2 mbar the broad base of the Balmer line profiles disappears and the bi-Gaussian profiles become single (Fig. 4). The variations of the kinetic temperatures at p = 0.2 mbar are shown in Fig. 5. A striking result is observed from these figures: hydrogen atoms excited in higher levels appear to be hotter than those excited in lower ones.

The observed result can be tentatively explained by the generation of two group of excited H atoms with different temperatures, i.e, a "hot" and a "cold" group. As already discussed "hot" excited H atoms can be generated due to the dissociation processes (R1). However, the generation of cold excited hydrogen atoms also exists due to electron impact excitation processes:

$$H(1) + e \rightarrow H(n \geq 2) + e \qquad (R2)$$

The population distributions, i.e., N_n^{hot} and N_n^{cold}, for both ensembles have been calculated in the framework of a global self-consistent model previously developed which describes the entire discharge structure [2]. The interplay of the relative contributions of (R1) and (R2) can produce an increase in the integral kinetic temperature when the principal quantum number increases. A good agreement between calculated and measured temperatures is observed in Fig. 5.

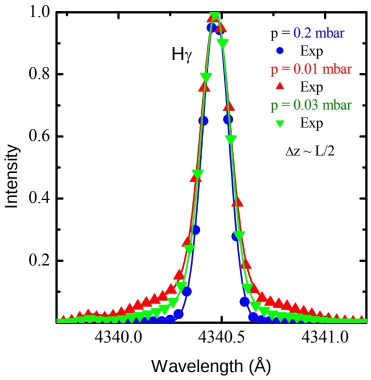

Fig. 4: Evolution of H_γ spectra with pressure.

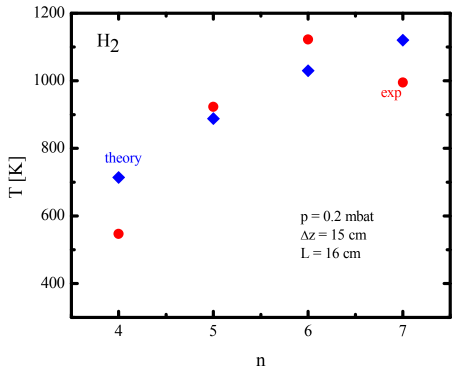

Fig. 5: H (n=4-7) atom temperatures *vs* quantum number.

References

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