Kinetics of atomic hydrogen in an expanding magnetized low-pressure plasma

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KINETIC OF ATOMIC HYDROGEN IN AN EXPANDING MAGNETIZED LOW-PRESSURE PLASMA

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The absolute density of atomic hydrogen excited states in a magnetized expanding thermal plasma is determined using emission and absorption spectroscopy. Depending on the conditions a population inversion is observed between the quantum states $3 \leq p \leq 7$. It is argued that molecular induced mutual recombination reactions of positive ions with negative ions should play an important role on hydrogen atomic level population. The absolute population density of hydrogen in the first excited state and a simple kinetic scheme were used to derive information on the absolute density of atomic hydrogen in the ground state and dissociation degree of hydrogen plasma. The properties of the charged particles in the plasma have been obtained from single and double Langmuir probe diagnostics. First evidences have been found for the presence of high densities of the negative ions in an expanding hydrogen plasma.

1. The experiments are carried out in an expanding thermal plasma produced in a cascaded arc described in detail elsewhere [1,2]. For the present studies a magnetic coil (diameter ≈ 0.5 m) is added at the location of the anode of the cascaded arc. This leads to an diverging magnetic field with a maximum induction of 40 mT on the axis. The motivation to apply a magnetic field is to extend the parameter range to lower pressure and thus to avoid the observed strong recombination in a freely expanding hydrogen plasma [1]. Applying a magnetic field keeps up charged particle and leads to a bright red to blue plasma jet. In comparison with previous experiments on the expanding hydrogen plasma jet, the hydrogen flow was low 8 scc/s, and with that the pressure in the cascaded arc was low as well (about 20 mbar in the cathode region). This makes the assumption of a thermal plasma questionable [1,2]. The pressure in the vessel and the arc current were kept constant at respectively 5 Pa and 50 A ($V_{arc} = 130$ V).

2. The lateral scans of the hydrogen Balmer spectral lines emissivities were performed at different axial positions. The lateral profiles were Abel inverted and absolutely calibrated against a tungsten ribbon lamp. In Fig. 1 the absolute population densities on the plasma beam axis are shown as a function of the ionization potential I_p of the level p for the case of $B_{max} = 40$ mT. As is shown, radiation from up to $p = 18$ is detected. Note the large population density per statistical weight for the levels $3 < p < 6$. Also an inversion is observed for the level $p = 7$ for large distances from the anode nozzle. In general the inversion is more pronounced downstream in the plasma jet and the maximum of n_p/g_p vs. I_p occurs for the higher quantum numbers.

To measure the absolute density of the first excited state of atomic hydrogen H*(p = 2) a method of reabsorption with a mirror (which is identical to the method of two identical light sources

[3]) been used. A concave mirror of reflectance r was placed behind the plasma beam, and the line intensity was measured with a mirror covered, or not covered [4]. For the determination of the line absorption function A_L [3] the mirror reflectance coefficient $r = r(\lambda)$ should be known. Coefficient $r(\lambda)$ has be measured using a spectral line for which the plasma was optically thin. The measured $r(\lambda)$ is the effective reflectance coefficient, which include the transmittance coefficient of the vessel windows.

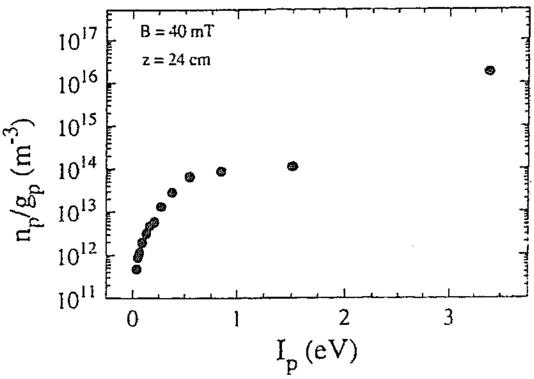

Fig. 1

Atomic hydrogen density in the first excited state H*(p = 2) has been determined in the atomic regime of an expanding hydrogen plasma by $H_\alpha(\lambda = 656.3$ nm) spectral line absorption. To the same spectral range as H_α belongs the spectral line of argon: λ = 660.5 nm (radiative transition $Ar(3p^5 4d \rightarrow 3p^5 4p)$). It has been shown, that the plasma was optically transparent for this line, therefore their emissivity can be used to determine the reflectance coefficient of the mirror. The measurements for the particular wavelength range gave a value of $r = 0.70 \pm 0.04$. The measured value of H_α line absorption function for the typical conditions of an expanding hydrogen plasma at a distance of x = 24 cm from the nozzle of the arc was A_L = 0.21. Therefore the averaged over the light of sight absolute density of the H*(n = 2) state can be derived $n_{H(p=2)} \simeq 1.4 \cdot 10^{17}$ m^{-3}. In Fig. 1 the absolute population density of H*(p = 2) on the plasma beam axis is shown as well.

3. Kinetic analysis of various processes in the expanding plasma shows, that in the discussed regime of an expanding magnetized hydrogen plasma only spontaneous radiative processes are controlling the density of H*(n = 2) state: namely, radiative decay from the high-lying atomic states, and partially trapped resonance radiation to the ground state. Therefore the general balance equation can be transformed to the following:

$$\sum_{n=3}^{\infty} \Phi_{n\rightarrow 2} = \Phi_{2\rightarrow 1} = n_2 A_{21} \Lambda_{21}, \qquad (1)$$

where $\Phi_{k\rightarrow i}$ are the radiation fluxes between the quantum states k and i, $n_{H(p=2)}$ is the absolute density of H*(p = 2) state, A_{21} is the absolute transition probability of the resonance Lyman-α spectral line, and Λ_{21} is the escape factor for resonance radiation. Another important conclusion can be derived from the kinetic analysis. Namely, in the plasma it should be a strong production source of highly excited hydrogen atoms H*(p $\geq$ 3), which then radiatively decay to H*(p = 2) state. This statement is confirming the same conclusion made earlier about the excitation mechanism of highly excited hydrogen states.

4. The experimental information on the population density of hydrogen atoms in the excited states H*(n $\geq$ 2), and known from the literature radiative transition probabilities [5], allow us to determine from (1) the escape factor Λ_{21} for resonance Lyman-α radiation. For the typical conditions of an expanding hydrogen plasma at a distance of x = 24 cm from the nozzle of the arc the escape factor was equal to $\Lambda \simeq 1.8 \cdot 10^{-3}$. So, generally speaking the plasma

under investigation can be described as an optically thick medium for the resonance Lyman-α radiation. The escape factor is related to the optical depth $\overline{kR}$ of the absorbing medium. The relation between escape factor and optical depth has been calculated for Voigt emission profiles in [6] for the case of cylindrically symmetric plasmas. In this treatment it was assumed that absorption and emission profiles of the spectral line can be described by the same Voigt profile and that the radial dependences of the densities of the lower and upper levels of the transition are weak. The effective optical depth is defined as [6]:

$$\overline{kR} = \frac{\sqrt{ln2}}{4\pi\sqrt{\pi}} \cdot \frac{\lambda_{21}^4}{c\Delta\lambda_{21}} \cdot \frac{g_2}{g_1} \cdot A_{21} n_{H(n=1)} \cdot \mu R, \quad (2)$$

where λ_{21} is the wavelength of the radiative transition, $\Delta\lambda_{21}$ is the half width (FWHM) of the emission profile, c is the velocity of light, g_i are the statistical weights of corresponding levels, $n_{H(n=1)}$ is the population density of the lower state of the transition, μ is a geometrical factor and R is the radius of the plasma beam.

Since the radius of the plasma beam is known Eq. (2) can be used to determine the absolute population density of H(n = 1) state. In the atomic regime of an expanding hydrogen plasma at the position x = 24 cm from the arc nozzle, the averaged atomic hydrogen ground state density will be $n_{H(n=1)} = 1.7 \cdot 10^{20}$ m^{-3}. The corresponding dissociation degree of hydrogen plasma is equal to β = 11 %. It is essential that an accuracy of the discussed procedure is determined practically only by the experimental accuracy (intensities of the spectral lines, absolute calibration of the optical system), and not by the uncertainties in the kinetic coefficients, since the radiative transition probabilities, which were used in the kinetic scheme are known with the high accuracy (better than 1 % [5]). That is an important advantage of the discussed procedure, since in the final kinetic calculations namely the uncertainties in the collisional kinetic coefficients usually represent the main source of statistical and systematical errors.

5. The correctness of the Langmuir probe diagnostic has been checked by comparison of the results with the Thomson scattering measurements, which is a non-intrusive optical diagnostic

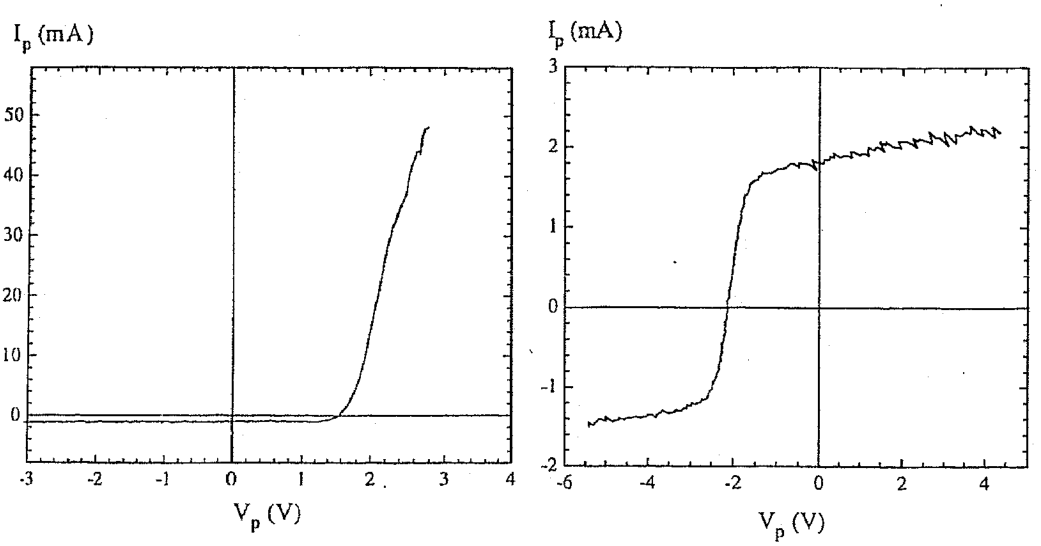

Fig. 2

to determine similtaneously the electron density and temperature [2]. It has been shown that the T_e and n_e values determined by the double Langmuir probe measurements in an expanding pure argon plasma were close to the results obtained by Thomson scattering within an accuracy of 15 % for T_e and of 30 % for n_e. Fig. 2 shows an example of the single voltage-current (probe) characteristic in pure argon plasma, and in pure hydrogen plasma. For both cases the gas flow rate was 8 scc/s, pressure in the vessel 5 Pa, arc current 50 A, magnetic field induction 40 mT (at a maximum). It can clearly be seen that the two presented characteristics are completely different. In the case of pure argon plasma it is a typical probe characteristic with a small positive ion saturation current, and much larger electron saturation current (at least a factor of 100). Such an expanding plasma under consideration can be interpreted as the electron-positive ion plasma. However for an expanding hydrogen plasma the saturation currents for both the positive voltage region and the negative voltage region have the same magnitude. It appears that we have an example of electron free plasma and the only important plasma component, which carry the negative charge in the expanding plasmas are the hydrogen negative ions. Double differentiation of the probe characteristic allow us to determine the parameters of positive and negative ions in the plasma. The mean ion energy were approximately 0.3 eV, whereas the ion density were in the range $(1.4 - 2.4) \cdot 10^{17}$ m^{-3}.

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