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Section 3. Poster papers

Comparative studies of ionised and excited hydrogen atoms and molecules distributions for plasma–target interaction in a linear simulator machine

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Abstract

Built-in mass spectrometers and spectrometers of visible radiation as well as Langmuir probes were used to measure the parameters of a hydrogen plasma and the concentrations of positively and negatively charged ions in a linear simulator. A plasma beam discharge with a low level of impurities was used to compare mass-spectroscopic measurements of ion species with a simple kinetic model. Qualitative agreement between calculations and measurements is achieved. This model can be used as a basis for the specification of very complicated optical diagnostics for the definition of the distribution features of rotational, vibrational and electron temperatures, and for the development of a more precise kinetic model for hydrogen plasma interacting with gas and solid targets. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The problem of plasma detachment in gas puffing tokamak divertors is actively discussed and investigated. To understand the main processes relevant to plasma detachment both computer and experimental simulations are widely used. Different linear machines (or simulators) with arc plasma or beam discharge plasma [1–5] are used for the investigation of plasma interaction with gas targets. But the interpretation of experimental results is very difficult due to the enormous number of different inelastic and molecular processes involved. For example, the spectroscopic data can be hardly interpreted by thermal cooling of the boundary layer [6] and can be better explained by the quasibeam model of this layer. The assumption about the local thermal equilibrium with free electrons in this conditions is unacceptable; the distribution of highly excited states can be explained by collisions with atoms and molecules [7,8]. Computer simulation codes like CRAMD [9], which was successfully used for interpretation of the plasma detachment data from ALCATOR C-Mod tokamak [10] and simulator NAGDIS-II [6], are very complicated, and need better knowledge of the plasma parameters. To know the rates of main processes in recombining plasma, it is necessary to have information not only about excited states (which is obtained by optical methods), but also about ground states. So, it seems that more experimental information is urgently needed to develop a relevant kinetic model of the plasma interacting with gas and solid.

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In this paper we present both optical and mass-spectroscopic measurements of the plasma in a simulator with a plasma-beam discharge BPD and arc discharges. We compare the results with a simple kinetic model as a first step for a better interpretation of the optical spectroscopy data and for the elaboration of the full scale kinetic model of a partly ionised hydrogen plasma in the edge region.

2. Experimental facility and diagnostic system

The experimental facility has been described elsewhere [5]. Briefly, the installation consists of three regions, separated by two diaphragms: the cathode volume, the central region and the collector region. The first and the latter regions are pumped with 2 m^3 s^{-1} speed. Both a dc arc and an electron beam driven BPD plasma in longitudinal magnetic field of 0.1–0.5 T can be generated. In the BPD mode the plasma parameters are governed by the electron gun voltage and current, and by the working gas pressure. The parameters of the electron beam are varied in the range of 0.3–3.0 A and 1.0–3.0 kV. The radius of the electron beam is 1.0–1.5 cm and the length 200 cm. The gas puffing can be made in the central zone up to the pressure of 0.1–5.0 mTorr, providing 10^{-5} Torr in the cathode chamber. In the dc mode (20–30 A, 80–100 V), the gas is puffed into the cathode chamber. So, some gradient of the neutral density along the plasma column takes place. The diagnostic system includes various Langmuir probes, retarding and dispersion energy analysers installed in the downstream (behind the collector), a review optical spectrometer with 0.3 nm resolution, a spectrograph for 250–800 nm range with 0.05 nm resolution, and two built-in mass spectrometers.

The latter ones are the 180° magnetic analysers that use the magnetic field of the installation. Ions are extracted perpendicular to the magnetic field lines and registered as a function of the accelerating voltage. Two modifications of the built-in mass spectrometer were made. The first spectrometer had two collectors located at radii 4 cm and 8 cm for light and heavy species, respectively. The second spectrometer had two collectors located at both sides relative the entrance slit at 0.5 cm radii (Fig. 1). So, simultaneous measurements of both the negatively and positively charged hydrogen ions were available. The mass resolution of the analysers depends on the central trajectory used for analysis, on magnetic field distribution and on plasma parameters including the level of their fluctuations. It is varied from 3 (for the second analyser) to 30 (for the first one).

For measurements of the difference of kinetics in the bulk plasma and plasma near the collector, a special high resolution ($\Delta\lambda \sim 10^{-3}$ nm) spectrograph for 200–800 nm range based on the profiled diffraction lattice is under development.

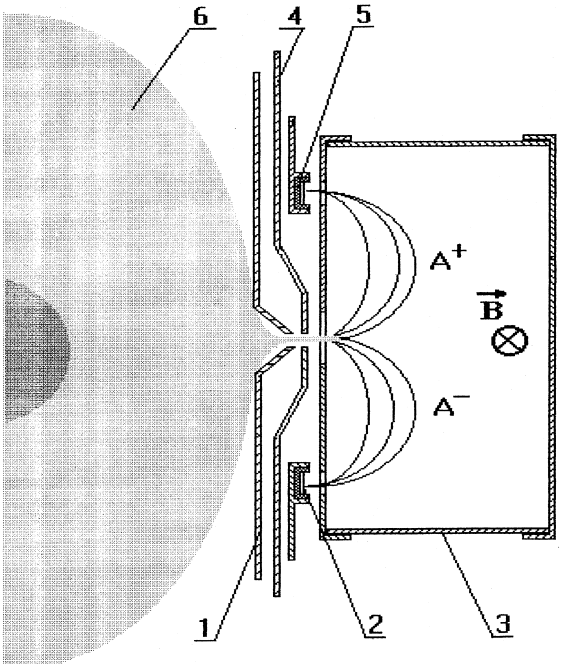

Fig. 1. Scheme of the movable mass spectrometer used for simultaneous measurements of negative and positive hydrogen ions (1 – screen plate; 2 – negative ion collector; 3 – dispersion segment; 4 – extracting electrode; 5 – positive ion collector; 6 – plasma column).

3. Experimental results

Fig. 2 represents the mass spectra of hydrogen ions measured in the BPD regime in the central zone with the movable built-in mass spectrometer shown in Fig. 1. For this small radius of the central trajectory, the mass resolution is high enough to measure all the hydrogen ion species. The basic facility operation parameters are the following: the electron beam current 0.3 A, the energy 2 keV, the neutral hydrogen pressure 1.1 mTorr. The plasma density near the analyser entrance slit measured with the Langmuir probe is 10^{12} cm^{-3}. In the arc regime the resolution of the mass spectrometers is 2–3 times better due to the decrease of plasma fluctuations, but in this regime an enhanced erosion of the cathode results in an increase of the concentration of impurities in plasma. For the BPD regime, both the mass spectrometry and the visible emission spectrometry show that the concentration of impurities is less than 0.1% as compared to 1–2% in the dc arc regime. So, the concentration of impurities in plasma in the arc regime is too high and can strongly influence the features of the kinetic pro-

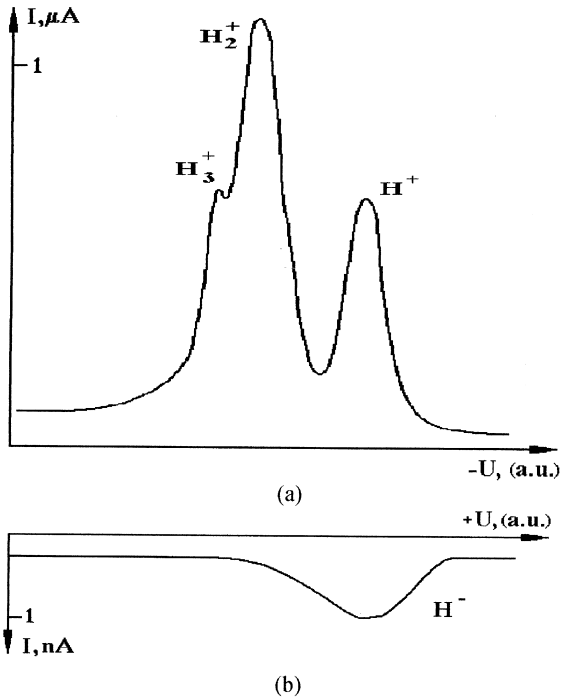

Fig. 2. Mass-spectra of hydrogen ions obtained with movable mass spectrometer, (a) positive ions; (b) negative ions.

cesses in hydrogen plasma in the machine. There is another very important reason to give the preference to the BPD regime for development of the kinetic model. In a strongly non-equilibrium such as BPD regime, the data on the molecular and atomic composition in different states of excitation and ionisation are simpler to interpret than in the highly contaminated arc regime. The kinetics for BPD is understandable and reliably depends on the cross sections of the elementary processes.

Visible emission spectra in these conditions (Fig. 3) allow to resolve about 150 lines for diagnostics of molecular and atomic species. Three Balmer series lines, molecular bands, and continuum are presented. The origin of the latter is possibly caused by the transitions to the 2 $\rho\sigma$ metastable state of the hydrogen molecule. One can conclude that the degree of the dissociation is low because the intensity of the molecular band is higher than that of the Balmer series. Fig. 4 shows the difference between the spectra measured (by the review spectrometer) in the central region and near the collector. The ratio of H_δ, H_γ, H_β, H_α lines is 1:10:50:200 in the central plasma, but near the collector it is 0:1:20:200 (the level of the molecular background is accepted to be equal to unity). So, the decrement of the Balmer series near the collector is more stronger than in the central zone, and that can be considered as an evidence of enhanced recombination in this region. The intensity of the

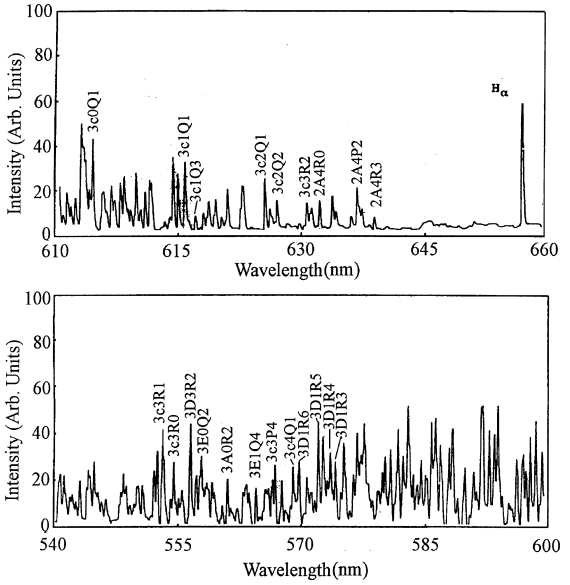

Fig. 3. Review optical spectrum.

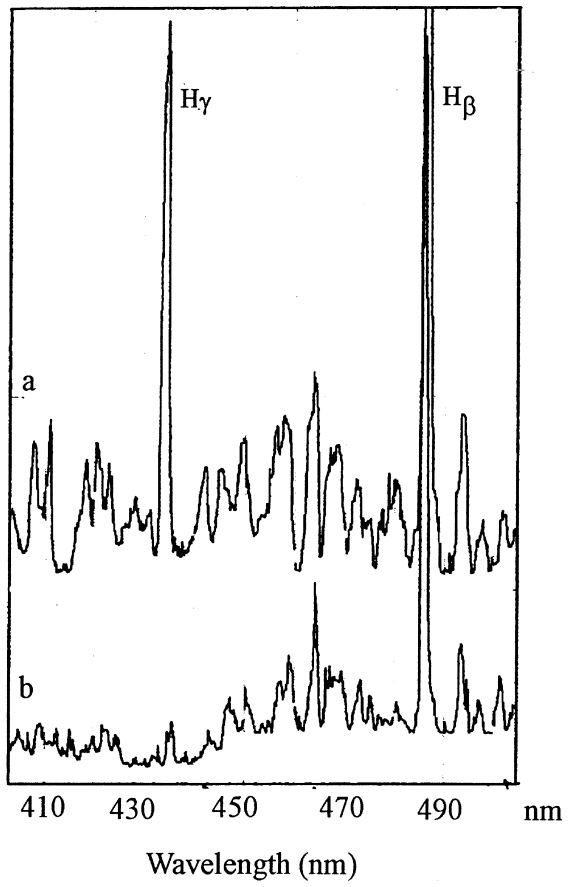

Fig. 4. Emission spectra from (a) central and (b) collector regions.

continuum in the centre is lower but the rotational lines becomes 1.5–2 times higher than near the collector.

4. Discussion

Let us discuss a simple model for evaluation of the concentrations of the ion species in the BPD plasma with the parameters mentioned above. As no impurities are seen, the first possible approximation is to neglect their influence. As the free length of hydrogen molecules is restricted by the walls of the installation, their distribution $f_m(v)$ can be assumed to be Maxwellian with the temperature T_0. The electron beam generates powerful Langmuir oscillations in BPD plasma, loosing for this (according to Ref. [11]) approximately a half of the primary beam energy. So, a longitudinal electric field, as high as 250 V/cm, is generated in plasma and accelerates secondary plasma electrons. Their distribution function reads [12]

$$f_{e\|}(v) \approx \text{const} \quad 0 < v < v_E \sim 100 \text{ eV} \tag{1}$$

$$f_{e\perp}(v) \ll f_{eu}(v) \quad v_\perp \sim 10 \text{ eV} \tag{2}$$

The density of the secondary electrons n_e is much higher than that of the beam electrons n_b, $n_e \gg n_b \approx 10^8$ cm^{-3} and can be calculated from the balance of the power losses for ionisation, radiation, longitudinal particles losses, and Bohm diffusion. Evaluation gives 2×10^{11} cm^{-3} $< n_e < 4 \times 10^{12}$ cm^{-3}.

The main processes that contribute to the birth and loss of ions and atoms of hydrogen plasma for the above mentioned parameters of the BPD are:

$$e + H_2 \rightarrow H_2^+ + 2e \tag{3}$$

$$e + H_2^+ \rightarrow H^+ + H^* + e \tag{4}$$

$$e + H_2^+(v) \rightarrow H + H^* \tag{5}$$

$$e + H_3^+ \rightarrow H + H + H \tag{6}$$

$$e + H_3^+ \rightarrow H^+ + 2H^* + e \tag{7}$$

$$e + H_2 \rightarrow H + H- \tag{8}$$

$$e + H_2^+ \rightarrow H^+ + H- \tag{9}$$

$$e + H_3^+ \rightarrow H_2^+ + H \tag{10}$$

$$e + H^- \rightarrow H + 2e \tag{11}$$

$$H_2^+ + H_2 \leftrightarrow H_3^+ + H \tag{12}$$

$$H^+ + H_2^*(v) \leftrightarrow H + H_2^+ \tag{13}$$

The rates of the direct processes Eqs. (3)–(11) are higher than those of the reverse ones, so calculations become simpler. But the calculated values of the relative concentrations of the species are more sensitive to the cross sections. The latter for Eqs. (3)–(11) were taken from Ref. [12], the reaction rates for Eqs. (12) and (13) - from Ref. [13]. The form of the $f_{e\|}(v)$ function was assumed to be as Eq. (1), while $f_{e\perp}(v)$ is assumed to be Maxwellian. The balance equations for concentrations of the species incorporate the ion losses due to Bohm diffusion as well as the escape of neutrals. The model includes also two normalising relations:

$$[H_2] + [H_2^+] + 1/2[H] + 1/2[H^+] + 3/2[H_3^+] = 1.1\ 10^{13} \text{ cm}^{-3}, \tag{14}$$

$$[H^+] + [H_2^+] + [H_3^+] = n_e \tag{15}$$

The concentrations $[H_2^+]$ and n_e were assumed to be some free parameters and were varied within a very narrow interval. The results of the calculations for three combinations of $[H_2]$ and n_e are given in Table 1. The relative compositions of the ion species were normalised to $[H_2^+]$ because the latter were measured with the highest accuracy

A systematic overestimation of $[H_2^+]$ and underestimation of $[H^-]$ is seen. The possible reason for the $[H_2^+]$ excess is an underestimation of the loss rate due to the conversion [Eq. (13)]. The deficit of $[H^-]$ can be explained by an underestimation of its source rates according to Eqs. (8) and (9) as the cross sections for these processes are known only for a restricted energy range. Taking into account these consideration, one can conclude that the calculated concentrations of the ion species qualitatively agree with the measurements.

Table 1
Comparison of the calculated concentrations of hydrogen ions in plasma with mass-spectrometer experiment data

Variant	$[H_2]$	$[H]$	N_e	$[H_2^+]$	$[H_2^+]$	$[H_3^+]$	$[H^-]$
Calculated	0.55×10^{13}	$2 \times 10^{11} - 2 \times 10^{12}$	1×10^{12}	5×10^{11}	2×10^{12}	2×10^{10}	1.5×10^{7}
1				1.00	4.00	0.04	3×10^{-5}
(relative)							
Calculated	0.77×10^{13}	$2 \times 10^{11} - 2 \times 10^{12}$	1×10^{12}	7×10^{11}	2×10^{12}	3×10^{10}	2×10^{7}
2				1.00	3.00	0.04	3×10^{-5}
Calculated 3	0.77×10^{13}	$7 \times 10^{10} - 7 \times 10^{11}$	3×10^{11}	7×10^{11}	$(0.6 - 1.0) \times 10^{12}$	1×10^{11}	3×10^{7}
				1.00	1.00–1.50	0.14	4×10^{-5}
Measured	$\sum M = 1.1 \times 10^{13}$	–	–	1.00	0.56	0.25	4×10^{-4}

So, this model can be used as a basis for the specification of very complicated optical diagnostics to study the distribution features of rotational, vibrational and electron temperatures, as well as for development of a precise kinetic model for hydrogen plasma which interacts with gas and solid targets.

5. Conclusion

A complex diagnostic technique for measurement of atomic and molecular species in different states of excitation and ionisation including the ground states for hydrogen plasma that interacts with solid and gas target is described. BPD is shown to be a very convenient object for testing of radiation-collision kinetic models and evaluation of the role of various inelastic processes. A simple kinetic model as a basis for a proper choice of the optical spectroscopic diagnostic is tested to give a reasonable agreement with measurements of the ion species distribution.

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