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Balmer-α spectroscopic study on hydrogen recycling and molecular effects in HT-7

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Abstract

When incidence on the plasma facing material in a fusion device, hydrogen and its isotopic ions and neutrals return by either reflection or desorption in the form of molecules or atoms, which collide with the main plasma. These recycling behaviors strongly influence the energy and particle transports in the edge plasmas. In previous HT-7 experiment, it was shown that Dα profile can be decomposed into two energy groups, a group of atoms in energy up to 10 eV and the other group of atoms in energy less than 1 eV. In this paper, we modeled the hydrogen and deuterium atom/molecular transport using DEGAS2 code. Emission of Balmer-α lines and its profile are in particular modeled and compared with the experiment. It was shown that the H_2/D_2 molecular dissociation into H(2s) or D(2s) plays important role and is the main contribution to the low component of the observed Balmer-α emission.
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1. Introduction

Hydrogen plasma or neutral incidences on materials can induce both atomic and molecular forms of hydrogen release from the material surface. The atomic form release is via reflection or ion-induced desorption. When hydrogen is released in molecular form, it would be broken-up via the collisions with electrons and ions. The break-up atoms of molecular hydrogen occupy large fractions of the hydrogen atoms in the edge plasma. Different dissociation channels give rise to the different energy distributions of the dissociated atoms, and even cause dissociated atoms in different quantum states [1]. In a linear device MAP (Material And Plasma), decomposed Hα spectra shows a low energy component with the energy about 1 eV and a high energy component [2]. A modeling on MAP plasma shows that one of main H_2 dissociation channels, $H_2 + e \rightarrow H_2(1s\sigma,\ nl\lambda|^1\Lambda) \rightarrow e + H(1s) + H(2s)$, contributes mostly the low energy component [3]. Further study revealed that although the vibrational distribution of H_2 causes the dissociated products to distribute in lower energy, H(2s) from this dissociation channel have almost the dominant contribution to the Hα emission in the low energy plasmas [4] because

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of the higher effective rates to be excited to the $n = 3$ state. This low energy component is also observed in Dα profile in TEXTOR [5], and in Balmer-α emissions HT-6M [6] and HT-7 [7].

In this paper, we modeled the hydrogen and deuterium in neutral transport using DEGAS 2 [8] code. Balmer-α emission is concentrated. After a brief description of the modeled experiment case, we give the modeling description and the modeling results.

2. Experimental

HT-7 is a medium sized superconducting tokamak with major radius of 1.22 m and minor radius of 0.32 m. Fig. 1 shows the outline of the experimental setup for an optical spectroscopic study in HT-7 device. Hα emission was observed in an top-down chord across the plasma center in a wavelength resolution of 0.02 nm. Deuterium molecular gas, as the primary gas, was puffed from the horizontal windows to the plasmas. Three belt toroidal limiters were installed, which are located in the up, bottom and the inner sides inside the vacuum chamber, respectively. In most of the cases, in particular for the shot number 68 520, which are modeled in this paper, the inner belt limiter limited the plasma which means that it received most of the plasma flux out of the plasma core.

The electron temperature and density are measured by Langmuir probes. For the shot 68 520, Fig. 2 shows the edge temperature and density distributions and solid line in Fig. 3 shows the Balmer-α emission profile.

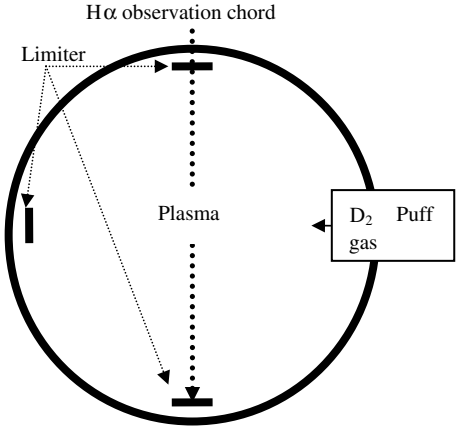

Fig. 1. Illustration of poloidal cross section of HT-7 tokamak for a spectroscopic study.

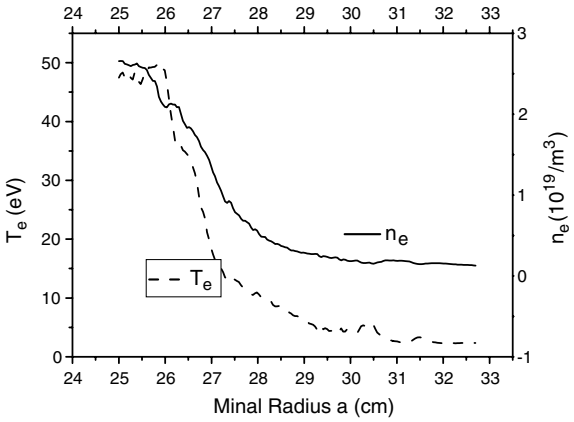

Fig. 2. The electron and temperature distributions in the edge of HT-7 plasma.

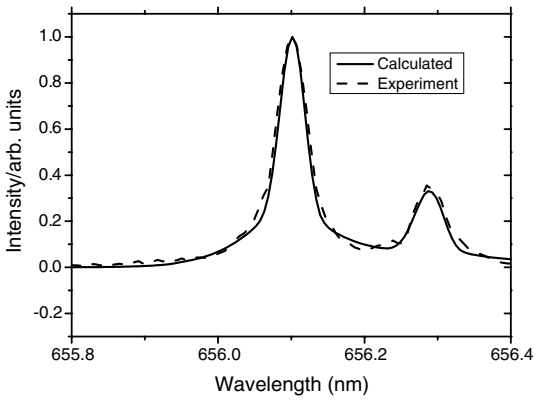

Fig. 3. Comparison of experimental observed and model calculated Balmer-α profiles.

3. Neutral transport modeling

The simulation was performed using DEGAS 2 code [8]. A line emission can be modeled in DEGAS 2 by recording the wavelength of the photon emitted within the observation volume. The wavelength can be computed according to the velocity of the atom which emits the photon, $\lambda = \lambda_0(1 - \vec{v} \cdot \vec{x}/c)$, where λ_0 is the wavelength center of a line, $\vec{v}$ the velocity of the atom, c the light speed and $\vec{x}$ the position unit vector relative to the detector. In the calculation, the Hα (Dα) intensity is recorded according to the atomic processes such as excitation and de-excitation, etc., and also the molecular processes which give rise to the generation of $n = 3$ excitation state of hydrogen atoms. The local Hα emission rate from the ground state atoms is according to the density of

the $n = 3$ population data from the calculation by a collisional-radiative model. Hydrogen atoms in the excitation state of $n = 3$ can also be reduced directly from the molecular dissociated products and thus the photon emission is determined directly from these pathways. It must be emphasized that a collisional-radiative model must be applied to the system with meta-stable atom H(2s) considered because it have much larger contribution to Hα emission in low temperature plasmas [4] and it is one of the dissociation products in the H_2 dissociation. To be concluded, in our modeling, the considered molecular and atomic processes are molecular dissociation, atomic collisional-radiative equilibrium, atomic ionization and charge exchange.

The atomic and molecular processes considered in the modeling are listed in Table 1.

It must be noted that the molecular dissociation channel 2 plays an important role in the Hα emission in the edge plasmas. This has been discussed in detail in Refs. [3,4]. Although the reaction cross sections for this process is lower by several times than that of dissociation channel 1, the Hα emission originating from this channel have large rate coefficients as one can see in Ref. [4]. To consider this process, effective Hα emission with H(2s) must be considered. This has been done in [4] by a modified model to the Sawada's code [9] which was discussed in [3,4]. It was pointed out in [4] that the meta-stable state, H(2s) has much higher Hα emission rate before being ionized than the ground state has. This result has been applied in the modeling in this paper. For the energy of the dissociated atoms from channel 1, the distribution calculated in Ref. [4] was applied. The energy of the dissociated atoms from channel 2 is an adjustment factor in the modeling.

Table 1
Atomic and molecular processes considered in the modeling

Reaction	Description
$e + H^* \rightarrow e + H^+ + e$	Ionization
$H_2\left(X^1\Sigma_g^+\right) + e \rightarrow H_2\left(b^3\Sigma_u^+, a^3\Sigma_g^+, c^3\Pi_u^+\right) + e \rightarrow H(1s) + H(1s) + e$	H_2 dissociation 1
$H_2\left(X^1\Sigma_g^+\right) + e \rightarrow H_2\left(1s\sigma, nl\lambda|^1\Lambda\right) \rightarrow e + H(1s) + H(2s)$	Molecular dissociation 2
$e + H_2 \rightarrow H_2^+ + e$	Molecular ionization
$e + H_2^+ \rightarrow e + H^+ + H$	Molecular ionization dissociation
$H^+ + H \rightarrow H + H^+$	Charge exchange
$e + H^+ \rightarrow H^*$	Recombination

The reflected particles from the material surfaces also play important role in the neutral transport. If the ions or neutrals impinge on material surface, the reflected neutrals are in energy, $E_{\mathrm{reflc}} = R_E E_i$, where R_E is the energy reflection coefficient and E_i is the incident energy. According to the sheath theory [10], The ions are accelerated by the sheath potential which is approximately $\sim 3T_e/e$ before it reaches the target materials if the target is isolated or is floated. Moreover, the ion flux is 0.5 $n_e C_s$, where C_s is the sound speed of ions which is taken to be $\sqrt{k(T_i + T_e)/m_i}$. For those incident ions or atoms which are not reflected, are desorbed as molecules. The dependence of reflection yield and energy reflection coefficient on the incidence energy used in this paper is from the 'refl.dat' in old DEGAS code which is calculated by VFTRIM code [11]. The angular distribution of reflected particles is assumed cosine distribution. For the desorbed molecules, the energy was assumed to be equal to the temperature of the target which in our case is about 0.04–0.1 eV.

Neutrals can be also injected into the plasmas by puffing or other fueling methods. In the experiment in this paper such as the shot no. 68 520, the D_2 gas was injected into the main plasmas through a horizontal window. Neutrals can be also released from the material surfaces which adsorbs some gases such H_2O and H_2 before the shot or during the shot. In the modeling, this kind of desorption is only simplified as H_2 puff in an arbitrary flux or rate from all the plasma facing walls, which is adjusted in the calculation to match the overall Hα emission.

The electron temperature and density are directly observed by the probe measurement, which are shown in Fig. 2. In the core plasma, the uniform electron temperature was assumed. For the shot 68 520, it is ~200 eV according to an ECE measurement. There is no direct measurement of ion density and temperature for shot 68 520, the equalities with the electron ones are assumed. From the measured Balmer-α line emission, which is shown in Fig. 3 as the solid line, it can be seen there is considerably fraction of hydrogen ions and atoms in the plasmas. This fraction is one of the adjustment parameters in the calculation, which is selected in a way to best match the measured Balmer-α line profile.

4. Results and discussion

In the modeling, there are several adjustment parameters. In the plasmas, H^+ occupies certain amount because of the wall desorption of hydrogen containing species such as water. The ratio of $n_{H+}/(n_{D+} + n_{H+})$ was an adjustment factor which was chosen to be 11%. Desorption of the preadsorbed hydrogen or hydrogen contain species was assumed as the hydrogen molecular puff. The ratio of this hydrogen desorption flux with respect to D_2 puff flux was also an adjust factor which was chosen to be 0.01. In addition, the energy of the H(2s) state from the molecular dissociation was arbitrary adjusted to 0.6 eV in order to best fit the experimental profile. Fig. 3 shows the comparison of the modeled Balmer-α profile with the experimental observed emission. The modeled profile has been convoluted by the instrument function. The general agreement has been obtained. The wing regions of the Hα and Dα profiles are mostly contributed from the charge exchanged and reflected particles while the shoulder of the profiles are mostly contributed from charge exchanged particles and partly by the molecular dissociation channel 1. The narrow component was mostly contributed by the dissociation channel 2, mostly by the dissociated product, H(2s).

The dominant processes, which generate atomic hydrogen or deuterium which emits Hα/Dα, are the charge exchange and molecular dissociation. There are some other important processes in the edge plasma conditions which are not considered in our modeling. Among them, the processes related with H_3^+ which is mainly formed by the collision of H_2^+ with H_2, the dissociative recombination of H_2^+ and the ion conversion collisions of vibrationally excited H_2 with H^+ may need enough consideration in the plasmas where molecules play an important role. However, in edge plasmas in a tokamak, the density of H_3^+ must not be high because of the short mean free paths of H_2^+ and H_3^+. Therefore, the hydrogen atoms originating from H_3^+ is negligible although its dissociation rate is several times to one order higher than the dissociation rate of H_2. The dissociative recombination rate of H_2^+ in the electron temperature higher than several eVs is rather low, so H_2^+ dissociative recombination has little influence to the atomic hydrogen in the current case. Another important channel, the charge exchange or ion conversion between H^+ and H_2 could be an important contribution to the atomic hydrogen if H_2 molecules were highly vibrational excited as estimated by Graaf et al. [12] that this ion conversion rate could be as high as $2.5 \times 10^{-9}\,cm^3/s$ when H_2 molecules are in the vibrational levels greater than 4 which is about the two orders higher than that of the molecules in the ground vibrational state. However, in the limiter plasma like HT-7, edge electron temperature is high. This would limit the molecules to be distributed in high vibrational excited states if one notices the dependence of molecular vibrational excitation on the electron temperature in Ref. [13]. Moreover, one may also notice in [13] that even in low temperature plasmas in MAP-II, the vibrational temperature is several thousands of Kelvins which means that the fraction of molecules distributed in the vibrational level higher than 4 is less than 1 or 2 percents. So this ion conversion does not play an important role in the atomic component of hydrogen in our case.

5. Summary

In summary, the modeling on the Balmer-α line emission for the shot 68 520 has been done. From the modeling, it is seen that the most dominant processes are the molecular dissociation in particular channel 2, the charge exchange and the wall reflection. It also reveals that the $n_{H+}/(n_{D+} + n_{H+})$ is about 11% and the wall hydrogen desorption flux is about two orders lower than the deuterium fueling flux. Current modeling only limits to one shot, and more modeling must be done on various cases and more knowledge on the ion temperatures is required.

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