THE REFLECTION AND RE-EMISSION COEFFICIENTS OF HYDROGEN PARTICLES IMPINGING FROM PLASMA ON THE WALL IN THE TORSATRON URAGAN-3M

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The modelling of the radial emissivity profiles of H_α and H_β lines radiated from hydrogen plasma of the torsatron Uragan-3M in a typical operational regime requires the usage of the programming code KN1D to consider a balance of atom and molecule fluxes on the walls. For this purpose, the reflection and re-emission coefficients were calculated of H atoms and H_2 molecules leaving the plasma and impinging on the plasma-facing surfaces of the stainless steel casings of a helical winding.

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INTRODUCTION

The methods of optical spectroscopy of hydrogen plasma created with RF discharge in the torsatron Uragan-3M (l = 3, m = 9) are associated with computing the emissivity profiles of H_α and H_β spectral lines radiated from plasma. Such profiles have been measured in the experiments [1-3]. The numerical modeling of torsatron plasma with the programming code KN1D [4] provides a possibility to consider a hydrogen atom and molecule flux balance on a stainless steel wall at the given time moment of the RF discharge. The ions H^+ and H_2^+ do not take part in the balance by reason of peculiarities of the movement. The balance has to be based on the reflection and re-emission coefficients of H atoms and H_2 molecules impinging from plasma on plasma-facing surfaces. In this study these coefficients are used at a normal incidence of particles.

An objective of this study is calculation of the reflection and re-emission coefficients of hydrogen atoms and molecules on the plasma-facing surface, using the program SRIM [5] and the solution of a diffusion equation. The coefficients were used as the input data of the code KN1D [4] in order to compute the particle flux to the plasma-facing surface and from it, and the balance of the fluxes at a quasi-stationary stage of RF discharge.

1. EXPERIMENTAL CONDITIONS

The plasma-facing surfaces are: 1) the casings of a helical winding of a magnetic system, 2) the remote walls outside of the helical winding of the torsatron. In Fig. 1 the poloidal cross-section D-D of the magnetic system is shown. Each casing is a shell on one of three turns (l = 3) of the helical winding. The walls and casings are made of stainless steel of the type 12KH18N10T (Fe, Cr, Ni, Mn, and others).

In this study, we consider a particle flux balance only on the plasma-facing surfaces which are inside the helical winding. The balance of fluxes on the remote walls is out of the scope of this paper. To guide the eye in Fig. 1, a poloidal circle was inscribed between the casings 1, 2 and 3 in D-D, and the circle's vertical diameter AB (D = 0.38 m) was drawn between the casings 2 and 3. The plasma-facing surface is on the boundary of the casings and the poloidal circle if the latter moves through all poloidal cross-sections.

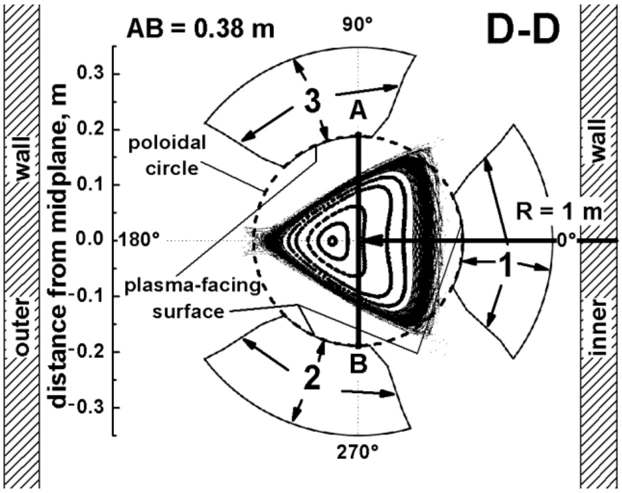

Fig. 1. The poloidal cross-section D-D. R is a major radius of the torsatron. The magnetic flux surfaces are located between the casings 1, 2, and 3. The vertical diameter AB of a poloidal circle connects the casings 2 and 3

To calculate the reflection and re-emission coefficients, we have studied the parameters of hydrogen plasma of the typical RF discharge in the torsatron Uragan-3M at a toroidal magnetic field B = 0.72 T.

The RF pulse of a three-half-turn antenna with anode voltage of U_2 = 6 kV and duration of 20 ms creates the preliminary ionization of the hydrogen.

Immediately after the shutdown of the RF pulse, the next pulse of a frame-type antenna with anode voltage of U_1 = 7 kV and duration of 40 ms is switched on and produces the plasma with a line-averaged density of $\bar{n}_{e,l} \leq 2 \times 10^{18}$ m^{-3} and an electron temperature of $T_e \leq 0.5$ keV. The time moment t_0 = 55 ms of measurements is in the middle of the second RF pulse creating and sustaining the plasma. Before both pulses, a hydrogen pressure in a vacuum vessel was $P_{H2} = 1.1 \times 10^{-5}$ Torr, and a density of hydrogen molecules was $n_{ini} = 3.2 \times 10^{17}$ m^{-3}.

2. THE REFLECTION AND RE-EMISSION OF HYDROGEN PARTICLES

H^+ and H_2^+ ions leaving plasma do not impinge on the plasma-facing surfaces of the casings directly because the ions move in a divertor region to the rear and lateral sides of the casings. After backscattering or re-emission from the surfaces, the ions contribute negligibly to the atom or molecule flux returning from remote walls to the plasma. The flux $\Gamma_i = 2 \times 10^{20}$ m^{-2}s^{-1} of H^+ ions drifting from the plasma was estimated at the plasma edge with the code KN1D, taking an average minor radius of the plasma $\bar{a}_p = 0.125$ m. The flux Γ_i is close to the flux $\Gamma = 3 \times 10^{20}$ m^{-2}s^{-1} measured by Langmuir probes in the divertor region in the similar experimental conditions [6].

Therefore, here we take into account only the atom and molecule fluxes leaving plasma and impinging on the plasma-facing surfaces where neutrals are involved in the processes of two types: reflection and re-emission.

2.1. THE REFLECTION OF ATOMS

The reflection process of impinging H atoms is, in principle, backscattering of them from atoms of the surface or atoms in the bulk of metal. A process product is H atoms [5]. We identify two types of atoms impinging from plasma on the plasma-facing surfaces, according to atom kinetic energy E_0. Therefore, two processes of reflection from the surface were taken into account:

$$\mathrm{H} + \mathrm{wall} \rightarrow \mathrm{H}, \quad (1)$$
$$\mathrm{H_{CX}} + \mathrm{wall} \rightarrow \mathrm{H}. \quad (2)$$

This means that the atoms impinge on the plasma-facing surface and reflect from it. The first type is the low-energy atoms ($E_0 = 3\ldots10$ eV), the second type – the high-energy charge exchange (CX) atoms ($\bar{E}_0 \approx 120$ eV). An energy range in process (1) was found using the code KN1D. The value $\bar{E}_0$ in process (2) is some average energy of the CX atom flux, also estimated with this code.

For the conditions of these experiments (Section 2), the energy of CX atoms is, approximately, in the range 120 eV…4 keV as is shown in Subsection 3.4.

The reflection coefficient of the atom flux is $R_N = I/I_0$. It was evaluated with a program SRIM [5] as a function of kinetic energy E_0, where I_0 is impinging flux, I – reflected flux. The energy reflection coefficient was determined using a formula shown in [7].

2.2. THE RE-EMISSION IN THE CASE OF IMPINGING ATOMS

The process of molecular re-emission is associated with implantation of impinging atoms into the bulk of metal [8-10]. In this case, an implanted H atom can diffuse to the surface and recombine with other atom to a molecule ($\mathrm{H + H \rightarrow H_2}$) which can leave the surface due to desorption. The left-hand sides of processes (3) and (4) coincide with those in (1) and (2), respectively, but the process product is a molecule:

$$\mathrm{H} + \mathrm{wall} \rightarrow \mathrm{H_2}, \quad (3)$$
$$\mathrm{H_{CX}} + \mathrm{wall} \rightarrow \mathrm{H_2}. \quad (4)$$

The re-emission coefficient $j_0 = J_0/I_{0i}$ of the desorbed flux was determined using formulas (5) and (6). Here J_0 is desorption flux of molecules, $I_{0i} = I_0(1 - R_N)$ – flux incoming into the bulk of metal, R_N – the reflected part of atoms [9, 10].

The hydrogen concentration $u(x,t)$ at the depth x, at the time moment t is included in diffusion equation (5) with an ion source located in the bulk. The boundary condition (6) implies the balance between the diffusion flux from the source to the surface and the desorption flux from the surface [9]:

$$\partial u(x,t)/\partial t = D\partial^2 u(x,t)/\partial x^2 + I_{0i}\varphi(x),\ 0 < x < \infty, \quad (5)$$
$$D\partial u(x,t)/\partial x = Ku^2(x,t),\quad x = 0. \quad (6)$$

Here D is the diffusion coefficient, K – the recombination coefficient at the surface ($x = 0$), $I_{0i}\varphi(x)$ – the ion source. The source $\varphi(x) = \delta(x - R_p)$ in (5) is located at the depth of an ion projected range R_p in metal. The solution of this system is expressed with the integral equation given in [9].

2.3. THE REFLECTION AND RE-EMISSION OF MOLECULES

A temperature of low-energy molecules escaping from the plasma-facing surface corresponds to the temperature of the surface [4], which is equal to ~35°C in the experiments.

To know more about the processes on the stainless steel surface of the casing, we show here some results of a quantum mechanical study of the dynamics of H_2 molecule dissociation on the Ni (100) surface [11]. The activation barrier V_A to molecular adsorption, the barrier V_D to dissociation ($\mathrm{H_2 \rightarrow H + H}$), and the barrier V_H to H atom diffusion along the metal surface are related to these processes.

There are three examples with the different ratios of the barrier heights V_D and V_H [11]:

1) $V_D < V_H$, the reflection process only; H_2 molecules dissociate to H atoms which reflect ($R = 99$ %) from the barrier V_H and desorb immediately to a gas phase;
2) $V_D \gtrsim V_H$, re-emission dominates; H_2 molecules dissociate to H atoms; the atoms travel along the surface and can recombine to molecules which can desorb;
3) $V_D \lesssim V_H$, reflection and re-emission are possible.

The process product is a molecule:

$$\mathrm{H_2} + \mathrm{wall} \rightarrow \mathrm{H_2}. \quad (7)$$

As is shown in [11], the reflection and re-emission coefficients of H_2 molecules are low at low kinetic energy of molecules, corresponding to the casing temperature of ~35°C. For the plasma-facing surface of stainless steel casings we assumed that the sum of both these coefficients, j_{0m7}, is equal to the experimental coefficient 0.07 given for H_2 molecules [12].

The average kinetic energy of molecules passed through the plasma is slightly less before the plasma-facing surface than that of molecules escaping from this surface as was calculated with the code KN1D. In this case, we decreased the coefficient j_{0m7} to the value of 0.05, following to the explanations related to Fig. 9 in [11].

2.4. THE COEFFICIENTS R_N AND j_0 FOR ATOMS

In Fig. 2, the reflection coefficient R_N of H atoms, impinging on the plasma-facing surface of the stainless steel casing in processes (1) and (2) is presented as a function of atom kinetic energy E_0. Also, the re-emission coefficient j_0 for processes (3) and (4), and the total coefficient $R_N + j_0$ are plotted in this figure.

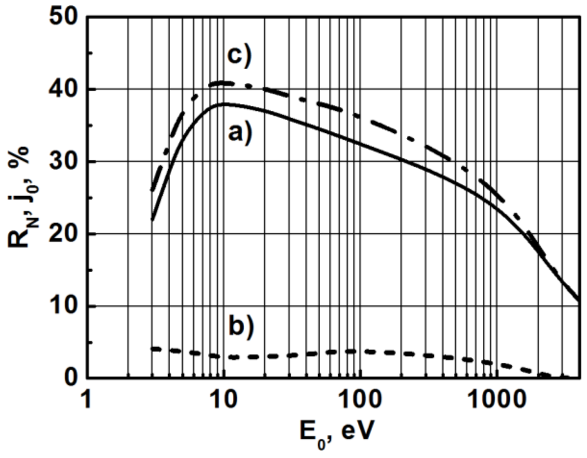

Fig. 2. a) The reflection coefficient R_N; b) the re-emission coefficient j_0; c) the total coefficient $R_N + j_0$ are the functions of kinetic energy E_0 of H atoms impinging on the stainless steel surface

To determine approximately the energies of CX atoms, we considered the results of [2, 13], related to the low-density plasma discharges in Uragan-3M, with the experimental conditions similar to those shown in Section 2.

The ion energy distributions in the range 0.4…4 keV, and the corresponding ion temperatures in the range 0.4…0.55 keV, presented in [13], were obtained with CX neutral particle diagnostics. These results and the results of Doppler spectrometry, described in [2], indicate the temperatures of ~40 and ~300 eV of C^{4+} ions, and the comparable temperatures of H^+ ions. Here we calculated the H^+ ion energy distributions and estimated the average energy $\bar{E}_0 \approx 120$ eV of CX atoms in energy distributions, using formula (2A11) from [14], as well as formulas and the data of Fig. 8 from [13].

The energy of CX atoms is, approximately, in the range 120 eV…4 keV. The energy range in Fig. 2 covers the ranges of low-energy H atoms and high-energy CX atoms.

3. THE BALANCE OF FLUXES

The impinging flux of atoms in processes (1)-(4) can be divided into the parts of reflected atoms, desorbed molecules, and implanted atoms, according to [9, 10]. In process (7) the impinging flux of molecules is modified into the fluxes of reflected and desorbed molecules as was shown for H_2 dissociation on Ni (100) [11].

Since the condition of the balance of atom and molecule fluxes has to be achieved, the net mass flux from the wall is zero (100 % recycling) [4]. According to this, the net flux of molecules from the wall (a difference of desorption flux and impinging flux) must be equal to the impinging flux of atoms. It is necessary to decrease the latter by the flux of reflected and desorbed atoms on condition that they exist.

The balance condition was applied at the quasi-stationary stage of the RF discharge, in the middle of the RF pulse of the frame-type antenna, creating and sustaining the plasma. The diagnostic oscillograms corresponding to the plasma density, the electron temperature, and the brightness of the H_α and H_β spectral lines were changed very slowly at the moment t_0. The fluxes were modeled with the code KN1D along the diameter *AB* (see Fig. 1).

The sum of the terms $I_{01}R_{N1}$ and $I_{02}R_{N2}$ corresponding to the left-hand sides in (1) and (2) is equal to the sum of the reflected flux terms I_1 and I_2 of the right-hand sides. The impinging flux terms are $I_{01} = 4.0 \times 10^{20}$ m^{-2}s^{-1} and $I_{02} = 7.4 \times 10^{20}$ m^{-2}s^{-1}. The reflection coefficients are R_{N1} and R_{N2}. The sum of the reflected flux terms is $1.2 \times 10^{20} + 2.4 \times 10^{20} = 3.6 \times 10^{20}$ m^{-2}s^{-1}. The values of the reflection and re-emission coefficients are shown above.

The sum of other terms $I_{03}j_{03}(1 - R_{N1})$, $I_{04}j_{04}(1 - R_{N2})$, and $I_{07}j_{0m7}$ in the left-hand sides of (3), (4) and (7) is equal to the sum of the desorption flux terms I_3, I_4 and I_7 in the right-hand sides. The impinging flux terms of atoms in (3), (4), and molecules in (7) are $I_{03} = I_{01}$, $I_{04} = I_{02}$, and $I_{07} = 2.5 \times 10^{18}$ m^{-2}s^{-1}. For impinging atoms, the re-emission coefficients are j_{03} and j_{04}. The total reflection and re-emission coefficient of molecules is j_{0m7}. The sum of the flux terms is $9.5 \times 10^{18} + 2.3 \times 10^{19} + 1.3 \times 10^{17} = 3.3 \times 10^{19}$ m^{-2}s^{-1}.

In the space between the plasma and the plasma-facing surfaces, the molecular flux exists with $\Gamma_{0,sp} = 1.5 \times 10^{20}$ m^{-2}s^{-1}, not crossing the plasma and impinging on these surfaces. The flux is reflected and desorbed from the surfaces with $\Gamma_{sp} = 1.1 \times 10^{19}$ m^{-2}s^{-1}, and the coefficient $j_{0m7} = 0.07$.

In the middle of the second RF pulse, the molecular density n_0 on the plasma-facing surfaces, calculated with the code KN1D, is lower by ~35 % than the density n_{ini} before the pulses.

CONCLUSIONS

In this paper, the reflection and re-emission coefficients are presented for the fluxes of H atoms and H_2 molecules impinging with given kinetic energy from hydrogen plasma on the plasma-facing surface of the stainless steel casings on a helical winding during a typical RF discharge in the torsatron Uragan-3M.

The fluxes of H^+ and H_2^+ ions do not take part in reflection and re-emission on the plasma-facing surface since the ions move mainly to the rear and lateral sides of the casings.

The reflection and re-emission coefficients of H atoms and H_2 molecules are used in the code KN1D. The values of the fluxes impinging on the plasma-facing surfaces and the values of the reflection and desorption fluxes were calculated. An atom and molecule flux balance was considered at the quasi-stationary stage of the RF discharge creating and sustaining the plasma in the torsatron Uragan-3M.

For H atoms, the energy dependences of the reflection, re-emission coefficients and the total of these coefficients were calculated in the energy range 3 eV…4 keV. For low-energy atoms, the total coefficient increases from 0.26 to 0.41 in the range 3…10 eV. For high-energy CX atoms, this coefficient is equal to 0.35 at energy of 120 eV, and 0.11 at energy of 4 keV (at the high-energy tail).

In prospect, the reflection and re-emission coefficients are supposed to be used in the modeling of the profiles of different particle parameters with the code KN1D for the hydrogen plasma or for the near-plasma region of the torsatron Uragan-3M.

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КОЭФФИЦИЕНТЫ ОТРАЖЕНИЯ И РЕЭМИССИИ ВОДОРОДНЫХ ЧАСТИЦ, ПАДАЮЩИХ ИЗ ПЛАЗМЫ НА СТЕНКУ В ТОРСАТРОНЕ УРАГАН-3М

В.Н. Бондаренко, А.А. Петрушеня

Моделирование радиальных профилей интенсивности линий H_α и H_β, излучённых из водородной плазмы торсатрона Ураган-3М в типичном рабочем режиме, требует использования программного кода KN1D для рассмотрения баланса атомных и молекулярных потоков на стенках. С этой целью были вычислены коэффициенты отражения и реэмисии атомов H и молекул H_2, покидающих плазму и падающих на обращённые к плазме поверхности кожухов винтовой обмотки из нержавеющей стали.

КОЕФІЦІЄНТИ ВІДБИТТЯ І РЕЕМІСІЇ ВОДНЕВИХ ЧАСТИНОК, ЩО ПАДАЮТЬ ІЗ ПЛАЗМИ НА СТІНКУ В ТОРСАТРОНІ УРАГАН-3М

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Моделювання радіальних профілів інтенсивності ліній H_α і H_β, випромінених з водневої плазми торсатрона Ураган-3М у типовому робочому режимі, вимагає використання програмного коду KN1D для розгляду балансу атомних і молекулярних потоків на стінках. З цією метою були обчислені коефіцієнти відбиття і реемісії атомів H і молекул H_2, які покидають плазму і падають на повернені до плазми поверхні кожухів гвинтової обмотки з нержавіючої сталі.