MODELING OF TIME BEHAVIOR OF H, H_2 NEUTRAL DENSITIES, AND H_α LINE INTENSITY IN THE RF PLASMA OF THE URAGAN-3M TORSATRON

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In this paper, the results of computer simulation of time behavior of hydrogen atoms and molecules in the plasma produced by RF power in the Uragan-3M torsatron are presented. The evolution of the density of fast charge-exchange H atoms, slow H atoms, H atom population on the chamber walls, the intensity of the H_α line, and the H_2 gas density and pressure has been studied using the system of differential equations.

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INTRODUCTION

The study of the time evolution of the atomic and molecular density in the plasma confinement volume of the Uragan-3M (U-3M) torsatron in experiments of hydrogen plasma confinement and heating represents an interest as a research topic at the present time. Emission spectroscopy of Balmer spectral lines H_α and H_β is an important part of plasma diagnostics, the passive and non-invasive means of observation, with a simple apparatus and a reliable scheme of measurements [1]. At the same time, to find the measured intensity of a spectral line correctly, the time dependence of the H and H_2 neutral density should be modeled on a computer.

The modeling procedure with the use of the numerical code KN1D was described in the papers [2, 3] where the radial profiles of hydrogen plasma ions and neutrals were calculated for the plasma produced in U-3M by RF power.

This paper presents the results of new simulation of the time behavior of the ion and atom density, atom population on the chamber wall, H_α line intensity, H_2 gas density and pressure in the operating regime of the U-3M torsatron. In this regime, the main RF pulse follows the pre-ionization RF pulse.

1. NUMERICAL MODELING

The analysis of the computer simulation possibilities for the U-3M torsatron demonstrates that solution of a system of four differential equations, based on a scheme of the DITE tokamak [4], is a reasonable approach to modelling the time-dependent functions associated with the hydrogen plasma and neutrals:

$$\frac{dN_i}{dt} = -\frac{N_i}{\tau_i} + N_0^f N_i \frac{S^f}{V} + N_0^s N_i \frac{S^s}{V}, \qquad (1)$$

$$\frac{dN_0^f}{dt} = -N_0^f N_i \frac{S}{V} - \frac{N_0^f}{\tau_f}(1-\beta) + N_0^s N_i \frac{X}{V} + \beta \frac{N_i}{\tau_i}, \qquad (2)$$

$$\frac{dN_0^s}{dt} = -N_0^s N_i \frac{S}{V} - N_0^s N_i \frac{X}{V} + \frac{N_i}{\tau_i} N_w \frac{\sigma}{A} + \frac{N_0^f}{\tau_f} N_w \frac{\sigma}{A}, \qquad (3)$$

$$\frac{dN_w}{dt} = -\frac{N_i}{\tau_i}\frac{\sigma}{A} N_w - \frac{N_0^f}{\tau_f}\frac{\sigma}{A} N_w + \frac{N_i}{\tau_i}(1-\beta) + \\ + \frac{N_0^f}{\tau_f}(1-\beta). \qquad (4)$$

The first three equations include the total number of H particles in the plasma confinement volume V: N_i – H^+ ions; N_0^f – fast atoms (charge-exchange atoms of the high energy); N_0^s – slow atoms (Franck-Condon atoms of low energy). Equation (4) includes a total number of particles N_w trapped in the area A of a wall, with which the plasma interacts. Only the values V and A are time-independent. The value S is the mean ionization rate coefficient of H atoms by an electron impact, X – the mean charge-exchange rate coefficient of H^+ ions with H atoms [5], σ – a cross-section for the particle-induced release of H atoms from a vacuum chamber wall [4].

The indices *i*, *f*, and *s* relate respectively to ions, fast and slow atoms. The index *w* relates to H atoms trapped on the wall, and index 0 – to fast and slow neutrals.

The value τ_i is the H^+ ion mean confinement time (the lifetime) in the volume V, τ_f – the lifetime of fast atoms [4], β – the reflection coefficient of ions or atoms from the wall. The remaining terms in the equations correspond to the generally accepted notations.

All terms in equations (1) – (4) [4] were validated for the conditions of U-3M, and the equations were used almost without changes. Only, the parentheses in (1) were expanded to use the terms of fast and slow atoms with the ionization rate coefficients S^f *and* S^s, respectively. The terms of slow atoms, containing τ_s and β_s, are missing since it is assumed that $\tau_s = \infty$ [4, 6]. Each of the first three time-dependent functions was supposed to be uniform along an average minor plasma radius $\bar{a}_p$ = 0.125 m at any time moment of the RF pulse, and the fourth function – uniform on the wall.

After solving the system, we calculated the specific values, assuming the volume $V = 0.3\ \text{m}^3$ and area $A = 3.8\ \text{m}^2$: the particle densities $n_i(t)$, $n^f(t)$, $n^s(t)$ (m^{-3}), and the population on the walls $n_w(t)$ (m^{-2}) by H atoms created with ions and fast atoms impinging on the stainless steel walls of the U-3M torsatron [2].

The flow of ions, fast, and slow atoms lost from the plasma is incident on the surfaces of two types in a vacuum chamber. The lost particles move to remote walls of the chamber through the slits between the casings of a helical winding (HW) of a magnetic field.

The surfaces of the first type (S1) are the parts of the walls of the vacuum chamber that are not shaded by obstacles from particles escaping from the plasma and can reflect these particles back to the plasma. The S1 surfaces are the plasma-facing parts (PFP) of the HW casings and the PFP of the remote walls of the vacuum chamber outside the HW. The lost atoms are reflected to the plasma by all the S1 surfaces. The lost ions are reflected to the plasma only by the PFP of the HW casings. Eventually, the lost atoms and ions are reflected as atoms with a significant probability or are re-emitted as molecules with a negligible probability [2].

The surfaces of the second type (S2) are those that are shaded by the HW casings from the lost ions and atoms and almost do not reflect the particles back to the plasma, even after multiple reflection events on S2 surfaces. These S2 surfaces are the remote walls, rear, and lateral sides of the casings. A significant portion of lost ions in the form of divertor streams walks around the HW casings to the S2 surfaces [2]. The lost atoms and ions can be reflected by S2 surfaces as atoms many times. A negligible portion of lost particles returns to the plasma as atoms. Eventually, the main portion of lost particles transforms to molecules due to re-emission and contributes to the background H_2 gas.

Therefore, only the surfaces of the first type reflect particles to the plasma effectively. The incidence angle relative to a normal to the S1 or S2 surfaces was taken to be 45° for atoms and about 0° for ions [7]. The reflection coefficients β_k ($k = i$, f, and s) depend on the particle kinetic energy E_0 that was estimated with the code KN1D [5]. The dependence $\beta_k(E_0)$ at the specified incidence angle was found using the SRIM program [8].

2. EXPERIMENTAL CONDITIONS

The results of the numerical analysis are presented here for two experimental operating regimes.

The parameters of the regime A were as follows. A toroidal magnetic field $B_0 = 0.6$ T, hydrogen pressure in the chamber before a discharge $p_{H_2}{}^{ini} = 1.2 \times 10^{-3}$ Pa. The main RF pulse is produced during the operation of the frame type antenna (FTA) when an average electron density in the poloidal cross-section $\bar{n}_e \leq 2 \times 10^{18}$ m^{-3}, and an electron temperature $T_e \leq 0.5$ keV [2].

The hydrogen breakdown was initiated using a three-half-turn antenna (THTA) with an anode voltage $U_2 = 5$ kV switched on at a time moment $t_{1T} = 15$ ms and switched off at $t_{2T} = 35$ ms. After this, the plasma was sustained by the FT antenna with an anode voltage $U_1 = 8$ kV at time moments $t_{1F} = 35$ ms and $t_{2F} = 75$ ms.

The parameters of the regime B: $B_0 = 0.72$ T, $p_{H_2}{}^{ini} = 1.1 \times 10^{-3}$ Pa, $\bar{n}_e \leq 1.2 \times 10^{18}$ m^{-3}, $T_e \leq 0.5$ keV; $U_2 = 6$ kV from $t_{1T} = 3$ ms to $t_{2T} = 20$ ms; $U_1 = 7$ kV from $t_{1F} = 20$ ms to $t_{2F} = 40$ ms.

3. RESULTS OF MODELING

The stages of operation of THT and FT antennas are identified here respectively as PI – the pre-ionization stage and MP – the main plasma stage.

The ion mean lifetime τ_i in the MP stage, according to [3], was evaluated as 2 ms in the regime A (a) and 1.86 ms in the regime B (b). The lifetime τ_i estimated in the PI stage was 1.1 ms (a) and 1.7 ms (b).

The fast atom mean lifetime τ_f in the MP stage, 0.6 µs (a) and 0.5 µs (b), was determined by a formula from [4]. The lifetime τ_f estimated in the PI stage is equal to 0.01 of τ_f in the MP stage.

In this model, we assumed that the ion temperature $T_i(t)$ is approximately equal to $T_e(t)$.

The electron temperature $T_e(t)$ as a key parameter was chosen to be proportional to the measured experimental ECE intensity, with some degree of approximation (Fig. 1). Four unknown functions depending on $T_e(t)$ are changing in the equations. For the solution stability, each ECE intensity dependence was smoothed (the black solid curves). There is a peculiarity in a form of a minimum of ECE intensity in the regime A at ~ 30 ms. All functions were not considered after the end of the MP stage in this study.

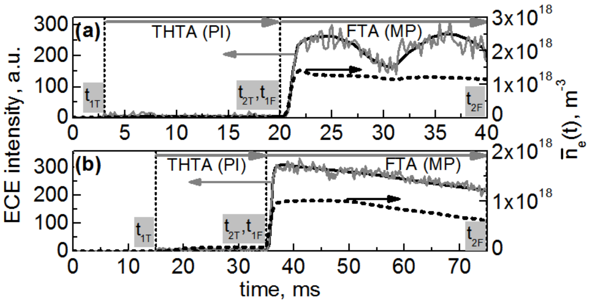

Fig. 1. The temporal evolution of the measured values: the ECE intensity and the average electron density $\bar{n}_e(t)$ in regime A (a) and regime B (b). An arrow near the curve indicates the related axis

In two studied regimes, the first RF pulse was generated by the THT antenna that pre-ionized hydrogen during this stage. The initial conditions of the unknown functions were specified at the moment t_{1T}: the density of ions $n_i{}^{ini}$, fast atoms $n^f{}_{ini}$, and slow atoms $n^s{}_{ini}$; the population $n_w{}^{ini}$ on the chamber wall by H atoms; the cross-section σ_{ini} for the particle-induced release of H atoms. The initial density $n_{H_2}{}^{ini}$ of the H_2 gas was found from the pressure $p_{H_2}{}^{ini}$ at the moment $t = 0$. During the PI stage, the electron temperature $T_e(t)$ was taken to be 4.5 eV in both regimes. In a procedure of equation system solving, the ion density $n_i(t)$ was fitted to the average electron density $\bar{n}_e(t)$ measured in the experiments. This follows from a plasma quasi-neutrality condition in the confinement volume. The argument in this fit is a cross-section $\sigma(t)$.

3.1. ATOMIC DENSITY AND POPULATION BEHAVIOR

The MP stage starts at the moment t_{1F} immediately after the PI stage end. The initial conditions for the functions N_i, $N_0{}^f$, and $N_0{}^s$ at the moment t_{1F} follow from the solution of equation system. In both regimes, the cross-section $\sigma(t)$, presented in Fig. 2, is a constant during the PI stage.

A sharp increase in the cross-section $\sigma(t)$ is seen after the start of the MP stage. After this, $\sigma(t)$ decreases sharply in the regime A and slowly in the regime B.

The H atom population $n_w(t)$ on the chamber wall grows, then remains in saturation up to the end of the PI stage, in both regimes. After the MP stage start, the population increases and decreases sharply, then grows gradually with some peculiarities.

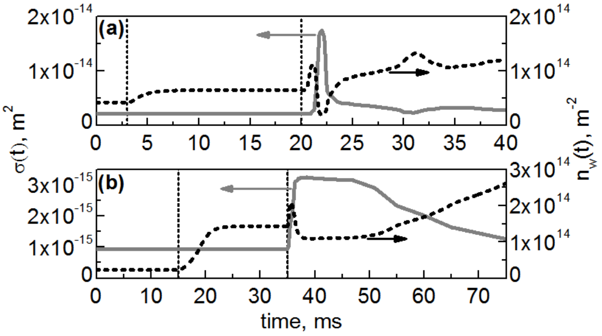

Fig. 2. The cross-section σ(t) for the particle-induced release of H atoms (a) and H atom population $n_w(t)$ on the wall (b)

Concerning atomic densities, the density $n^f(t)$ of fast atoms is significantly lower than the density $n^s(t)$ of slow atoms in both regimes, as is clear from Fig. 3.

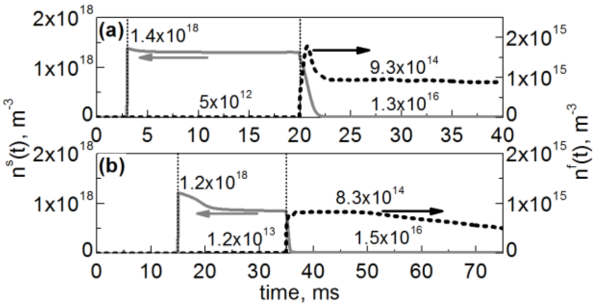

Fig. 3. The density of slow atoms $n^s(t)$ (a) and fast atoms $n^f(t)$ (b). The magnitudes are labeled near the curves

The fast atom density is low in the PI stage, but increases at the time moment t_{1F} sharply and resembles the electron density $\bar{n}_e(t)$ behavior in the MP stage. The production efficiency of charge-exchange atoms depends directly on the H^+ ion and slow H atom densities, and the H^+ ion temperature [5].

The slow atom density $n^s(t)$ is the highest among atomic densities and slowly decreases in the PI stage. Then it falls to a low constant level after the MP stage start. The slow atom production from molecules and ionization of such atoms dominate respectively in the first and second stages [5]. The density $n^s(t)$ anti-correlates with the electron density $\bar{n}_e(t)$ in the PI stage due to atom ionization losses.

The temporal evolution of the H_α line brightness $B(t)$ from the plasma was measured in the middle plane of the poloidal cross-section *D-D* of the U-3M torsatron, using methods described in [1, 2]. The intensity $I(t)$ of the H_α line, shown in Fig. 4, was calculated using the densities $\bar{n}_e(t)$, $n^s(t)$, and the mean rate of hydrogen atom excitation $\langle\sigma v\rangle_{exc}$ [1, 5].

The functions $B(t)$ and $I(t)$ were superimposed together at the middle of the MP stage to compare them. The calculated function is close to measured one, excluding the calculated peak of overestimated magnitude at the MP stage start. This peak starts to rise before the measured one. This discrepancy may be associated, probably, with the omitted molecular contribution in the calculated intensity.

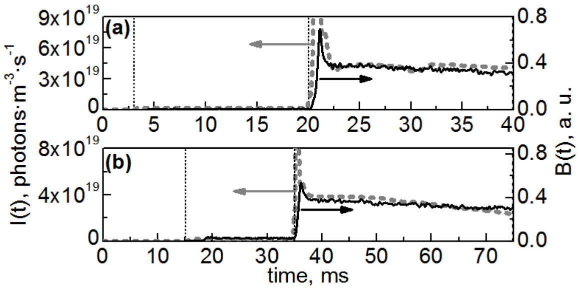

Fig. 4. The intensity I(t) of the H_α line, calculated from equations (1) - (4), and this line brightness B(t) measured in the experiment

The contribution of slow atom emission to the H_α line intensity is much higher than that of fast atoms. The reason is that the slow atoms density significantly dominates that of fast atoms.

3.2. H₂ GAS PRESSURE BEHAVIOR

The H_2 gas pressure $p_{H_2}{}^{meas}(t)$ was measured by a magnetron pressure sensor installed at a distance of 2 m above the helical coils [3]. For comparison, the pressure $p_{H_2}{}^{calc}(t)$ was calculated using a differential equation. The gas temperature is ~308 K outside the plasma before the PI stage.

The pressure $p_{H2}{}^{calc}$ is proportional to the gas density $n_{H2}{}^{calc}$, according to the ideal gas law [5]. The gas density $n_{H_2}{}^{calc}(t)$ was determined from the differential equation (2) [9], but three new terms were added next to the term *D*:

$$dn_{H2}/dt = -(D+SI+DI+HI)n_{H2}\bar{n}_e + \Gamma^{in}_{H2} - \Gamma^{out}_{H2}, \quad (5)$$

where *D* is the mean rate of molecular dissociation in the collisions with plasma electrons $e^- + H_2 \rightarrow H + H$, n_{H2} – the H_2 gas density, Γ^{in}_{H2} and Γ^{out}_{H2} – the density of molecular flux entering and leaving the plasma, respectively. We added three terms that are actual for plasma in an ionizing stage: *SI* – the mean ionization rate to H_2^+ ion, $e^- + H_2 \rightarrow H_2^+$; *DI* – the mean dissociative ionization rate, $e^- + H_2 \rightarrow H + H^+$; *HI* – the mean ionization rate to ions, $e^- + H_2 \rightarrow H^+ + H^+$. Almost all the gas flow entering the plasma is transformed to atoms and ions, and the molecular flow leaving the plasma is negligibly low: $\Gamma^{out}_{H2} \ll \Gamma^{in}_{H2}$ [2, 3]. The term Γ^{in}_{H2} was evaluated as a) $n_{H_2}(t)/6.6$ and b) $n_{H_2}(t)/7.2$.

The calculated gas pressure was normalized, for clarity, to the initial condition, $p_{H_2}{}^{calc}(t)/p_{H_2}{}^{ini}$ as well as the measured pressure, $p_{H_2}{}^{meas}(t)/p_{H2}{}^{ini}$, as Fig. 5 demonstrates for the regime A.

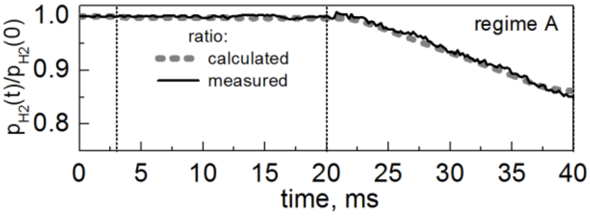

Fig. 5. The normalized H_2 gas pressure: the calculated and measured dependence

The calculated and measured pressure functions are very close to each other. Both functions decrease in a typical exponential form: very slowly in the PI stage and noticeably in the MP stage.

In the regime B, the functions behave similarly, but the pressure at the end of the MP stage amounts to ~75 % of the initial value.

CONCLUSIONS

In this paper, the numerical technique of modeling [4] was applied to time-dependent parameters of the hydrogen ions and neutrals in two operation regimes of the U-3M torsatron. A system of four differential equations was solved in the pre-ionization (PI) stage and in the main plasma (MP) stage.

With this technique, the time-dependent H^+ ion density, fast (charge exchange) atom density, slow atom density, and H atom population on the wall were calculated. Also, the H_α line intensity, H_2 gas density and pressure were found.

The H^+ ion density was approximated to the average electron density $\bar{n}_e(t)$ measured in the experiments. The argument of this fit is the cross-section for the particle-induced release of H atoms from chamber walls.

The fast atom density is significantly lower than that of slow atoms. The fast atom density is low in the PI stage, but increases after the MP stage start sharply. The density level of fast atoms corresponds to the production efficiency of these atoms in the charge-exchange process.

The slow atom density decreases in the PI stage moderately and drops to a low constant level after the MP stage start. The slow atom production from molecules dominates in the PI stage, and the ionization of atoms – in the MP stage.

The H atom population on the chamber wall grows and saturates in the PI stage. After the MP stage start, this value increases and decreases sharply, then grows gradually.

The modeled H_α line intensity is similar qualitatively to the brightness of this line measured in the experiment on the U-3M torsatron. The contribution of slow atoms in the H_α intensity is much higher than that of fast atoms.

An additional differential equation was solved with the intention to determine the temporal evolution of the H_2 gas density and pressure near the chamber wall remote from the plasma. The calculated pressure function is very close to the measured one. The pressure decreases very slowly in the PI stage, and significantly – in the MP stage.

REFERENCES

1. V.N. Bondarenko, V.G. Konovalov, et al. Investigation of radial distributions of spectral line radiation emissivities in torsatron “URAGAN-3M” // *Problems of Atomic Science and Technology. Ser. “Plasma Physics” (9).* 2003, № 1, p. 23.
2. V.N. Bondarenko, A.A. Petrushenya. The reflection and re-emission coefficients of hydrogen particles impinging from plasma on the wall in the torsatron URAGAN-3M // *Problems of Atomic Science and Technology. Ser. “Plasma Physics” (23).* 2017, № 1, p. 14.
3. V.K. Pashnev et al. Methods for measuring hydrogen balance in vacuum chamber of U-3M torsatron during plasma experiments // *Problems of Atomic Science and Technology. Ser. “Plasma Physics” (23).* 2017, № 1, p. 44.
4. S.J. Fielding et al. // *J. Nucl. Mater.* 1978, v. 76, № 77, p. 273.
5. B. La Bombard. *Tech. rep. PSFC-RR-01-3.* Cambridge, 2001, USA.
6. *Physics of plasma-wall interactions in controlled fusion* / Ed.: D. E. Post, R. Behrisch. New York, USA : Plenum Press, 1986.
7. P.C. Stangeby. *The plasma boundary of magnetic fusion devices* / Ed.: P. Stott, H. Wilhelmsson. Bristol, Philadelphia: “IOP”, 2000.
8. J.F. Ziegler et al. // *Nucl. Instrum. Methods Phys. Res.* Sect. B. 2010, v. 268, iss. 11-12, p. 1818.
9. K. Sawada, T. Fujimoto // *J. Appl. Phys.* 1995, v. 78 (5), p. 2913.

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МОДЕЛИРОВАНИЕ ВРЕМЕННОГО ПОВЕДЕНИЯ ПЛОТНОСТЕЙ НЕЙТРАЛОВ H, H_2 И ИНТЕНСИВНОСТИ ЛИНИИ H_α В ВЧ-ПЛАЗМЕ ТОРСАТРОНА УРАГАН-3М

В.Н. Бондаренко, А.А. Петрушеня

Представлены результаты компьютерного моделирования временного поведения атомов и молекул водорода в плазме, полученной с помощью ВЧ-мощности в торсатроне Ураган-3М. С использованием системы дифференциальных уравнений были изучены эволюция плотности быстрых атомов перезарядки H, медленных атомов H, популяции атомов H на стенках камеры, интенсивности линии H_α, плотности и давления газа H_2.

МОДЕЛЮВАННЯ ЧАСОВОЇ ПОВЕДІНКИ ГУСТИН НЕЙТРАЛІВ H, H_2 ТА ІНТЕНСИВНОСТІ ЛІНІЇ H_α У ВЧ ПЛАЗМІ ТОРСАТРОНУ УРАГАН-3М

В.М. Бондаренко, А.А. Петрушеня

Представлено результати комп'ютерного моделювання часової поведінки атомів і молекул водню в плазмі, отриманої за допомогою ВЧ-потужності в торсатроні Ураган-3М. З використанням системи диференціальних рівнянь було вивчено еволюцію густини швидких атомів перезарядження H, повільних атомів H, популяції атомів H на стінках камери, інтенсивності лінії H_α, густини і тиску газу H_2.