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SIMULATION OF THE ELECTRON DENSITY AND THE H_α SPECTRAL LINE INTENSITY IN HYDROGEN PLASMA OF URAGAN-2M STELLARATOR

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Time-dependent signals of the average electron density and H_α spectral line intensity were measured during the RF discharge, which created the dense hydrogen plasma in the Uragan-2M stellarator. These data were used as the basis for simulating the time-dependent local electron density and H_α line emission coefficient in a system of differential equations. The local electron densities were significantly modified as a result of the simulated increase in electron temperature. The similarity of the average electron density signals, the H_α line intensity signals and the corresponding simulated dependencies was confirmed.

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INTRODUCTION

The numerical simulation of hydrogen plasma in modern tokamaks and stellarators attracts significant attention due to its fundamental importance in investigating the processes of plasma creation and confinement in thermonuclear devices [1, 2].

The capabilities of simulation allow the calculation of electron, ion, atom, and molecular densities in hydrogen plasma under various initial conditions and during a discharge. The particle densities are determined using a system of differential equations (SDE).

The efficiency of numerical simulation of the time-dependent particle densities in the hydrogen plasma of the Uragan-2M (U-2M) stellarator is determined by the correspondence between the simulated dependencies and the signals obtained from experiments. This is particularly true for the key experimental data on the electron density of hydrogen plasma and the intensity of the H_α spectral line (λ = 6562.8 Å) in U-2M [3].

A detailed study of the time evolution of electron density and other plasma parameters plays an important role. The results of the study will make it possible to explain the pulse shape of these dependencies, caused by the processes of particle interaction in hydrogen plasma.

The first results of numerical simulation of time-dependent signals of the electron density of hydrogen plasma and the intensity of the H_α line were calculated in the SDE based on data from the experiment at the Uragan-3M (U-3M) stellarator [4]. The simulated dependencies were similar in pulse shape to the experimental signals. The latest data, similar to those obtained at the U-3M stellarator, were registered in an experiment with hydrogen plasma at U-2M [5].

The objective of this study is to develop a technique for numerical simulation of the time dependencies of the hydrogen plasma electron density in U-2M and the intensity of the H_α line emitted from this plasma. The simulated results must be similar in pulse shape to the experimental data.

1. EXPERIMENTAL SCENARIO AND SETUP

Experimental signals of the electron density and the intensity of the H_α spectral line were obtained in the following scenario for the hydrogen plasma created in the pulsed mode of U-2M [5].

One studied pulse included two sequential RF discharges. Hydrogen was pre-ionized using the first stage discharge in a time interval of 1…10 ms. The RF generator K-2 was used at this stage with a frame antenna at a constant anode voltage of U_a = 4 kV. The average electron density was low, $\bar{n}_e$= 2.4·10^{17} m^{-3}. The role of pre-ionization, constant in discharges, was to increase the stability of discharges [6].

Dense plasma was generated using the second stage discharge in the interval of 14…22 ms. The anode voltage of the RF generator K-1 at this stage increased with each pulse in the range of U_a = 6…9 kV. The generator operated with a three-half-turn antenna.

Other discharge parameters remained constant, including the hydrogen pressure in the chamber before the RF discharge p_{H2} = 3.2·10^{-3} Pa, the toroidal magnetic field on the toroidal axis B_0 = 0.359 T, and its components. The operating parameter K_φ = 0.367, the frequencies of the generators f_2 = 5.44 MHz, f_1 = 5.1 MHz, and the time moments of their switching on and off also remained unchanged.

The time-dependent signals of the average electron density $\bar{n}_e(t)$ are reproduced in Fig. 1, according to data from [5]. The parameter U_a of the signals increases in the range of 6…7.5 kV. Comparison of experimental signals and simulated density dependencies was carried out with the parameter U_a in this range.

Other density signals at the anode voltage U_a = 8…9 kV from [5] are not presented here. They are similar in shape to the signals shown in the figure, but higher in magnitude.

The maximum measured average electron density $\bar{n}_e$ at the second stage reached ~$3.9 \cdot 10^{18}$ m^{-3} at the anode voltage of 9 kV.

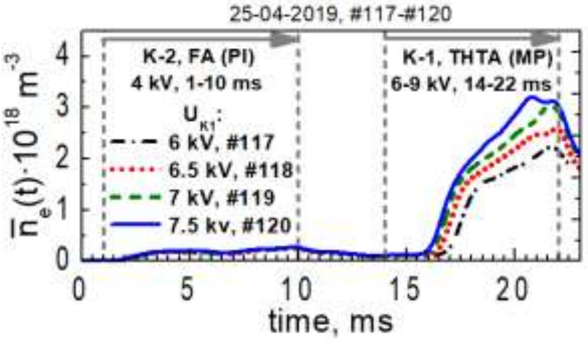

Fig. 1. Time-dependent signals of the average electron density, $\bar{n}_e(t)$, at the anode voltage in the range of 6…7.5 kV

The measurement scheme of time-dependent signals of average density $\bar{n}_e(t)$ and intensity $I_\alpha(t)$ in the experiment on U-2M is described in [5, 7].

The line-averaged electron density $\bar{n}_e(t)$ was measured by a single-channel 2 mm microwave superheterodyne interferometer. The measurements were taken in the poloidal cross-section of U-2M, where the plasma is vertically elongated [7, 8]. The electron density at the moment of measurement is averaged over the horizontal line of sight through the plasma. This line passes along the major radius R_0 of U-2M.

The intensity signal $I_\alpha(t)$ of the H_α line was measured using optical emission spectroscopy in the poloidal cross-section of U-2M, where the plasma is horizontally elongated [5, 8]. The intensity of the H_α line at the moment of measurement is summed over a horizontal line of sight similar to that used in the density measurement.

2. SETS AND DISCHARGE PARAMETERS

The time dependencies of the electron, ion, atom, and molecule densities in the U-2M hydrogen plasma were simulated using the SDE. The atoms in the plasma were classified as the slow atoms, with an average kinetic energy in the range of 3…10 eV, and the fast charge exchange atoms, with an average kinetic energy close to that of H^+ ions [2]. The radial transport of particles was not included in these equations.

The time evolution of the simulated density depends on the electron temperature $T_e(t)$, in accordance with the concept of C. Breton [9]. The curve $T_e(t)$ starts at zero magnitude and evolves into the left half of a Gaussian function. This function grows to a maximum and then transforms into a horizontal stage with a stationary temperature T_M.

The temperature profile $T_e(r_p)$, dependent on the minor plasma radius r_p, was not measured in the experiment [5]. Therefore, the specified temperature profile was specially chosen to substitute the experimental one, using a two-dimensional temperature set.

The dependence $T_e(t)$ with a stationary temperature T_M = 1 eV was multiplied by a similarity ratio ranging from 6 to 60 with a step of 1. The obtained set of temperatures $T_e(t,T_M)$ with the parameter T_M ranging from 6 to 60 eV contained dependencies $T_e(t)$ that were similar to each other. The profile $T_e(T_M)$ extracted from this set at a given time t is linear. The dependence of T_e on the minor plasma radius r_p in the plasma can be expressed by a Gaussian function in the future.

The plasma periphery corresponded to a stationary stage temperature of T_M = 6 eV, and the plasma center – to a temperature of T_M = 60 eV. The upper temperature limit of 60 eV was identified in the experiment by the emission of the O IV spectral line at a wavelength of 3736.85 Å [3]. The lower limit of 6 eV was determined by the criterion that the simulated electron density reduced to zero.

The SDE was run for each value of the parameter T_M ranging from 6 to 60 eV, with a step of 1 eV. The results of the solution are sets of the densities of electrons $n_e^c(t,T_M)$, ions $n_H^+(t,T_M)$, and other particles. The simulated electron density $n_e^c(t)$ has the superscript "c" to distinguish it from the density signal $\bar{n}_e(t)$. The calculated density $n_k(t)$ of particles of k-th kind represents a local value at a specific location along a direction of a minor plasma radius.

Each set consists of 55 plasma layers of equal thickness. The number of layers is equal to the number of temperature values T_M. The equal thickness of the layers is obtained due to the linearity of the temperature profile. The local density or temperature of particles of any kind in each layer at a given moment is assumed to be homogeneous.

The charge exchange rate coefficients of H^+ ions on hydrogen atoms H depend on the temperature of H^+ ions. This temperature in the set $T_i(t,T_{i,M})$ is assumed to be 20% higher than the electron temperature in the set $T_e(t,T_M)$.

The limiting electron density $n_{e,M}$ is found at the maximum of the set $n_e^c(t,T_M)$, usually in the central region of the plasma. The limiting densities of $n_{e,M}$ in different plasma pulsed modes were divided into three variants: A) low at $3 \cdot 10^{18}$ m^{-3}; B) medium at $5 \cdot 10^{18}$ m^{-3}, and C) high at $1 \cdot 10^{19}$ m^{-3}. The simulated density $n_e^c(t)$ does not reach a stationary stage, in contrast to the temperature $T_e(t)$.

The simulation in this study was performed only for variant A in the discharge of the second stage. The discharge of the first stage was not simulated in the SDE because of its low density.

The stationary temperature T_M increased from 6 to 60 eV. The maximum density $n_{e,M}$ of this variant was achieved using the initial condition for the density $N = 3.61 \cdot 10^{18}$ m^{-3} of H atoms in H_2 molecules before the start of the discharge.

3. SYSTEM OF DIFFERENTIAL EQUATIONS

Two different systems of equations describing hydrogen plasma were combined to form the SDE used in this study. The first system was completely incorporated into the SDE, and two equations from the second system were also included. The distribution of particles of any type inside the selected hydrogen plasma layer, as shown in Section 2, is considered homogeneous in both systems.

The first system described by C. Breton [9] allows simulating the time evolution of particle densities in the plasma. The second system developed by S.J. Fielding et al. [1] was based not on density, but on the number of particles in the plasma volume. This system also uses the number of atoms implanted into the chamber wall surface. After solving the system, the number of particles was transformed into density, as demonstrated for U-3M [4].

The first differential equation in the SDE represents the time evolution of the density n_{H2} of hydrogen molecules (1):

$$\frac{dn_{H2}}{dt} = -n_e n_{H2}(Q_1 + Q_2) - n_{H2} n^+_{H2} Q_8, \quad (1)$$

where n_e is the electron density and n^+_{H2} refers to the density of H_2^+ ions.

The designation of functions as time-dependent was omitted. The terms on the right-hand side of each equation in the system are numbered after all brackets have been expanded. An expression of the form $(1 - \beta)$ was considered a single term.

The processes in Equation (1) are associated with the numbering of the terms: 1) dissociation of H_2 molecules forming slow atoms; 2) ionization of H_2 molecules forming H_2^+ ions, and 3) formation of H_3^+ ions. The rate coefficients Q_1, Q_2, and Q_8, proposed by C. Breton [9], were updated according to the data from [10]. The previous designations of the coefficients were retained.

The second equation of the SDE describes the time evolution of the density n_H of slow hydrogen atoms:

$$\frac{dn_H}{dt} = n_e(2n_{H2}Q_1 + n^+_{H2}(Q_5 + 2Q_7) - n_H Q_9) + n_{H2} n^+_{H2} Q_8 - n_H n^+_H X + \left(\frac{n^+_H}{\tau^+_H} + \frac{n_f}{\tau_f}\right) n_w \sigma + n_e n^+_H \alpha_{RR} , \quad (2)$$

where n^+_H is the density of H^+ ions; n_f is the density of fast charge-exchange atoms; τ^+_H and τ_f are the confinement times of H^+ ions and fast atoms, respectively; n_w is the surface density of H_{wall} atoms implanted into the chamber wall, and σ is the cross-section for the release of H_{wall} atoms from the wall, induced by H^+ ions or fast atoms incident on the wall.

The terms numbered 6, 7, and 8 from the third equation of the system of S.J. Fielding [1] were applied in Equation (2) after being transformed into densities. The processes, based on the numbering of the terms, in addition to those already introduced, include: 2) dissociation of H_2^+ ions; 3) dissociative recombination of H_2^+; 4) ionization of slow atoms; 6) charge exchange of H^+ ions with H atoms; 7) loss of H^+ ions from the plasma, followed by implantation into the wall and release of H_{wall} atoms from the wall; 8) a similar process for fast atoms, and 9) radiative recombination of H^+ ions with electrons. The last process was added from the KN1D code [2].

Equation (2) contains the cross-section σ for the release of H_{wall} atoms from the wall [11]. The rate coefficients for processes Q_1, Q_5, and $Q_7 – Q_9$ [9] were revised using the data from [10]. The rate coefficients for charge exchange X and radiative recombination α_{RR} were derived from [10].

Hydrogen ions H^+ and fast hydrogen atoms incident on the stainless-steel wall of U-3M are implanted into it and transformed into H_{wall} atoms. These atoms are released from the wall due to ion-induced or atom-induced desorption. The cross-section data $\sigma(E)$ for hydrogen was unavailable and was replaced by the cross-section $\sigma_D(E) = 1.11 \cdot 10^{-19}$ m² for deuterium incident on type 304 steel [11].

The surface density of H_{wall} atoms forming a fully covered monolayer on the surface of steel is $n_{w,M} = 1/\sigma \approx 9.04 \cdot 10^{18}$ m^{-2} [12]. The density $n_w(0)$ of atoms before the discharge was chosen to be equal to $6.51 \cdot 10^{16}$ m^{-2}. The desorption rate of H_{wall} atoms by other particles present in the plasma (H, H_2^+, and H_3^+) was negligible compared to the desorption rate by H^+ ions.

The mean ion confinement time τ^+_H of H^+ ions in the plasma magnetic field was modeled with a Gaussian profile that increases from the plasma periphery toward the plasma center. For example, the time τ^+_H at the periphery is 0.22 ms and in the central region is 4.5 ms. The confinement times of H^+, H_2^+, and H_3^+ ions follow the relation $\tau^+_H : \tau^+_{H2} : \tau^+_{H3} = 1 : \sqrt{2} : \sqrt{3}$ [13].

The confinement time τ_f of a fast atom is the time for this atom to fly through the diameter of the poloidal cross-section [1]. Each modeled confinement time is independent of the discharge time in each layer described in Section 2. The loss terms for H^+, H_2^+, H_3^+ ions, and fast atoms are represented as $-\frac{n^+_H}{\tau^+_H}$, $-\frac{n^+_{H2}}{\tau^+_{H2}}$, $-\frac{n^+_{H3}}{\tau^+_{H3}}$, and $-\frac{n_f}{\tau_f}$, respectively.

The equations for the time-dependent densities of the ions n^+_{H3}, n^+_{H2}, and n^+_H are as follows: (3)–(5)

$$\frac{dn^+_{H3}}{dt} = n_{H2} n^+_{H2} Q_8 - \frac{n^+_{H3}}{\tau^+_{H3}}, \quad (3)$$

$$\frac{dn^+_{H2}}{dt} = n_e(n_{H2}Q_2 - n^+_{H2}(Q_5 + Q_7)) - n_{H2} n^+_{H2} Q_8 - \frac{n^+_{H2}}{\tau^+_{H2}}, \quad (4)$$

$$\frac{dn^+_H}{dt} = n_e(n^+_{H2}Q_5 + n_H Q_9) + n_e n_f Q_9 - \frac{n^+_H}{\tau^+_H} - n_e n^+_H \alpha_{RR} . \quad (5)$$

The third term in the last equation relates to the ionization of fast charge-exchange atoms due to electron-atom collisions.

The electron density n_e is the sum of the H^+, H_2^+, and H_3^+ ion densities, due to plasma quasi-neutrality [14] (6):

$$n_e = n^+_H + n^+_{H2} + n^+_{H3}. \quad (6)$$

The equation for the time-dependent density of fast charge-exchange atoms n_f in plasma, derived from the second equation in the system of S.J. Fielding, is as follows (7):

$$\frac{dn_f}{dt} = -n_e n_f Q_9 - \frac{n_f}{\tau_f}(1 - \beta_f) + n_H n^+_H X + \beta_i \frac{n^+_H}{\tau^+_H}, \quad (7)$$

where β_f and β_i are the reflection coefficients of fast atoms and H^+ ions from the wall, respectively.

Terms not mentioned above include: 2) the loss of fast atoms from the plasma, followed by their implantation into the wall, and 4) the loss of H^+ ions from the plasma, followed by their reflection back into the plasma. The reflection coefficients from the stainless-steel chamber wall were calculated using the SRIM program [15] for a 45° incidence angle, expressing the average angle of particles striking the wall.

The equation for the time-dependent surface density n_w of hydrogen atoms implanted into the wall was derived from the fourth equation in the system of S.J. Fielding:

$$\frac{dn_w}{dt} = \frac{V}{A}\Big[\frac{n_H^+}{\tau_H^+}(1-\beta_i) + \frac{n_f}{\tau_f}(1-\beta_f) - \Big(\frac{n_H^+}{\tau_H^+} + \frac{n_f}{\tau_f}\Big)\sigma n_w\Big], \quad (8)$$

where V/A is the ratio of the plasma volume to the surface area of the vacuum chamber wall.

The first term, not introduced above, is the loss of H^+ ions from the plasma, resulting in their implantation into the wall with a coefficient of $1-\beta_i$.

4. RESULTS OF SIMULATED DENSITIES AND EMISSION COEFFICIENTS

The sets of particle densities in hydrogen plasma with the low electron density of variant A, observed only in the second RF discharge, were used for the analysis. Fig. 2 shows the plots of local density $n_e^c(t)$ at temperatures T_M = 8, 10, 30, and 60 eV.

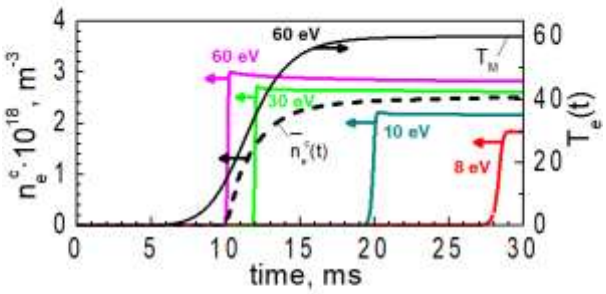

Fig. 2. Simulated local electron densities $n_e^c(t)$ with parameters T_M = 8, 10, 30, and 60 eV, the simulated average electron density $\bar{n}_e^c(t)$, and the local electron temperature $T_e(t)$ at the parameter T_M = 60 eV

The simulated average electron density $\bar{n}_e^c(t)$, shown in Fig. 2, was obtained by averaging the local densities $n_e^c(t)$ in the set $n_e^c(t, T_M)$ in the range of T_M = 6…60 eV. The densities were assigned the same statistical weight because the plasma layers have the same thickness, as shown in Section 2. This figure also shows the electron temperature $T_e(t)$ reaching a value of T_M = 60 eV at the stationary stage.

The moment of appearance of the simulated density $n_e^c(t)$ was defined as the moment of its increase from zero density. The densities $n_e^c(t)$ at T_M = 8, 10, 30, and 60 eV in Fig. 2 initially increase sharply, reach a maximum, and then decrease slowly toward the end of the discharge at t = 60 ms. The density $n_e^c(T_M)$ at the selected moment t = const increases with increasing parameter T_M.

The signal of the average density $\bar{n}_e(t)$ in Fig. 1 and the simulated average density $\bar{n}_e^c(t)$ in Fig. 2 are similar in shape. The signal of the average density in Fig. 1 reaches its maximum, and then decreases after the RF generator is switched off. The simulated average density $\bar{n}_e^c(t)$ in Fig. 2 reaches its maximum and then decreases very slowly to the end of the discharge. The simulated temperature $T_e(t)$ in this case continues to be stationary.

The delay of the electron density $n_e^c(t)$ appearance is the time interval from the start of the discharge to the density appearance. This delay, as shown in Fig. 2, is small in the plasma center (T_M = 60 eV) and increases toward the periphery (T_M = 6 eV) as the parameter T_M decreases. The density profile $n_e^c(T_M)$ decreases from the plasma center to the periphery at all stages of the discharge.

The description of particle density given here is for H^+ ions only. The density of H^+ ions is the highest among all hydrogen ions. The calculation showed that the electron density plots $n_e^c(t)$ slightly exceed the corresponding ion density plots $n_H^+(t)$ and approximately repeat their shape. The electron density $n_e^c(t)$ is higher than the ion density $n_H^+(t)$ by no more than 4.3, 3.5, 1.6, and 0.7% for the corresponding values of the parameter T_M = 8, 10, 30, and 60 eV. This difference is equivalent to the summary density $n_{H2}^+(t)$ + $n_{H3}^+(t)$ of ions, as follows from Equation (6). Each of the densities $n_{H2}^+(t)$ and $n_{H3}^+(t)$ is significantly lower than $n_H^+(t)$.

The emission intensity I of the spectral line emitted from the plasma is, by definition, an integral of the local emission coefficient ϵ along the line of sight [16]. Integration can be represented as the sum of emission coefficients $\epsilon_\alpha(t)$ of the H_α line, using the set $\epsilon_\alpha(t, T_M)$ in the interval T_M =6…60 eV. The line of sight and the layers of equal thickness are taken into account. The result is the simulated intensity $I_\alpha^c(t)$ of the H_α line.

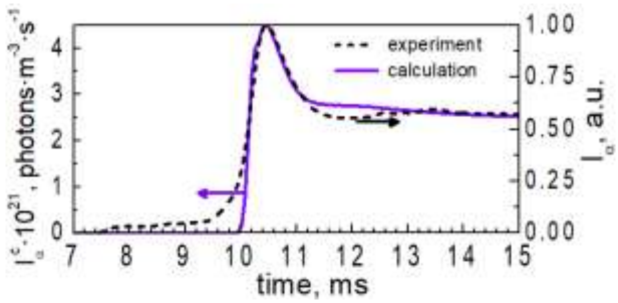

Fig. 3. The time-dependent experimental intensity $I_\alpha(t)$ of the H_α line and the simulated intensity $I_\alpha^c(t)$ of the H_α line

The coefficients $\epsilon_\alpha(t)$ were calculated in the range of T_M = 6…60 eV to create a set $\epsilon_\alpha(t, T_M)$. The densities $n_e^c(t)$, $n_H(t)$, and the rate coefficient of electron excitation $\overline{\sigma v}_{exc}$ of the H_α line were used to calculate the coefficients $\epsilon_\alpha(t)$ [4, 10]. Fig. 3 shows the intensity signal $I_\alpha(t)$ with the parameter U_a = 7 kV from Fig. 1 and the simulated intensity $I_\alpha^c(t)$.

Both curves are similar in shape, except for the increase in the I_α(t) signal in the interval from 7.5 to 10 ms after the pre-ionization stage.

The developed technique for simulating electron density and H_α line intensity using the SDE can be applied to the study of hydrogen injection into hydrogen plasma. This technique can also be used to study the effect of hydrogen pressure applied before the RF discharge on the average electron density of hydrogen plasma.

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CONCLUSIONS

The technique of numerical simulation of time-dependent particle densities in hydrogen plasma in the Uragan-2M stellarator was applied to the variant with low electron density. The simulation focused on two main signals: the average electron density and the intensity of the H_α spectral line.

This technique was applied in an experimental scenario involving two successive RF discharges: hydrogen pre-ionization and plasma creation. The signals were simulated during the second RF discharge, using the calculated local dependencies of electron density and the emission coefficient of the H_α line.

The increase in electron temperature caused a shift in the simulated time-dependent electron density toward the start of the RF discharge and an increase in its magnitude.

These data were used to calculate the average electron density and the intensity of the H_α line in the specified electron temperature range. The calculation results and the corresponding signals demonstrated similar pulse shapes.

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МОДЕЛЮВАННЯ ЕЛЕКТРОННОЇ ГУСТИНИ ТА ІНТЕНСИВНОСТІ СПЕКТРАЛЬНОЇ ЛІНІЇ H_α У ВОДНЕВІЙ ПЛАЗМІ СТЕЛАРАТОРА УРАГАН-2М

В.М. Бондаренко

Залежні від часу сигнали середньої електронної густини та інтенсивності спектральної лінії H_α були виміряні під час ВЧ-розряду, що створював густу водневу плазму в стелараторі Ураган-2М. Ці дані стали основою для моделювання локальної електронної густини та коефіцієнта емісії лінії H_α, що залежать від часу, в системі диференціальних рівнянь. Локальні густини електронів значно змінювалися внаслідок змодельованого підвищення електронної температури. Підтверджено схожість сигналів середньої електронної густини, сигналів інтенсивності лінії H_α та відповідних змодельованих залежностей.