INVESTIGATION OF RADIAL DISTRIBUTIONS OF SPECTRAL LINE RADIATION EMISSIVITIES IN TORSATRON "URAGAN - 3M"

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The determination of the radial distributions of the radiation emissivity of the spectral lines relating to the working gas and impurities in the different ionization stages is an important object of the plasma spectroscopy diagnostics. The measured radiance chord distributions of the plasma in the specified spectral lines serve as a basis to obtain the radial distributions of the atom and ion concentrations. For the axially asymmetric magnetic surfaces in the torsatron "Uragan-3M" (U-3M) the approach of Pearce is realized by the computer program in an interpretation of the data on the radiance measured along the slanting lines of sight. The volumetric constants were computed with an interval between the lines of sight equals to 1 mm along the vertical plasma diameter in the DD cross-section. Such a small step excludes the roughness of the constants interpolation when turning to the radial distributions. The set of the 19 nested magnetic surfaces was chosen as an optimal one compared to any other number in the range of 10-24 surfaces. The chord measurements of the plasma volume radiance were carried out in the regular working regimes of U-3M. Using the experimental chord distribution data, the radial distributions of the radiation emissivity of several spectral lines were obtained: Hα, CV, CIII, OV, OIV, OIII, OII, etc. In the paper the radial profiles of concentrations of C^{4+} and C^{2+} carbon ions and hydrogen atoms in the ground and in excited states were presented found from the radiation emissivity data.

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1. INTRODUCTION

Many spectral methods are routinely used for the plasma diagnosing in the fusion devices with magnetic confinement of plasma. From a radial distribution of the emissivity of different spectral lines the radial distributions of important plasma parameters can be obtained such as: the concentrations of working gas atoms and impurity ions, the ion temperature, and, in some cases, the electron temperature (by analysing the selected spectral lines ratios). In addition, the time evolution of the chord and radial distributions allows to control the behavior of the working gas, the evolution of some plasma instabilities and to define the impurity influx localization. The radial distributions of the axially symmetrical sources of light are obtained usually by the methods of the abelization, such as the solution of the Abel equation [1] or the solution of the system of linear algebraic equations by the numerical method of Pearce [1, 2]. In the torsatron U-3M all the poloidal cross-sections of magnetic surfaces are not axially symmetric. However, for U-3M magnetic configuration the numerical method discussed in [1, p. 182] for the non-symmetry case (so-called, Pearce approach) is acceptable. Within this approach, all the plasma characteristics are considered to be the constants inside every of 19 curvilinear ring zones. Besides, it was supposed that the presence of the plasma does not distort essentially the configuration of the vacuum magnetic surfaces.

2. EXPERIMENTAL SETUP

As **Fig.1** shows, the plasma radiation at the chosen spectral line in the visible and UV wavelength range passes through the side quartz window (W) centered in the poloidal cross-section DD, which is symmetrical relatively to the central plane. Then it passes through the optical tract: the lens (L) d94 mm, the monochomator (M) of a MDR-23 type blocked with the photomultiplier (PM). The PM signal was amplified and recorded. The chord distributions of the plasma volume radiance for each spectral line were obtained shot by shot for several identical discharge pulses. In the plane of the DD cross-section (**Fig. 1**), the geometric axis of the helical coils specifies the origin of coordinates, with the vertical axis OX and horizontal axis OY. The chord distribution of the radiance is measured along OX as a function of a chord height h from the torus central plane. The vertical stepped scan of the sight chords is obtained by the lens displacement. The plasma outermost vertical coordinates are -145 mm and +145 mm. The vertical minor radius serves here to plot the radial distributions.

3. PREPARATION OF THE VOLUMETRIC CONSTANTS AND CREATION OF THE RADIAL DISTRIBUTIONS OF SPECTRAL LINE EMISSIVITIES

The constants of the volumetric elements a_{ij} for the DD cross-section were prepared for the permanent use when obtaining the emissivity radial distributions. **Fig. 1*** shows the D-type ring zones, bounded by the smooth magnetic surfaces that were calculated using the magnetic field of equiform helical coils, without taking into account the island structures. The developed here emissivity radial distributions are of two types: the function of a ring zone number K (K=1..19) is designated here as J_K**;** the function of a radius r is designated here as J(r). The chord distribution of a radiance is named B(h).

The volumetric constants were computed by a program along the respective slanting lines of sight (LOS). These lines (total number 291) intersect a vertical diameter with an interval of 1 mm. To test the availability of this interval choice, a chain of computer reconstructions was provided. After a substitution of a constant emissivity into each K-th zone of J_K, the resulting B(h) was calculated, then it is reconstructed again into J_K. The resulting error in this chain has an appropriate value of 0,1 %. In a variant with the minimal number of LOS (38–40) the test showed an error up to 10 %. From several LOS, situated between the pair of neighbor magnetic surfaces, the optimal one was chosen during the tests.

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* All Figures are presented in Figures Section

In the Pearce method realization on the experimental material, the standard solution of the linear equations system yields the spectral line radiation emissivity J_K dependence on the rings numeration. Using the conventional relation between the ring number and the ring edge vertical coordinate, the radial distribution of J(r) along the vertical radius is obtained from the distribution of J_K by a standard procedure. The experimental chord distributions were smoothed to acquire information on the correct profiles of the radiance to be operated in the radial distribution reconstruction.

4. RADIAL DISTRIBUTIONS OF SPECTRAL LINE EMISSIVITY OF WORKING GAS AND IMPURITIES

The chord measurements of plasma radiance for the spectral lines were carried out in the regime of U-3M, typical for the last campaigns: the toroidal magnetic field 7 kG, the power radiated by the RF-antenna P_{RF}=200-300 kW, RF voltage applied to the antenna 8 kV, the discharge pulse duration ~50 ms, the mean electron density $\bar{n}_e \sim 1.5\cdot10^{12}$ cm^{-3}, the working gas – hydrogen. In such conditions the plasma is optically thin for all emission under the investigation.

The stationary corona model was considered here as basic, including the existence of the metastable states and the different excitation and ionization processes of atoms and ions [3, 4]. The radiance chord distributions for the spectral lines H_α 656.3 nm, H_β 486.1 nm, CII 514.5 nm, CIII 464.7 nm and 229.7 nm, CIV 465.8 nm and 253.0 nm, CV 227.1 nm, OII 441.5 nm, OIII 376.0 nm, OIV 373.7 nm, OV 278.1 nm, etc. were obtained. The most important lines are shown in **Fig. 2b**: the line H_α (656.3 nm) of the transition 3–2 with the upper level n=3, the line CV (227.1 nm) of the transition 1s2p($^3P_2$)–1s2s($^3S_1$) with the upper level named "5", the line CIII (464.7 nm) of the transition 2s3p($^3P_2$)–2s3s ($^3S_1$) with the upper level named "9".

The radiance of the spectral lines B(h) in the absolute units (photons•cm^{-2}•s^{-1}•sr^{-1}) were obtained, using calibration, based on the comparison with the emissivity of the standard tungsten ribbon lamp. The data in **Fig. 2a** are shown in the arbitrary units. The respective radial distributions of emissivity J(r) were calculated in the absolute units (photon•s^{-1}•cm^{-3}). Then the radial distributions of the concentrations n*(r) of the excited particles: hydrogen atoms, CV and CIII ions **(Fig. 3)** were found by the expression $n^*(r)=J(r)/A_{ik}$, where A_{ik} is a spontaneous decay constant.

The shape of the distribution $n_3^*(r)$ of H atoms excited to the level n=3, related to the H_α line, has a small drop near r~0. This shape is consistent with one, predicted by the program on the plasma modeling, used in [5], for the plasma conditions similar to the nowaday experiments (the mean values: T_e~300 eV, $\bar{n}_e \sim 1.5\cdot10^{12}$ cm^{-3}), where the influence of the H_2 molecules dissociative excitation was evaluated as significant for the plasma central region.

The radial distribution of the concentration of hydrogen atoms in the ground state, $n_H(r)$, can be evaluated from the radial distribution (**Fig. 3**) of excited H atoms, $n_3^*(r)$. It is assumed, that the level n=3 of H atom is populated, mainly, by the two processes [3], the electron excitation from the atom ground state:

$$e^- + H \rightarrow H^*(n=3) + e^- \qquad (1)$$

and the dissociation of excited molecules H_2^{**}:

$$e^- + H_2 \rightarrow H_2^{**} \rightarrow H^*(n=3) + H^*(n, l). \qquad (2)$$

The H atoms in the ground state with total concentration n_H are produced, mainly, due to three processes: dissociation of H_2 molecules, dissociation of molecular ions H_2^+, and from the charge exchange process, leading to production of hot H atoms. Assuming that the disposition of the H atom along the radius is negligibly small during the time of a spontaneous decay, the quantity of atoms in cm^3, excited to the level n=3, accounting these processes, is defined by the expression:

$$n_3^*=n_e(\langle 6v_a\rangle n_H + \langle 6v_m\rangle n_{H2})/(A_{31}+A_{32}), \qquad (3)$$

where n_e, n_H, n_{H2} (cm^{-3}) are: the density of electrons, the concentrations of hydrogen atoms and molecules; $\langle 6v_a\rangle$, $\langle 6v_m\rangle$ (cm$^3\cdot$s^{-1}) – rate coefficients for excitation of H_α by the electron impact, respectively on H atoms and H_2 molecules [3]; the constants A_{ik} are taken from [6].

The radial distribution $n_H(r)$ of hydrogen atoms in the ground state, shown in **Fig. 4**, is found from (3), using the series of computed radial distributions:

(a) $n_3^*(r)$ – the concentration distribution of H atoms, excited to the level n=3, see **Fig. 3**;

(b) $n_e(r)$, $T_e(r)$ – the electron density and temperature radial distributions, measured in the experiment;

(c) $n_{H2}(r)$ – the distribution of the concentration of molecules in the axially asymmetric cross-section DD. This distribution is transformed from the axially symmetric distribution, calculated numerically by the modeling program used in [5], with the experimental $n_e(r)$, $T_e(r)$ parameters accepted. All the distributions a)–c) correspond to the same time moment of the regular working discharge, (**Fig. 2b)**, taking into account the independent measurements of n_e and T_e in plasma.

In **Fig. 4** the radial distributions of the C^{2+} and C^{4+} ions in the nonexcited state are shown, which were computed from the radial distributions of excited ion concentrations $n^*_{CIII}(r)$ and $n^*_{CV}(r)$, using the method and some designations, described in [4].

The values of the averaged distributions of the excited and nonexcited ions (respectively, $\langle n^*(r)\rangle$, $\langle n_z(r)\rangle$), and the averaged ratio of $\langle n_z(r)/n_e(r)\rangle$ are given in the Table. For comparison, the values for H_α are specified. The averaging was taken over the plasma radius.

Table Average values from data of Fig. 3, 4.

	$\langle n^*(r)\rangle$, cm^{-3}	$\langle n_z(r)\rangle$, cm^{-3}	$\langle n_z(r)/n_e(r)\rangle$, %
CV	$8.8\cdot10^3$	$8\cdot10^9$	0.7
CIII	$5.3\cdot10^3$	$6.3\cdot10^8$	0.07

	$\langle n_{H^*(3)}(r)\rangle$, cm^{-3}	$\langle n_H(r)\rangle$, cm^{-3}	$\langle n_H(r)/n_e(r)\rangle$, %
H_α	$3.4\cdot10^5$	$3.7\cdot10^9$	0.4

We used here the calculated magnetic surfaces, which are idealized ones in comparison to those measured in the experiment. Therefore the given radial profiles have the character of estimation and are used for evaluation of averaged concentrations. Also, the excitation function for CIII 464.7 nm [4, p.7] is reliable at T_e<160 eV, that provides reasonable $n_{z,CIII}(r)$ distribution at radius value of r≥4 cm (**Fig. 4**).

5. CONCLUSIONS

1. The program is developed for calculation of the radial distributions of the line intensity using chord measurements.
2. The obtained results look convincingly enough with taking into account the independent measurements of $n_e(r)$ and $T_e(r)$ in the U-3M plasma.
3. The procedure of the radial distribution calculation was found to be useful for treatment of the diagnostic data obtained in experiments on the U-3M torsatron.

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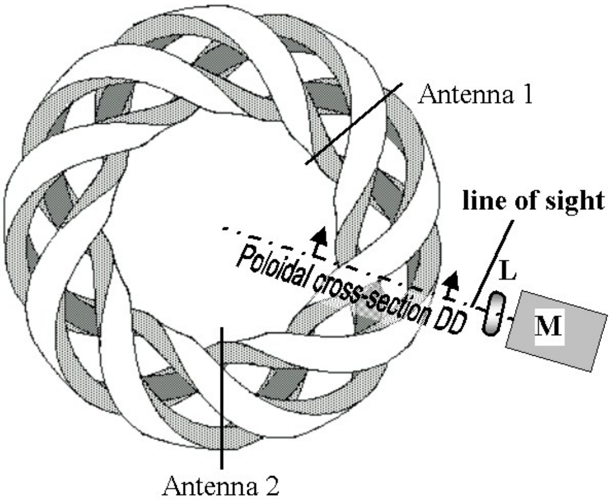
FIGURES SECTION

the top view of U3-M magnetic system:



the view along toroidal magnetic axis:

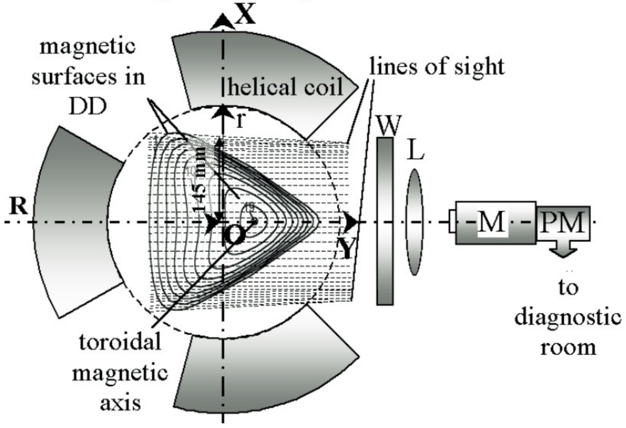


Fig. 1. The scheme of measurement of the emitted line radiance chord distribution.

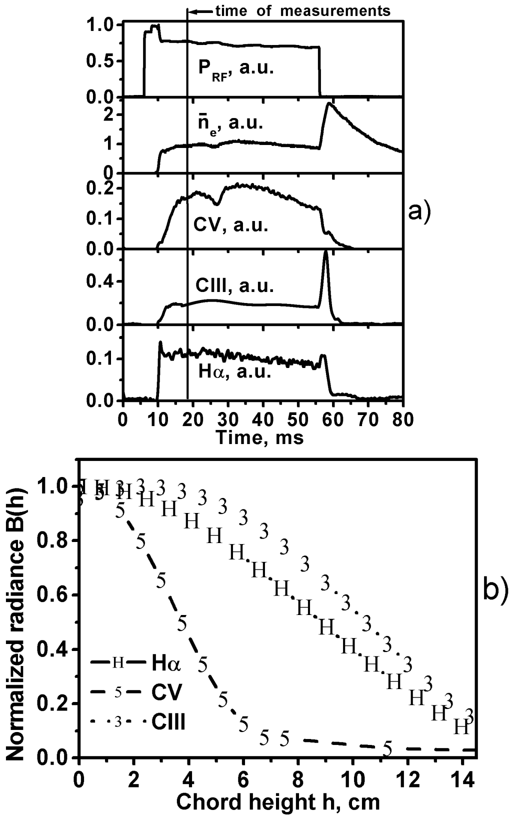


Fig.2. (a): time evolution of some signals. (b): chord distributions of some spectral line radiances B(h).

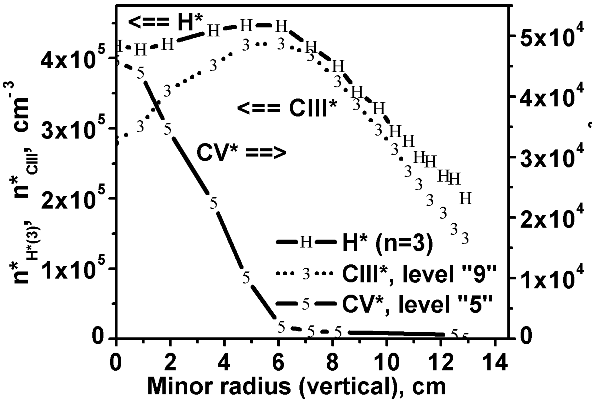


Fig. 3. Radial distributions of concentrations n(r) of the excited radiants. For CIII the ordinate scale must be divided by 55.*

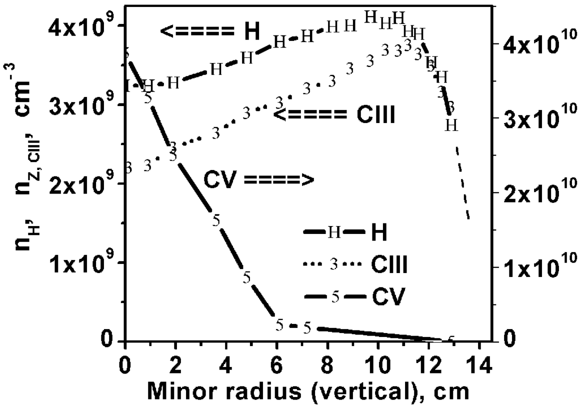


Fig. 4. Radial distributions of concentrations of nonexcited H atoms, ions CV, and CIII. For CIII the ordinate scale must be divided by 5

ДОСЛІДЖЕННЯ РАДІАЛЬНИХ РОЗПОДІЛІВ ИНТЕНСИВНОСТЕЙ ЕМІСІЇ СПЕКТРАЛЬНИХ ЛІНІЙ У ТОРСАТРОНІ УРАГАН-3М

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Одним з методів, використовуваних спектроскопічною діагностикою плазми в установках термоядерного синтезу, є визначення радіальних розподілів інтенсивності емісії спектральних ліній, що відносяться до робочого газу і домішок, які знаходяться на різних стадіях іонізації. Вимірювані хордові розподіли яскравості світіння плазми з застосуванням обраних спектральних ліній є основою для одержання радіальних розподілів концентрації атомів і іонів. Для аксиально-асимметричних магнітних поверхонь у торсатроні "Ураган-3М" (У3-М) підхід Пірса реалізується за допомогою комп'ютерної програми в інтерпретації нахилених ліній спостереження. Розрахунковий набір даних з 19 магнітними поверхнями був обраний як оптимальний з наборів з кількістю поверхонь 10–24. Хордові виміри яскравості з об'єму плазми проводилися в постійних робочих режимах "Урагану-3М". Використовуючи експериментальні дані хордових розподілів, були отримані радіальні розподіли інтенсивності емісії випромінювання спектральних ліній H_α, CV, CIII, OV, OI, OIII, OII та ін. Радіальні профілі концентрації частинок в основному й у збудженому станах визначені для атомів водню й іонів вуглецю C^{4+}, C^{2+} за даними інтенсивності випромінювання.

ИССЛЕДОВАНИЕ РАДИАЛЬНЫХ РАСПРЕДЕЛЕНИЙ ИНТЕНСИВНОСТЕЙ ЭМИССИИ СПЕКТРАЛЬНЫХ ЛИНИЙ В ТОРСАТРОНЕ УРАГАН-3М

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Одним из методов, используемых спектроскопической диагностикой плазмы в установках термоядерного синтеза, является определение радиальных распределений интенсивности эмиссии спектральных линий, относящихся к рабочему газу и примесям, находящимся на различных стадиях ионизации. Измеряемые хордовые распределения яркости свечения плазмы с применением выбранных спектральных линий служат основой для получения радиальных распределений концентрации атомов и ионов. Для аксиально-асимметричных магнитных поверхностей в торсатроне "Ураган-3М" (У3-М) подход Пирса реализуется при помощи компьютерной программы в интерпретации наклонных линий наблюдения. Расчетный набор данных с 19 магнитными поверхностями был выбран как оптимальный из наборов с количеством поверхностей 10..24. Хордовые измерения яркости из объема плазмы проводились в постоянных рабочих режимах "Урагана-3М". Используя экспериментальные данные хордовых распределений, были получены радиальные распределения интенсивности эмиссии излучения спектральных линий H_α, CV, CIII, OV, OIV, OIII, OII и др. Радиальные профили концентрации частиц в основном и в возбужденном состояниях определены для атомов водорода и ионов углерода C^{4+}, C^{2+} по данным интенсивности излучения.