DYNAMICS OF THE EMISSION SPECTRUM OF THE HYDROGEN-OXYGEN PLASMA OF PULSED DISCHARGE IN WATER IN THE RANGE OF THE BALMER SERIES WITH A MINIMUM OF IMPURITIES

O.A. Fedorovich, L.M. Voitenko
Institute for Nuclear Research NASU, Kiev, Ukraine
E-mail: oafedorovich@kinr.kiev.ua

The results of experimental investigations of the spectral distribution of radiation of hydrogen-oxygen plasma pulsed discharges in water in a minimum difference of radiation from the blackbody radiation (BBR) are given. The pressure in the plasma channel was changed from 5000 to 80 atm, the brightness temperature of 24·10^4 to 7·10^4 K. The difference in brightness temperatures of the violet and the red area does not exceed ± 2000 K of the average temperature. With the relaxation of plasma electron density decreased from 2·10^{10} to 10^{17} cm^{-3}. It is shown that at high concentrations of electron spectral distribution of the radiation in the spectral range of the Balmer series differs little from the blackbody radiation is not observed and none of the hydrogen Balmer line. This indicates "non-realization" even the top level line H_{α} (656.2 nm, with excitation energy of the upper level of 12.09 eV). As the relaxation of the plasma to be consistent line H_{γ}, H_{β}, H_{α}. There is a redistribution of the broadening of the hydrogen lines of the Balmer series. At N_e ≤ 10^{17} cm^{-3} hydrogen emission spectrum coincides with the traditional.

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INTRODUCTION

Optical radiation nonideal plasma is practically the only source of information on plasma parameters, the structure of the plasma channel, the mean free path of photons, radiant thermal conductivity, line broadening in a plasma, "optical reduction of the ionization potential", reducing the oscillator strengths, "non-realization" of individual, high-lying levels, and so on [1]. The study of the spectral distribution of radiation is necessary for the calculation of the energy and the particles balance in the channel of a pulsed discharge in water, revealing the influence of non-ideal effects on the emission spectra of hydrogen-oxygen plasma, the development and testing of the methods for measuring the basic plasma parameters and to identify the range of applicability of these methods depending on the electrons concentration in the plasma. The hydrogen-oxygen plasma produced in a pulsed discharge in water (PDW) on 2/3 is composed of atoms and ions of hydrogen. It is one of the significant advantages in the study of such plasma to determine the effects of nonideality influence on the emission spectra and their dependence on the electron concentration and temperature.

The spectrum of the hydrogen is the simplest for theoretical description as a hydrogen atom consists of a single electron and proton. But the published data on the hydrogen spectra at high electron densities are insufficient and they often contradictory (see in particular [2 - 8]). This is due to the fact that these data have been obtained at essentially different research facilities parameters, different methods of nonideal plasma obtaining and different initial conditions. Theoretical estimates of the non-ideal properties of the plasma are given in (see in particular [1, 10, 12]).

This paper presents the results of experimental investigations of the spectral distribution of radiation of hydrogen-oxygen plasma, and the evolution of the emission spectra at the stage of relaxation, depending on the temperature and on the optical thickness reducing. Also, presents the results of testing of different methods to determine the main parameters of the plasma.
To eliminate the influence of impurities of metal vapors coming from the electrodes [15] we chosen for study the spectrum of the discharge with electrode gap length 100 mm and investigated the middle of the channel.

As follows from Fig. 1, the emission spectrum of the hydrogen-oxygen plasma at an initial stage of the discharge (9 ± 2) microseconds) differs little from the blackbody radiation at a temperature (20 ± 1)⋅10^3 K. In near-threshold region, as well as in the area of most intense spectral H\(\alpha\) lines of hydrogen Balmer series no singularities of the spectrum is observed.

The plasma pressure, calculated by the hydrodynamic characteristics of the channel and model of quasi-incompressible fluid is \(\sim 2\cdot10^3\) at, and the electron density is less than \(N_e\sim 5\cdot10^{19}\) cm\(^{-3}\) at a concentration of atoms \(N_a\sim 5\cdot10^{20}\) cm\(^{-3}\) [18].

In the wall region of the plasma channel is always a colder region. The degree of ionization of the plasma in the colder region not exceeding 10%, and at this temperature there is always excited hydrogen atoms. In this case, inevitably had be observed in the absorption lines of hydrogen H\(\alpha\) (\(\lambda = 656.2\) nm). However, as shown in Fig. 1, this does not occur, which indicates the manifestation of the effect of "non-realization" of the upper level of the most intense line of the Balmer series.

Over time, as the pressure reduction, the emission intensity of the absorption line H\(\alpha\) begins to rise somewhat, while in other areas it is somewhat reduced (Fig. 2), (t = (12 ± 2) µs). To detect absorption in the H\(\alpha\) line also fails. At the time (t = (22 ± 2) µs) is already clearly seen in the absorption line H\(\alpha\) (Fig. 3).

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Over time, as the pressure reduction in the emission intensity at the spectrum-threshold and begins to rise somewhat, while in other areas it is somewhat reduced (see Fig. 2), (t = (12 ± 2) µs). To detect absorption in the H\(\alpha\) line also fails.

At the time (t = (22 ± 2) µs) is already clearly seen in the absorption line H\(\alpha\) (see Fig. 3). The intensity of the emission spectrum in the supercritical region corresponds to \((22 ± 2)\cdot10^3\) K. If at the same time to measure the temperature in the center of the reabsorb line H\(\alpha\) it is \(\sim 14.5\cdot10^3\) K. The pressure in the plasma channel at the same time about \(\sim 300\) at and \(N_e\sim 3\)
Fig. 4. The dependence of the radiation intensity
$I = f (\lambda)$ hydrogen-oxygen plasma. $W$, $d = 20 \mu$m;
$U_0 = 30 \text{kV}; l_0 = 100 \text{mm}; t = (48 \pm 2) \mu\text{s}$

These results indicate an inaccuracy of theoretical calculations of line broadening at high values of the micro-fields [15], in spite of the Debye screening accounting for the electron and ion components and the line broadening at high concentrations.

As already noted, the pressure drop as the optical thickness and temperature of the plasma decreases and continuous emission spectrum is transformed into a line spectrum. Fig. 5 shows the emission spectrum of the hydrogen-oxygen plasma, when the lines $\text{H}_\alpha$, $\text{H}_\beta$, $\text{H}_\gamma$ become prominent in a continuous spectrum of radiation. The optical thickness in the distant wing of the line $\text{H}_\alpha$, is reduced to $\tau = 1.5...2$ [13, 17].

Note that the values of $\tau$, obtained by the method of plasma transillumination under PRW give overestimated $5...8$ times values. This is due to the passage of the rays through the plasma. Plasma is in the water with a refractive index $n = 1.34$, while for $n = 1$ the plasma [20]. This cylindrical plasma channel works as a cylindrical lens.

Given that the boundary of the channel are not always strictly cylindricity due to instabilities of the plasma channel is correctly taken into account in determining the curvature of the intensity of the transmitted beam is not possible.

Fig. 5. The dependence of the radiation intensity
$I = f (\lambda)$ hydrogen-oxygen plasma. tungsten, $d = 20 \mu$m;
$U_0 = 30 \text{kV}; l_0 = 100 \text{mm}; t = (37 \pm 3) \mu\text{s}$

Because of this value of $\tau$, obtained by the method transillumination essentially overestimated and they can not be used, although plasma is possible to enlighten in the later stages the discharge.

In violet part of the continuous spectrum of the value of $\tau$ should be even smaller. The parameters of the plasma channel, defined by several independent methods are: $P = 120 \text{ bar}, N_e = 10^{19} \text{ cm}^{-3}, T = 17 \cdot 10^3 \text{ K}$. At the same time temperature as determined by the intensity at the maximum reabsorbs line $\text{H}_\alpha$ [13] and in the threshold of the Balmer series of the spectrum are the same. The temperature obtained by $I$ for the line $\text{H}_\beta$ somewhat higher.

A characteristic feature of the emission spectrum is the fact that the half-width of the line $\text{H}_\beta$ more than $\text{H}_\alpha$ and $\text{H}_\gamma$, although according to the theory of line broadening [15] should be the opposite. The same effect is observed upon further reduction of $P$ and $T$ (Fig. 6). Here the half-width of the line $\text{H}_\alpha$, $\text{H}_\beta$ is $150$, $140$ A, $\text{H}_\gamma$ $65$ A. The optical thickness in the red region of the continuous spectrum $\tau < 1$ [15].

Therefore, the effect of the near-wall cold regions of the plasma can be neglected. They partially affect reabsorption in the central region of the line $\text{H}_\alpha$, where $\tau$ more ($\tau > 10$), but their influence on the radiation in the violet part of the spectrum should be negligible.

The parameters of the plasma channel are follows: $P = 100 \text{ atm}, T_{\max} = 15.5 \cdot 10^3 \text{ K}, N_e = 6 \cdot 10^{18} \text{ cm}^{-3}$, the bore diameter $d = 23.4 \text{ mm}$.

In Figs. 7, 8 show the dynamics of the emission spectrum at lower plasma concentrations and low temperatures. These figures show that the half-width of the lines $\text{H}_\alpha$ and $\text{H}_\beta$ are compared, and then, when at $N_e \leq 2 \cdot 10^{17} \text{ cm}^{-3}$ lines $\text{H}_\beta$ are wider than $\text{H}_\alpha$, as predicted by the theory [19], and the values of $N_e$, obtained by the half-widths of these lines are virtually identical. Decreases while the intensity $\text{H}_\beta$ line and $\text{T}$ defined poney becomes smaller than defined by certain intensity in $\text{H}_\alpha$ which could be evidence of small optical thickness in line $\text{H}_\beta$.

In the adjacent and threshold areas of the series spectrum regions intensity is slightly higher than in other areas.

In the near-threshold areas and threshold areas a series of intensity of the spectrum is somewhat higher than in other areas. Line $\text{H}_\alpha$ observed only a few microsec-
onds, and its half width is less than Hβ, microseconds, and its half width is less than the line Hβ [5, 6]. Line Hβ from the continuous spectrum was unable to locate.

According to [10, 11] Hα line should "not be realized" when the electron density \( N_e \geq 2 \times 10^{19} \text{ cm}^{-3} \), Hβ when \( N_e \geq (1.5...3) \times 10^{18} \text{ cm}^{-3} \), Hγ when \( N_e \geq 0.9 \times 10^{18} \text{ cm}^{-3} \). These \( N_e \) values are somewhat lower than those obtained experimentally by several methods [20].

Perhaps this is due to colder regions near the walls, and realization of the lines with higher levels just in them.

The above results indicate a decrease or redistribution of oscillator strength, predicted in [21], and the "non-realization" of lines level in the micro-fields, comparable in magnitude to the strength of intra-atomic fields, and in this range includes most intense level of Hα lines.

**CONCLUSIONS**

The plasma parameters can be measured outside the boundaries of the series or on lines that are not affected by non-realization, as predicted theoretically in [5, 6]. Especially strongly last effect is manifested with increasing rate of energy input into the channel [3].

From the above results and results in [13] it can also be concluded that it is permissible to determine the electron density from the Stark broadening of the lines Hα when \( N_e < 10^{19} \text{ cm}^{-3} \) and Hβ when \( N_e < 10^{18} \text{ cm}^{-3} \).

To measure the maximum temperature along the line monitoring the intensity of the radiation maximum Hα line can be reabsorbed immediately after discharge from the continuous spectrum.

**REFERENCES**

5. O.A. Fedorovich. Empirical formula for the dependence of the “optical gap” value on the electron concentration \( N_e \) within the range of \( 10^{17} \text{ cm}^{-3} \leq N_e \leq 10^{19} \text{ cm}^{-3} \) // Problems of Atomic Science and Technology. Series “Plasma Electronics and New Methods of Acceleration”. 2013, №4, p. 223-228.
6. O.A. Fedorovich. Experimental Investigation of Optical Properties of Nonideal Plasma within the Electron Concentration Range \( 10^{17} \text{ cm}^{-3} \leq N_e \leq 10^{19} \text{ cm}^{-3} \) // TPHT. 2014, v. 52, №4, p. 524-534 (in Russian).
ДИНАМІКА СПЕКТРА ИЗЛУЧЕННЯ ВОДОРОДНО-КИСЛОРОДНОЇ ПЛАЗМИ ИРВ В ДІАПАЗОНО СЕРИЇ БАЛЬМЕРА С МІНІМАЛЬНИМ КОЛИЧЕСТВОМ ПРИМЕСІЙ

О.А. Федорович, Л.М. Войтенко

Приведені результати експериментальних ісследований спектральних розподілів нерелаксації плазми на електронів концентрації над 10^17 см^-3.

ДИНАМІКА СПЕКТРА ВИПРОМИНАННЯ ВОДНЕВО-КИСНЕВОЇ ПЛАЗМИ ИРВ У ДІАПАЗОНЕ СЕРИЇ БАЛЬМЕРА З МІНІМАЛЬНОЮ КІЛЬКІСТЮ ДОМІШОК

О.А. Федорович, Л.М. Войтенко

Наведено результати експериментальних досліджень спектральних розподілів випромінення воднево-кисневої плазми в межах діапазону короткого випромінювання (АЧТ).