DEPENDENCE OF NONEQUILIBRIUM OF RADIATION OF A PULSED DISCHARGE IN WATER IN THE VISIBLE RANGE ON THE ELECTRIC FIELD STRENGTH

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The results of experimental studies of nonequilibrium of radiation in the visible range of a nonideal plasma (NP) are presented. The plasma was produced in pulsed discharges in water (PDW) with minimum amount of impurities. The PDW was initiated by explosion of a tungsten wire with diameter of 20 microns. The radiation from the PDW channel is nonequilibrium. The brightness temperature measured at wavelengths 400 and 700 nm differs up to two times, especially at high rates of energy input into the PDW channel. The dependences of NP nonequilibrium radiation on electrical parameters of the plasma channel were investigated. It was found that the oscillations of the plasma channel radiation intensity do not correlate with the power input to the channel. At the same time, the value of nonequilibrium of radiation, i.e., $\Delta T/\Delta\lambda$ (K/nm), does correlate with oscillations of power. The highest values of the nonequilibrium correspond to the first or the third current maximums. The dependences of the maximum intensity of nonequilibrium radiation on the electric field strength in the first current maximum, on the initial electric field strength in the discharge, and on the length of the discharge gap are examined at a constant initial battery voltage. Possible mechanisms of the observed effects are discussed.

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INTRODUCTION

Optical radiation of pulsed discharges in water is one of the most important sources of information about the structure and parameters of the plasma in the discharge channel. Investigation of the emission spectrum is necessary for the calculation of the energy balance and the balance of the particles in the channel, as well as for finding the most important parameters of the non-ideal hydrogen-oxygen plasma by measuring of the plasma continuous and line emission (absorption) spectra.

Using the emission and absorption spectra one can obtain information about the chemical composition of the plasma, the temperature of the plasma channel, the concentration of electrons in the plasma, their time dependences, and the distributions on the radius and length of the channel. After obtaining the spectral and spatial-temporal characteristics of the plasma channel, it is possible to calculate the radiation losses from the plasma channel during its development, as well as an entire energy balance in the channel.

The primary intent of the researches presented in this paper is to provide the measurements of the brightness temperature of nonideal plasma in PDW and to study the time variation of the brightness temperature depending on the conditions of input power in channel.

It was shown in [1, 2] that the radiation from the PDW channel is nonequilibrium, and the plasma channel brightness temperatures measured at different wavelengths can differ significantly. Note, that radiation of a nonideal plasma obtained in magnetoplasma erosive type compressor, is also nonequilibrium [3].

The degree of radiation equilibrium deviation from the radiation of an absolutely black body increases with increasing electric field strength, as was obtained in this work. In [4] this effect was explained by appearance of ultra-fast non-Maxwellian electrons, what results in an increase of the emission of high energy photons. A more detailed study of the PDW channel nonequilibrium radiation and its dependence on the discharge parameters are given in the present work.

1. RESULTS AND DISCUSSION

The techniques for obtaining the PDW emission spectra with good space and time resolution, and calibration of photographic film on the intensities that differ by 100 times, are given in [5, 6]. To calibrate the film the reference source EV-45 [7] was used. The processing of the spectra was performed by the method of homochromatic photometry having intensity determination accuracy better than 10 % [8].

The experiments were provided at the installation with following parameters: the energy of the capacitor bank (capacitance 14.6 μF) reached 10 kJ at 37 kV; the period of discharge can be variable T =15.5…110 μs; the discharge current – up to 200 kA; the length of discharge channel 10…100 mm. The discharge was initiated by explosion of a tungsten wire with diameter 20 μm. The initial battery voltage was ranged from 7.5 to 37 kV. Below, if the discharge period is not mentioned it was equal to 15.5 μs.

The results of brightness temperature measurements at different wavelengths are shown in Fig. 1. We see that the brightness temperatures measured at different wavelengths differ up to two times, especially at the initial stage of the discharge. With time the results of measurements approach one another, and starting from 60 μs they are almost identical. Fig. 1 shows that the curves of the time evolution of the brightness temperature have several specific stages. The first stage is characterized by an active heating of the plasma in the channel after breakdown of tungsten vapor caused by intense input of energy stored in the capacitor bank.

After the emission maximum, a relatively rapid decrease of the intensity up to a certain value is

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occurred, then there is very slow decay of plasma to the state close to a plateau-like state. The length of this latter state depends on the energy introduced into the plasma channel. As plasma is decaying, the brightness temperatures measured at different wavelengths are becoming closer each other in magnitude. At a certain stage of plasma decay there is a sharp decrease in the emission intensity of the plasma channel what correlates with appearance of hydrogen emission lines – first H_α line, then H_β line, and later on – H_γ. The moments of appearance of these lines and the time intervals between their appearances depends on the energy deposited into the discharge channel. These effects, as shown in [9, 10], are associated with changes of the recombination coefficients in the dense PWD plasma, which, in turn, are connected with appearance of line levels at which the recombination of electrons is possible.

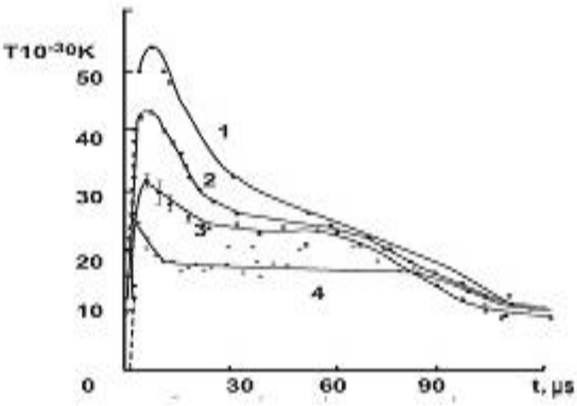

Fig. 1. Dependence of PDW brightness temperature versus time measured at different wavelengths: 37 kV; l = 40 mm. 2 – λ = 400 nm; 3 – λ = 550 nm; 4 – λ = 700 nm; 1 – is a linear extrapolation to 200 nm

The moment of occurrence of maximum brightness temperature depends essentially on: the power input speed, the length of the discharge gap, initial voltage of the battery, the wavelength at which the measurement is made, and the discharge period. At T=15.5 μs, the maximum of the radiation does not always coincide with the maximum of the power dissipated in the channel (Fig. 2).

It should be noted one peculiarity of PDW channel radiation with this discharge period. It consists in the fact that the radiation intensity oscillations do not correlate with oscillations of power input. On the contrary, in the second and fourth current maxima, despite the energy input into the channel, the radiation intensity is slightly reducing.

For long discharge periods (T= 45…110 μs) the correlation is observed between power contribution, the oscillations of the continuous radiation spectrum intensity and the intensity of the hydrogen line H_α (656.3 nm).

Fig. 3 shows the time dependences of the values of nonequilibrium, ΔT/Δλ (K/nm), for four modes of discharge. In Fig. 3,a the dependences are shown for two ranges of wavelengths, 450…550 nm and 400…700 nm at initial voltage 37 kV and the discharge gap length 40 mm. In the wavelength range of 450…550 nm, there is a strong correlation between changes in the degree of nonequilibrium and current fluctuations (especially for the first and third current maxima). When the wavelength range is 400…700 nm, this dependence becomes less apparent.

Fig. 3,b presents time variation of ΔT/Δλ (K/nm) for 10 kV and gap length 40 mm for the spectral range 400…700 nm. It is seen that positions of ΔT/Δλ (K/nm) maxima do coincide with positions of first and third maxima of the discharge current.

In the case of Fig. 3,c the discharge voltage was 30 kV and the length of a discharge gap 20 mm for same wavelength interval (400…700 nm).

Fig. 3,d shows similar dependence (voltage 30 kV and Δ=400…700 nm) but when the discharge length was 60 mm. Again positions of maxima do coincide, however, the third half period is much more pronounced than the first.

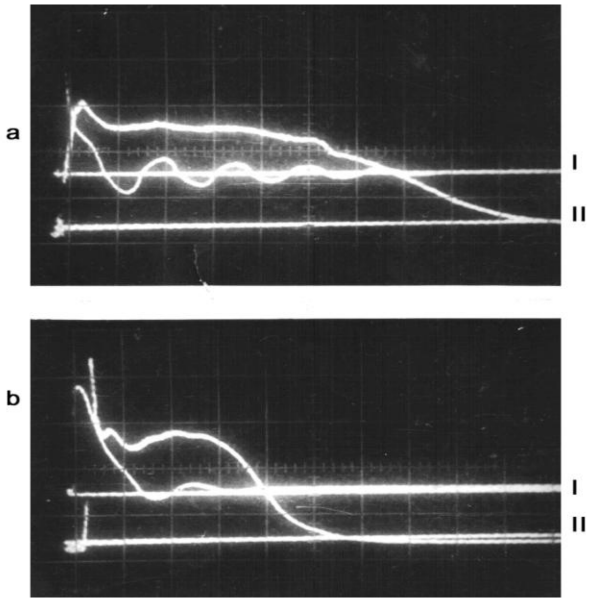

Fig. 2. The oscillograms of voltage drop (I) on the discharge with length 40 mm, and PWD radiation intensity(II) at different initial battery voltage 30 kV (a), 10 kV (b)

At discharge period 15.5 μs for all above mentioned discharge modes a nonequilibrium PDW radiation is taking place, and the characteristic feature of radiation is that immediately after the channel breakdown, the radiation also can be nonequilibrium, but with a *negative* value of nonequilibrium. The value of nonequilibrium, ΔT/Δλ (K/nm, is greatest in the first or third current maxima. In the second and fourth current maxima the reduction of emission intensity is observed. This is especially noticeable in the shorter wavelengths of the visible light range. Further increase of energy contributions into the channel are minor and do not cause significant changes in the radiation intensity of the channel. A certain increase in the intensity of radiation near the H_α line is associated with an increase of the recombination rate [9, 10] when plasma concentration is decreasing.

Fig. 4 shows a typical time dependence of the electric field strength *E*. The maximal electric field strength correlates with the moment of the breakdown of vapors of the initiating conductor. After breakdown, when plasma becomes hotter and plasma channel expands, a rapid decrease of *E* does occur. The maximum of *E* does not always coincide with the maximum current in the discharge, but with longer discharge lengths (after the rapid decline of *E*) an increase of field strength with increasing current in the first half-period of the discharge is observed. It was therefore decided to take as the maximum strength of the electric field in the plasma its value in the first maximum of the PDW current.

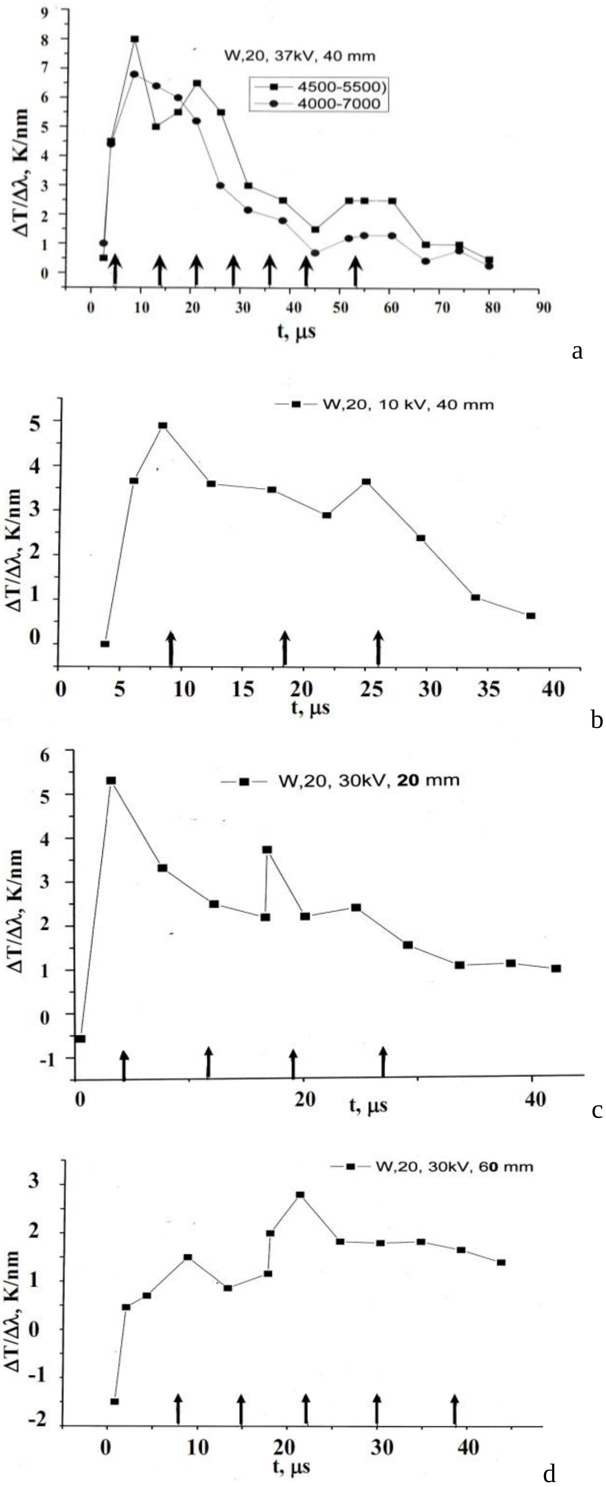

Fig. 3. The dependence of the nonequilibrium radiation PDW on the time. Arrows indicate the positions of current maxima

It was found in [3, 4] that there exists the dependence of radiation nonequilibrium of a nonideal plasma in a plasma focus on the external electric field strength. Fig. 5 shows the dependence of the nonequilibrium plasma emission values in PDW on the maxima of the electric current in the first half-period of discharge.

In Fig. 6 is shown the dependence of the maximum value of nonequilibrium of the PDW radiation on the maximum electric field strength in the PDW channel. In both figures, a significant dependence of the degree of nonequilibrium on the electric field strength in the PDW channel is seen.

The values of electrical microfield strength of dense plasma can be much greater, but their impact on behavior of free electrons will last for shorter time interval. Apparently, in the dense plasma under the influence of a electric field, that is a quasi-static field in comparison with electrical eigen-micro-fields, free electrons are accelerated, as was observed in [3, 4].

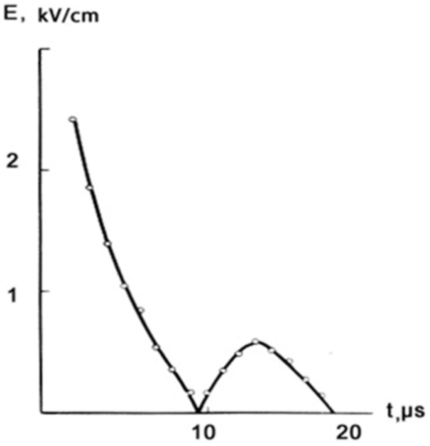

Fig. 4. The time dependence of the electric field strength

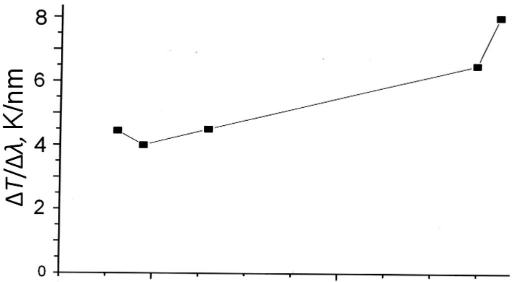

Fig. 5. The dependence of the nonequilibrium radiation PDW on the electric field in the first current maximum

Fig. 7 shows the dependence of nonequilibrium of epy PDW emission on the current in the first current maximum (T=15.5 μs). An increase of the nonequilibrium of PDW emission on the current amplitude is evident. However, considering that the second and fourth discharges half periods do not show an increase but show a reduction of the radiation nonequilibrium, this dependence should be considered as dependence on the electric field strength, but not on the current.

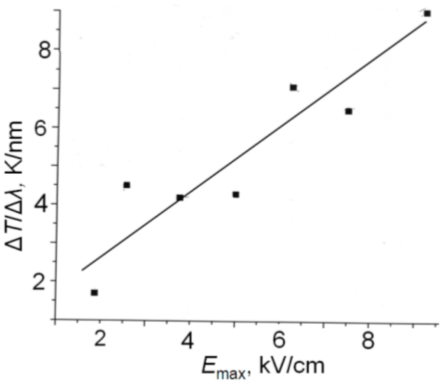

Fig. 6. The dependence of the nonequilibrium radiation values of the maximum field strength in the PDW channell

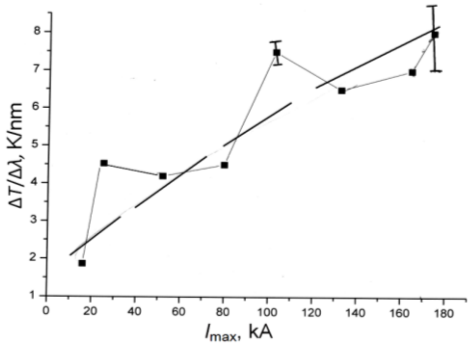

Fig. 7. The dependence of the nonequilibrium of the PDW radiation on the current value in the first current maximum

In the even half periods, on the contrary, the deceleration of electrons occur because of changing the voltage polarity along the PDW channel, what results in reduce of the intensity of radiation in the paired half periods of current.

In [2, 11] the nonequilibrium of radiation of NP in the PDW was explained by the influence of the temperature gradient of the outer layers of the plasma channel on the output of short-wave radiation from the inner plasma. The temperature of deep plasma volume can be higher than in the outer layers of the plasma channel. However at the initial stage of discharge the most intense H_α (656.3 nm) line of hydrogen Balmer series is not observed (even in the absorption spectrum). The parameter of hydrogen plasma inhomogeneity for the H_α line is M=0.95 according to [12], (and M=0.91 at λ=600 nm for the continuous spectrum). Therefore, the influence of non-uniformity of the plasma channel on the plasma emission intensity of hydrogen, according to [12], should be negligible (not more than 15 %).

One more explanation of nonequilibrium of radiation of NP is given in [13]. In that paper considered is the effect of non-ideality on the bremsstrahlung continuum, with electrons concentrations in the plasma up to 10^{20} cm^{-3}. However, according to theoretical calculations, the absorption (radiation) coefficient has to be reduced in the red region of the spectrum.

In the presented experimental results, the opposite effect was observed. Therefore, the most probable explanation for the observed effect is the acceleration of electrons under the influence of the quasi-stationary external electric field generated by capacitor bank, compared with rapidly varying effect of intraplasma microfields.

CONCLUSIONS

It was found that the difference in brightness temperatures of PDW, measured at wavelengths between 400 nm and 700 nm, can be up to two times, especially at high speeds of the power input to the discharge channel. Plasma channel radiation intensity oscillations do not correlate with the power input to the channel. The value of the degree of nonequilibrium, ΔT/Δλ (K/nm), is in correlation with oscillations of input power during the odd half periods of discharges. The highest degree of nonequilibrium does practically always coincide with the first or third current maximum. The most probable explanation for the observed effect is the acceleration of electrons under the influence of the external electric field, which are quasi-stationary in comparison with rapidly varying intraplasma electric microfields.

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ЗАВИСИМОСТЬ НЕРАВНОВЕСНОСТИ ИЗЛУЧЕНИЯ ИМПУЛЬСНОГО РАЗРЯДА В ВОДЕ В ВИДИМОМ ДИАПАЗОНЕ ОТ НАПРЯЖЁННОСТИ ЭЛЕКТРИЧЕСКОГО ПОЛЯ

О.А. Федорович

Приведены результаты экспериментальных исследований неравновесности излучения сплошного спектра в видимом диапазоне неидеальной плазмы (НП) импульсных разрядов в воде (ИРВ) с минимальным количеством примесей. Разряд инициировался взрывом вольфрамового проводника диаметром 20 мкм. Излучение из канала ИРВ является неравновесным. Яркостные температуры, измеренные на длинах волн 400 и 700 нм, могут отличаться вдвое, особенно при больших скоростях ввода энергии в канал ИРВ. Приводятся результаты исследований влияния электрических параметров плазменного канала на неравновесность излучения НП. Колебания интенсивности излучения плазменного канала не коррелируют с вкладом мощности в канал. Но величина неравновесности $\Delta T/\Delta\lambda$ *(*К/нм) коррелирует с колебаниями мощности. Наибольшая величина неравновесности совпадает с первым или третьим максимумами тока. Рассматриваются зависимости максимального значения неравновесности от: начальной напряжённости электрического поля в разряде, максимального тока в разряде, напряжённости электрического поля в первом максимуме тока, длины разрядного промежутка при неизменном начальном напряжении на батарее. Обсуждаются возможные механизмы наблюдаемого эффекта.

ЗАЛЕЖНІСТЬ НЕРІВНОВАЖНОСТІ ВИПРОМІНЮВАННЯ ІМПУЛЬСНОГО РОЗРЯДУ У ВОДІ У ВИДИМОМУ ДІАПАЗОНІ СПЕКТРУ ВІД НАПРУЖЕНОСТІ ЕЛЕКТРИЧНОГО ПОЛЯ

О.А. Федорович

Наведено результати експериментальних досліджень нерівноважності випромінювання суцільного спектру у видимому діапазоні неідеальної плазми (НП) імпульсних розрядів у воді (ІРВ) з мінімальною кількістю домішок. Розряд ініціювався вибухом вольфрамового провідника діаметром 20 мкм. Випромінювання з каналу ІРВ є нерівноважним. Яскравістні температури, виміряні на довжинах хвиль 400 і 700 нм, можуть відрізнятися вдвічі, особливо при великих швидкостях введення енергії в канал ІРВ. Наводяться результати досліджень впливу електричних параметрів плазмового каналу на нерівноважность випромінювання НП. Коливання інтенсивності випромінювання плазмового каналу не корелюють з вкладом потужності в канал. Але величина нерівноважності $\Delta T/\Delta\lambda$ (К/нм) корелює з коливаннями потужності. Найбільша величина нерівноважності збігається з першим або третім максимумами струму. Розглядаються залежності максимального значення неравноважності від: початкової напруженості електричного поля в розряді, максимального струму в розряді, напруженості електричного поля в першому максимумі струму, довжини розрядного проміжку при незмінній початковій напрузі на батареї. Обговорюються можливі механізми.