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LIFETIME OF ELECTRONS IN DENSE PLASMA

The experimentally determined average lifetimes of electrons and ions in the dense plasma of pulsed discharges in water are reported. The lifetimes of charged particles in dense plasma are shown to be practically independent of the time. The specific lifetime values are found to lie in a vicinity of 10^{-5} s and vary from 5×10^{-6} to 3×10^{-5} s at various discharge stages, when the parameters of discharge plasma are changed. In particular, the concentration of electrons in plasma is changed from 10^{15} to 10^{22} cm^{-3}, and the temperature from 7×10^{3} to 64×10^{3} K. We explain this phenomenon by the "non-realization of levels" in the radiation spectra and by the strong broadening of observed spectral lines in high microfields of dense plasma, when the latter achieve values close to intraatomic ones. Experimental data obtained for the lifetimes of charged particles are compared with the results of theoretical calculations made by various authors.

Keywords: nonideal plasma, pulsed discharges in water, electric microfields, lifetime of charged particles, recombination of charged particles.

1. Introduction

In the last decades, the interest in elementary processes running in media under extreme conditions, i.e. at high temperatures and high pressures, has grown. This is a result of the pure academic interest in the properties of substances in such states, as well as practical needs in the research of such states, because the substance in those states is used as a working one in many technological devices that are in service or development. These are pulse-discharge devices for the punching, beading, and molding clearing; units of high-voltage discharge devices for the commutation in high-current circuits; high-voltage and high-current dischargers; powerful MHD generators; gas-phase nuclear reactors; designed rocket engines; and various military-grade devices.

When calculating the path lengths of quanta in dense plasma and, accordingly, the radiative heat conductivity, information is required concerning the cross-sections for excited atoms. If the concentration of electrons in plasma exceeds 5×10^{18} cm^{-3}, the "blooming" of dense hydrogen-oxygen plasma is observed [1]. All absorption (emission) lines of hydrogen within the optical spectral interval disappear, including the most intensive line of Balmer series H$_\alpha$ (656.3 nm). Oxygen lines are also absent, because they have high excitation potentials, close to the ionization one, in this spectral range [2]. They appear only at the late stage of a plasma decay.

Such absence of absorption can naturally be explained by a reduction of the effective cross-section of interaction between excited atoms in plasma. The corresponding reduction of the effective cross-section is associated with the "non-realization" of upper atomic levels, i.e. the "clipping" (disappearance) of upper levels by fluctuation perturbations of electric microfields, the magnitude of which reaches the values of intraatomic electric field strength [3]. As a result, the number of levels, onto which the recombination is possible, diminishes. This reduction in the number of free electron states for an excited atom (ion) strongly reduces the recombination coefficient in dense plasma and should increase the lifetime of electrons (ions) in it. In this work, the influence of plasma parameters on the lifetime of charged particles in dense plasma is studied.

2. Lifetime of Electrons in Dense Plasma

One of the most important plasma parameters is the lifetime of electrons and ions, τ_{life} [4]. It determines the time interval, within which plasma formations exist. In the course of its ionization, a gas acquires absolutely new properties, which appear as a manifestation of the influence of electric microfields in plasma and transform the ionized gas into a specific collective state of interacting particles.

The key parameters of the pulse discharge installation used for researches in this work are as follows. The capacitance was 14.5 μF, and the contour inductance 0.47 μH. The voltage across the capacitor bank was changed from 3 to 37 kV, which allowed an energy of 10 kJ to be stored. The current at the first maximum reached 160 kA. The discharge gap width was varied from 5 to 100 mm.

In order to make the results reproducible, the discharge in water was initiated by exploding thin metal (pure metals or alloys) or carbon conductors, which were used to short-circuit the discharge gap before the discharge. This method allowed us to obtain rather high plasma parameters, not reachable at standard discharges in water. Long-time intervals are required for the electric breakdown to take place in water. The breakdown itself of the discharge gap filled with pure water takes place at relatively large transverse cross-sections of streamers in comparison with the transverse dimensions of the region occupied by the vapor of the blown up conductor, so that high current densities cannot be obtained in the merely spark plasma channel. The discharge in water initiated by electrically induced explosions of conductors also makes it possible to obtain a more uniform surface glow, than the spark discharge does. At the same time, the inertial properties and the low compressibility of water do not allow the plasma channel to broaden rapidly. As a result, the diagnostics and the measurement of basic plasma parameters and their variations in time become easier.

Literature data contain the results of researches concerning the lifetime of electrons in plasma with the electron concentrations $N_e \le 10^{17}$ cm^{-3} [5]. Long-term (0.5–5.0 s) plasma formations, the so-called plasmoids, were experimentally observed in water [6]. For rarefied plasma (at concentrations lower than 10^{17} cm^{-3}), the values obtained theoretically and experimentally for the coefficient of electron bulk recombination lie in the wide interval $\alpha^*_{e,i} \sim$ $\sim 10^{-8} \div 10^{-14}$ cm^3/s and decrease, as the temperature grows [4].

In order to analyze the dynamics of creation and annihilation of charged particles in the plasma of a high-voltage pulsed discharge in water, we used the balance equation for the particles in the hydrogen-oxygen plasma of this discharge. The balance equation for particles in the channel is written in the form [7]:

$$\frac{dN_e}{dt} = N_e\,N_a\,\beta - N_i\,N_e^2\,\alpha, \tag{1}$$

where α is the recombination coefficient [cm^6/s]; β the ionization factor [cm^3/s]; and N_e, N_i, and N_a are the concentrations of electrons, ions, and atoms, respectively [cm^{-3}]. Taking the dimensionality issue into account, let us introduce the effective coefficient of recombination α^* with the dimensionality $[\alpha^*] =$ $=$ cm^3/s, so that $\alpha^* = N_e\alpha$.

The mean lifetime of an ion or electron at the recombination in the plasma bulk (neglecting ionization) can be determined from the equation [4]

$$\frac{dN_{e,i}}{dt} \approx \frac{N^0_{e,i}}{\tau_{\text{life}}} \approx \alpha^*_{e,i}(N^0_{e,i})^2, \tag{2}$$

where $N^0_{e,i}$ is the initial concentration of charged particles in plasma. From whence, we obtain

$$\tau_{\text{life}} \approx \frac{1}{\alpha^*_{e,i}\,N^0_{e,i}} \tag{3}$$

for the lifetime τ_{life} [s], where $\alpha^*_{e,i}$ is the effective coefficient of recombination for electrons and ions [cm^3/s], and $N_{e,i}$ the concentration of electrons or ions [cm^{-3}].

It is difficult to determine the recombination coefficient from the results of direct measurements carried out at high temperatures. Under those conditions, plasma is strongly ionized. From the experimental data, only the decay factor can be calculated with the use of the balance equation for particles in plasma corresponding to the detailed balance principle [7],

$$\frac{dN_e}{dt\,N_e^2} = \frac{N_a}{N_e}\,\beta - \alpha^*, \tag{4}$$

where $\frac{dN_e}{dt\,N_e^2}$ is the decay factor.

If the ionization is not taken into account, the recombination coefficient α^* corresponds to the left-hand side of Eq. (3). Hence, the values of recombination coefficient correspond to the values of decay factor. If the ionization is taken into account, we obtain

$$\tau_{\text{life}} \approx \frac{1}{N_a\,\beta - \alpha^*\,N_e} = \frac{\Delta t\,N_e}{\Delta N_e}, \tag{5}$$

Evidently, just this quantity is the experimentally observed lifetime of electrons and ions, in which the ionization and recombination processes are involved.

Experimentally obtained values for the decay factors of nonideal plasma are very small and amount to 10^{-12}–10^{-16} cm^3/s [8–10]. From Eq. (3), it follows that the value of recombination coefficient $\alpha^*_{e,i}$ is very close to the value of the quantity $\frac{N_a}{N_b}\,\beta$, which means that one should not neglect the ionization process, when calculating the recombination coefficients in the nonideal plasma of pulsed discharges in water, especially at the initial discharge stage.

The experimental dependences of the mean lifetime of electrons (ions) in dense plasma on the electron concentration are depicted in Fig. 1. At temperatures within an interval of $(7{\div}64) \times 10^3$ K and if the electron concentration changes from 10^{15} to 10^{22} cm^{-3}, the electron lifetimes calculated from the time dependences of the concentration of electrons generated at pulsed discharges in water remain practically constant. Their values are concentrated in a vicinity of 10^{-5} s and vary from 5×10^{-6} to 3×10^{-5} s for various discharges. The mean lifetime of charges becomes shorter at the initial stage of discharges, when a considerable contribution of the energy to the plasma channel is made and the ionization of atoms in the plasma channel takes place. Furthermore, in those cases, the ionization considerably exceeds the plasma recombination. Figure 1 illustrates a discharge mode initiated by a tungsten wire 20 μm in diameter, with an initial voltage of 37 kV, and at a discharge gap width of 40 mm. In this case, the obtained values of electron concentration were maximum and reached 5.5×10^{20} cm^{-3}. Thus, when the electron concentration is varied by seven orders of magnitude, the mean lifetime of electrons in dense plasma practically is not changed.

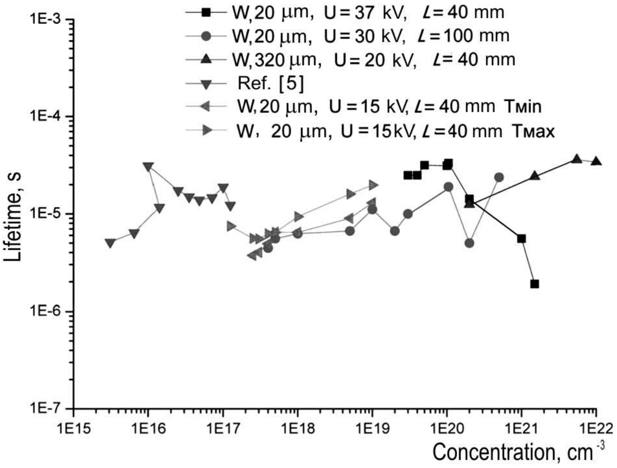

Fig. 1. Dependence of the mean lifetime of electrons in dense plasma on the electron concentration

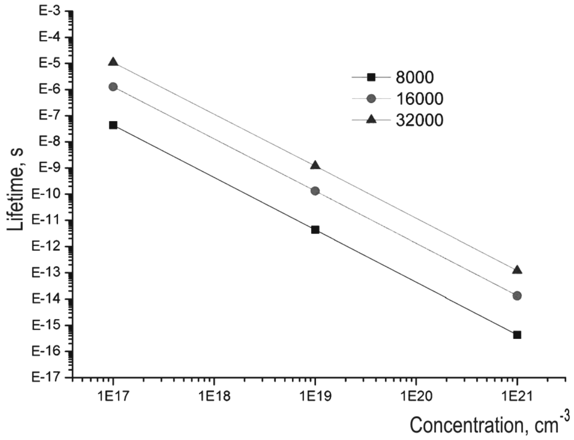

Fig. 2. Dependence of the mean lifetime of electrons on the electron concentration calculated according to work [11]

The calculation results obtained for the lifetimes of electrons in hydrogen plasma, which is opaque for the Lyman series lines according to work [11], are exhibited in Fig. 2. One can see that, in the dense hydrogen plasma opaque to the Lyman series lines, the lifetimes of electrons should decrease from 10^{-5} to 10^{-12} s if their concentration changes within an interval of 10^{17}–10^{21} cm^{-3} and the temperature equals $T = 32000$ K. At a temperature of 16000 K, the theoretical value of electron lifetimes decreases by almost an order of magnitude provided the same

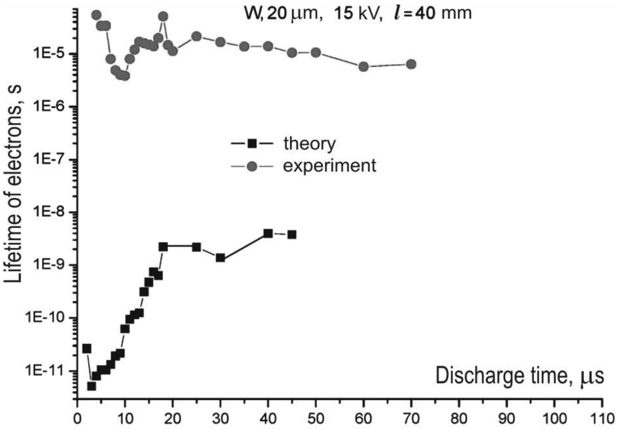

Fig. 3. Dependence of the mean lifetime of electrons in dense plasma on the discharge time calculated, by using the results of work [11] for the ionization and recombination coefficients obtained at various concentrations and temperatures of hydrogen plasma

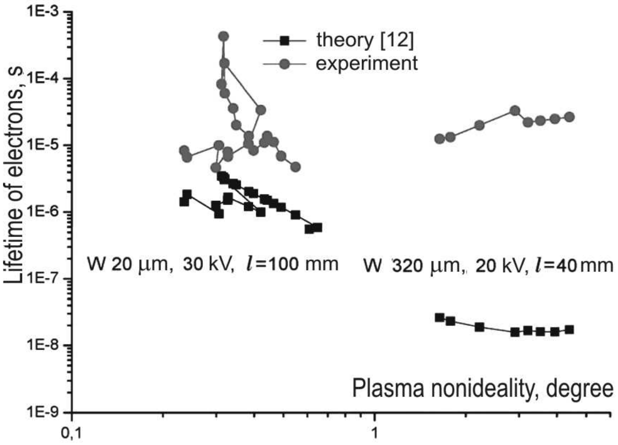

Fig. 4. Dependence of the mean lifetime of electrons on the plasma nonideality degree

electron concentration values. However, it has to be noted that the authors of work [11] calculated, for the first time, not only the recombination coefficients, but also the ionization ones for relatively dense hydrogen plasma. At concentrations above 10^{18} cm^{-3}, the cited authors recommended to simply increase the value of ionization coefficient proportionally to the electron concentration growth. They also assumed that the major mechanism of recombination had a ternary character: electron-electron-ion. Certainly, the effect of "level non-realization", which experimentally manifests itself at electron concentrations corresponding to dense plasma, was not taken into account at that. At a concentration of 3×10^{19} cm^{-3}, even the line H_α completely disappears from the emission (absorption) spectra [2]. Accordingly, the ionization from this and higher levels, as well as the recombination onto them, does not take place anymore. When calculating the partition functions for atoms, those effects were taken into consideration (only those hydrogen levels, which were observed in the experimental spectra, were taken into account). Accordingly, if the effective cross-section of an ion, for which all upper levels disappear, diminishes, the recombination rate decreases, whereas the lifetime of charged particles substantially grows.

In Fig. 3, the time dependences of the electron lifetimes determined from the experimental data and calculated according to works [7, 11] are depicted. A small reduction of the electron lifetimes at the initial discharge phase (the first half-period) is associated with the intense contribution of the electric energy to the plasma channel and the influence of the atomic ionization at the plasma channel heating. The values of experimental and theoretical lifetimes at the initial discharge stage differ from each other by six orders of magnitude. As the temperature and the plasma concentration decrease, this difference diminishes to three orders of magnitude. Hence, the experimental and theoretically calculated values of electron lifetimes gradually approach each other. It should be noted that the experimental results obtained in work [5] for the electron concentrations lower than 10^{17} cm^{-3} also differ considerably from the calculated ones.

Only at the electron concentrations lower than 10^{16} cm^{-3}, the electron lifetime decreases with a reduction of the electron concentration [5], as follows from theoretical calculations for the three-particle recombination (electron-electron-ion). In other words, when two electrons collide, one of them gives its energy to the other and, if being in the field of an ion, can recombine onto one of its existing levels. Probably, this may be the electron concentration threshold, below which the mechanism of ternary recombination is active. However, in order to verify this statement, special additional researches are required.

Figure 4 demonstrates the calculation results obtained for the lifetimes according to the method of work [12]. One can see that the application of the data of work [12] to the calculation of the lifetimes τ_{life} brings about values of $(1 \div 4) \times 10^{-6}$ s, if the electron concentration is varied in an interval of 10^{17}–10^{20} cm^{-3} and the corresponding change of the plasma nonideality degree equals $\gamma = 0.2{\div}5$. Those results agree rather well with experimental data. However, it should be noted that an insignificant distinction between the experimental and theoretical values of lifetimes for charged particles is observed only at the values of plasma nonideality degree $\gamma = 0.2{\div}0.7$.

Furthermore, both the theoretical and experimental dependences of the charged-particle lifetimes τ_{life} on the plasma nonideality degree γ have an ambiguous character. This ambiguity appears because the same τ_{life} value corresponds to different γ values, which testifies that τ_{life} ambiguously depends on γ. At large γ values ($\gamma \geq 1$), the theoretical and experimental values of τ_{life} differ from each other by three orders of magnitude. This fact also testifies that theoretical calculations are imperfect, and attempts to connect all calculations with the plasma nonideality parameter are inexpedient. This parameter turns out ambiguous: various combinations of the temperature and electron concentration can result in the same γ value.

In dense plasma, the concentration of charges has a more considerable influence on the properties of atoms and ions than the temperature. This statement is valid for both the dependence of the decay factor on the electron concentration in dense plasma [10] and the dependence of the "optical gap" magnitude on the concentration of charges in low-temperature dense plasma [1, 2].

In our opinion, the growth of the lifetime of charged particles in dense plasma by several (up to six) orders of magnitude is associated with the "non-realization" of atomic levels and their large broadening in strong microfields taking place in dense plasma [2, 13], as well as with the substantial ionization of atoms that occurs again under the conditions of production of nonideal plasma at pulsed discharges in water. The obtained experimental data will enable theorists to orient themselves, when developing theoretical models of recombination processes and calculating the lifetimes of charged particles in dense plasma. Those data are rather important for the calculation of switching-on/off devices. It is not excluded that the very large values obtained for the lifetimes of charged particles in dense plasma will allow the existence of a ball lightning and other long-term objects in the Earth atmosphere to be explained at least in part.

3. Conclusions

The mean lifetime of charged particles in low-temperature dense plasma produced by high-voltage pulsed discharges in water has been measured experimentally. At electron concentrations in plasma of 10^{17}–10^{22} cm^{-3}, the lifetime of electrons in plasma falls within an interval from $5{\times}10^{-6}$ to $3{\times}10^{-5}$ s, when the electron temperature changes from 7000 to 45000 K. Taking the results of work [5] into account – they were obtained for a pulsed discharge in hydrogen – the indicated interval of lifetimes becomes extended to a temperature of 64000 K and to a concentration of 10^{15} cm^{-3}. The lifetimes calculated by formulas for the ternary recombination turned out three to six orders of magnitude shorter than the lifetimes obtained experimentally. Although the theoretical dependences that make allowance for the plasma nonideality degree also do not describe the lifetimes of electrons obtained experimentally, they are much closer to the experimental ones. We assume that the substantial growth of the lifetimes of charged particles in dense plasma is a result of the "non-realization" of levels in atomic spectra, which is observed experimentally under the influence of large values of rapidly changing electric microfields arising in low-temperature dense plasma, as well as the large broadening of the levels responsible for the appearance of emission lines in spectra.

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ЧАС ЖИТТЯ ЕЛЕКТРОНІВ У ЩІЛЬНІЙ ПЛАЗМІ

Резюме

Наведено результати експериментального визначення середнього часу життя електронів (іонів) щільної плазми імпульсних розрядів у воді. Було показано, що час життя заряджених частинок у щільній плазмі практично не змінюється в часі. Його значення лежать біля 10^{-5} с і змінюються на різних стадіях розрядів від $5 \cdot 10^{-6}$ с до $3 \cdot 10^{-5}$ с при зміні параметрів плазми розряду. При цьому концентрація електронів в плазмі змінюється в діапазоні 10^{15}–10^{22} см $^{-3}$, а її температура змінюється від $7 \cdot 10^3$ K до $64 \cdot 10^3$ K. Поясненням цього явища може служити “нереалізація рівнів” у спектрах випромінювання (поглинання), а також сильне уширення ліній, що спостерігаються в великих електричних мікрополях щільної плазми, які за величиною близькі до всерединоатомних полів. Проведено порівняння експериментальних даних з теоретичними розрахунками часу життя заряджених частинок, зроблених різними авторами.