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POSITIVELY CHARGED MICROPARTICLE IN PLASMA WITH HIGH-ENERGY ELECTRON BEAM

Aleksander A. Bizyukov[a], Dmitry V. Chibisov[a]*, Oleksandr D. Chibisov[b], Oksana A. Zhernovnykova[b], Kostyantyn V. Borysenko[b], Dmytro Ye. Bobyliev[c], Oksana H. Shtonda[b]

[a]*V.N. Karazin Kharkiv National University, Svobody Sq., 4, 61022, Kharkiv, Ukraine*
[b]*H.S. Skovoroda Kharkiv National Pedagogical University, Alchevskyh St., 29, 61002, Kharkiv, Ukraine*
[c]*Kryvyi Rih State Pedagogical University, Universytetskyi Ave., 54, 50086, Kryvyi Rih, Ukraine*
**Corresponding Author e-mail: dmitriychibisov@karazin.ua*
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The processes of recharging, heating and evaporation of a positively charged microparticle (MP) introduced into the plasma with an injected high-energy electron beam are considered. It is assumed that the MP is charged outside the plasma and then introduced into the plasma by an accelerating field, where plasma and beam electrons hitting the MP heat and evaporate it. In addition to introducing the MP into the plasma, the positive MP charge provides an additional source of energy needed to heat and evaporate it. Using the OML theory, the system of current and energy balance equations was numerically solved and the conditions, under which the MP is heated to the boiling point of its substance, resulting in its intense evaporation, were determined. The influence of the energy of the electron beam on the process of MP recharging, as well as on the rate of its heating and evaporation, has been studied. An estimate of the particle entry velocity into the plasma has been made; the distances at which its recharging, heating to the boiling point and complete evaporation occur are determined. The work is carried out in order to creating plasma of a given elemental composition.
Keywords: *Microparticles; Producing plasma; Electron beam; Evaporation of microparticles*
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INTRODUCTION

Currently, a number of methods for producing ion beams and plasma from elements initially in the solid phase are known; the main ones are evaporation from a furnace, cathode sputtering of a solid, evaporation by a vacuum arc or a laser beam [1]. Previously [2,3], we reported one more method for producing plasma from elements in the solid phase, that consists of introducing MPs into a previously created plasma. To introduce the MPs into plasma, we proposed to charge MPs up to a high positive potential and then accelerating them using the method developed in [4, 5] for creating a flow of micrometeorites of micron and submicron size in laboratory conditions. Microparticles introduced into the plasma are heated and evaporated as a result of collisions with plasma and beam electrons; the resulting vapor is then ionized by electrons. The positive charge of the MPs is used to introduce them into the plasma and is also an additional source of energy necessary for heating and evaporation. This method of creating plasma from elements in the solid phase, in addition to producing ion beams, can be used for plasma isotope separation technologies [6-9]. The advantage of this method over traditional methods of creating plasma is its economic efficiency, what is important, for example, when separating rare earth elements [6]. Another important aspect is the higher level of environmental safety compared to evaporation in a furnace, what can be important when separating radioactive elements and their isotopes [7].

In this work, we study the effect of an electron beam injected into the plasma on the processes of recharging, heating and evaporation of a single MP. Previously, the high-energy electron beam was proposed to be used to evaporate micro-droplets of cathode material in plasma generated by a vacuum-arc discharge when coating a substrate [10-12]. The addition of an electron beam to the plasma in this case makes it possible to reduce the positive charge of the MP, which is necessary for its acceleration when they are introduced into the plasma, and also creates additional ability for its heating, evaporation and subsequent ionization. For calculations, we used a previously proposed model [2,3], in which terms, that take into account the electron beam, were added. We also investigated the effect of the electron beam on the evaporation of heated MP and also estimated the distances at which recharging, heating to the boiling point and evaporation of the MP occurs.

MODEL DESCRIPTION

A positively charged MP in plasma with an electron beam absorbs electrons from the plasma and beam, resulting in its recharging and heating. After recharging, the MP also absorbs plasma ions, what is an additional source of its heating. Thermionic and secondary electron emissions also have a significant influence on the MP, which form its equilibrium potential and also determine its temperature. The temperature of the MP is also influenced by thermal

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radiation and evaporation of the MP substance. All these processes are taken into account in the system of equations that describe the dynamics of changes in the potential and temperature of a MP in plasma:

$$\begin{cases} I_i^{pl} - I_e^{pl} - I_e^b + I_e^s + I_e^{th} = dQ/dt; \\ P_e^{pl} + P_i^{pl} + P_e^b - P_s - P_r - P_{th} - P_{vap} = mc\,dT/dt. \end{cases} \tag{1}$$

The first equation of system (1) describes the changing of the MP charge and includes charging processes listed above and denoted as follows: I_i^{pl} and I_e^{pl} are the ion and electron currents from the plasma onto the MP surface, I_e^b is the electron beam current, I_e^s is the secondary electron emission current from the MP surface caused by electron of the plasma and the beam, I_e^{th} is the thermionic electron emission current from the MP surface caused by heating of the MP due to interaction of MP surface with the plasma and the beam MPs. It should be noted, that the secondary electron emission and the thermionic electron emission only take place for negatively charged MPs. Q is the charge, T is the temperature, m is the mass, c is the specific heat capacity of he MP.

Interaction of plasma and electron beam particles with the MP surface is given by the OML theory and particles currents have the form

$$I_\alpha^{pl,b}(\varphi) = e\cdot\Gamma_\alpha ,$$

where $\alpha = i, e$ denote the particle species.

$$\Gamma_\alpha = \sqrt{8\pi}a^2 n_0 v_{T\alpha}\left(1 + \frac{|e\varphi|}{kT_\alpha}\right),$$

is the current of particles α in a case of attractive MP potential and

$$\Gamma_\alpha = \sqrt{8\pi}a^2 n_0 v_{T\alpha}\exp\left(-\frac{|e\varphi|}{kT_\alpha}\right),$$

in a case of repulsive MP potential, n_0 is the plasma number density, $v_{T\alpha}$ is the thermal velocity of particles α, a is the initial MP radius, φ_a is the MP potential. Secondary electron emission is described by the relation:

$$I_e^s = \delta I_e ,$$

where

$$\delta = \delta_{\max}\frac{|e\varphi|}{E_m}\exp\left(2(1 - \sqrt{\frac{|e\varphi|}{E_m}})\right)$$

is the secondary electron emission yield: E_m is the energy of the primary electrons that corresponds to the maximum of secondary emission yield $\delta_{\max}$. Thermionic emission current is described by the Richardson's law

$$I_e^{th} = 4\pi a^2 AT^2\exp\left(\frac{e\Phi - \Delta W}{k_B T_a}\right),$$

where, $A = \frac{4\pi m_e k_B^2 e}{h^3}$, h is the Planck constant, k_B is the Boltzmann constant, $e\Phi$ is the work function, T_a is the temperature of the MP. $\Delta W = \sqrt{e^3\varphi_a / a}$ is the decreasing of the electron work function (Schottky effect).

The second equation of the system (1) describes the changing of MP temperature caused by energy flows the following processes: $P_{i(e)}^{pl}$ is the energy flow associated with the absorption plasma particles by the MP; P_e^b is the energy transferred by the electron beam to the MP P_r is the energy radiated from the MP surface, P_{vap} is the cooling of the MP due to evaporation of its substance, P_{th} is the energy flow from the MP surface is transferred by the electrons of thermionic current, P_s is the energy flow due to the secondary electron emission. The values of the respective energy flows are determined by the following relations:

$$P_e^{pl} = \Gamma_e\cdot(2kT_e + e\Phi),\ P_i^{pl} = \Gamma_i\cdot(2kT_i + e\varphi + I + e\Phi),\ P_e^b = \Gamma_e\cdot(2kE_b + e\Phi)\ \ P_r = \sigma T^4,$$

$$P_{th} = \Gamma_e^{th} \cdot (2k_b T)\,,\ P_e^s = \Gamma_s \cdot (\varepsilon_s + e\Phi)\,,\ P_{vap} = \Gamma_a \cdot (2k_B T + p)\,,$$

where I is the ionization energy, $\Gamma_a = n' \sqrt{\frac{k_B T_a}{2\pi m_a}} \exp\left(-\frac{p}{k_B T_a}\right)$ is the atom flow of evaporated MP substance, n' is the concentration of atoms in metal, p is the energy of evaporation an atom, $\Gamma_e^{th} = I_e^{th}/e$, $\Gamma_s = I_s^{e-e}/e$, ε_s is the averaged energy of the secondary electrons, E_b is the energy of electron beam.

By numerically solving the system of equations (1), we determine the change in time of the potential and the temperature of the MP at different values of its initial potential, as well as depending on the energy of the electron beam.

RECHARGING AND HEATING OF THE MP

We consider the positively charged spherical cooper MP with a diameter of 1 micron placed into the plasma, the parameters of which are: number density n_0 is $10^{10}\,\mathrm{cm}^{-3}$ electron T_e and ion T_i temperatures are $50\,\mathrm{eV}$ and $1\,\mathrm{eV}$ respectively. Initial MP temperature is $T_0 = 300\,\mathrm{K}$. We suppose that the boiling point of copper is the limiting point for the increase in MP temperature, which is approximately equal to 2800 K, and we also neglect the change in boiling temperature with decreasing pressure of the residual gas. Therefore, the presented calculations represent a qualitative assessment of the processes occurring.

When a positively charged MP is introduced into the plasma with the electron beam, it is recharged due to collisions with electrons. Figure 1a shows the dependence of the MP potential on time for various values of its initial potential φ_0 and electron beam energy $E_b = 20\,\mathrm{keV}$.

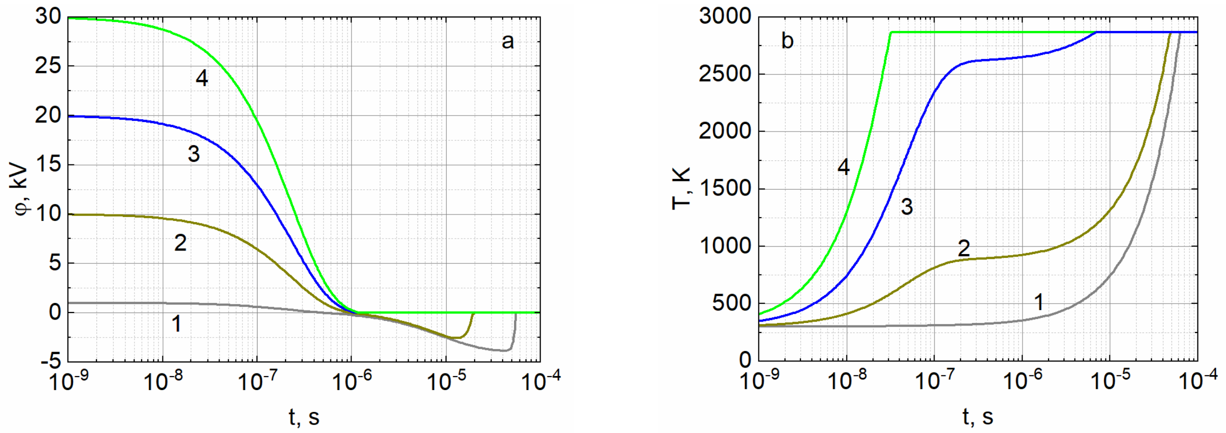

Figure 1. The dependence of MP potential (a) and related temperature of MP (b) on the time at different values of the initial MP potential φ_0, electron beam energy $E_b = 20keV$: 1 – $\varphi_0 = 1kV$, 2 – $\varphi_0 = 10kV$, 3 – $\varphi_0 = 20kV$, 4 – $\varphi_0 = 30kV$

Here we can see two cases of time dependence of MP potential. In the first case, at the initial values of $\varphi_0 = 1\,\mathrm{kV}$ and $\varphi_0 = 10\,\mathrm{kV}$ (curves 1 and 2), within a time of about 10^{-6} s, the MP potential reaches approximately zero value, which corresponds to the floating potential, due to charging by plasma electrons. A further decrease of the potential to a value of the order of –4 kV is caused by the charging of the MP by beam electrons. In the second case, at the initial potentials $\varphi_0 = 20\,\mathrm{kV}$ and $\varphi_0 = 30\,\mathrm{kV}$ (curves 3 and 4) after recharging, the MP has approximately zero potential, which does not change subsequently. This effect is explained by the fact that as a result of heating the MP by plasma electrons, its temperature reaches a value exceeding the value at which thermionic emission occurs (~2500K), compensating for the influx of plasma and beam electrons onto the MP. In the first case, the electrostatic energy of the MP, due to the initial charge, is insufficient to heat to a given temperature. However, due to the beam electrons, the MP continues to heat up and at a time from $2\cdot10^{-5}$ s to $5\cdot10^{-5}$ s its temperature reaches the required value, so that thermionic emission becomes possible and the MP potential decreases to a value close to zero.

Figure 1b shows curves of the MP temperature versus time for the same values of the initial MP potential. At the initial potential of the MP $\varphi_0 = 1$ kV (curve 1), the change in the MP temperature as a result of charging by plasma electrons is insignificant. The main contribution to the heating of the MP in this case is made by the electrons of the beam, which in a time of ~$5\cdot10^{-5}$ s increase its temperature to the value when thermionic emission occurs and the MP potential drops to zero (curve 1 in Fig. 1a). Further heating of the MP leads to an increase in its temperature to the boiling point. At the initial potentials of the MP $\varphi_0 = 10\,\mathrm{kV}$ (curve 2) and $\varphi_0 = 20\,\mathrm{kV}$ (curve 3), the heating of the MP by plasma electrons is already significant and ends during the recharging time of the MP (~10^{-6} s). In the case of $\varphi_0 = 10\,\mathrm{kV}$, its reached temperature ($\sim 800\,\mathrm{K}$) which is lower than the temperature of thermionic emission, and the potential of the MP decreases to –4 kV (curve 2 in Fig. 1a) due to charging by beam electrons. Simultaneously, the electron beam heats the MP first to the thermionic emission temperature and then to the boiling temperature. At the initial potential $\varphi_0 = 20\,\text{kV}$ the electrostatic energy stored on the MP is sufficient for thermionic emission, but not sufficient for heating to the boiling point. This temperature is achieved due to the beam electrons. At the initial potential of the MP $\varphi_0 = 30\,\text{kV}$ (curve 4), the electrostatic energy of the MP is sufficient to heat it to the boiling point. In this case, the electron beam only maintains a given temperature, compensating for losses due to thermal radiation.

We also investigated the effect of electron beam energy on the change in MP temperature over time for a MP with an initial potential $\varphi_0 = 20\,\text{kV}$; the calculation results are shown in Fig. 2.

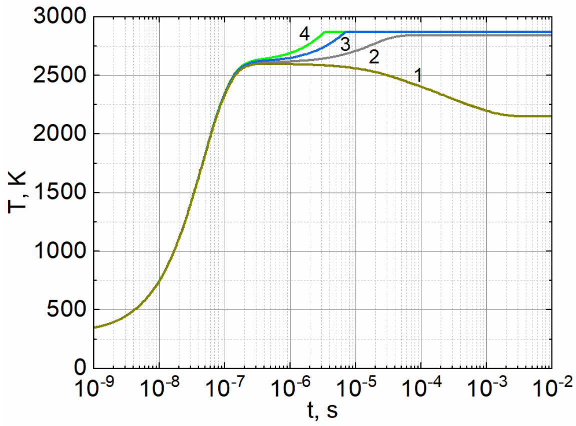

Figure 2. The dependence of the MP temperature on the time at different beam energies:
1– $E_b = 1\,\text{keV}$, 2 – $E_b = 10\,\text{keV}$, 3 – $E_b = 20\,\text{keV}$, 4 – $E_b = 30\,\text{keV}$.

As can be seen from the Fig. 2, in a time of about $2\cdot10^{-7}$ s, the MP is heated to a temperature of about 2600 K due to plasma electrons during recharging, regardless of the beam energy. With increasing time at the beam energy $E_b = 1\,\text{keV}$ (curve 1), the MP cools down to a certain equilibrium value, which is determined by the equality of the energy coming from the beam and from the plasma, as well as heat losses due to radiation. At beam energies $E_b = 10,\ 20,\ 30\,\text{keV}$ (curves 2-4), further heating occurs due to the beam electrons, while the cooling of the MP due to radiation is compensated by the incoming energy from the beam electrons. It also follows from Fig. 2 that an electron beam with an energy exceeding $E_b = 10\,\text{keV}$ heats the MP to the boiling point.

EVAPORATION OF THE MP

We assume that particle evaporation occurs when the boiling point T^b of the substance is reached, neglecting evaporation at lower temperatures. The change in MP mass at the boiling point is described by the equation:

$$4\pi a^2 p_{evpr}(T^b, \varphi^b)\cdot dt = Hdm\,, \tag{2}$$

where $p_{evpr}(T^b,\varphi^b) = \dfrac{1}{4\pi a^2}\left(P_e^{pl} + P_e^{pl} + P_i^{pl} - P_s - P_r - P_{th}\right)$ is the power density on the MP surface that is spent to evaporation of the MP substance, H is the specific heat of evaporation, φ^b is the MP potential at $T = T^b$.

Equation (2) gives the relation between specific parameters of MP substance such as density and heat of evaporation and parameters of plasma and electron beam as well as critical MP radius that can be evaporated. Critical means that the obtained parameters separate regions of the parameters where MPs can be evaporated and where is not. Time of complete evaporation of the MP with a radius a is calculated by integrating equality (2):

$$t_{evpr} = \frac{a\rho H}{p_{evpr}(T^b,\varphi^b)}\,. \tag{3}$$

Dependence of the complete evaporation time of the MP with an initial potential $\varphi_0 = 20\,\text{kV}$ on the energy of the electron beam for different values of the initial MP radius is shown in Fig. 3. As can be seen from Fig. 3, at beam energies $E_b < 3\,\text{keV}$ complete evaporation of the MP does not occur for all considered values of the initial MP radius. This occurs because, that for given plasma parameters the MP is not heated to the boiling point.

It follows from (3) that the dependence of the time of complete evaporation on the initial radius of the particle $t_{evpr}(a)$ is linear. This is also confirmed by Fig. 3. In particular, for a beam energy $E_b = 20$ keV, the time of complete evaporation of a particle with a radius $a =$ 0.1 μm is $t_{evpr} = 6\cdot10^{-5}\,\text{s}$, at $a =$ 0.5 μm we have $t_{evpr} = 3\cdot10^{-4}\,\text{s}$ then at

$a =$ 1 μm $t_{evpr} = 6\cdot10^{-4}$s and for $a =$ 5 μm the time of complete evaporation is equal $t_{evpr} = 3\cdot10^{-3}$s . Thus, for a given beam energy we have the relation $t_{evpr} = 6\cdot10^{-4}a$, where a is measured in micrometers.

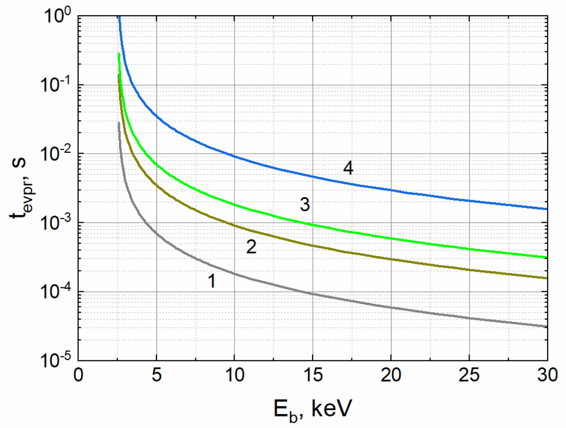

Figure 3. Dependence of the time of complete evaporation of a MP on the energy of the electron beam: $1 - a = 0.1\,\mu\text{m}$, $2 - a = 0.5\,\mu\text{m}$, $3 - a = 1\,\mu\text{m}$, $4 - a = 5\,\mu\text{m}$.

MICROPARTICLE SPEED IN PLASMA

Let us estimate the speed of a charged MP v at the moment of its entry into the plasma, assuming that all the electrostatic energy of MP is converted into its kinetic energy as a result of acceleration by a potential difference equal to the initial potential of the MP φ_0 . From the law of conservation of energy

$$\frac{mv^2}{2} = \frac{C\varphi_0^2}{2},$$

where $C = r$ is the capacity of a spherical MP, m is its mass, we find that the speed is equal to

$$v \approx \frac{\varphi_0}{2r\sqrt{\rho}},$$

where ρ is the density of the substance of the MP. For a copper MP the counting formula is

$$v \approx \frac{0.56\varphi_0}{r},$$

where v measured in *cm/s*, φ_0 in kV, r in cm. For a MP with a diameter of 1 micron we get

$$v \approx 1.12\cdot10^4\varphi_0 .$$

Now we estimate the characteristic distances at which the considered processes occur. For a MP with an initial potential of 20 kV, the speed is $v \approx 2.24\cdot10^4$ cm/s. From the Fig. 1 (curve 3) it follows that the MP recharge occurs over time $t \approx 10^{-6}$s and thus the MP completely loses its initial charge at a distance of about 0.02 cm from the point of entry into the plasma. Heating to the boiling point occurs over time $t \approx 7\cdot10^{-6}$s (Fig. 2, curve 3), which corresponds to the MP passing a distance of 0,16 cm from the point of entry into the plasma. Finally, the time for complete evaporation of the MP, depending on the energy of the electron beam, is equal to $t \approx 10^{-4} - 10^{-3}$s (Fig. 3, curve 2). Over this time, the MP travels a distance from 2 to 10 cm. Thus, for complete evaporation in plasma with the stated parameters and for plasma devices of suitable sizes it is desirable that the initial radius of the MP does not exceed 1 micron.

CONCLUSIONS

To obtain plasma of a given elemental composition, the introducing MPs into previously created plasma, followed by their evaporation and ionization is proposed. For more efficient evaporation, as well as ionization, a high-energy electron beam is injected into the plasma. As an example, the evaporation of a copper MP with a diameter of 1 micron is considered. To be introduced into the plasma, the MP is charged to a high positive potential and then accelerated by the created potential difference. It is shown that, regardless of the initial potential, the MP loses charge due to collision with plasma electrons with a density of 10^{10} cm^{-3} in a time of the order of 10^{-6} s. The initial positive potential serves not only to introduce the MP into the plasma, but also as an energy source for heating the MP by plasma electrons. It is shown that a MP with an initial potential of 30 kV can reach the boiling point of copper as a result of heating by electrons. At the same time, the MP is cooled due to thermal radiation and other processes. To additionally heat the MP and maintain its temperature at the boiling point, when the evaporation rate reaches its maximum, it is proposed to introduce a beam of high-energy electrons into the plasma. It has been shown that the introduction of an electron beam with a density of 10^9 cm^{-3} and an energy of more than 10 keV leads to heating of the MP to the boiling point, regardless of its initial potential. Assuming that the evaporation of the MP substance occurs only at the boiling point, conditions under which complete evaporation of the MP occurs were obtained. The dependence of the time of complete evaporation of a MP on the energy of the electron beam was also obtained. The velocity of introducing of MP into plasma is estimated and the characteristic distances at which the main processes occur with it are determined. It is shown that the MP recharge occurs over time $t \approx 10^{-6}\,s$ and that the MP completely loses its initial charge at a distance of about 0.02 cm from the point of entry into the plasma. Heating to the boiling point occurs in a time $t \approx 7 \cdot 10^{-6}\,s$ corresponding to the passage of the MP at a distance of 0.16 cm from the point of entry into the plasma. Finally, the time for complete evaporation of a MP, depending on the energy of the electron beam, is equal to $t_{evpr} \approx 10^{-4} - 10^{-3}\,s$. During this time, the MP passes a distance from 2 to 10 cm. Comparing the time and distance for complete evaporation of MPs of different sizes allows us to conclude that the optimal MP diameter is less than or on the order of 1 micron.

Thus, the possibility of evaporation MP in previously created plasma with the presence of a high-energy electron beam and thereby creating conditions for creating plasma of a given elemental composition is shown. This method of evaporation a substance is an alternative to existing methods such as evaporation from a furnace, cathode sputtering of a solid, evaporation by a vacuum arc.

ORCID
Aleksander A. Bizyukov, https://orcid.org/0000-0003-0192-5219; **Dmitry V. Chibisov**, https://orcid.org/0000-0002-6154-9772
Oleksandr D. Chibisov, https://orcid.org/0000-0001-9670-3912; **Oksana A. Zhernovnykova**, https://orcid.org/0000-0002-5383-4493
Kostyantyn V. Borysenko, https://orcid.org/0000-0002-8172-0215, **Dmytro Ye. Bobyliev,** https://orcid.org/0000-0003-1807-4844
Oksana H. Shtonda, https://orcid.org/0000-0001-7601-487X

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ПОЗИТИВНО ЗАРЯДЖЕНА МІКРОЧАСТИНКА В ПЛАЗМІ З ЕЛЕКТРОННИМ ПУЧКОМ ВИСОКОЇ ЕНЕРГІЇ

Олександр Бізюков[a], Дмитро Чібісов[a], Олександр Чібісов[b], Оксана Жерновникова[b], Костянтин Борисенко[b], Дмитро Бобилєв[c], Оксана Штонда[b]
[a]*Харківський національний університет імені В.Н. Каразіна 61022, Україна, м. Харків, майдан Свободи, 4*
[b]*Харківський національний педагогічний університет імені Г.С. Сковороди, 61002, Україна, м. Харків, вул. Алчевських, 29*
[c]*Криворізький державний педагогічний університет, 50086, Україна, м. Кривий Ріг, проспект Університетський, 54*
Розглянуто процеси зарядки, нагрівання та випаровування позитивно зарядженої мікрочастинки (МЧ), введеної в плазму, що містить пучок електронів високої енергії, з метою створення плазми заданого елементного складу. Передбачається, що МЧ заряджається поза плазмою, а потім вводиться в плазму прискорювальним полем, де плазма та електрони пучка, стикаючись з МЧ, нагрівають і випаровують її. На додаток до введення МЧ у плазму, позитивний заряд МЧ забезпечує додаткове джерело енергії, необхідної для її нагрівання та випаровування. За допомогою теорії OML чисельно розв'язано систему рівнянь балансу струму та енергії та визначено умови, за яких МЧ нагрівається до температури кипіння його матеріалу, що призводить до його інтенсивного випаровування. Досліджено вплив енергії електронного пучка на процес перезарядки МЧ, а також на швидкість його нагрівання та випаровування. Зроблено оцінку швидкості входу частинок у плазму; визначено відстані, на яких відбувається її перезарядка, нагрівання до температури кипіння і повне випаровування.
Ключові слова: *мікрочастинки; створення плазми; електронний промінь; випаровування мікрочастинок*