PHASE STATES OF MACROPARTICLES UNDER INTERACTION OF keV ION BEAM WITH DUSTY PLASMA

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Peculiarities of the keV-energy charge-compensated ion beam interaction with dusty plasma macroparticles are studied theoretically in this paper. Negative potential of the dusty plasma macroparticles makes conditions for their capture into the core of ion beam and their efficient interaction with beam ions. Heat and mass balances of the macroparticles in ion-beam system are considered. It is shown that it takes several milliseconds for the temperature of macroparticles to reach the boiling temperature under the intensive keV ion beam bombardment. Decreasing of the macroparticles mass is associated with both sputtering by the ion beam and evaporating after reaching the boiling temperature.

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1. INTRODUCTION

Dusty plasma is one of the most intensive developing branches of the modern plasma physics. Dusty plasma research is of huge practical importance because of macroparticles (MP) presence in a lot of vacuum-plasma processes [1].

Peculiarities of the keV-energy charge-compensated ion beam interaction with dusty plasma MPs is studied theoretically in this paper. Special attention is paid to the heat and mass balance of MPs in keV ion beam – plasma systems.

2. DESCRIPTION OF THEORETICAL MODEL

The interaction of a MP with the quasineutral ion-beam plasmas is considered. This plasma is produced by the middle energy ion beam (*1…10 keV*) and electrons which compensate the beam space charge.

Neutralizing the space charge of the beam with middle energy can be realized without external source of compensating particles [2]. The accumulation of electrons in the beam is caused by the ionization in the beam drift space and ion-electron emission from the beam collector [3-6]. The density of compensating electrons is of the same order as that of ion beam. The temperature of electrons is about *1…10 eV*.

The thermal electron current on a MP is greater than ion current under these conditions. The electrical potential of a MP is negative and is defined by the electron temperature. The ion energy is much greater than electron temperature. That is why we can neglect the electrical potential of a MP during the calculation of the cross-section of ion-MP interaction. Cross-section of interaction between ion and the MP is equal with high accuracy to that of the MP [7]. Negative potential of the dusty plasma MPs makes conditions for their capture into the core of ion beam and their efficient interaction with ion beam. The physical sputtering and evaporating is taken into account during the calculation of the MP radius - time dependence. Sputtering is the main mechanism of mass decreasing before reaching the boiling temperature T_{boil}. Evaporating gives the substantial addition to the mass decreasing only after reaching T_{boil}. The mass balance equation before reaching T_{boil} is:

$$dm_{mp}(t)/dt= -\pi\alpha J_i m_a r^2_{mp}(t)/e, \qquad (1)$$

where α is the sputtering coefficient, J_i is ion flux, m_a is the atomic mass of MP material, e is elementary charge, m_{mp} is MP mass, r_{mp} is MP radius. Eq. (1) gives the linear decreasing of radius with time:

$$r_1(t)=r_0 - \alpha J_i m_a t/(4e\rho), \qquad (2)$$

In (2) r_0 and ρ are initial radius and mass density of MP.

The power P_{EVAP} spent for evaporating is defined by the energy E_{EVAP} spent for evaporating the single atom multiplied by the number ΔN of atoms which leave the MP per interval Δt after reaching T_{boil}. Energy required for the single atom evaporating is proportional to specific heat of evaporation λ: $E_{EVAP}=\lambda\, m_a$.

Let consider the energy balance to get the speed of evaporation $\Delta N/\Delta t$ from the MP surface. Ion beam transmits the following energy to the MP:

$$P_{ib}(t)=\pi J_i E_{eff} r^2_{mp}(t)/e. \qquad (3)$$

In (3) E_{eff} is the energy that is transmitted to the MP by one incident ion. E_{eff} is equal to the incident ion kinetic energy if the collision with MP is perfectly inelastic.

The power spent for sputtering of the atoms from the MP surface is defined by the energy loss per one sputtered atom E_{out}:

$$P_{SPUT}(t)=\pi\alpha J_i E_{out} r^2_{mp}(t)/e. \qquad (4)$$

Radiative cooling power is

$$P_r(t)=4\pi r^2_{mp}(t) \in \sigma_{sb} T^4_{mp}(t), \qquad (5)$$

where $\in$ is emissivity, σ_{sb} is Stephan-Boltzmann constant.

Margin of the power P_{ib} over $P_{SPUT}(t)$ and $P_r(t)$ before reaching T_{boil} results in growing of the MP temperature $T_{mp}(t)$:

$$m_{mp}(t)\, C_p\, dT_{mp}(t)/dt=P_{ib}(t) - P_{SPUT}(t) - P_r(t). \qquad (6)$$

In (6) C_p is specific heat.

MP boiling goes on without change in the temperature. The margin of power from the beam is completely spent for the MP evaporating after reaching T_{boil}:

$$\frac{\Delta N}{\Delta t}=\frac{P_{ib}(t)-P_{SPUT}(t)-P_r(t)}{\lambda m_a}. \qquad (7)$$

One can define the velocity of radius decreasing during the boiling from the following equation:

$$\frac{4}{3}\pi\rho\, r_{mp}^{2}(t)\,\frac{dr_{mp}(t)}{dt}=-\frac{P_{ib}(t)-P_{SPUT}(t)-P_{r}(t)}{\lambda}. \quad (8)$$

Integrating the Eq. (8) gives the radius-time dependence in the result of evaporating after reaching T_{boil} with taking into account the sputtering:

$$r_2=r_{01}+\left[\frac{\in\sigma_{SB}T_{boil}^{4}}{\rho_{melt}\,\lambda}-\frac{J_i\left(E_{eff}-\alpha\, E_{out}\right)}{4\rho_{melt}\,\lambda e}-\frac{\alpha\, J_i m_a}{4e\rho_{melt}}\right]t\,. \quad (9)$$

Consideration of MP melting is also important for studying the time dynamics of temperature and phase state. MP melting goes on without any change in temperature. The margin of power from the beam over P_r and P_{SPUT} is completely spent for the MP melting after reaching the melting temperature T_{melt} and is proportional to the specific heat of melting L:

$$P_{melt}(t) = P_{ib}(t) - P_{SPUT}(t) - P_r(t) = L\, dm_{mp}(t)/dt. \quad (10)$$

Integrating of Eq. (10) from melting start to the melting finish gives us the duration of melting phase τ_{melt}:

$$\tau_{melt}=\frac{-4\,e\,\rho}{\alpha\, J_i\, m_a}\left[\left[r_{mp}^{3}(t_{melt})\ -\ -\frac{r_{mp}^{3}(t_{melt})\,\alpha\, J_i\, Lm_a}{J_i\left(E_{eff}-\alpha E_{out}\right)-4e\in\sigma_{SB}T_{melt}^{4}}\right]^{1/3}-r_{mp}(t_{melt})\right]. \quad (11)$$

3. ANALYSIS OF THE OBTAINED RESULTS

The temperature-time dependences are found numerically for copper, titanium and tungsten MPs with initial radius 10^{-4} cm. The results of numerical investigation are shown on Fig. 1, 2. Ion beam energy is *2 keV*.

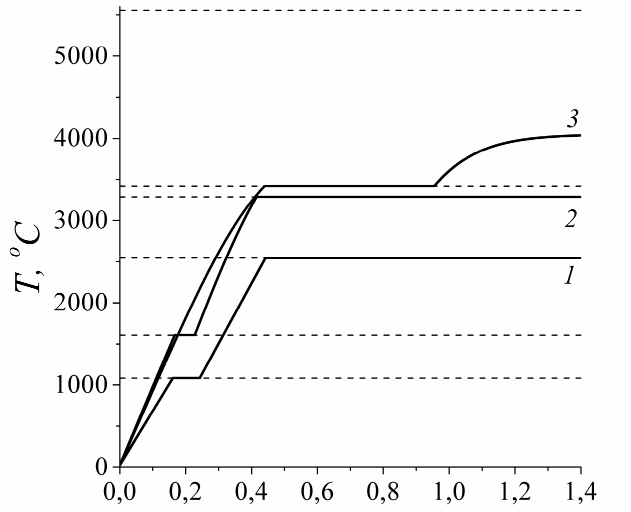

Fig. 1. The temperature-time dependence for copper (1), titanium (2) and tungsten(3) MPs. Beam current density is J_i=1,5 A/cm^2

T_{melt} and T_{boil} of copper, titanium and tungsten are shown on Fig. 1, 2 with dashed horizontal lines. The Fig. 1 shows that *1,5 A/cm^2* beam current density doesn`t allow to heat tungsten MPs up to T_{boil}. The beam power is compensated by huge power losses on radiative cooling at high temperatures and sputtering. The *5,25 A/cm^2* beam current density is feasible for our experimental conditions. The tungsten MP boiling becomes reachable for such beam current density.

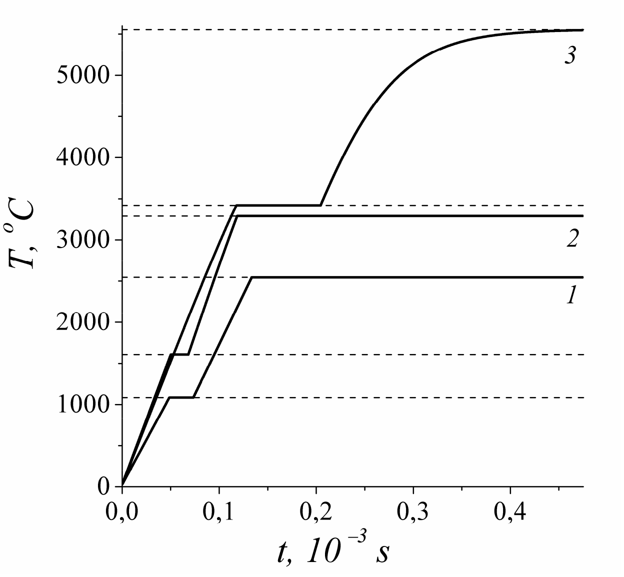

Fig. 2. The temperature-time dependence for copper (1), titanium (2) and tungsten(3) MPs. Beam current density is J_i=5,25 A/cm^2

It is shown on Fig. 2 that *5,25 A/cm^2* beam current density allows to heat tungsten MP up to T_{boil} in 5×10^{-4} s.

The radius-time dependences for two different beam current densities are shown on Fig. 3, 4. Fig. 3 shows the radius of tungsten MP versus time. The following issue should be underlined. Boiling is unreachable for tungsten MP at *1,5 A/cm^2* current density. Nevertheless, the MP is completely sputtered in *2,3 s*. While at *5,25 A/cm^2*, tungsten MP escapes in *0,5 s* due to sputtering and evaporation.

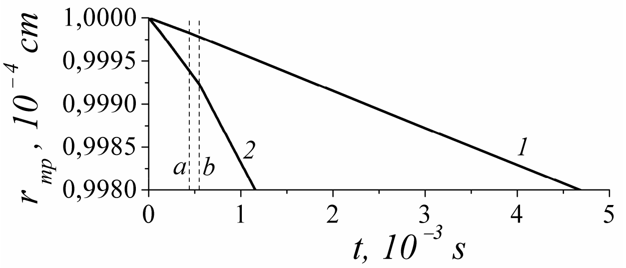

Fig. 3. The radius of tungsten MP versus time under the bombardment of ion beam with 1,5 A/cm^2 (line 1) and 5,25 A/cm^2 (line 2). Dashed vertical line (a) shows the start of melting for the line 1 and (b) – for 2

The boiling is reachable for copper and titanium MPs at both beam current densities. Titanium MP is evaporated faster than copper one at both current densities – at first glance this looks like an absurd statement. But titanium MP fast evaporating can be explained by the following facts: it has about *1,5* times higher heat capacity and two times lower mass density in comparison with copper one.

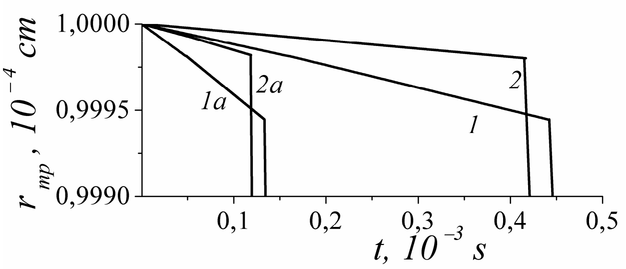

Fig. 4. The radius of copper (1) and titanium (2) MPs versus time under the bombardment of ion beam with 1,5 A/cm^2. 1a and 2a lines show the same under the 5,25 A/cm^2 beam current density

4. CONCLUSIONS

Heat and mass balances of the MPs in ion-beam-plasma system are considered. It is shown that it takes several milliseconds for the temperature of MPs to reach the boiling temperature under the intensive keV ion beam bombardment. Decreasing of the MPs mass is associated with both sputtering by the ion beam and evaporating after reaching the boiling temperature. Numerical simulations demonstrated that the ion beam – dusty plasma system can compete in the respect of energy efficiency of substance evaporating with existing industrial evaporating systems which are designed for thin films depositing and utilize containers in the form of crucibles for the substance to be evaporated.

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ФАЗОВЫЕ СОСТОЯНИЯ МАКРОЧАСТИЦ ПРИ ВЗАИМОДЕЙСТВИИ ИОННЫХ ПУЧКОВ СРЕДНИХ ЭНЕРГИЙ С ПЫЛЕВОЙ ПЛАЗМОЙ

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Теоретически исследованы особенности взаимодействия компенсированного по заряду ионного пучка средних энергий с макрочастицами пылевой плазмы. Отрицательный потенциал макрочастиц создает условия для захвата пылевых частиц в остов ионного пучка, который обычно имеет положительный потенциал, и эффективного взаимодействия с ионным пучком. Рассмотрены тепловой и массовый балансы макрочастиц в ионно-плазменной системе. Показано, что при облучении пылевой плазмы интенсивными пучками ионов средних энергий за времена порядка десятка миллисекунд температура макрочастиц достигает температуры кипения. Уменьшение массы макрочастиц связано как с распылением ионным пучком, так и с испарением после достижения температуры кипения.

ФАЗОВІ СТАНИ МАКРОЧАСТИНОК ПРИ ВЗАЄМОДІЇ ІОННИХ ПУЧКІВ СЕРЕДНІХ ЕНЕРГІЙ З ПИЛОВОЮ ПЛАЗМОЮ

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Теоретично досліджено особливості взаємодії компенсованого за зарядом іонного пучка середніх енергій з макрочастинками пилової плазми. Від’ємний потенціал макрочастинок створює умови для захоплення пилових частинок до остову іонного пучка, який зазвичай має позитивний потенціал, та ефективної взаємодії з іонним пучком. Розглянуто тепловий та масовий баланси макрочастинок в іонно-плазмовій системі. Показано, що при опроміненні пилової плазми інтенсивними пучками іонів середніх енергій за інтервали часу порядку десятка мілісекунд температура макрочастинок сягає температури кипіння. Зменшення маси макрочастинок пов'язано як з розпиленням іонним пучком, так і з випаровуванням за температури кипіння.