Influence of different processes of the electron emission on the ultrahigh charging of a dust particle in plasma by the energetic e-beam.

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Abstract. Results of numerical modeling of dynamics of ultrahigh charging of the dust particle surrounded with plasma and irradiated by an electron beam with high electron energy are given in the presented work. The e-beam was created by the pulsed open discharge in strongly overvoltage regime. The maximum negative charge accumulated on the irradiated particle is defined by the intensity of processes of charging and discharging of a target. In general, the process of charging is defined by e-beam parameters (its energy and the current density) while the discharging of a target depends on many processes, such as delivery of positive ions from the plasma onto a negatively charged target and also an emission of electrons from a target surface. In its turn, the electron emission from a surface is caused by the various processes including kinetic emission of electrons due to impact of the target by fast ions, secondary electron emission by e-beam, thermo-emission and auto-emission of electrons in case of strong heating of a particle and emergence of the strong electric field on a surface of the highly charged target. The ultrahigh charging of the dust particle irradiated by an e-beam with the energy of 25 keV was modeled. Results of numerical calculations about influence of the listed above discharging processes of a target on its maximum negative charge and potential have shown that the greatest contribution to the target discharging process belongs to the kinetic electron emission caused by fast positive ions.

1. Introduction

High-current medium-energy electron beams (up to 25 keV) are used in various applications. One of the recent and promising applications of such beams is the ultra-high charging of dust particles [1-3] located in plasma. When such particles are irradiated by an electron beam, a large negative electric charge is accumulated on them. At the same time, positive plasma ions are accelerated in a strong field of a negatively charged particle and can acquire, by the time of collision with a target, energy close to the energy of the electron beam charging the particle. If plasma ions are deuterium or tritium ions, and a charged target also contains deuterium or tritium, then the above-mentioned energy is sufficient to carry out thermonuclear reactions, accompanied by neutrons, but the energy is not enough to create concomitant hard X-rays. This circumstance is very important for the development of small-sized neutron radiation sources suitable for medical applications [4].

Thereby, it is of great interest to find out the maximum amount of negative charge that can be accumulated on the irradiated particle. The maximum charge value is determined by the rates of charging and discharging processes on the target. In this case, the charging process is mainly
determined by the parameters of the e-beam (its energy and current density), while the discharge of the target depends on many processes, such as the arrival of positive ions from the plasma to a negatively charged target, as well as the emission of electrons from the target’s surface (ion-electron emission, secondary emission caused by e-beam, thermal and auto-emission).

In the papers [2, 3], calculations showed that around the target being charged a rapid depletion of the plasma takes place due to the escape of positive ions to the negatively charged particle and repulsion of plasma electrons from the particle charged by e-beam. It should be noted that the calculations in [2, 3] took into account the ionization of the gas around the particle due to slow secondary electrons emitted from its surface with a large ionization cross section. However, only secondary electrons knocked out by the e-beam were taken into account. In this paper, the numerical model of a dust particle charging dynamics, developed in [2, 3], is modified to take into account all the above-mentioned electron emission processes and their influence on the ionization of gas around the target, as well as on the maximum charge of the target and its potential relative to the plasma. The results of numerical calculations showed that positive ions make the largest contribution to the discharge of the target by neutralizing the negative charge of the target and due to the kinetic emission of electrons caused by the fast ion collisions with the target.

2. Model description
A detailed description of the mathematical model for charging a spherical particle in plasma by an e-beam is given in [3]. The numerical calculation for the potential radial distribution $\varphi(x,t)$ around the target was carried out on the basis of a self-consistent solution of the continuity equations for charged particles and the Poisson equation, including their space charges. In addition to positive ions, plasma electrons, beam electrons and electrons emitted from the surface of a spherical target were taken into account. The motion of the plasma ions and electrons was described in the one-dimensional diffusion-drift approximation up to the target surface. The electric potential at the beam input into the plasma is zero: $\varphi(x = x_{\text{max}}) = 0$. The electric field strength on the surface of a spherical particle is determined by the electric charge of the particle $q(t)$:

$$-\varphi'(x = d_p/2) = \frac{q(t)}{\varepsilon_0 d_p^2},$$

(1)

The origin $x = 0$ corresponds to the center of the spherical target, the coordinate $x_{\text{max}} = 10$ mm corresponds to the boundary of the unperturbed plasma, where the electron beam enters the plasma. The computational domain was specified by the inequality $d_p/2 \leq x \leq x_{\text{max}}$, where $d_p/2 = 250$ μm is the radius of the spherical target. At the initial time $t = 0$, it was considered that the entire calculated domain was uniformly filled with a quasi-neutral plasma: $n_i(x, t = 0) = n_0(x, t = 0) = n_0$, and the charge $q(t=0)$ on the target was set equal to zero.

The equation describing the dynamics of the negative charge $q(t)$ over time has the form:

$$\frac{dq}{dt} = \{(1 + r_i) \cdot eI_l - J_{eb}[1 - \gamma_e(\varepsilon_{eb})]\}n(d_p)^2$$

(2)

In the absence of a positive ions flow from plasma, the target is being charged with a negative charge until the energy of the beam electrons hindered at the target surface decreases to a value at which the secondary emission coefficient $\gamma_e$ exceeds unity. Usually this energy is about 1.5 keV. In the presence of positive ions flow, the target charging stops earlier. In this case, the potential energy of the target may be several keV less than the energy of the incident electrons.

3. Calculation results
Below everywhere, the results obtained using the modified ultrahigh-charge model are compared with the results obtained earlier in [3] under the same conditions, i.e. the particle radius, plasma density around the particle, the energy and density of the beam current are taken to be the same in both versions of the calculation. At the same time, the results of the calculations [3] are named for convenience the basic ones and are represented on the graphs by dashed lines, and the results of the modified model are shown by solid lines. To compare the results, three time points were selected ($t = 5, 40, \text{and} 500$ ns), for which the curves are shown in blue, green, and red, respectively. The presented
results for the selected moments quite clearly show the difference in the dynamics of ultra-high particle charging, whilst taking into account additional processes of gas ionization near a spherical target by slow emitted electrons and the relaxation processes listed above.

As the negative charge on the target increases, the plasma electrons will move further away from it. The information in Figure 1a about the distribution of the plasma electron concentration around the target at different points in time gives an idea of how quickly plasma electrons leave the area adjacent to the target. It is seen that the inclusion of additional ionization by slow electrons, knocked out by the e-beam and fast ions, as well as the relaxation caused by these electrons, leads to a slower departure of plasma electrons from the target.

![Figure 1a](image1a.png)  
*Figure 1a.* The plasma electrons concentration distribution around a spherical target for different moments in time: 5, 40 and 500 ns (blue, green and red curves). Dotted line - the basic version; solid curves are a modified variant with ion-electron emission and gas ionization by emitted electrons switched on.

![Figure 1b](image1b.png)  
*Figure 1b.* The beam electrons and emitted electrons concentration distribution around the target for the same moments in time. The target radius is \( r = 250 \mu m \), \( x = 0 \) corresponds to the center of the sphere. Dotted line - the basic version; solid curves are a modified variant with ion-electron emission and gas ionization by emitted electrons switched on.

From Fig. 1b it can be seen that as the target charges up, resulting in ever greater deceleration of the e-beam, the electron density of the beam at the target increases with time, and this effect is weakened when electron emission is turned on by the ion flux. The density of the emitted electrons around a spherical target increases with time, but due to geometric effects decreases as they move...
away from the target. It is important to note that in the modified version, the density of emitted electrons at \( t > 5 \) ns always exceeds the density of these electrons in the base version. However, the density of the emitted electrons around the target is everywhere much less than the density of plasma electrons, as well as the density of positive ions, the distribution of which is shown in Fig. 2. In other words, a layer of positive space charge forms around a negatively charged particle.

It is also seen from Fig. 2 that the expansion of the positively charged layer around the target in the modified version is slower compared to the basic model because of the inclusion of electron emission due to the ion flow and ionization of the gas by emitted electrons. The observed increase in the density of ions as they approach the target is due to the geometric effect — focusing the ions on the sphere. In general, the expansion of the layer is accompanied by a decrease in the density of positive ions. This effect is valid for basic and modified versions.

Figure 3 shows the rate of gas ionization by beam electrons and emitted electrons vs the distance to the center of the target at time moments of 5, 40 and 500 ns. It can be seen that the gas ionization rate in the plasma-depleted layer increases as it approaches the target and near the target increases noticeably with time, and this effect is more pronounced for the modified version, which considers electron emission due to ion flow and gas ionization by emitted electrons.

The radial distribution of the negative electric potential around the target at times 5, 40 and 500 ns after the start of charging is shown in Fig. 4. It can be seen that the main potential change occurs in the plasma-depleted layer with positive space charge. At times up to 5 nanoseconds, the energy of the ions bombarding the target does not exceed 3 keV, therefore, the kinetic knock-out of electrons by ions is practically absent and the potential distribution curves for basic and modified versions coincide. However, at large times, when the kinetic ion-electron emission is turned on, the charging of the target slows down and in the modified version at the same time a smoother increase of the negative potential is observed. This effect is especially clearly seen in Fig. 5, which shows the potential dynamics on the target surface. If in the basic case the target was charged to a potential equal to the e-beam energy (25 keV) in 75 ns, then in a modified version that takes into account the relaxation of the target’s charge due to the ion-electron emission, the target potential did not exceed 20 kV.

Note that in all previous versions of the calculations, we did not take into account the thermal and auto-emission of electrons from the target’s surface. In special calculations, we took into account the heating of the target during its charging and found that this heating does not exceed several tens of
degrees. With the characteristic value of emission potential of the target material $\varphi \approx 4.5$ eV the thermionic emission is absent.

The density of cold emission current depends on the strength of the electric field on the target surface and is determined by the well-known Fowler – Nordheim formula:

$$j(\alpha) = \frac{a}{\varphi} E^2 \cdot \exp \left\{ -\frac{b\varphi^{3/2}}{E} \right\},$$

(3)

here $a = 1.54 \times 10^{-6}$ [A·eV·V⁻²]; $b = 6.83 \times 10^9$ [eV⁻³/²·V/m]. The electric field on the surface of a spherical target is determined by its charge $q$ and diameter $d$ or potential $U$:

$$E = \frac{q}{\varepsilon_0 \pi d^2} = \frac{U}{d},$$

(4)

How electric field $E$ on the surface of the target depends on target’s potential $U$ at different radii $r$ of the target is shown in Fig.6.

**Figure 6.** The electric field on the surface of the target vs its potential for different radii of the target. $E^* = b\varphi^{3/2}$ denotes the characteristic magnitude of the field at which the autoemission becomes noticeable. $E^* \approx 6.5 \times 10^8$ V/cm for $\varphi \approx 4.5$ eV.

As can be seen from Fig. 6, even an electric field on a target with 50 μm radius is two orders of magnitude less than $E^*$ at a maximum potential of $U = 30$ kV. In our case, the target radius is five times larger, which guarantees the complete absence of field emission currents under our conditions.

### 4. Conclusion

In this paper, the numerical model of a dust particle charging dynamics, developed in [2, 3], was modified by taking into account electron emission from the particle surface due to impact by fast ions, thermal emission and auto emission of electrons in the case of strong heating of the particle and strong electric field appearance on a charged target’s surface. The aim of the work was to elucidate the influence of all the above-mentioned processes on the ionization of gas around the target, as well as on the magnitude of the target’s maximum charge and its potential relative to the plasma. It was showed that positive ions make the largest contribution to the relaxation of the target by neutralizing it’s charge and due to the kinetic emission of electrons caused by the flow of fast ions on the target.

### 5. References

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