Dust Particle Evolution in the Divertor Plasma

S. K. Kodanova, N. Kh. Bastykova, T. S. Ramazanov, and S. A. Maiorov

***Abstract*— The influence of magnetic field on the charge, dynamics, and lifetime of dust particles in the divertor plasma has been studied. A computational model based on the particle-in-cell and Monte Carlo methods has been constructed, and the time dependence of the dust particle charge and plasma fluxes on its surface has been calculated. It has been shown that a strong magnetic field has a significant impact on the process of dust particle charging in the divertor plasma. The numerical model describing heating and evaporation of dust particles in the plasma has been developed, and the lifetime and the path of dust particle in the divertor plasma have been calculated.**

***Index Terms*— Charge of dust particle, dust transport.**

I. Introduction

INVESTIGATION into formation and evolution of dust particles in controlled fusion devices has become an important part of large-scale fusion plasma experiments [1]–[4]. The flux of hot particles from the central region to the walls of the reactor can cause destruction and evaporation of the wall surface, as a result of which solid particles of various shapes, ranging from irregular forms to almost perfect spheres, can be injected into the plasma. These particles consist of materials used for divertor plates, the first inner wall, and other structural elements, namely, graphite, titanium, tungsten, beryllium, and steel.

As the speed of electrons is much greater than that of ions, dust particles usually acquire a negative charge in the plasma. The mean value of the charge and its fluctuations are mainly determined by the ratio of masses between ions and electrons, their temperature, and sizes of dust particles. It should be noted that even rare collisions of ions near the dust particle can significantly affect its charge and form a cloud of bound ions on finite orbits. A more detailed description of the charging process without a magnetic field may be found in [2] and [5]–[9].

Magnetic field can also have a significant impact on the process of dust particle charging in the plasma. In order to study the impact of dust on the operation of fusion reactors, it is necessary to take into account the influence of a strong magnetic field on the process of dust particle charging in the edge plasma. In [10] and [11], the charge of dust particles in the presence of a magnetic field was calculated in the approximation of the orbital motion limited (OML) theory. In this paper, ion collisions with atoms were calculated using the Monte Carlo method and the dependence of the dust particle charge and plasma fluxes on the magnetic field was obtained.

Migration of dust particles from the surface of the wall deep into the fusion reactor and their evaporation are the main factors determining the composition and characteristics of the edge plasma, and therefore, they can have a significant impact on the operation of the fusion reactor. To take into account migration of dust particles in the divertor plasma, it is necessary to solve the equations of dust particle motion in the given electric and magnetic fields and equations of mass and energy balance.

II. Dust Particle Charging

At the first stage of this work, the charge of a fixed, initially neutral dust particle with an infinite mass was calculated. The dust particle charge was calculated using the particle-in-cell method, whereas the number of collisions between ions and atoms was determined by the Monte Carlo method [5], [6], [12], [13].

We considered a cube centered at the origin of coordinates, into which a spherical neutral dust particle of a given radius, absorbing charges of all incident ions and electrons, was placed. It was supposed that the initial distribution of electrons and ions was equiprobable throughout the volume of the cube. The velocity distribution was assumed to be equal to the Maxwell distribution at infinity. Depending on the initial distance from the macroparticle, the Maxwell speed distribution was shifted by the energy of interaction with a macroparticle. The direction of the velocity was supposed to be isotropic. Thus, the initial distribution without any bound particles, which under certain conditions can strongly affect the kinetic characteristics, was formed [5], [6], [13].

The equations of motion for electrons and ions were solved taking into account a constant and uniform magnetic field

$$\frac{d^2\mathbf{r}_k}{dt^2} = \frac{q_k}{m_k}\left(\mathbf{E}_k + \frac{1}{c}[\mathbf{v}_k \times \mathbf{B}]\right), \quad k = 1, 2, \ldots, N_p \qquad (1)$$

where $\mathbf{E_k} = Q\mathbf{r_k}/|\mathbf{r_k}|^3$, $\mathbf{r_k}$ is the radius vector of the kth particle with mass $m_\mathbf{k}$ and charge q_k, Q is the charge of the dust particle, and N_p is the total number of ions and electrons. The radius vector of the dust particle is equal to zero and does

Manuscript received July 22, 2015; revised October 9, 2015 and November 18, 2015; accepted November 18, 2015. Date of publication December 8, 2015; date of current version April 8, 2016. This work was supported in part by the Ministry of Education and Science, Republic of Kazakhstan, under Grant 3112/GF4 and in part by the Russian Foundation for Basic Research under Grant 14-02-00779.

S. K. Kodanova, N. Kh. Bastykova, and T. S. Ramazanov are with the Institute of Experimental and Theoretical Physics, Al-Farabi Kazakh National University, Almaty 050040, Kazakhstan (e-mail: kodanova@mail.ru; bastykova_nuriya@physics.kz; ramazan@physics.kz).

S. A. Maiorov is with the Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow 119991, Russia, and also with the Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow 127412, Russia (e-mail: mayorov_sa@mail.ru).

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Digital Object Identifier 10.1109/TPS.2015.2502607

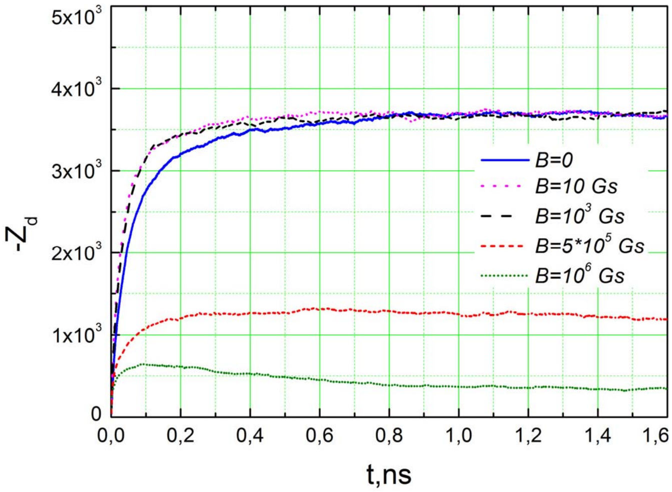

Fig. 1. Time dependence of the dust particle charge for different values of the magnetic field.

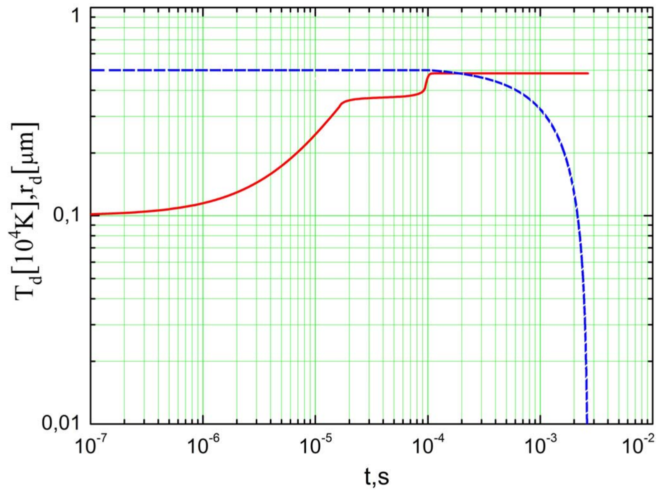

Fig. 2. Time dependence of the dust particle temperature (red solid line) and radius (blue dotted line) during heating.

not change. The formula for the electric field $\mathbf{E_k} = Q\mathbf{r_k}/|\mathbf{r_k}|^3$ corresponds to the exact solution to a spherically symmetric distribution function of the charge density, when according to the Gauss theorem the field on the sphere surface is determined by the total charge inside the sphere.

The charge of dust particles was calculated for the following parameters of the divertor plasma [14]: 1) the density of electrons and ions equal to 10^{14} cm^{-3} and 2) the temperature of ions -0.7 eV and electrons -3 eV. The charges of dust particles with radii of 0.5, 1, and 2 μm for various values of the magnetic field $B \div (10\text{–}10^5)$ Gs were obtained. Fig. 1 shows the time dependence of the dust particle charge for different values of the magnetic field. In the plasma without a magnetic field, most electrons reflect from the Coulomb barrier of the dust particle, and only a small fraction of fast electrons can reach the dust particle. On the contrary, ions are attracted by the dust particle and its collision cross section becomes much larger than the geometrical cross section of the dust particle πa^2.

In [7], the influence of magnetic field on the charge of dust particles in the approximation of the OML theory was studied. It was found that the magnetic field started to affect the charge of the dust particle when its strength was higher than $B^e_{\rm cr}(k\text{Gs})a(\mu\text{m}) > 41.37(T_e(\text{eV})/3(\text{eV}))^{(1/2)}$. In this paper, it is shown that for the parameters of the divertor plasma and the dust particle with a radius of $a = 0.5$ μm, the strength of the critical magnetic field is equal to $B^e_{\rm cr} = 8.5 \cdot 10^4$ Gs.

Magnetic field affects the dust particle charging mainly through the magnetization of electrons. In a weak magnetic field $B < B^e_{\rm cr}$, when the gyroradius of the electron is greater than the size of the dust particle, the influence of the magnetic field on the charge of the dust particle is very small. The picture changes when the strength of the magnetic field increases to values at which the gyroradius of electrons is equal to the radius of electron capture of the dust particle. The electrons move along the magnetic field lines and can reach the surface of the dust particle only if the magnetic field line intersects it. However, low-energy electrons, as in the case without a magnetic field, are reflected from the Coulomb barrier in the reverse direction.

III. Energy Balance for the Dust Particle in the Plasma

In the plasma, the dust particle is subjected to the action of the flows of ions, electrons, atoms, and radiation. The kinetic energy of incident electrons and ions and the energy of their recombination on the surface of the dust particle contribute to the heating of the dust particle. In addition, on the surface of the dust particle, there are such processes as heat emission during deposition, exothermic reactions, and recombination of dissociated molecules (see a more detailed description of the model in [3] and [4]).

The model takes into account heating of the dust particle by the heat fluxes of electrons and ions, their recombination on its surface, and cooling by radiation and evaporation. Every event of ion absorption on the dust particle leads to the formation of an atom and the energy released in this case is equal to the ionization potential of the gas atom. The loss of energy in the form of radiation is taken into account in accordance with the law of black body radiation, with the corrections of the Mie theory [15]. The mass loss due to evaporation is estimated by the Hertz–Knudsen formula [16]. As the temperature of the dust particle rises, its matter may undergo phase transitions. In our calculations, we supposed that first it passes from the solid to the liquid state, and then, when its temperature reaches the boiling point, it rapidly loses its mass through evaporation. During the phase transition, the temperature is assumed to remain constant.

The heating process of initially cold dust particles in a homogeneous deuterium plasma near the wall of the divertor was calculated.

Fig. 2 shows the time dependence of the temperature and radius of the dust particle. The following parameters were chosen for calculations [14]: $T_e = 3$ eV, $T_i = 0.7$ eV, and $T_a = 0.2$ eV are the temperatures of electrons, ions, and neutral atoms, $n_e = n_i = n_a = 2 \times 10^{14}$ cm^{-3} are the

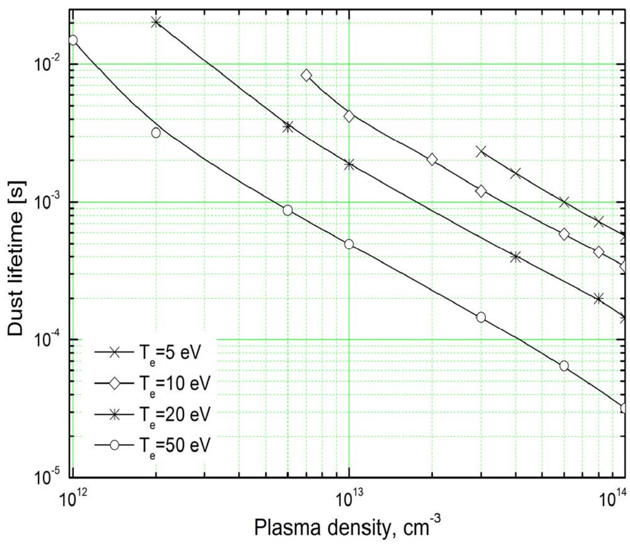

Fig. 3. Lifetime of the dust particle in a homogeneous deuterium plasma.

densities of electrons, ions, and neutral atoms, respectively, the initial temperature of dust particles is $T_{d0} = 1000$ K, and the radius is $R_{d0} = 0.5\ \mu$m. In Fig. 2, a phase transition from the solid to the liquid state at the melting point of the material of the dust particle $T_{\text{melting}} = 3695$ K is seen. During the first 20 μs, the dust particle temperature rises up to 3695 K, then in the time interval from 20 to 100 μs, the temperature does not change, as the incoming energy is spent on the process of melting of the dust particle. After the transition to the liquid state, the temperature starts to rise quickly up to the boiling point of the dust particle at $T_{\text{vaporation}} = 4850$ K. In the process of boiling, the dust particle quickly loses its mass, and 3000 μs after the beginning of boiling, its radius decreases to zero.

Fig. 3 shows the dependence of the lifetime of dust particle in a deuterium plasma on its density for different values of the electron temperature. It is seen that as the temperature of electrons and plasma density increase, the lifetime of dust particles monotonically decreases mainly due to high energy flux, which raises the temperature of dust particles and enhances their evaporation.

IV. Conclusion

The influence of magnetic field on the charge, dynamics, and lifetime of dust particles in the divertor plasma has been studied. The charge of the dust particle was determined taking into account the influence of the magnetic field on the trajectory of ions and electrons using the particle-in-cell method, and the collisions of ions with atoms were calculated using the Monte Carlo method. This paper is the first where the influence of bound ions on the charge of dust particles in the presence of strong magnetic fields is taken into account. The dust particle charge of a radius of 0.5 μm at values of the magnetic field in the range $B = 10 \div 10^6$ Gs was calculated. The results of calculations show that the magnetic field starts to affect the dust particle charge when its strength reaches a certain critical value determined from the equality of the electron gyroradius and the diameter of the dust particle. It has been shown that the magnetic field can have a significant impact on the process of charging of the dust particle in the divertor plasma reducing its path and lifetime. As a result of these calculations, the time dependence of the dust particle charge and plasma fluxes on its surface was obtained. These data enable us to calculate transport properties of dust particles in the edge plasma and to determine their lifetime. Migration of dust particles and their evaporation are the main factors that determine the ionic composition of the edge plasma, its transport, and radiation characteristics. Based on the model of evaporation of dust particles under the influence of fluxes of plasma particles and radiation, the numerical data for the dust lifetime and its path in the divertor plasma were obtained.

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