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The Effect of Magnetic Field on Dust Dynamic in the Edge Fusion Plasma

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

***Abstract*— In this paper, the effect of the magnetic field on dust dynamic and lifetime in the edge fusion plasma has been studied. A computational model of tungsten dust evolution formed on the surface of the reactor wall was constructed on the basis of particle-in-cell and Monte Carlo methods. The time dependence of the characteristic parameters (charge, temperature and radius, and heat fluxes) of the dust particle was determined. On the basis of these calculations, estimates of the tungsten dust lifetime in the edge fusion plasma were made. It was found that the magnetic field can have a significant effect on charging processes and lifetime of dust particles in the edge fusion plasma. The obtained results show that the larger the dust particle size, the stronger the magnetic field affects its charge, which leads to the suppression of the heat flux of plasma particles on the dust surface and an increase in its lifetime. Also, the magnetic field increases the charging time of small dust particles due to the limitation of the trajectory along the magnetic field lines.**

***Index Terms*— Dust lifetime, dust particle charge, edge fusion plasma.**

I. Introduction

THE mechanisms of appearance of dust particles and their confinement in the plasma volume are of great importance, therefore they are intensively studied both theoretically and experimentally [1]–[10]. The edge dusty plasma is formed due to the interaction of energy flows with the wall materials, as a result of which dust particles with a macroscopic (micrometer) size are injected into the plasma. These dust particles, retaining in the plasma, may affect not only heat transfer but also play an important role in the general concept of plasma interaction with the reactor wall and formation of a positive energy yield. Dust migration from the surface of the wall deep into the reactor core and its subsequent evaporation can have a significant impact on the operation of the reactor.

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Investigation of the charging processes of dust particles is one of the key problems in the dusty plasma physics, as it provides information of the charge and interaction potential of dust particles [11]–[13]. This information is needed for constructing a theory of dusty plasmas, capable of describing the processes of formation, existence, evolution, and destruction of dust formation in the fusion plasma. The injected dust particles, getting into the plasma, acquire a large negative charge, as the thermal velocities of electrons are much higher than the ion velocities. Sometimes dust particles can be charged positively, e.g., if the loss of electrons due to irradiation with ultraviolet radiation in the discharge exceeds the electron charging current.

The results of studies of dust from the installation TEXTOR with a scanning electron microscope show that the majority of the particles are flakes of the deposited layers [6]. It was found that about 15% of the dust is ferromagnetic; in this case, the magnetic particles will interact with the magnetic fields and gradients. In this connection, it is very important to take into account the magnetic field in the process of dust particle charging in the edge fusion plasma. It is necessary to study the influence of dust particles on the operation of fusion reactors at consideration of the strong magnetic field effect on the dust particle charging processes. The charge of dust particles with allowance for the magnetic field was calculated on the basis of orbital motion limited theory in [14] and [15]. It was found that the effect of the magnetic field on the dust charge starts from a certain critical value of the magnetic field, which is determined from the equality of the electron gyroradius and the size of dust particle.

The value of the charge and the floating potential of the dust particle affect its lifetime, as they determine ion and electron fluxes on the dust particle. The lifetime is the most important characteristic of the dust particle dynamic in fusion plasma, as it characterizes the depth of their penetration into the reactor and their influence on its operation.

II. Influence of Magnetic Field on Dust Particle Charge

The magnetic field affects the dust particle charging mainly through the magnetization of electrons. In a weak magnetic field $B < B^e_{\mathrm{cr}}$, when the electron gyroradius is greater than the dust particle, this influence is very small. The picture changes when the strength of the magnetic field increases to the values, where the electron gyroradius is equal to the radius of electron capture of the dust particle. Electrons move along the magnetic field lines and can reach the surface of the dust particle only

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if the magnetic field line intersects it. Low energy electrons, as in the case without a magnetic field, are reflected from the Coulomb barrier in the reverse direction. In this paper, the effect of magnetic field on the dust particle charge in the edge fusion plasma is investigated. 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 [16]–[18]. A cube with the center at the origin of coordinates is considered, where 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.

The equations of motion for electrons and ions were solved taking into account 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 $\mathbf{r_k}$ is the radius vector of the kth particle with mass $m_\mathbf{k}$ and charge q_k, $\mathbf{E_k}$ is the electric field acting on the kth particle, and N_p is the total number of ions and electrons. The radius vector of the dust particle is equal to 0 and does not change. The formula for the electric field $\mathbf{E_k} = \mathbf{r_k}/|\mathbf{r_k}|^3(Q + \sum_{r_i<r_k}^{N_p} q_i)$, where Q is the charge of the dust particle. This expression corresponds to the exact solution for 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 charges of dust particles were calculated for the following parameters of the edge fusion plasma: the density of electrons and ions equal to 10^{18} m^{-3} and the temperature of electrons and ions -18.7 eV. The charges of dust particles with radii of 0.5–6 μm for various values of the magnetic field $B \div (4 - 10)$ T were obtained.

Fig. 1 shows the time dependence of the dust particle charge with radius $a = 3$ μm for different values of the magnetic field. As can be seen from Fig. 1, an increase in the value of the magnetic field causes a decrease in the charge of the dust particle and an increase in the charging time. In strong magnetic fields ions and electrons are magnetized and move along the magnetic field lines and can be caught by the dust particle only when the magnetic field lines cross its surface. Figs. 2 and 3 show the results of calculation of the dependence of the charge and charging time of dust particles on their radius. Fig. 2 shows the ratio of the charge of a dust particle in the presence of the magnetic field to the charge of dust particles without taking into account the magnetic field. At the values of the magnetic field 4 and 6 T, a moderate effect of the magnetic field on the charge of the dust particle is seen. In the case when the magnetic field is equal to 10 T, a strong difference in the charge of dust particles with an increase in the dust radius is observed.

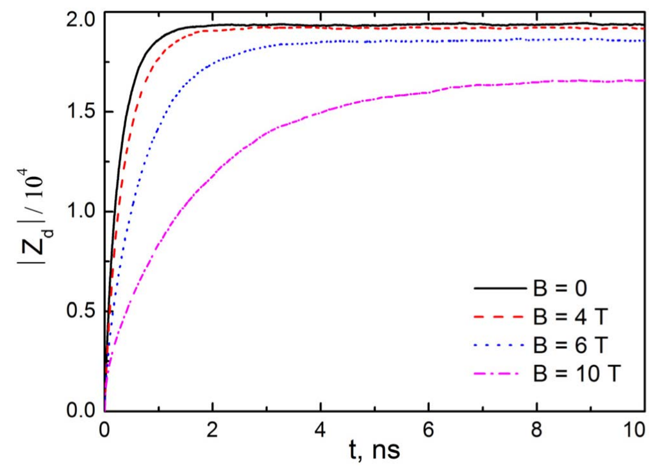

Fig. 1. Time dependence of the dust particle charge for different values of the magnetic field.

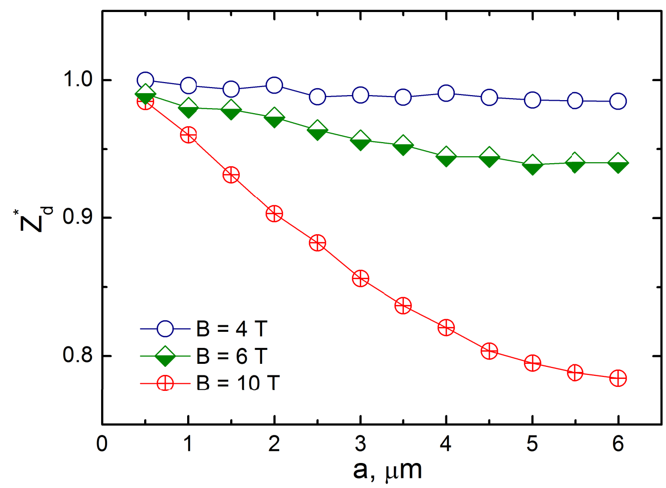

Fig. 2. Ratio of the dust particle charge with/without taking into account magnetic field.

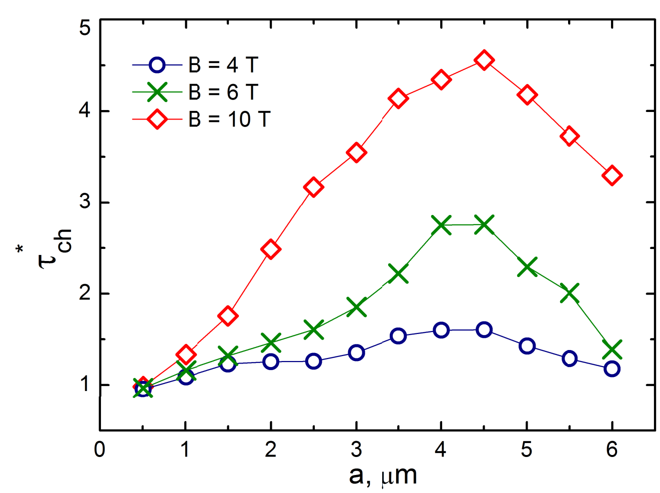

Fig. 3. Ratio of the dust particle charging time with/without taking into account magnetic field.

As can be seen from Fig. 3, account for the magnetic field increases the charging time of dust particles for $a < 5$ μm due to the limitation of the trajectory along the magnetic field lines. With the increase in the radius of the dust particle, the charging time decreases, and as a result the ratio decreases. The larger the dust particle size, the shorter the charging time.

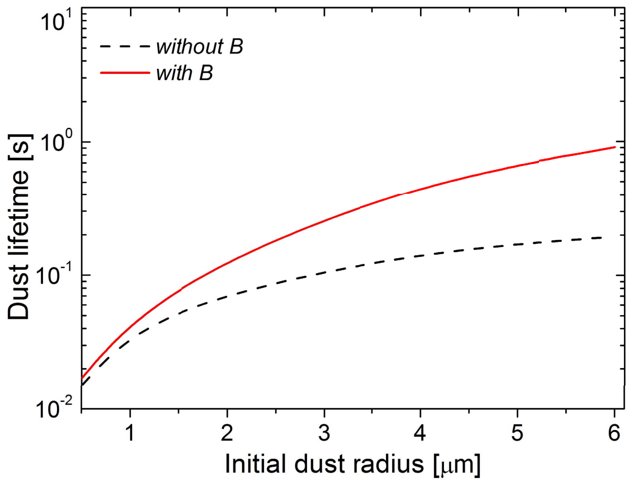

Fig. 4. Dust lifetime in a homogeneous deuterium plasma at initial dust particle radius (dashed line), taking into account magnetic field (solid line).

III. Influence of the Magnetic Field on the Dust Lifetime

To estimate the dust lifetime it is necessary to study the dynamics of the dust particle in the edge fusion plasma. For this purpose, the equations of motion, the equations of mass and energy balance, and equations for the dust particle charge are solved [16]. In this paper, it is assumed that processes of mass ablation are spherically symmetric and the dust particle retains its spherical shape.

The process of heating the initially cold tungsten dust particles in a homogeneous deuterium plasma near the edge of fusion plasma was calculated. In calculations, the following parameters were used: $T_e = T_i = 18.7$ eV, $T_a = 0.3T_i$, $n_e = n_i = n_a = 10^{18}$ m^{-3}, the initial temperature of the dust $T_{d0} = 1000$ K, and the initial radius of the dust $R_{d0} = (0.5 - 6)$ μm.

Fig. 4 shows the dependence of the tungsten dust lifetime in a homogeneous deuterium plasma on the initial radius of the dust particle at magnetic field strength $B = 10$ T. As the results show, taking into account the strong magnetic field leads to an increase in the lifetime of the dust particle. As can be seen from Fig. 2, the larger the dust particle size, the stronger the magnetic field affects its charge modulus, which leads to the suppression of the heat flux of plasma particles on the dust surface and an increase in its lifetime.

IV. Conclusion

The effect of the magnetic field on dust dynamic and lifetime in the edge fusion plasma has been studied. On the basis of particle-in-the-cell and Monte Carlo methods, a computational model of evolution of tungsten dust particle formed on the surface of the reactor wall was constructed. In the model the equations of motion, the equations of mass and energy balance, and equations for the dust particle charge are solved. The time dependence of the characteristic parameters (charge, temperature and radius, heat fluxes) of the dust particle was determined. On the basis of these calculations, the tungsten dust lifetime in the edge fusion plasma was estimated. It was found that the magnetic field can have a significant effect on charging processes and the lifetime of dust particles in the edge fusion plasma. The obtained results show that the magnetic field causes a decrease in the charge modulus of the dust particle, which leads to suppression of the heat flux of plasma particles on the dust particle, thereby increasing its lifetime. Also, the magnetic field increases the charging time of small dust particles due to the limitation of the trajectory along the magnetic field lines.

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Authors' photographs and biographies not available at the time of publication.