Computation of Dust Particle Evolution in Divertor Plasma

N.Kh. Bastykova[1)], S.K. Kodanova[1)], T.S. Ramazanov[1)], S.A. Maiorov[2,3)]

[1] *Institute of Experimental and Theoretical Physics, Al-Farabi Kazakh National University, Almaty, Kazakhstan*

[2] *Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow, Russia*

[3] *Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia*

Introduction. Investigation of 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 - 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 electron is much greater than that of ions the 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 of ions and electrons, their temperature and size of dust particles. A more detailed description of the charging process without a magnetic field may be found in [2, 5-7].

The 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 this paper, ion collisions with atoms were calculated using the Monte Carlo method and the dependence of the dust particle charge and fluxes of plasma particles on the dust particle on the magnetic field were obtained.

Migration of dust particles from the surface of the wall into the depth of the reactor and their evaporation largely determine the composition and characteristics of the edge plasma, and can therefore have a significant impact on the operation of the reactor. To take into account migration of dust particles in the reactor 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.

Dust particle charging. At the first stage of this research 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, and the number of collisions between ions and atoms was determined by the Monte Carlo method [5-6, 10-11].

The charge of dust particles was calculated for the following parameters of the divertor plasma [12]: the density of electrons and ions equal to 10^{14} cm^{-3}, the temperature of ions – *0.7 eV* and electrons – *3 eV*. The charges of dust particles with radii of *0.5;1* and *2μm* for various values of the magnetic field $B \div (10\text{-}10^5)G$ were obtained. Fig. 1 shows the time dependence of the charge of the dust particle with a radius of *0,5 μm*, initially neutral, obtained using the particles-in-cell method and calculated according to the OML theory. Figure 2 shows the distribution of the dust particle charge as a function of time for different values of the magnetic field. In a plasma without a magnetic field most electrons reflect from the Coulomb barrier of the dust particle, and only a small part of fast electrons can reach the dust particle. On the contrary, ions are attracted by the dust particle and the collision cross-section becomes much larger than the geometrical cross section of the dust particle πa^2.

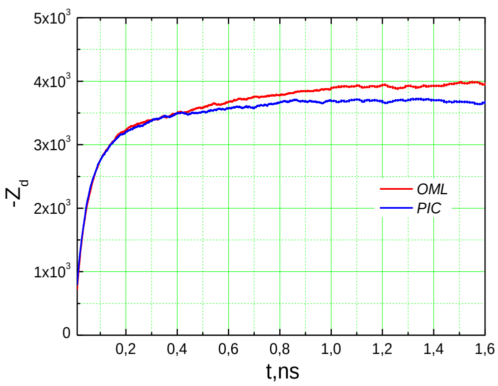

Fig. 1 – The distribution of the dust particle charge as a function of time

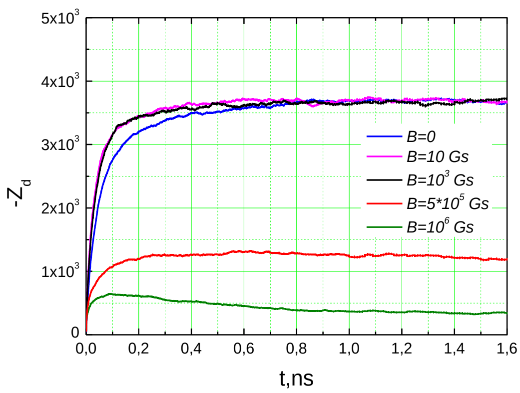

Рис. 2 – The distribution of the dust particle charge as a function of time (ns) for different values of the magnetic field

It was found out in [8] that the impact on the charge of the dust particle begins at a certain critical value of the magnetic field $B_{cr}^{e}(kG)a(\mu m) > 41.37\sqrt{T_e(eV)/3(eV)}$. In this paper it was found out that for the parameters of the divertor plasma and the dust particle with a radius of $a = 0.5\mu m$ the strength of the critical magnetic field is equal to $B_{cr}^{e} = 8.5 \cdot 10^4 G$. The magnetic field affects charging of the dust particle mainly due to the magnetization of electrons. In a weak magnetic field $B < B_{cr}^{e}$, when the gyro-radius 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. As the strength of the magnetic field increases to the values where the gyro-radius of electrons is equal to the radius of electron capture by the dust particle the picture changes. 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, the electrons with a low energy, as in the case without a magnetic field, are reflected from the Coulomb barrier in the reverse direction.

Energy balance for a 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 energies 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, recombination of dissociated molecules, etc. (see a more detailed description of the model in [3, 4]).

The model of this research 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 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. As the temperature of the dust particle rises, its matter may undergo phase transitions. In our calculations, it first 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. The following parameters were chosen for calculations [12], $T_e = 3.0eV, T_i = 0.7eV$, $T_a = 0.2eV$, $n_e = n_i = n_a = 2\times10^{14} cm^{-3}$, the initial temperature of dust particles $T_{d0} = 1000K$, radius $R_{d0} = 0.5\mu m$.

Fig. 3 shows the time dependence of the temperature and radius of the dust particle. In During the first 20 μs the dust particle temperature rises to $3695K$, then in the time interval from 20 μs and 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 $T_{vaporation} = 4850K$. In the process of boiling the dust particle quickly loses its mass, and in 3000 μs its radius decreases to zero.

Fig. 4 shows the dependence of the lifetime of dust particles in a deuterium plasma on its density for different values of the electron temperature. It is seen that as the temperature of electrons increases, the lifetime of dust particles decreases, and the analysis shows that the main reason for this is an increase in the charge of dust particles.

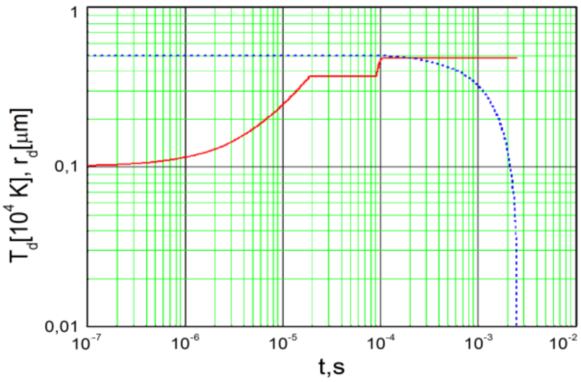

Fig. 3 –Time dependence of the dust particle temperature (solid line) and radius (dot line) during heating

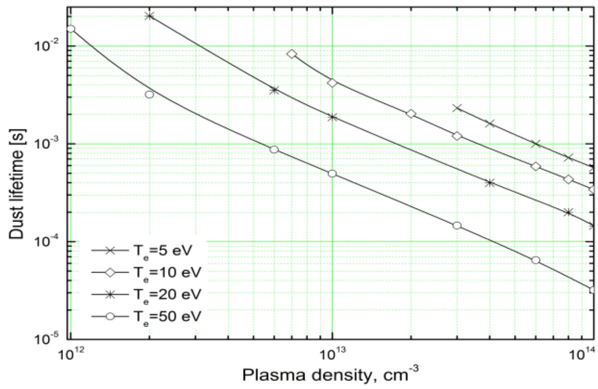

Fig. 4 – The lifetime of the dust particle in a homogeneous deuterium plasma

Conclusions

The influence of the magnetic field on the charge, dynamics and lifetime of dust particles in the edge divertor plasma is investigated. A computational model based on the particle-in-cell and Monte Carlo methods was constructed and the time dependence of the dust particle charge and plasma fluxes on its surface was calculated. It has been shown that a strong magnetic field has a significant impact on the process of charging of dust particles in the divertor plasma. The numerical model describing heating and evaporation of dust particles in the plasma has been developed, and calculations that allow us to estimate the lifetime of the dust particle and its path in the edge divertor plasma have been made.

References

[1]. V.N. Tsytovich and J. Winter, 1998 Phys.-Usp. **41,** 815.

[2]. V.E. Fortov, A.G. Khrapak, S.A. Khrapak, V.I. Molotkov, and O.F. Petrov, 2004 Phys. Usp. **47**, 447.

[3]. A. Yu. Pigarov, S. I. Krasheninnikov and et al., 2005 Physics of Plasmas **12**, 122508.

[4]. L. Vignitchouk, P. Tolias and S. Ratynskaia, 2014 Plasma Phys. Control. Fusion **56,** 095005.

[5]. S.A. Maiorov, S.V. Vladimirov, and N.F. Cramer, 2002 Plasma Physics Reports **28,** 946.

[6]. S.A. Maiorov, 2005 Plasma Physics Reports **31,** 749.

[7]. T.S. Ramazanov, S.K. Kodanova et al., 2011 Eur. Phys. Letters, **96**, 45004.

[8]. V. N. Tsytovich, N. Sato, G.E. Morfill, 2003 New Journal of Phys. **5**, 43.1-43.9.

[9]. Y. Tomita, G. Kawamura, T. Yamada, O. Ishihara, 2009 J. Plasma Fusion Ser. **8**, 273-276.

[10]. S.A. Maiorov, 2006 Plasma Physics Reports **32,** 802.

[11]. S.A. Maiorov, B.A. Klumov, 2013 Bullletin of the Lebedev Phys. Inst. **40,** 285.

[12]. F.Taccogna, R. Schneider, K. Matyash, S.Longo, M. Capitelli, D. Tskhakaya 2008 Contrib. Plasma Phys. **48**, 147-152.