Increasing of an electrostatic probe capacity and efficiency for metal dust collection in ITER

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Abstract. Formation of dust particles and clusters is observed in almost all modern fusion devices. Accumulation of dust in next-generation thermonuclear installations can significantly affect plasma parameters and lead to accumulation of unacceptably large amounts of tritium. The use of a specially developed electrostatic probe is planned in the international thermonuclear experimental reactor ITER to collect dust for further analysis. The article describes a numerical model of dust particles movement in an electrostatic probe. Dust particles trajectories inside the probe were analyzed. Several electrostatic probe design modifications were proposed on the basis of the analysis in order to increase the efficiency of dust collection.

1. Introduction
The experiments in modern thermonuclear facilities show that most of the material sputtered from the plasma-facing elements – the first wall and the divertor – eventually transforms into dust which negatively impacts discharge parameters and leads to tritium retention in the facilities. For dust diagnostics in the International Thermonuclear Experimental Reactor (ITER), utilization of a specially designed electrostatic probe for collecting dust particles and their removal from the facility for further analysis is expected.

The article presents the work completed to increase the efficiency of the probe: modelling of the tungsten dust particles trajectory in the probe, modification of the probe and experimental testing of the obtained results.

2. Electrostatic probe and models for calculation
The probe’s main component is the reservoir composed of thin-sheet stainless steel, with the front wall being made into a grid [1, 2]. During the operation, a bias is applied between the probe and the lower plate with dust particles on it. Under this bias, dust particles detach from the plate and fall into the probe’s reservoir through the grid. A deflecting plate is attached to the top of the grid that limits scattering of the particles deflected from the grid.

In the model, particles were affected by gravitational force (Fmg), electrostatic field force (FE) and force of adhesion (Fadh). To assess Fmg and FE, the particles were divided into four groups: a) singular spherical particles 1-5µm in size; b) singular polyhedral particles 7-15 µm in size; c) elongated cubic dust particles, 20-26 µm in height; d) conglomerates of particles shaped into a cube with an edge of 30-40 µm. An averaged mass and electric charge gained in the electrostatic field was used for each of these groups. Forces of adhesion were calculated experimentally (section 3) and were assumed to be applied on a distance equal to the average size of particles (15 µm) used in the model.
The entrance grid was modelled as a wall with an average penetration probability by particles equal to 85%. Energy loss coefficient during collision events of particles with the wall and the plate, as well as angular distribution of differently shaped particles scattering after collision, was determined for usage in the model (section 3).

Figure 1. Electrostatic probe’s principal scheme.

The modelling was conducted using the COMSOL universal modelling environment, consisting of two blocks. In the first block, electric field strength distribution was deduced, while in the second one, the trajectories of charged tungsten particles in the field were calculated.

3. Model parameters

Coefficients of energy loss during particles’ collision with surfaces were deduced using high-speed video recorder. The framerate was 1200 fps, at which the motion of particles between two steel plates was detected. The distance between the plates was 4 mm, and the potential difference was changed from 1500 to 7500V with the increments of 1500V. The results obtained showed that the energy loss coefficients did not change significantly at different potentials between the plates. As such, an average of $k_{Eloss} = 0.3$ was used for the entire range of 1500-7500V potential difference, which corresponds to the electric field strength of 375-1875 V/mm, was used.

Force of adhesion was determined experimentally. For each of the four particle groups, a critical electric field strength at which the particles detached from the lower plate was determined, and from the equation $F_{mg} + F_{E} + F_{adh} = 0$, $F_{adh}$ for each particle group was calculated. An averaged force of adhesion, which was equal to 12 times average gravitational force of each particle group, was used for modelling.

To determine the patterns of deflection of differently shaped particles from the walls of the system, a numerical model was created, in which particles of different geometric forms (cuboid, cone, cube, octahedron) were launched into the gravitational field and electrostatic field between two horizontal plates, from which they elastically scattered. The surface of the plates was randomly set with the condition of it being less than 0.1 µm (the size of the smallest particles used in the modelling was 1 µm). Angular distribution of elastic scattering of tungsten dust particles with varying forms and incident angles was obtained. The analysis of obtained distributions showed a possibility of using a combination of mirror-like deflection with the probability of 0.7 and cosine law diffusion scattering with the probability of 0.3 in a model.

4. Modelling of particles motion and discussion

Modelling of the dust particles’ movement in the electrostatic field of the reservoir showed that a portion of particles already inside the equipotential space of the probe leave the probe after a few collisions due to a low energy loss coefficient (figure 2). To reduce the percentage of “runaway” particles, a proposition was made to install grids composed of thin metallic vertically placed plates on the inner walls of the probe. A dust particle gets into the gap between the grid plates and, due to multiple collisions, loses most of its energy. After that, the particle has insufficient energy for leaving the probe, and stays inside (figure 3).
Modelling of particle motion in the reservoirs with varying types of grids showed that, while the efficiency of particle collection was 68% for the probe with smooth walls and 72% for the probe with the grid on the bottom, the efficiency for the probe with the grids on the top, bottom and the back was 73%. The best efficiency of the probe with the grids was at the height of the grid plates of 1-1.5 mm, thickness of no more than 0.1 mm, and distance between the grid plates less than 0.5 mm.

Distribution of captured particles on the bottom of the probe and the top of the probe showed that most of the particles were accumulated near the entrance grid. For a large amount of accumulated dust, that would hinder the collection of new particles into the reservoir, as well as lead to the spill of dust from the probe during transportation. To shift the distribution of collected particles into the depths of the probe, as well as reducing the number of particles leaving the probe, a grid with plates angled towards the back wall of the probe was installed on the top. Modelling has shown that, when choosing optimal parameters of the grid (grid plate skew angle, distance between the plates, height of the plates), the efficiency of dust particle collection rises to 83%, and the probe is able to collect more dust.

5. Conclusions
The research on increasing the efficiency of electrostatic probe for collecting dust particles inside the ITER plasma chamber, as well as its removal for further analysis, has been shown in this paper. A mathematical model has been created, and the movement trajectories of tungsten dust particles in the electrostatic probe have been calculated. A design of the probe was modified using the data obtained. An increase of efficiency to 83%, as well as the ability of the probe to collect up to 1 cm³ of tungsten dust, was experimentally shown.

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