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Transport of dust in plasmas with magnetic field and UV-radiation

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Abstract

We have extended a 2-D fluid model for dusty radio-frequency discharges by including the effect of a homogeneous axial magnetic field and a homogeneous flux of UV photons. Both influence the evolution and final shape of the dust cloud and the dust-free void in a symmetric discharge under micro-gravity conditions.

Introduction

Many dusty plasma experiments have been done over the last few years. Microgravity experiments in the "Plasma-Kristall-Experiment" (PKE) reactor on the International Space Station (ISS) showed the formation of three-dimensional dust structures, dust free voids, crystalline structures and dust vortices. A 2-D fluid model was developed to model the transport of dust in this axially symmetric reactor.[1]
In space, dust is observed, for instance in star formation regions. Young stars emit a flux of UV photons. Matter outflow and accretion are often observed in star formation regions and it is believed that magnetic fields play an important role in both phenomena.
We extended the model to include the effect of a magnetic field and an UV flux to better understand dust transport in plasmas with magnetic fields and UV-radiation under microgravity conditions.

The model

The balance equation for plasma particles is solved in the drift-diffusion approximation. With the Poisson equation and the equation for the electron energy density, these form a closed set. These equations can be found in [1]. The different timescale for the electrons and ions is important; the heavy ions have a much lower mobility and diffusion coefficient.
Dust particles in a plasma collect ions and electrons and get charged. Due to the higher electron mobility, they usually get negatively charged. If the dust density is high, plasma parameters change and the dust and plasma parameters are solved simultaneously.
Dust transport is the result of forces acting on the dust: ion- and neutral drag, the electrostatic and thermophoretic force. Charged dust particles repel each other by the Coulomb force. If the potential energy is larger than the thermal energy, crystallization occurs, changing the dust-diffusion.[2]

Magnetic field and UV flux

Charged particles gyrate around magnetic field lines, reducing their perpendicular mobility and diffusion. The electron mobility and diffusion coefficient are modified through the Hall factor:

$$\mu_{e,\perp}\ (D_{e,\perp}) \rightarrow \left[\frac{1}{1+\frac{\omega_c^2}{\nu_m^2}}\right]\ \mu_{e,\perp}\ (D_{e,\perp}), \qquad (1)$$

where ω_c is the cyclotron frequency and ν_m is the momentum transfer frequency. Via ambipolar diffusion, this results in a change in ion transport as well.
We added an UV photon flux. The background gas is optically thin, but the photons "ionize" dust, releasing electrons from the dust, adding them to the plasma with an average energy of $T_{ph,e} = 1.5$ eV. The current from the UV flux $J_{uv} \approx 10^{21} m^{-2} s^{-1}$ absorbed by the dust particle with probablility $Q_{abs} = 1$, an electron yield $Y \approx 0.05$[3], radius a and surface potential ϕ_s, is given by [4]:

$$I_{ph,e} = 4\pi a^2 e Q_{abs} Y J_{uv} \exp\left[-\frac{e\phi_s}{kT_{ph,e}}\right] \quad \phi_s > 0, \tag{2}$$

$$I_{ph,e} = 4\pi a^2 e Q_{abs} Y J_{uv} \quad \phi_s < 0. \tag{3}$$

The exponent comes in because positively charged dust recaptures part of the emitted electrons and is derived from 'Orbital-Motion-Limited Theory' (OML) [5].

Results

We modeled the symmetric PKE reactor on the ISS. The diameter is 10 cm and the height is 5.4 cm. The electrodes are 3 cm apart with a radius of 2.1 cm. We applied a 13.56 MHz RF potential, 100V peak-to-peak. The neutral Argon pressure was 40 Pa. When the plasma reached a periodic steady state, we added spherical dust particles with a radius of 6.8 μm at a rate of $7 \cdot 10^5$ per second. This was stopped when the total number was $1 \cdot 10^6$.

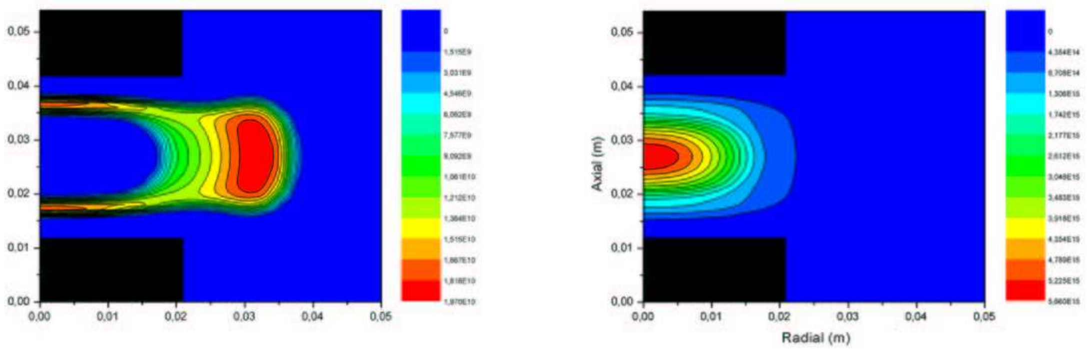

Figure 1: Final dust density for unmagnetized discharge.(left). The number of dust particles is $1 \cdot 10^6$. The ion density for the same discharge (Right).

Figure 1 shows results for the simulation without magnetic field. The dust is introduced above/below the electrodes (black areas), is transported away and a void forms through the ion drag force of the ions moving out of the discharge. Note in the right figure how the ion density has a maximum inside the void. After the maximum number of dust particles is reached, a large local dust structure is formed by radial transport
Repeating the simulation for an axial magnetic field of 0.25 T, shows that the void is formed much faster, after 0.5 seconds. The void boundary is sharper and the void shape is different, as seen in figure 2.
The difference in the shape of the void is due to the difference in ion density, shown on the right in figure 2. The transport of ions in the quasi-neutral bulk results from diffusion, since there is only a very low radial electric field in the quasi-neutral bulk.

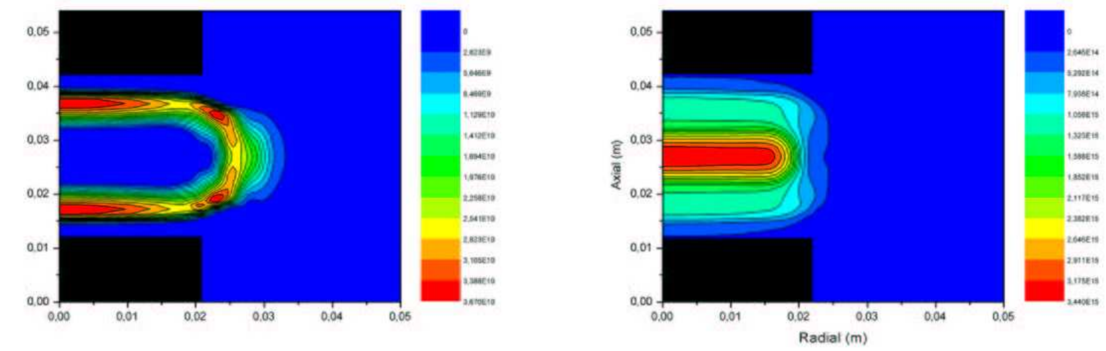

Figure 2: Same figure, but with an axial magnetic field of B=0.25 T.

The input power for both the simulations was ± 0.1 Watts. This means there is no change in ionization. The total radial flux towards the outer walls is also the same.
What happens, is that the ambipolar diffusion is less with a magnetic field. Between the electrodes, the ionization raises the ion density, resulting in a higher density in the bulk. Outside the electrodes a higher density gradient is needed to reach the same flux. We indeed see a much sharper radial ion density gradient in this magnetized simulation compared to the unmagnetized simulation. This results in the sharp inner boundaries of the dust structure.
We started with the unmagnetized simulation and switched on the UV source after $7 \cdot 10^5$ dust particles were added. The charge of the dust (figure 3, left side) is less negative. This changes the electrostatic force and the ion drag force. The position where force balance occurs changes and moves towards the center. There is no local maximum in the dust density formed outside the electrodes, shown in figure 3, right side.

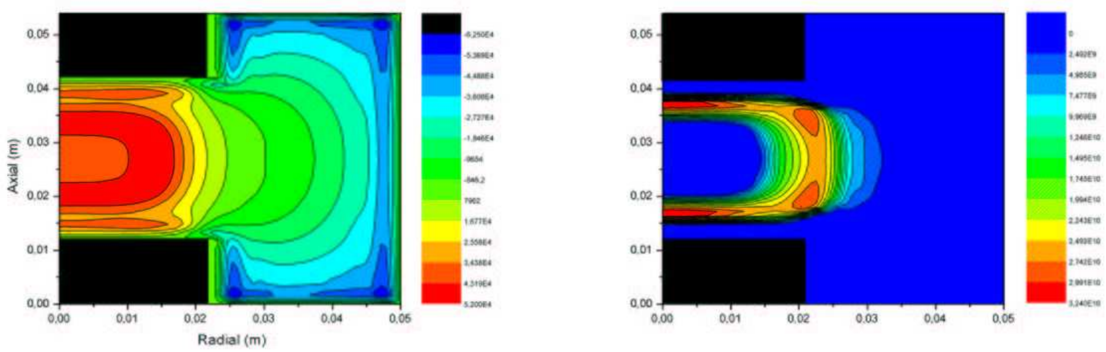

Figure 3: Number of electrons on a dustparticle with the UV source on. The right figure shows the final dust density.

Conclusions

The magnetic field reduces the radial diffusion of plasma particles, changing the ion density in the plasma bulk. This causes a higher bulk ion density and a sharp gradient in the ion density. The resulting change in the ion drag reduces the time needed to form the void and causes the sharp boundary seen in the dust structure.
The UV source changes the dustcharge, reducing both the electrostatic force and the ion drag force. This lowers the radially outward acceleration of dust particles. The places where force balance occurs, which are the places where the dust is moving to, are more to the centre of the discharge. Therefore the local maximum in the dust density towards the outer edge of the reactor, which was seen in the simulation without magnetic field, is no longer formed within 2 seconds after the first dust was introduced.

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