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Hydrodynamic modelling of dust clouds in a radio-frequency discharge

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Introduction

When a large amount of micron-sized particles is injected into a radio-frequency discharge, a Coulomb crystal is formed as the result of the confining sheath electric fields and the repulsion of the negatively charged particles. On earth, gravity plays an important role in the crystal formation for this size of particles. This results in a 2-D crystal, confined to one or several horizontal latice layers. Under micro-gravity conditions a three-dimensional structure appears, usually consisting of a crystalline region surrounding a central dust-free void. This void is created by drag forces exerted on the dust particles. Especially the ion drag force exerted by positive ions that are accelerated out of the discharge and the thermophoretic force resulting from a temperature gradient in the background gas are responsible for the creation of the void.

We have developed a hydrodynamic model for dusty radio-frequency discharges in argon and used it to study the behaviour of dust particle clouds created by injection of particles from the electrodes. The evolution of the clouds is followed up to the full development of a central dust-free void surrounded by a crystalline region. Here we also report on the behaviour of the dusty discharge when either the driving rf voltage or the gas pressure is reduced. Various aspects of the dusty plasma are discussed, including the generation of space charge double layers that accelerate the positive ions before they enter the crystalline region. This strong interaction of the particle cloud and the discharge shows the importance of fully self-consistent modelling, where the particles move according to the average parameters of the discharge, while processes like the charging of the particles and the loss of plasma by recombination affect these plasma parameters.

The hydrodynamic model

Like many other models, our model for the rf discharge is based on the density balance for each charged species, using the drift-diffusion expression for the fluxes. The mobility and diffusion coefficient for the electrons, as well as the rate coefficients for electron-induced inelastic processes are tabulated as a function of the average electron energy, using the results of a Boltzmann solver. The dust is treated as a separate charged fluid. The drift velocity of the dust fluid is obtained from the equilibrium between the neutral drag force and the other forces (ion drag, thermophoretic force and electric force). Diffusion is added by introducing a pressure gradient. Crystallisation of the dust is modelled by a density dependent dust diffusion coefficient that exponentially enhances the diffusive flux of the dust fluid when crystallisation becomes important. Experimental values for the density are used to set the threshold for crystallisation.

Simulations

We have modelled the PKE reactor operated in argon at a pressure of 300mTorr, an rf frequency of 13.56 MHz, driven in push-pull mode at V_{pp}=70V. Particles with a radius of 7.5 μm are introduced at a total rate of 800000 s^{-1}, using a source just above both electrodes. When the amount of dust particles in the discharge reaches a preset value, the injection is stopped and the plasma-crystal system evolves further toward its equilibrium state. The evolution of the dust cloud is shown in figures 1a-d. Figure 1c is at the end of the injection phase, figure 1d is the final equilibrium state. Starting from the equilibrium state, either the driving rf voltage or the gas pressure is reduced in order to study the collapse of the void. This collapse is also observed in experiments, where it is often accompanied by instabilities. Assumptions in the model, especially the neglection of the inertia of the dust particles, prohibit modelling of these instabilities. In the simulation the discharge extincts because the recombination losses on the dust cannot be compensated when the rf voltage becomes too low. The reduction in pressure (at constant rf voltage) leads to a reduction of the electric field strength, thus reducing the compressive force on the crystal. Dust density profiles just before the extinction of the discharge and at a pressure of 160 Pa are shown in figures 2a-b. The large influence of the dust on the plasma parameters is visible in figures 3, showing the average potential profile and the average electron energy, respectively, for the dust-free discharge and for the final equilibrium. Figure 4 shows the generation of a space charge double layer at the void-crystal transition, and its influence on the potential distribution along the axis of symmetry. Also ion energy distribution functions obtained from a 1-D particle-in-cell simulation for a discharge with a prescribed dust density profile are presented. The acceleration of the ions when going from the void into the crystal is clearly visible.

[1] M.R. Akdim and W.J. Goedheer, Phys.Rev.E **65** (2002) 015401.

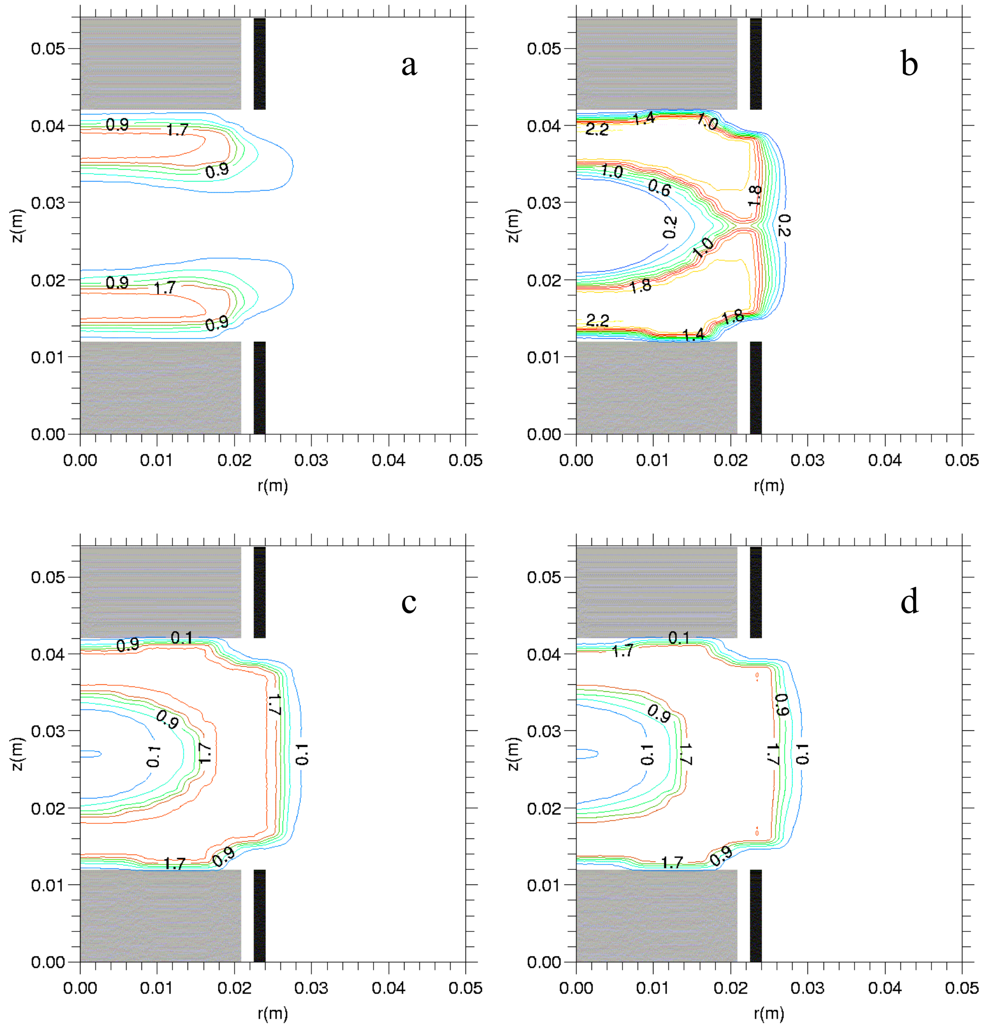

Figure 1: Dust density profiles during continuous injection (a-c) and after full relaxation (d).

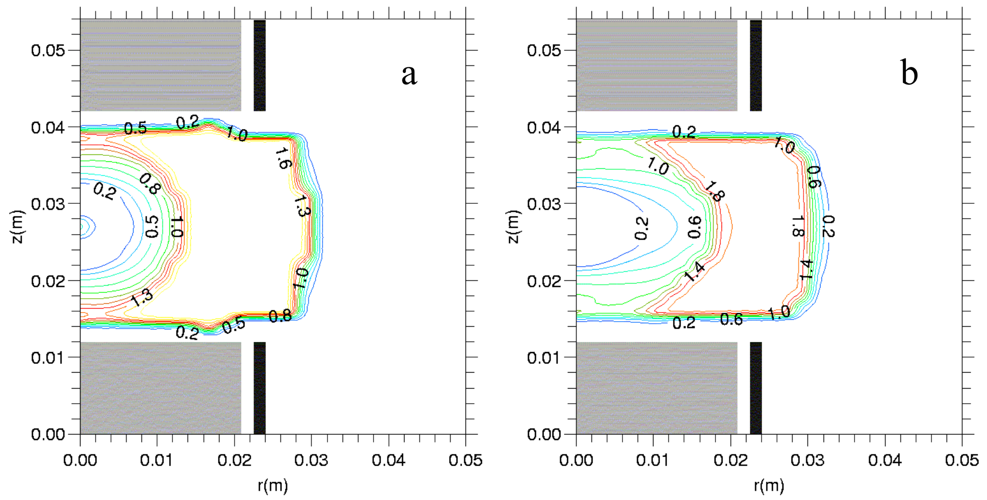

Figure 2: Dust density profiles at a reduced rf voltage (V_{pp}=45.4 V, a) and a reduced pressure (160 mTorr, b)

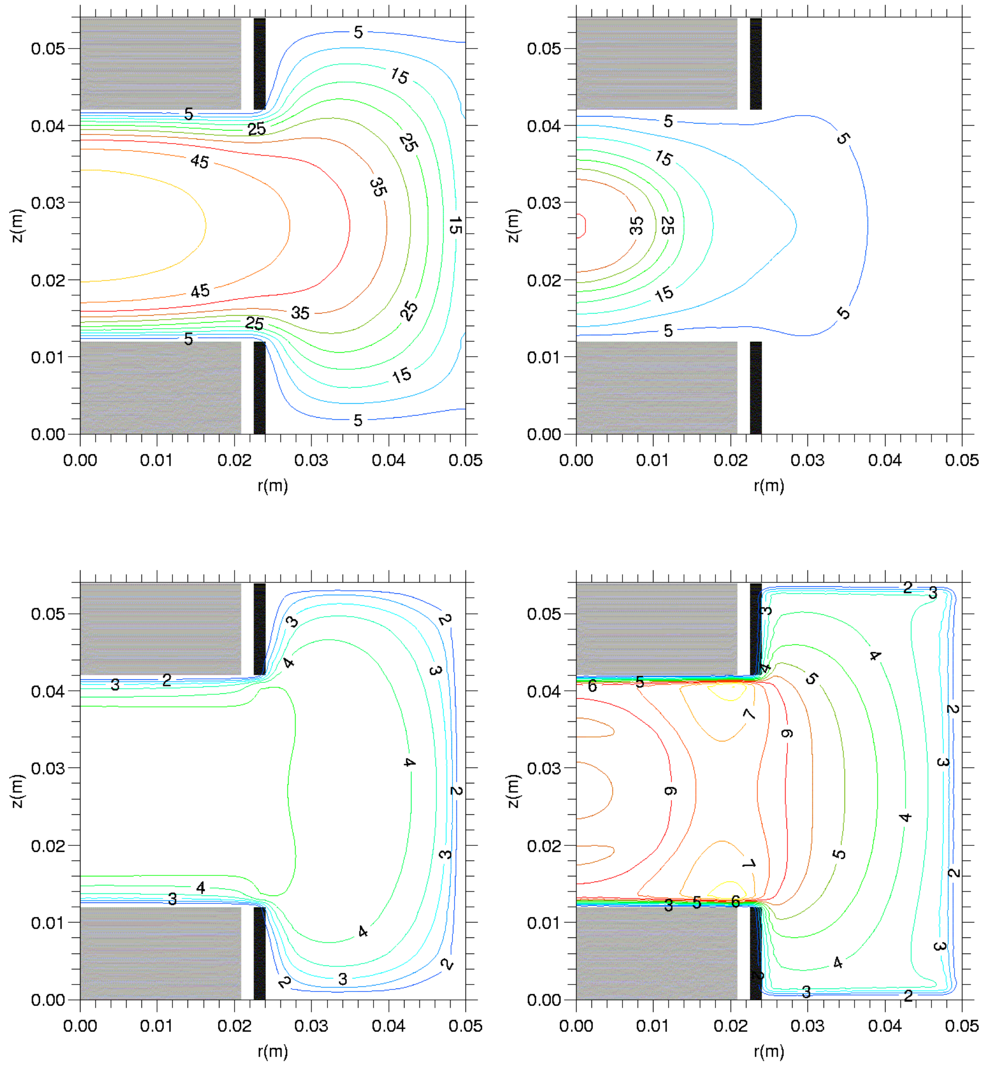

Figure 3: The average potential (top) and electron energy (bottom) in a dust-free (left) and in a dusty discharge (right).

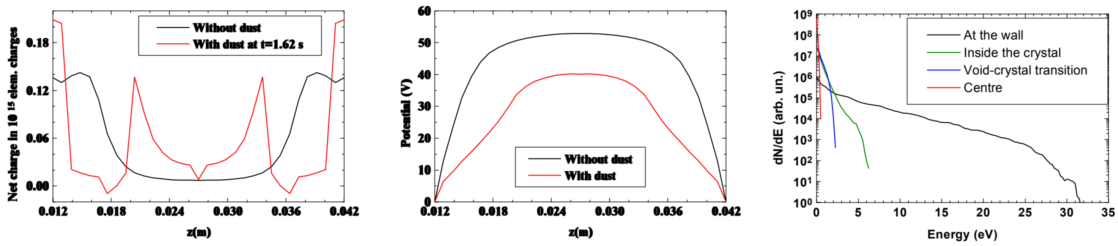

Figure 4: The net charge and the potential distribution along the axis for a dust-free and a dusty discharge and ion energy distributions from a 1-D PIC/MC simulation.

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