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Electrons in a dust free void: "Hotter or denser?"

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Dust particles in plasma act as additional sinks of plasma and energy, similar to the way the walls enclosing a plasma do. From a global point of view, see for instance [1], the response of the (volume averaged) electron temperature is then determined by the particle balance. When dust particles are distributed homogeneously through the plasma, the losses can be described by a volume recombination process;

$$n_{gas}n_e\langle\sigma v\rangle \times V = 0.6n_e v_B \times S + n_D n_e k_{rec} \times V. \quad (1)$$

The LHS is the ionization in the plasma volume V. The first term on the RHS corresponds to the Bohm losses to the walls with surface S, the second term to the volume losses on the dust, with the recombination rate k_{rec} given by the OML rate [2]. The global response of the electron density is given by the power balance, which, assuming constant input power, is given by,

$$P_{input} = n_{gas}n_e\langle\sigma v\rangle \times V \times \varepsilon_{ion}, \quad (2)$$

with ε_{ion} the *effective* ionization energy, which takes additional losses of electron energy into account, for instance those due to electron impact excitation and due to the Bohm flux to the walls.

Solving equation 1 for the Bohm velocity v_B, and assuming that half of the electron losses are on the walls, the other half on the dust, we indeed find a shift to higher temperatures, as shown in the top panel of figure 1, which corresponds to a spherical plasma volume with a radius of 2.3 cm, homogeneously filled with dusty plasma. The temperature rise corresponds to a roughly doubled ionization rate $n_{gas}\langle\sigma v\rangle$. Assuming that ε_{ion} remains constant, we then find from equation 2 that *the electron density must go down by a factor of 2* for constant input power!

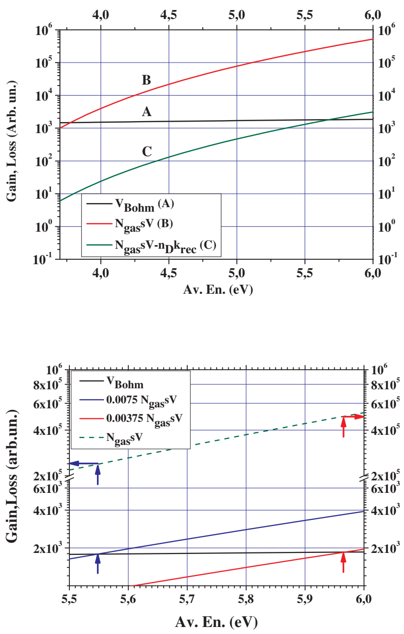

Figure 1: Particle balances. Dust as volume loss (top) and surface loss (bottom).

When larger dust particles are present, gravity becomes the dominant force and only a thin dusty layer exists. Either by doing zero-g experiments, or by using thermophoresis, 3D dust crystals form, in which usually a dust free void is observed [3]. The interface between this void and the dust cloud, with surface area S_{void}, can then act as a wall [4], in which the particle balance reads

$$n_{gas} n_e \langle \sigma v \rangle \times V_{void} = n_e v_B \times S_{void}. \tag{3}$$

We will show that indeed the plasma production really takes place inside the volume of the void, V_{void}. It should be noted that the ions do not necessarily reach the Bohm velocity at the void-dust cloud interface, but the density is higher inside the void, so that the total ion flux might equal the Bohm flux. Again solving for the balance, but now both for a void with a radius of 2.3 cm and half this radius, we find that for smaller voids, the balance is obtained at higher temperature, as shown in the bottom panel of figure 1, which in this case leads to a roughly two times higher production.

Now, it follows from equation 2 that *the electron density has to go up by a factor of four*, since the volume goes down by a factor of eight. Thus, a global consideration predicts both a hotter as well as a denser electron population inside the void.

One might wonder however, why the ionization is high inside the void volume. This is not immediately obvious, since the depletion of the electrons takes place inside the dust clouds. We would therefore expect a rise in electron temperature there, to increase the local ionization to compensate for the losses.

We use a fully self-consistent 2D dusty plasma model [5] to investigate how the ionization is distributed in a dusty plasma with a void and where the energy required for the ionization comes from. Applying this model to a RF (13.56 MHz) argon discharge at 30 Pa, with 100 V peak-to-peak driving potential, which has 500.000 dust particles introduced with a radius of 6.8 μ, we indeed see a void. We also see that the plasma is contained inside the volume of this void. This is shown in the panels of figure 2.

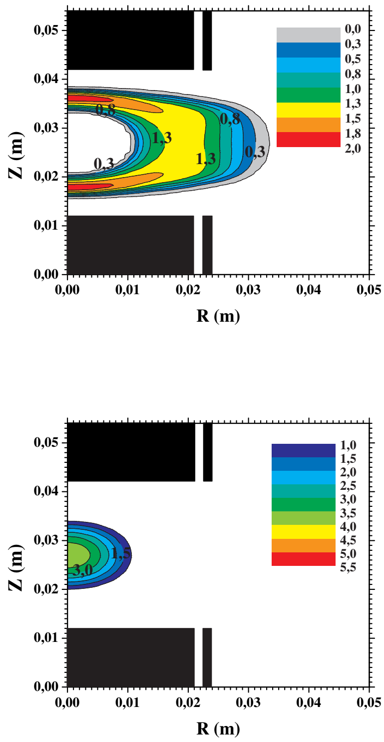

Figure 2: Density profiles of the dust ($\times 10^{10}$m^{-3}) (top) and electrons ($\times 10^{15}$m^{-3}) (bottom).

When we look at the energy taken up by the electrons, we see how the depletion of electrons in the dust cloud indeed causes a high amount of power picked up by the electrons locally. However, the ionization indeed peaks inside the volume of the dust free void. This is shown in the panels of figure 3.

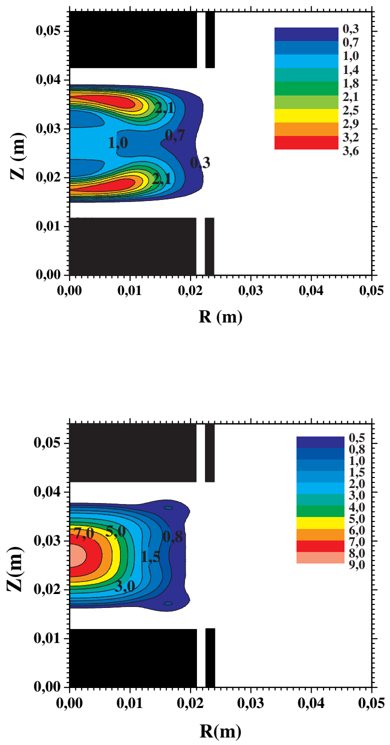

Figure 3: Energy taken up by electrons (kW m^{-3}) (top) and ionization rate ($\times 10^{20}$m^{-3}s^{-1}) (bottom).

Apparently, the electron energy gained in the region of electron depletion inside the dust cloud is transported to the inside of the void, where it is used to produce the ionization which compensates the losses on the dust. The time averaged (over an RF cycle) electron energy balance solved in the model is given by $\nabla \cdot \langle \Gamma_w \rangle = \langle \mathbf{J}_e \cdot \mathbf{E} \rangle - \langle S_w \rangle$. The LHS is the divergence of the electron energy density flux, the first term on the RHS is the Ohmic heating of electrons and the last term contains all the losses of electron energy, with a main contribution from electron impact ionization.

Over the central axis, this equation simply becomes an equation for the derivative of the energy density flux. Whenever this derivative becomes negative, there is more energy lost by the electrons (mainly in ionization) than there is gained by heating. Whenever the derivative is positive there is more energy gained by the electrons than lost. Figure 4 shows the electron energy density flux between the electrodes. Comparing with the dust density shown in figure 2 we conclude that the heating indeed takes place inside the dust, but the ionization inside the void. The flux of energy is directed from the dust clouds to the void.

Assuming that the drift of energy in the electric field is much larger than the diffusion, we can write the divergence of the heat flux as $\nabla \cdot \langle \Gamma_w \rangle = -\frac{5}{3}\left(\mu_e \varepsilon \mathbf{E} \cdot \nabla n_e + n_e \mathbf{E} \cdot \nabla \varepsilon\right)$ (all terms are time-averaged), with $\varepsilon = \frac{3}{2} k_B T_e$. The time averaged electric field points from the highest plasma density inside the void towards the electrodes. This means that the first term is always positive. The negative value of $\nabla \cdot \Gamma_w$ is therefore due to the electron temperature gradient working together with the time averaged electric field. This temperature gradient increases by the electron depletion on the dust. Therefore, the transport of heat from the dust towards the void increases for an increasing amount of dust introduced into the plasma. From figure 4 it is clear that in the dust free discharge a similar heating and ionization mechanism is present. Indeed, a small amount of dust introduced in a discharge also form a void, which was shown in [6].

Using a 1D Particle-In-Cell plus Monte Carlo model [7], we can determine the electron energy distribution function (EEDF) inside the dust cloud and inside the void. Even though the ionization profile in the discharge is not the same, the EEDF does indicate the non-local mechanism behind the void formation, shown in figure 5, namely the appearance of a high energy electron population inside the dust cloud which is transported inwards, the loss of this population inside the void, together with the appearance of a cold electron population (note that the plots are logarithmic, so that the cold population in the void is about 90 % of the complete population inside the void).

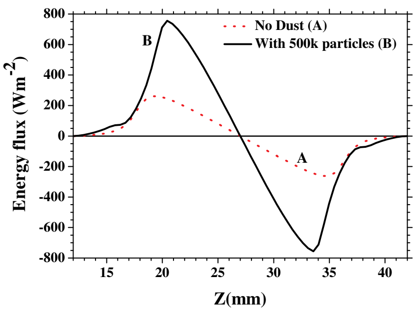

Figure 4: Γ_w along the central axis of the discharge, between the electrodes.

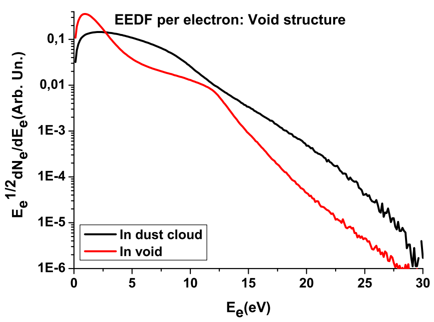

Figure 5: EEDF per electron.

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