

Dynamic responses of dusty plasma

V. Land¹, W. J. Goedheer¹

¹ FOM-Institute for Plasma Physics Rijnhuizen, Nieuwegein, the Netherlands,
www.rijnhuizen.nl

Dust acts as a contaminant in microchip industry, but novel applications, for instance the fabrication of poly-crystalline solar cells or quantum dots, require tailor made particles to be formed in plasma enhanced processes, often involving carbon or silicon. To control the coagulation or transport of dust in a discharge, one needs to actively change the charge on the dust. One way to control the charge on small particles in a plasma is to use an external source of ultraviolet light, which detaches electrons from the dust by the process of photo-detachment [1].

In this paper we focus on the response of a dusty plasma to a short pulse of UV light. We model a cylindrical argon radio frequency discharge with two clouds of micrometer sized dust particles inside, using the 1D Particle-In-Cell/Monte Carlo model as described in [1]. The discharge is run at a pressure of 13 Pa, driven at 80 Volts. The distance between the electrodes is 5 cm, the radius of the electrodes is 9 cm. From one side a short (0.4 millisecond) UV pulse is introduced, with an intensity of 25 W m^{-2} , at a wavelength of 311 nm. Note that this wavelength is much longer than the wavelength required to photo-ionize the background argon atoms.

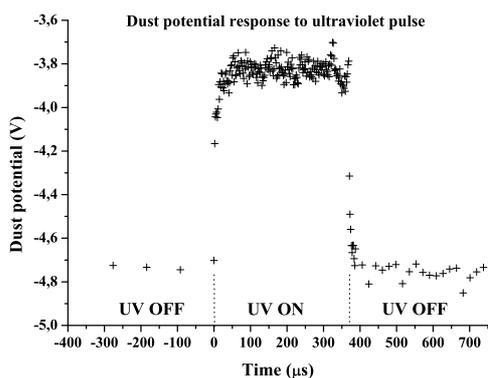


Figure 1: The average dust particle potential during the UV pulse.

The response of the average dust potential ($\langle V_D \rangle = \Sigma_i V_{D,i} / N_D = \Sigma_i (Q_{D,i} / 4\pi\epsilon_0 R) / N_D$) is shown in figure 1. We see that the dust potential jumps from the initial equilibrium value (~ -4.8 V) to the equilibrium value with UV (~ -3.9 V) and back almost instantaneously.

In figure 2 we take a closer look at the response at UV switch-on, and UV switch-off. We assume that dust particles respond like a capacitor and fit the average dust potential with an exponential curve, from which we then derive the "RC-time".

We clearly see that the exponential curves fit quite well. It is clear that the response at UV switch-on is much faster (on the order of $1 \mu\text{s}$) than the response at UV switch-off (roughly $15 \mu\text{s}$), which will be discussed below.

It is of course important to see how the plasma responds to the changes in dust charge. This response has two causes, first of all, the change in currents to the dust particles affects the recombination of plasma on the dust. In fact, the photo-detached electrons act effectively as an extra ion current towards the dust. Current equilibrium thus requires an increase in electron current from the plasma to the dust. Therefore, the dust acts as a bigger sink of plasma when the UV is switched on. The second effect comes from the photo-detached electrons themselves. These are of course added to the plasma and change the plasma properties as well.

Figure 3 and 4 show the electron energy distribution function in one of the two dust clouds present in the discharge, and in the dust-free volume in the center of the discharge. It is multiplied by the electron velocity $v_e = \sqrt{E_e}$, so that the slope gives information on T_e . It is normalized to the number of electrons, so that the different lines can be compared.

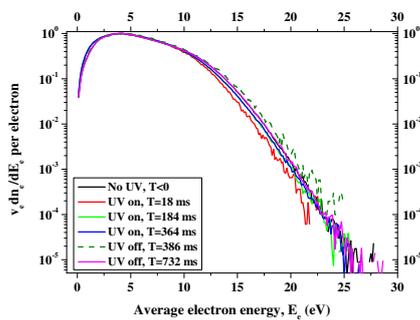


Figure 3: The response of the electron energy distribution during the pulse inside one of the dust clouds.

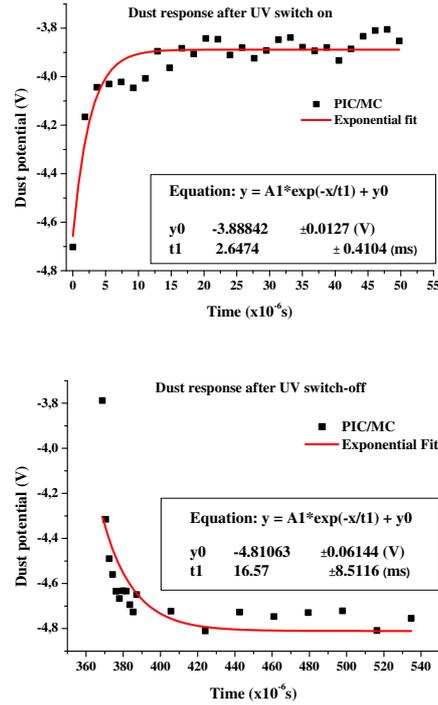


Figure 2: The response at switch-on and switch-off fitted with exponential "RC" curves.

We see that immediately after switch-on, the population of the high energy tail of the distribution decreases, which is due to the increase in recombination on the dust. The equilibrium with UV differs mostly in the dust free volume between the dust clouds, with a much higher population of electrons with intermediate energies below the inelastic processes. These are in a sense trapped within this volume. At switch-off there is a sudden heating of these electrons. The electric field in the discharge changes, due to the increasing negative charge on the dust, resulting in this heating. The final equilibrium is similar to

the initial equilibrium.

The electron impact ionization in the discharge is of course directly coupled to the change in electron energy, especially to the behavior of the high-energy electrons (with energies above the excitation and ionization threshold, at 11.5 and 15.7 eV respectively). Figure 5 shows the electron impact ionization rate, plotted for half of the discharge. It is clear that the ionization rate with UV is lower, especially outside of the dust cloud, which is due to the strong decrease in the high energy electron population. At UV switch-off there is a short overshoot in ionization, due to a sudden increase in the high energy tail of the electron energy distribution.

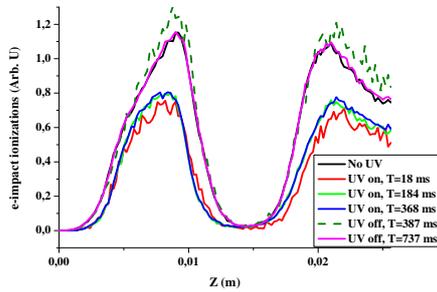


Figure 5: The response of the electron impact ionization rate in the discharge during the pulse.

charge under micro gravity. Three time scales are important for the de-charging of the dust, namely the OML charging time τ_z , the plasma loss timescale τ_L , which consists of losses on the dust, with a corresponding timescale τ_A , and the (ambipolar) diffusion timescale τ_D ($\tau_L = (1/\tau_A + 1/\tau_D)^{-1}$), and finally the electron temperature relaxation timescale, τ_T .

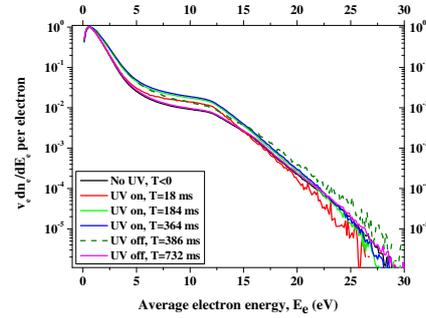


Figure 4: The response of the electron energy distribution during the pulse in the dust free center of the discharge.

For comparison, the response of the dust potential in the same discharge to a complete shut down of the driving power is shown in figure 6. We again see that a RC-like behavior fits well, but with a much longer (de-)charging time. It is also interesting to note that this fit does not evolve to dust that is on average neutral. There is a final negative charge remaining, corresponding to a potential of approximately -0.2 V.

In [2] experiments were reported on the de-charging and gelation of micrometer sized dust particles in the afterglow of a very similar discharge

The charging timescale is found as $\tau_z = \sqrt{2\pi}\lambda_{+,0}^2/[v_{T,+}r_D(1+z_{eq})(n_e/n_0)]$, with $z = e|Z|_D/4\pi\epsilon_0r_D T_e$ (eV) ($z_{eq}^0 \sim 1.5$), the dimensionless dust potential, $\lambda_{+,0}$ the ion Debye length, $\sim 4 \cdot 10^{-5}$ and $v_{t,+}$ the ion thermal speed $\sim 10^2$ m s⁻¹. The initial charging time is then roughly 3 μ s.

The initial diffusion timescale is given by $1/\tau_D = (2\sqrt{2}(n_N\sigma_{+N})^{-1}v_{T,+})(1+T_e/T_N)/3\sqrt{\pi}\Lambda_D^2$, with $(n_N\sigma_{+N})^{-1}$ the ion mean free path $\sim 10^{-4}$ m, Λ_D the typical diffusion length scale $\sim 5 \cdot 10^{-3}$ m. This leads to a diffusion time scale $\tau_D \sim 46 \mu$ s.

The initial dust recombination timescale is given by $1/\tau_A = 2\sqrt{2}\pi r_D^2 N_D v_{T,+} (1+z_{eq}^0 T_e/T_N)$. Our dust density $N_D = 5 \cdot 10^{10}$ m⁻³ and dust particle radius $r_D = 5 \cdot 10^6$ m. This gives $\tau_A \sim 10 \mu$ s. Therefore, the loss time scale $\tau_L \approx \tau_A \sim 10 \mu$ s. τ_T is close to 500 μ s.

We see that the ambipolar time fits reasonably with the time found from the exponential fit in figure 6. The response to the UV pulse can be divided into the response on the UV switch-on, which is dominated by the short time scale of the charging time, and the response to the UV switch-off, which is determined by the loss time scale. However, at that time, the electron temperature is elevated, which shortens the loss timescale.

To conclude, we see that a dusty plasma responds very quickly to a short pulse of UV light. At UV switch-on, the response time is determined by the OML charging time, which is on the order of a microsecond. At UV switch-off, the response time is determined by losses of plasma, mainly by diffusion, but at an elevated temperature. On plasma shut-off, the (de-)charging time is completely determined by the ambipolar diffusion on a timescale between 10 and 100 microseconds. It seems that it is quite possible to affect a dusty plasma on very short timescales, without affecting the plasma too much. As a next step, modelling a pulse train of several consecutive, but shorter pulses might be interesting. This does however, require a large computational effort.

References

- [1] V. Land, W.J. Goedheer, IEEE Trans. Plasma. Scie. **35** Issue 2, 280-285 (2007)
- [2] A. V. Ivlev *et al.*, Phys. Rev. Lett. **90**, 055003 (2003)

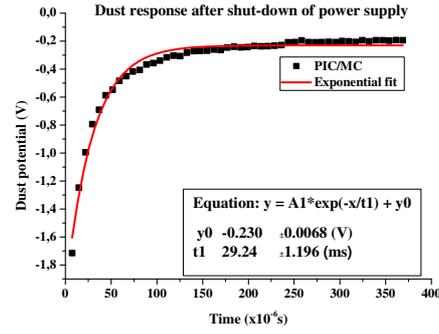


Figure 6: The dust potential after shut down of the driving potential and the exponential fit to the curve.