Understanding unexpected charging processes of microparticles in a low-pressure spatiotemporal afterglow plasma.

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1 Introduction

With the ever decreasing size of computer chips, maintaining a high level of cleanliness in the manufacturing equipment becomes increasingly crucial. To eradicate any contaminating particles in the governing ultra-clean low-pressure systems [1], the concept of a so-called “plasma seal” has been introduced, where a plasma is used to charge the particles which then can be deflected using an externally applied electric field. Since the plasma inherently shields externally electric fields, this deflection must occur at a distance from the plasma or shortly after termination of the plasma, or a combination of both: the spatiotemporal afterglow. In our earlier work [2], research has been conducted to understand the fundamental principles of particle charging mechanisms and how these are affected by spatiotemporal afterglow conditions. Although there is no clear evidence of different charging mechanisms for conducting versus insulating particles, material properties might play a role. Typically, Orbital Motion Limited (OML) theory explains charging mechanisms, modeling particle potential using its capacitance and calculating residual charge based on incoming ion and electron currents. OML theory suggests particle (de)charging timescales on the order of milliseconds [2], implying initial charge becomes irrelevant after this period in plasma. However, our work observes that for insulating particles, the plasma may not reset the charge as expected within these timescales. To bridge the gap between this fundamentally oriented research and its potential application, ongoing research aims to investigate the effect of particle properties such as conductivity. Until now, only conducting particles were used. To study the effect of the conductivity insulating silica (SiO_2) particles are used.

2 Experimental setup

In this section the experimental setup is briefly summarized, more details can be found in earlier publications [2]

2.1 Main setup

The main setup consists of a 1 m long tube with a square cross-section of 0.1 m, which can be evacuated to $3 \cdot 10^{-5}$ pa. On the top there is a gas inlet for argon and a particle shaker. A

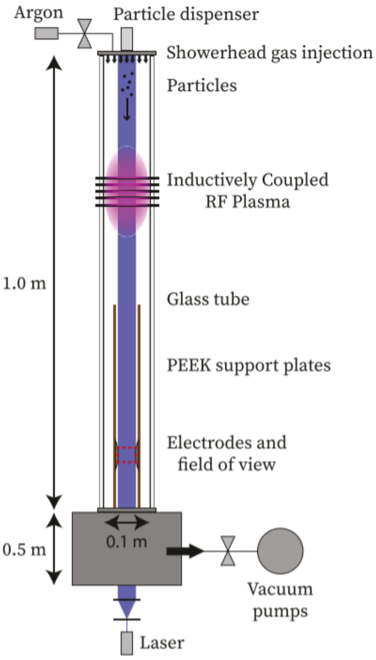

Figure 1: Schematic overview of the experimental setup. The red rectangle corresponds to the field of view of the high speed camera. Adapted from [4].

schematic of the setup can be found in Figure 1. An inductively coupled plasma of 2 W is generated by a 13.56 MHz RF current, produced by an RF generator and automatic matchbox. For a charge measurement, the tube is filled with argon to a pressure of 60 Pa. During the measurement the flow is stopped and the pressure is held constant. Particles are injected by shaking ten times with 0.03 s pulses and a 0.01 s delay. The falling particles are illuminated by a laser sheet. Two Rogowski electrodes at the bottom of the tube deflect the particles, with a horizontal uniform electric field of 1.5 kV/m. The recorded particle trajectories are then analyzed to calculate the velocities and accelerations. Between measurements, the tube is pumped down to less than 10^{-3} pa and the procedure is restarted.

2.2 Charge determination

To calculate the residual particle charge, particles are deflected by an electric field. By recording their trajectories, the charge can be determined through a force balance analysis. As described in [2], the horizontal force balance consists of adding the electrostatic force due to the electric field E_x produced by the electrodes and the horizontal Epstein neutral drag force, which results in a horizontal acceleration a_x of the particle having mass m_p and radius a. Rewriting the force balance gives the equation for the particle charge Q_p shown in equation (1), where v_x represents the horizontal velocity, v_{th} and ρ_g the thermal velocity and mass density of argon, respectively. δ is a constant concerning microscopic atom–particle interactions for which a value of 1.442 is used.

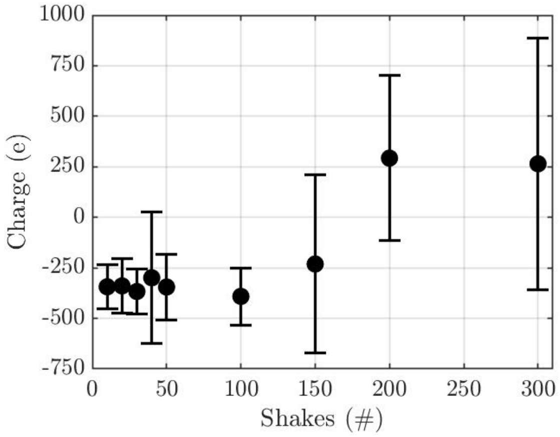

Figure 2: Mean residual charge as function of shakes for SiO_2 particles, measured at 60 Pa. In one measurement the shaker is shaken ten times and the error bars represent the standard deviation of the charge distribution of one measurement.

$$Q_p = \frac{1}{E_x}\left(m_p a_x + \frac{4\pi}{3}\delta v_{th}\rho_g a^2 v_x\right) \tag{1}$$

3 Results

In this section shows the results of the measurement for the particle charge of SiO_2 as a function of shakes. The experiment was conducted at a fixed pressure of 60 Pa. The results, shown in Figure 2 and repeated twice for reproducibility, show that increasing the number of shakes makes the average residual charge of the particles more positive. This unexpected result was not observed for the conducting particles used in our earlier work. This might indicate a difference in charging mechanisms between insulating and conducting particles. Repeating the measurement without plasma showed a similar trend, suggesting the plasma might not fully reset the initial charge of insulating particles.

3.1 Tribo-electric charging

From the results, it appears there is an addititional effect that causes the particles to charge more with increasing shakes. A possible explanation could be tribo-electric charging. Although there is no complete theory for tribo-electric charging, this part covers the most important ideas of our current understanding, starting with the name. In literature one can find two terms: tribo-electric charging and contact electrification, where tribo-electric charging is generally used for charging due to rubbing of particles and contact charging for particles passively in contact with another object. For more information on tribo-electric charging, the reader is referred to [3]. In this work, the particles are injected using a dispenser, similar to a salt shaker. It is hypothesized that the shaking of the particles lead to an initial particle charge due to the tribo-electric effect.

To estimate the magnitude of charge due to tribo-electric charging, a simple model is applied, using the capacitance C_p of a sphere such that $Q_p = C_p\phi_p$, where the potential ϕ_p is the difference in work function ΔW of the particle W_p and the stainless steel W_s shaker, giving the expression shown in equation (2). The shaker, made of 316L stainless steel, has a work function of 4.15 eV whereas SiO_2 has a work function of 5.1 eV. For 5 μm particles this results in a particle charge of -1694 e.

$$Q_p = C_p\frac{\Delta W}{e} = 4\pi\varepsilon_0 a\frac{-(W_p - W_s)}{e} \tag{2}$$

4 Conclusions

This work showed the relation the between shaking of particles and particle charge, due to the tribo-electric effect. It is shown that there is a difference in measured charge for conducting versus insulating charges which is not expected from OML theory. While there is no convincing explanation for this behavior, it highlights a critical gap in understanding that requires further investigation.

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