Studies on plasma profiles and its effect on dust charging in hydrogen plasma

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Abstract. Plasma profiles and its influence on dust charging are studied in hydrogen plasma. The plasma is produced in a high vacuum device by a hot cathode discharge method and is confined by a cusped magnetic field cage. A cylindrical Espion advanced Langmuir probe having 0.15 mm diameter and 10.0 mm length is used to study the plasma parameters for various discharge conditions. Optimum operational discharge parameters in terms of charging of the dust grains are studied. The charge on the surface of the dust particle is calculated from the capacitance model and the current by the dust grains is measured by the combination of a Faraday cup and an electrometer. Unlike our previous experiments in which dust grains were produced in-situ, here a dust dropper is used to drop the dust particles into the plasma.

1. Introduction
During the last few decades interest in the field of dusty plasmas has intensified because of its importance for a number of applications in space and laboratory plasmas. Plasma and dust grains exist in the vast variety of cosmic environments, such as interstellar, circumstellar, interplanetary, circumplanetary, cometary’s environments and in the planetary rings [1,2]. Dusty plasmas occur in devices for industrial plasma deposition, etching and sputtering where they cause serious problems by particle contamination and also play an important role in fusion devices [3,4]. It is, therefore, necessary a deeper understanding of the particles growth, charging, levitation and transport to reduce the contaminations. The charge on a dust grain is of fundamental interest of dusty plasmas. Massive dust grains can collect a large amount of the highly mobile plasma electrons, and thus affect the overall charge balance in the plasma. The dust grain in plasma acquires an electric charge ranging from zero to hundreds of thousands of electron charges, depending on the particle size and plasma conditions [5]. Dust grain immersed inside the plasma consisting of electrons, ions and neutrals is usually charged by electron and ion currents which flow to its surface. When emission processes are not important, the equilibrium charge attained by a dust grain will be negative, because the flux of electrons to the uncharged surface is higher than that of ions. For a dust grain of spherical shape, these currents are given by the orbit motion limited theory [6]. For an isolated spherical dust grain in plasma, the electron and ion currents to it are given by the relations

\[ I_e = -\varepsilon_e n_e z_e m_e \frac{4}{3} \pi R^3 \sqrt{m_e \varepsilon_0 / \mu_0} \] \quad and \quad \[ I_i = \varepsilon_i n_i z_i m_i \frac{4}{3} \pi R^3 \sqrt{m_i \varepsilon_0 / \mu_0} \left(1 - \frac{e\phi}{k_B T_e} \right) \] \quad for \quad \phi < 0

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In these relations e, φ, k_B, r_d, Z_i, n_e(i), T_e(i), m_e(i) are the electronic charge, dust grain surface potential, Boltzmann’s constant, radius of dust grain, ionic charge, electron (ion) density, electron (ion) temperature, mass of electron (ion) respectively.

These currents keep flowing till the dust grain acquires a floating potential (φ_f) at which these currents become equal. Since a spherical dust grain is like a charged conducting sphere, therefore the number of charge on the grains (q_c) can also be calculated from the relation

\[ q_c = eZ_i = \frac{4\pi r_d^2}{\varepsilon_0} \phi_f \]

where \( q_c \) is the total charge on grains, \( e \) is the electronic charge, \( r_d \) is the radius of the dust grain and \( \phi_f \) is the floating potential of the dust grain relative to the plasma potential. The floating potential can be experimentally measured by using a Langmuir probe and the charge on a dust grain can thus be found out. There have been few laboratory works on dusty plasma using electrometer and Faraday cup [7, 8].

The goal of this work is to study the charging of micron sized dust particles in hydrogen plasma. In this report, the measurement of low current (~ nA) carried by dust grains at various discharge conditions is described. The dust grains are dropped into the plasma with the help of a dust dropper. The dust grains get negatively charged in the plasma environment, because the flux of electrons to the uncharged surface of grains is high relative to that of ions. A Faraday cup is placed in the bottom of plasma chamber to collect the dust particles. After coming out from the plasma column, the dust grains strike the Faraday cup and the current so produced is measured by an electrometer. The dust current profiles for a discharge current range of 100-500 mA are studied for 4x10^{-4} mbar pressure to see the effect of ambient plasma conditions on dust current. The present experimental setup is aimed to study the parametric operational conditions for optimum production of negative hydrogen ion through surface production mechanism on dust surface having coating of low work-function material.

2. Experimental setup
The experiment has been carried out in a high vacuum plasma device. A schematic of the experimental device is shown in figure 1. It consists of two stainless steel chambers, placed one above the other. The lower chamber is the plasma chamber which is placed horizontally and the vertical upper chamber facilitates the holding of dust dropper and also the cesium (Cs) oven which will be used to inject Cs to coat the dust particles later on. These chambers are pumped down to a base pressure of 2x10^{-6} mbar with the help of a diffusion pump (1000 lit/s) backed by a rotary pump (600 lit/min).

![Figure 1. Schematic of experimental device.](image-url)
Hydrogen gas is fed to the plasma chamber of length 100 cm and diameter 30 cm with the help of a fine needle valve attached to this chamber. The working pressure is set at $4 \times 10^{-4}$ mbar. Hydrogen plasma is produced in the plasma chamber by striking a discharge (65 V) between incandescent tungsten filaments of total length 150 mm & diameter 0.25 mm and the magnetic cage, which is grounded. The discharge current is in the range of 100-500 mA. Plasma thus produced is confined by a full line cusped magnetic field confinement system consisting of a cylindrically shaped cage made up of stainless steel channels filled up with cube shaped magnets having 1.2 kG field strength at its surface. A cylindrical Espion advanced Langmuir probe having 0.15 mm diameter and 10.0 mm length is used to study the plasma parameters for various discharge conditions.

A dust dropper is designed to drop the dust particles into the plasma. The dust particles are dropped by agitating a mess sieve with the help of an electromagnet which is obtained from a 12 VDC relay. The electronic circuit is designed with IC 555. The output frequency is controlled by a variable resistor so that dust grains fall according to the required density. A schematic of the dust dropper is shown in the figure 2.

**Figure 2.** Schematic of dust dropper.

Solid spherical alumina particles are used as the dust grains. The density and average size of particles are 3970 kg/m$^3$ and 3 $\mu$m respectively. The OEM photograph of dust grains is shown in figure 3.

The dust grains while passing through plasma are charged by interactions with plasma particles (electrons and ions). Due to the higher mobility of the electrons, these grains are charged negatively. A Faraday cup is placed below the magnetic cage and is connected to the electrometer, which is capable of measuring current up to the Pico ampere range.

Faraday Cup (FC), a charge collector, assembly mainly comprises of a copper plate as inner electrode, which is encircled by a cylindrical stainless steel shield used as the outer electrode. The schematic of Faraday cup is shown in figure 4. The entrance pinhole of the FC is 2 mm in diameter. The detailed description of FC is found elsewhere [8]. The incoming charged dust beam strikes the copper collector surface inside the cup and flows to the ground through electrometer and thereby produce a current (~ nA), which can be directly measured from electrometer reading.
3. Results and discussion

Keeping the discharge voltage (65 V) and working pressure (4x10⁻⁴ mbar) constant, the charge on the dust grains is determined by changing the discharge current. The discharge current is changed from 100-500 mA by changing the filament current which in turn increases the number of primary electrons. There is an increase of plasma density as well as the electron temperature with an increase in discharge current (figure 5). The floating potential with respect to plasma potential is determined at each discharge current and the charge on the grains is calculated from the capacitance model. It has been seen that the magnitude of floating potential with respect to plasma potential increases with an increase in discharge current and correspondingly the number of charges accumulated on the dust grains also increases with an increase in discharge current (figure 6). This is due to the fact that when electron temperature increases, the charge on dust grains also increases [9].

The electrometer observes minimum current ~ 0.01 pA when it is connected to the Faraday cup. The dust grains acquire no charge in the absence of plasma and the observed current is only the stray current.

The dust current profile for different discharge currents in presence of plasma is shown in figure 7. The figure shows that for a discharge current 100 mA, the dust current is maximum. The
maximum dust current is found to be 4 nA. The effect of ambient plasma conditions is studied by varying the discharge current from 100-500 mA keeping the discharge voltage (65 V) and operating pressure (4x10^{-4} mbar) fixed. It is seen that there is a decrease in the magnitude of the dust current as the discharge current increases. This is due to the effect of reduction of charge due to secondary emissions from the dust grains due to increase in the number of primary electrons which was reported earlier[10].

![Figure 7. Variation of dust current with discharge current.](image)

4. Conclusions
An experiment for the study of plasma profiles and its influence on dust charging is presented. Through this experiment we have been able to measure current carried by dust grains. The charging of grains with different ambient plasma conditions is studied by varying the discharge current keeping discharge voltage and operating pressure constant. Our results have shown variation of dust current for different discharge currents and the effect of ambiance on it. Experimentally it appears that a low discharge current at a particular pressure may help in higher charging of dust grains. As a continuation of the present experiment, the parametric operational conditions for optimum production of negative hydrogen ion through surface production mechanism on dust surfaces having coating of low work-function material will be studied.

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