Experimental study of charging of dust grains in the presence of energetic electrons

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Abstract
The role of hot electrons in the charging of dust grains is investigated in a two temperature hydrogen plasma. A variety of dust particles are introduced into the system and secondary electron emission (SEE) from each of the dust types has been reported. A cylindrical Langmuir probe is used for determining the plasma parameters and a Faraday cup is connected to an electrometer in order to measure the dust current. The electrometer readings confirm the electron emission from the dust and SEE is observed from the tungsten dust in a low-pressure experimental plasma device for the first time.

Keywords: dusty plasma, low temperature plasma, secondary electron emission, two-electron temperature

(Some figures may appear in colour only in the online journal)

1. Introduction
Charging of dust grains has altogether been a fascinating field of research for several decades. The ability of dusty plasmas to explain the various astrophysical phenomena as well as its relevance in the industrial applications establishes it as a potential field of research \[1\]. Among the numerous known mechanisms of dust charging, electron impact ionization is the most probable agent in low-pressure plasmas. In such plasmas, the temperature of the incident electrons play a pivotal role in charging processes. An increase in the temperature increases the kinetic energy of the electrons, thereby enhancing the current contribution to the dust grains \[2\]. Usually, a high-energy tail in the electron energy distribution is observed in low-pressure laboratory plasmas \[3\]. In the presence of such an energetic electron group, the dust charging scenario may change significantly. The advent of fusion research has led to the quest for a material that can be sustained in such an extreme environment. Research shows that tungsten (W) may be the most promising material in this regard \[4, 5\]. Exposing W to high heat flux region of tokamak might result in the generation of nano to micron-sized dust particles in the system, which are often regarded as contaminants \[6\]. Therefore, understanding the dust charging mechanism becomes essential for removing them from the fusion devices \[1\]. The present study investigates the response of micron-sized W dust in the presence of energetic electrons in a low-pressure plasma environment. In fusion devices, it is usually seen that there is a fuel loss due to the retention of the fuel (H\(^+\)) by the dust \[6\]. This is a prime concern for the fusion devices, which may be avoided if the dust present in the device \[6\] is positively charged \[7\]. The present work establishes an alternative and a simpler method of reducing negative charges on the dust surface, which may help in producing positively charged dust. For the present work, the plasma environment is comparable to the outer strike point and low-field side of the divertor region of the COMPASS tokamak \[8\], hence this study might

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be useful in overcoming the dust-related complexities often encountered in such fusion devices. To verify the effectiveness of the present method, W dust has been replaced by alumina (Al$_2$O$_3$), as earlier studies confirm secondary electron emission (SEE) from Al$_2$O$_3$ [9]. Moreover, cesium coated W dust is also chosen in this study due to its relatively low work function than W and Al$_2$O$_3$ dusts. It also plays a noteworthy role in producing negative ions that are then used for neutral beam injection systems in the fusion devices [10, 11].

This paper has been divided into the following sections: section 2 discusses the apparatus and the experimental system. Section 3 analyzes the experimental findings and a brief conclusion is presented in section 4.

2. Apparatus and experimental setup

A two-temperature electron plasma is produced by a hot cathode discharge method. The experimental setup consists of two stainless steel chambers placed one above the other, as shown in figure 1. The lower chamber, placed horizontally, is the plasma chamber, and the upper chamber placed vertically holds the dust dropper. The plasma chamber is 100 cm in length and 30 cm in diameter. The dust dropping unit, on the other hand, has a height of 72 and 15 cm in diameter. The chamber is evacuated by a pumping arrangement consisting of a diffusion pump (1000 l s$^{-1}$) backed by a rotary pump (600 l min$^{-1}$).

Two cylindrical magnetic cages of different field strengths are used for confining the plasma. Cage I is a rectangular-shaped samarium cobalt magnets (surface magnetic field of 3.5 kG), filled inside 12 stainless steel channels and requires a water cooling system. The total length of the magnetic cage is 40 cm and the outer diameter is 28 cm. Cage II on the other hand, has cubical-shaped strontium ferrite magnets (surface magnetic field strength of 1.2 kG) inside ten stainless steel channels. The total length of Cage II equals that of Cage I but the outer diameter is 29 cm. The rectangular and cubical shape are the physical configurations of the permanent magnets used inside the channels of the cages. Both cages individually produce cusp-shaped magnetic profiles where the magnetic field strengths at the center is minimum and increases towards the surface of the cages. The cross-sectional view of the magnetic field profiles inside the chamber including the junction is shown in figure 2. The Gauss meter reading, as shown in figure 3 confirms that the junction of the two cages is magnetic field free. On moving from the center to the periphery of the junction, a nominal increase can be observed in the magnetic field strength. Thoriated tungsten filaments are used as a source of
primary electrons in the system. The electrons emitted from the filaments are accelerated by applying a 80 V discharge voltage. Plasma is produced by striking a discharge between the filaments and the grounded magnetic cage. A Hiden Analytical Limited's ESPION advanced Langmuir probe system is used for determining the plasma parameters at the junction.

In fusion-like environments, the generated dust is of various shapes and sizes where flake-like structures are common. A numerical study shows that the total current on the dust depends upon the surface area rather than the shape of the dust [12]. Thus, the charging mechanism of flake-like dust particles will be similar to that of spherical dust grains of similar diameter as that of the flake thickness. In the present study, the chosen dust is almost spherical in shape and has a similar radii (1.5 µm). Dust particles are introduced in the plasma using a dust dropping unit placed above the horizontal chamber. The dust dropping unit comprises of a dust dropper connected externally to an oscillator circuit used for vibrating the dropper. The dust dropper is made up of a container with a stainless steel mesh as the base and same mesh is used for dropping the dust grains inside the system. The vibrating frequency can be varied by controlling the input voltage applied from an external power supply. Al2O3 dust is lighter than W dust, and a suitable input voltage and frequency is applied to the dust dropper to maintain a uniform dust density inside the chamber. For all the samples, the dust density is of the order of 10⁵ cm⁻³ measured using the laser scattering technique [13]. The dust particles interact with the diffused plasma and eventually get charged. The charging time of the dust [14, 15] inside the plasma in the case of a single cage operation is approximately equal to a few microseconds depending upon the plasma density and electron temperature [16]. On the other hand, the time taken by the dust particle to cross the plasma volume under gravity is approximately equal to a few milliseconds [16]. Thus, the dust grains have enough time to attain the equilibrium charge state within the plasma volume. In order to measure the dust current, a sensitive electrometer (Keithley Instruments, 6514) is used. It is attached to a Faraday cup with a low noise tri-axial cable as shown in figure 4. The Faraday cup assembly sits exactly below the junction of the two cages and is separated by a distance of approximately 5 cm from them. Two permanent magnets (surface field strength 1.2 kG each) are axially placed across the Faraday cup, which creates a strong transverse magnetic field.

3. Results

Hydrogen plasma is produced through a hot cathode discharge method inside the two individual cages maintained at a constant working pressure of 2 × 10⁻⁴ mbar. Cage I has a surface field strength of 3.5 kG and provides better confinement. This is due to the fact that it produces a plasma of density of the order of 10¹⁷–10¹⁸ m⁻³ depending upon the discharge current. On the other hand, Cage II has a surface field strength of 1.2 kG and has comparatively lower confining ability, thus, produces plasma of density of the order of 10¹⁶ m⁻³. The plasmas so formed are then allowed to diffuse at the edge of the cages. The diffused plasma at the junction contains two electron groups of distinct temperatures and densities as seen in figures 5 and 6. Traces of two electron groups can also be observed in the semi-logarithmic plot of the I–V curve as shown in figure 7. Additionally, electron energy distribution function (EEDF) is calculated and is shown in figure 8(a). A theoretical prediction of the EEDF corresponding to the same discharge condition is displayed in figure 8(b). The theoretically obtained EEDF is consistent with the experimentally calculated one to a reasonable extent. However, the dips and peaks observed in the tail of figure 8(a) is mainly due to the inelastic collisions occurring between hydrogen molecules and the other hydrogen species such as H⁺, H₂⁺, H⁻, etc [16]. Such reactions were not taken into consideration while predicting the EEDF theoretically. Usually, in single cage operation, it is seen that a high-density plasma is obtained in Cage I due to its higher confining ability, while, Cage II has a low-density plasma due to its lower surface field strength. Kakati et al [16] have found a high-energy tail for a discharge at a lower pressure (10⁻⁵ mbar) which gradually fades away with the increase in the gas pressure. However, the present arrangement ensures...
that for a pressure of $10^{-4}$ mbar the high energetic tail of the EEDF is retained. By maintaining a higher discharge current in Cage I and that of a lower one in Cage II provides an optimum condition for attaining two electron population in the system. Hence, the discharge current in Cage II is kept constant at 0.2 A and that in Cage I is varied from 2 to 4 A. Figure 9 shows the EEDFs for various discharge conditions. It can be seen that as the discharge current in Cage I is increased, the high-energy tail shifts to the right, indicating an increase in the hot electron population. Also, with the increase in discharge current, the number of thermionic electrons emitted from the filaments increases thereby enhancing the degree of ionization. Due to this increase in the primary population, the effective electron temperature increases, which is also accompanied with an increase in the electron density as observed from figure 9.

The two temperature electron plasma production mechanism has been explained and the details of which can be found here [17].

With the introduction of dust in the plasma, it is observed from the previous study [16] that the higher energy tail of the EEDF increases and the bulk population peak decreases. The mid-energy electrons get attached to the dust, results in a decrease in the bulk electron population. Due to this reason, the overall electron saturation current decreases in the presence of dust and was first reported by Barkan et al [18]. However, a completely different scenario has been observed in the present study. EEDFs in presence of different dust particles at the same plasma conditions has been calculated and is shown in figure 10. In the presence of dust, there is a significant rise in the bulk electron population along with a left-handed shift in the EEDF and a depletion in the high-energy tail is observed. In addition, the overall electron saturation current increases in the presence of dust and can be seen from the I–V curve in figure 11. This phenomenon is observed for all the chosen dust samples. Among them, Al$_2$O$_3$ has the highest SEE yield (in the range of 2–3) for the primary electrons in the energy range of 60–100 eV [9] as compared to the others. Due to this reason, SEE from alumina dust has been observed earlier in a single cage operation [9]. However, tungsten (W) dust has a comparatively lower SEE yield (in the range of 0.5) for the above mentioned energy range. Hence, SEE was not observed for W dust in the previous study [9]. Although, the primary electrons, in the present arrangement, fall within the same energy range, it is observed that W dust also exhibits SEE.

There are many well-known possible mechanisms through which a dust grain can acquire charge in a plasma environment [1]. In astrophysical plasmas, the dust charging often arises due to photoemission [19]. For the present case, however, it appears that the most suitable means by which dust can be charged is its interaction with the energetic particles. Among the plasma species present in the system, electrons are only responsible for charging the dust particles. Usually, in low-pressure laboratory plasmas, the lower energetic electrons are in bulk as compared to the hot electrons. This leads to the attachment of these cold electrons on the dust surface. Consequently, dust grains becomes negatively charged. SEE can occur in situations, where the hot electron population is significant and have energy above 10 eV, such electrons can tunnel through the dust surface and initiate SEE [20, 21]. When they strike the particles, a part of their energy is lost to the dust. The lost energy is used in exciting the electrons as a result of which an emission of electrons takes place from the dust grain [22]. The emitted electrons have energy comparable to that of the cold electrons. Due to this reason, the low-energy electron population increases significantly and is reflected in the EEDF plots as shown in figure 10. On the other hand, a depletion in the hot population is also observed in the EEDF plot in figure 10 indicating an absorption of the energetic electrons by the dust grains. Goertz [23] predicted that the emitted electrons will have a Maxwellian distribution and will lie in the energy range between 1–5 eV. This is reflected in the EEDFs.
Figure 8. (a) Experimentally calculated EEDF and (b) corresponding theoretically predicted EEDF for a discharge current 4 A in cage I and 0.2 A in cage II.

Figure 9. EEDF for different discharge currents in cage I ($I_{d1}$) and a constant 0.2 A discharge current in cage II.

curves as shown in figure 10. Therefore, in the present scenario, the deviation from the familiar theoretical result for the observed dust current with the increasing electron temperature might be credited to secondary electrons emitted from the dust surface [24]. Cesium coated W dust grains also show similar SEE behavior as seen in figure 10.

The variation of dust current for W, Cs coated W and Al$_2$O$_3$ dusts with varied discharge current is shown in figure 12. Usually, dust becomes negative by absorbing electrons from the ambient plasma for which the electrometer readings indicate a negative dust current confirming electron absorption by the dust grains [9]. However, an opposite behavior is observed in this particular study as seen from figure 12. Here, the dust current measured for all the dust samples consequently refers to an emission of electrons from the dust grains. This decrease in the dust current also confirms the occurrence of SEE from the dust surfaces. This indicates that the negative charge accumulated on the dust surface decreases with the increase in the discharge current. Many theoretical findings [24–27] suggest that positively charged dust is a stable state that arises due to the emission of electrons from the dust surface. D’Angelo [28] measured positively charged dust in the presence of negative ions experimentally. A similar method has been adopted by Kim and Merlino [29] for obtaining positively charged dust. But, the present method is quite different from the above stated techniques. A comparison of dust currents between the dust samples as shown in figure 12 reveals that Cs coated W dust emits a larger fraction of electrons than that of pure W and Al$_2$O$_3$ dusts. The reason lies in the fact that Cs layer on W lowers the work function [10] (from 4.5 to 1.8 eV) facilitating a higher emission rate. Al$_2$O$_3$ dust on the other hand, has a higher SEE yield as compared to W dust, so the electrons are emitted easily from the dust surface that is reflected by a higher dust current in comparison to W. The rate
of decrease in the measured dust current with respect to the increase in the discharge current is maximum for Cs coated W, followed by $\text{Al}_2\text{O}_3$ and W. Since, decrease in the dust current consequently refers to electron emission from the dust surface, hence confirms the EEDF findings and validates our assumption about SEE.

Since the chosen dusts are spherical in shape, the charge accumulated on the dust is often calculated by the capacitance model. When the net current on the dust grain vanishes, the dust surface acquires a floating potential ($\phi_p$). At this equilibrium state, the floating potential is related to the charge on the dust grain ($q$) as:

$$q = 4 \pi \varepsilon_0 \ r_d \phi_p,$$

where $r_d$ is the radius of the chosen dust grain. The dust surface potential, $\phi_p$ is calculated as:

$$\phi_p = V_f - V_p,$$

where $V_f$ and $V_p$ are the respective floating and plasma potentials. This theoretical model is useful in calculating the amount of charge gathered on the dust. But, in case of secondary emissions, as this model does not incorporate electron emissions, hence it becomes inadequate for such situations [30]. Therefore, a new model [31] has been adopted in this study for calculating the dust charge. According to this model, the peaks in the EEDFs in the presence of dust corresponds to the floating potential ($\Phi$). According to the theoretical solution for EEDF, as the emission takes place from the dust, electrons are injected into the plasma with an energy comparable to the dust floating potential.
Figure 13. Dust charge calculation for various dust samples for different discharge currents in cage I ($I_{d1}$) and a constant 0.2 A discharge current in cage II.

| Single cage | Double cage |
|-------------|-------------|
| Pristine plasma | $T \approx 0.7–3.5$ eV | $T_c \approx 3.91–4.96$ eV |
| Temperature | $T_h \approx 11.02–14.46$ eV | $n_c \approx 10^{18}$ m$^{-3}$ |
| Density | $n \approx 10^{16}$ m$^{-3}$ | $n_h \approx 10^{17}$ m$^{-3}$ |
| EEDF | Maxwellian | Maxwellian with a distinct high energy population |
| Dusty plasma | Electron-saturation current | Decreases | Increases |
| Low energetic electrons | Population decreases | Population increases |
| EEDF | Primary peak decreases | Primary peak increases |
| Dust charge | Negatively charged | Negative charge decreases |
| Dust samples | | |
| Al$_2$O$_3$ | SEE observed | SEE observed |
| W | SEE absent | SEE observed |
| Cs coated W | SEE may be possible | SEE observed |

As the observed peaks are due to the emitted electrons from the dust samples, hence the corresponding potential depicts the actual floating potential of the dust. This potential is used in calculating the dust charge ($Q$) from the Coulomb’s law given by:

$$\Phi = Q/(4\pi\epsilon_0 r_d), \hspace{1cm} (3)$$

where $r_d$ is the radius of the chosen dust grain. A comparison is drawn between these two models and is shown in figure 13 for all the dust samples. The capacitance model shows an increasing trend for all the dusts with the increase in the discharge current. But this result is contrary to the electrometer findings as shown in figure 12 where dust current decreases with increase in discharge current. On the other hand, the charge calculated using the Coulomb law model shows a decreasing trend that resembles the dust current readings. This decrease in the dust charge consequently stands for less negatively charged dusts measured by the electrometer. The decrease in the negative charge symbolizes emission of electrons from the dust thereby indicating SEE from the dust grains.

Two possible scenarios arise due to the emission of electrons from the dust grains, viz., when the incoming electron flux is greater than the outgoing flux and when the situation reverses. For the first case SEE yield ($\delta$) is less than unity, and for the latter $\delta$ is greater than unity. An estimation of $\delta$ can be made from the following equation [32]:

$$(1 - \delta) \exp(-V_d) = \left( \frac{\theta}{\mu} \right) \left( 1 + \frac{V_d}{\theta} \right), \hspace{1cm} (4)$$

where $V_d = -e\phi_d$, $\theta = \frac{T}{\mu}$ and $\mu = \frac{m_i}{m_e}$. The dust potential $\phi_d$ is calculated in the similar manner as that of the already mentioned $\phi_p$. For the present case, the estimated $\delta$ value for W dust from the above equation is 0.9 which is more than the maximum $\delta$ value (0.5) for the electrons in the energy range 60–100 eV. This indicates that a significant number of electrons has been emitted from the dust surface. Since $\delta < 1$, the
The data that support the findings of this study are available upon reasonable request from the authors.

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