Surface Potential of Spherical Objects in a Magnetized RF Discharge Plasma

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We report measurements of the floating potential of magnetic and non-magnetic spherical probes immersed in a magnetized rf discharge plasma. The discharge is ignited between a transparent indium tin coated (TIO) glass electrode and a metal electrode after applying an rf signal (13.56 MHz). A strong superconducting electromagnet (0 to 4 T) with Helmholtz coils configuration is used to magnetize the plasma species. In this study, the size of the spherical probes are taken either in the range of or greater than the Debye length. To determine the surface potential, the plasma potential is measured using an emissive probe. The surface potential of the spherical probe first increases, i.e. becomes more negative, at low magnetic field, attains a maximum value at some field strength, and after that it starts to decrease with increasing magnetic field. The rate of increase and decrease of the surface potential mainly depends on the magnetized plasma environment and types of materials (magnetic or non-magnetic) of the object. The surface potential of the magnetic spherical probe in the plasma is found to be higher (more negative) than that of the non-magnetic spherical probe in the presence of a magnetic field. In other words, the non-magnetic probe collects less negative charges on its surface than a smaller sized magnetic probe in the magnetic field. Also, the magnetic probes show less size dependence in the presence of a magnetic field. The variation of the floating potential or negative charge of the spherical probes is understood on the basis of a modification of the collection currents to the spherical object due to charge confinement and cross field diffusion in the presence of an external magnetic field.

I. INTRODUCTION

A spherical object attains an equilibrium potential when it is immersed in a plasma. At the equilibrium potential, which is termed as floating potential, it draws a net zero current, i.e. the net flux of electrons and ions to the surface of the spherical object is zero. In a low-temperature plasma, where the electron temperature is much higher than the ion temperature ($T_e \gg T_i$), the floating potential of the object mainly depends on the flux of the energetic electrons to its surface and is always negative with respect to the plasma potential. In the plasma, a spherical object is assumed to be a spherical capacitor. Therefore, the potential on the surface directly measures the charge of the spherical object.

In recent years, the research field of dusty or complex plasmas, which are admixtures of a plasma and sub-micron to micron sized solid particles, has been created an interest due to its applications in space or solar plasmas1–3, plasma processing technologies4,5, fusion devices6, colloidal solutions7 etc. To determine the dynamics of dust grains immersed in a plasma the floating potential must be known to estimate the charge on the grain. The charge on the dust grain, either conducting or dielectric, in the plasma has been experimentally determined by various indirect methods8–12 and compared with the theoretical obtained values using the OML approximation13,14 and numerical simulations12. Usually, in this case the radius of the particles $r$ is much less than the electron Debye length $\lambda_{De}$. For larger dust grains or spherical objects with $r \geq \lambda_{De}$ the surface potential of the object is determined by a modified OML approximation15,16. In experiments, it is easy to determine the floating potential of large spherical conducting bodies in different plasma environments, which helps to understand the charging of a spherical object or dust grains in the plasma environment17,18. It was initially assumed that the floating potential of an object in the plasma does not depend on the size of the object but theoretical studies15 as well as experimental work17 confirmed that this is not the case.

In laboratory as well as space plasmas containing dust grains of radius, $r < \lambda_{De}$ or $r > \lambda_{De}$, also magnetic fields can be present such as in magnetized dusty plasma devices19–21, tokamak plasmas22, magnetospheres23 etc. Although researchers have been working on the charging mechanism of dust grains or spherical objects in magnetized plasma24,25, there are still many unanswered questions about the floating potential of spherical objects in the presence of a magnetic field. How does the floating potential of spherical objects with different sizes depend on the magnetic field? What would be the role of gas pressure on the charge of a spherical object or dust grain in the magnetized plasma? How does the surface potential of magnetic and non-magnetic spherical objects in the plasma alter with the application of a magnetic field? To get the answers to the above highlighted problems, it is required to measure the floating potential of magnetic and non-magnetic spherical probes in a weakly collisional plasma in the presence of a magnetic field, from which the surface potential and charge of the probe can be derived.

The investigations are carried out in a magnetized complex plasma device where an rf glow discharge is ignited between two electrodes and a superconducting electromagnet is used to introduce the magnetic field to the plasma. The floating potential of various sized mag-
netic (stainless steel) and non-magnetic (bronze) spherical probes has been measured in the unmagnetized and magnetized plasma environment at different discharge conditions. At lower magnetic field, the magnitude of the surface potential of spherical objects increases to a maximum value and then starts to decrease with increasing strength of the external magnetic field. This trend is found to be independent of size and types of materials of the spherical object. In other words, the charging mechanism of magnetic and non-magnetic spherical objects depends on the external magnetic field. The charge or surface potential of a non-magnetic spherical object in the plasma are found to be smaller (less negative) than that of a magnetic sphere if a magnetic field is applied. The experimentally observed results are explained on the basis of the current collection to the surface of the object in the presence of an external magnetic field.

The manuscript is organized as follows: Section II deals with the detailed description of the experimental set-up and magnetized plasma production. The characteristics of the floating potential variation at various discharge conditions in unmagnetized and magnetized plasmas are presented in Section III. A qualitative explanation of the floating potential variation for magnetic and non-magnetic spheres is given in Section IV. A brief summary of the work along with concluding remarks is provided in Section V.

II. EXPERIMENTAL SETUP AND DIAGNOSTICS

The experimental setup consists of an aluminum made vacuum chamber and a strong superconducting electromagnet, which is shown in Fig. 1(a). The same setup was previously used to study dusty plasmas in the presence of a magnetic field\textsuperscript{20}. The schematic diagram of the experimental setup is presented in Fig. 1(b). The electromagnet has a Helmholtz coils configuration to produce a uniform magnetic field in the central region of the coils up to maximum 4 Tesla. The superconducting magnet consists of a helium compressor, a cooling head, 8 sensors for temperature measurements, and a superconducting magnet power supply (0 to 80 A). The vacuum chamber with pumping assembly and gas injection valve is placed at the center of the magnet to provide a uniform magnetic field in the preferred experimental region. An rf generator (13.56 MHz) is used to ignite the gas discharge between a stainless steel electrode (lower) and a TIO coated glass electrode (upper) of 6.5 cm diameter. The gap between powered and grounded electrodes is 3 cm. The plasma chamber can be evacuated below $10^{-2}$ Pa using a turbo molecular pump (TMP) and the operational argon gas pressure is set between 15 to 50 Pa where the gas flow is adjusted by a mass flow controller (MFC). For the spherical objects, stainless steel (magnetic) spherical probes of radius 1, 1.25 and 1.7 mm and a bronze (non-magnetic) spherical probe of radius 1.5 mm are used. These spherical probes are placed inside the homogeneous bulk plasma as shown in Fig. 1(b), using a ceramic tube of diameter 2 mm which protrudes into the plasma by a feed-through in the chamber wall and holds the spherical probes at its end. To avoid perturbations on the floating potential of the probe, the length of the ceramic tube was longer than the radius of the electrode or plasma bulk. For measuring the floating potential ($V_f$) of a spherical probe, a high-impedance voltage divider (1200:1) is used. The spherical probe is connected to a high value resistor ($R_2 = 100$ kΩ) to minimize the current flowing in the voltage divider circuit. First the voltage drop ($V_2$) due to this small current is measured across a low value resistor ($R_2 = 100$ kΩ) and then the floating potential of the spherical probe ($V_f$) is calculated by using the expression, $V_f = (R_1 + R_2)V_2/R_2$. The plasma parameters such as plasma density ($n$) and electron temperature ($T_e$) are measured using a double Langmuir probe for various discharge conditions\textsuperscript{26,27}. An emissive probe is used to measure the plasma potential ($V_p$) in the absence and presence of the magnetic field\textsuperscript{28-31}.

III. RESULTS ON THE SURFACE POTENTIAL OF SPHERICAL OBJECTS

A spherical object or dust grain immersed in a plasma gets negatively charged because of the highly mobility of the electrons and slower ions impinging on its surface. The potential distribution around the charged body repels the electrons and attracts the ions to balance the both currents. This equilibrium surface potential is termed as floating potential\textsuperscript{32,33}. In a plasma, the floating potential is in general a function of the electron and ion temperatures. For glow discharges, where $T_e \gg T_i$, the floating potential of spherical object can be represented as a function of $T_e$\textsuperscript{32}.

$$V_f = V_p - aT_e,$$ \hspace{1cm} (1)

where $a$ is a constant factor which varies from 0.7 to 4 for various discharge conditions\textsuperscript{14,17,32} and $V_p$ is the plasma potential with reference to the chamber wall or ground. The surface potential of spherical probes or grains with respect to the plasma is

$$V_s = V_p - V_f,$$ \hspace{1cm} (2)

The correlation between the surface potential and charge is given by the capacity of a spherical object

$$Q_s = CV_s = 4\pi\varepsilon_0rV_s.$$ \hspace{1cm} (3)

Hence the charge of a spherical object or dust grain is proportional to the surface potential. For getting the correct value of $V_s$ of the spherical conducting probe in the plasma, it is necessary to measure the reference potential, i.e. $V_p$. In the present set of experiments, an emissive probe with the floating point method technique
FIG. 1. (a) Experiment setup. (b) Schematic diagram of the experiment setup. (1) Superconducting magnet, (2) superconducting coils, (3) power supply, (4) vacuum chamber, (5) lower electrode, (6) upper electrode, (7) 13.56 MHz rf generator, (8) emissive probe and (9) spherical probes.

is used to measure the plasma potential in the absence and presence of a magnetic field.

A. Surface potential of spherical probes without magnetic field

The present work deals with spherical objects with radius larger than the electron Debye length i.e., $r > \lambda_{De}$. Stainless steel spheres of radius 1 mm, 1.25 mm and 1.7 mm are used to study the size dependence of the floating potential. The spherical probes and the emissive probe are placed in the uniform argon plasma bulk (Fig. 1) for the simultaneous measurements of the floating potential ($V_f$) and plasma potential ($V_p$) at given discharge conditions. Fig. 2(a) and Fig. 2(b) display $V_p$, $V_f$ and $V_s$ for different rf powers at constant pressure and for different pressures at constant power, respectively. The potentials show only a slight variation at various discharge conditions in the absence of a magnetic field. To see the effect of the object size on $V_s$ at a given discharge conditions, the floating potential of stainless steel spherical probes of different sizes are measured. The variation of $V_s$ for different sized spherical probes is depicted in Fig. 3, which confirms that the surface potential of spherical objects depends on their size. It essentially means that charges on a spherical object or dust grain in a plasma is a non-linear function of the radius, in contrast to the OML-theory.

B. Surface potential of spherical probes with magnetic field

To magnetize the plasma, a magnetic field (B) is applied in the z-direction, which is perpendicular to the plane of electrodes. The strength of the B-field can be varied up to 4 T but we restrict the present study to 0.2 T to maintain the plasma homogeneity at low pressure. In Fig. 4 the surface potential of spherical stainless steel probe of 1.25 mm radius at various strength of the magnetic field is depicted. It should be noted that the B-field is uniform in the entire bulk plasma for a given current in the superconducting coils. The plot in Fig. 4(a) shows the variation of $V_s$ for different input rf powers, $P = 3.5$, 6.5, and 12 W, respectively at constant pressure, $p = 30$ Pa. It is clearly seen in this figure that $V_s$ first increases (becomes more negative) at low B (B < 0.05 T), attains a maximum value at some B-field strength and after that it starts to decrease (becomes less negative) at higher magnetic field strength (B > 0.05 T). The surface potential $V_s$ increases faster than it decreases with increasing B-field at a given input power. It is also noticed that $V_s$ attains its maximum value at lower strength of B at higher input power and at higher B-value at lower input power. Also $V_s$ depends stronger on the magnetic field for smaller input power.

The variation of $V_s$ at a given power ($P = 12$ W) and different pressures (for $p = 15$, 30 and 50 Pa) with the magnetic field strength is presented in Fig. 4(b). The dependence of $V_s$ in the magnetized plasma is observed to be stronger at lower pressure ($p = 15$ Pa). The rate of the variation of $V_s$ at higher B (B > 0.05 T) is less at higher pressures indicating a dependence on the colli-
FIG. 2. (a) Floating potential \( V_f \), plasma potential \( V_p \) and surface potential \( V_s \) of spherical stainless steel probe \( r = 1.7 \) mm for different input rf power at pressure, \( p = 30 \) Pa in an unmagnetized plasma. (b) \( V_f, V_p \) and \( V_s \) of the same spherical probe for different argon pressures at power \( P = 12 \) W in an unmagnetized plasma. The errors of the measured values of \( V_f \) and \( V_p \) are within \( \pm 5\% \).

FIG. 3. Floating surface potential \( V_s \) of different sized stainless steel spherical probes \( r = 1, 1.25 \) and 1.7 mm) at rf power \( P = 12 \) W and gas pressure \( p = 30 \) Pa in an unmagnetized plasma \( B = 0 \).

FIG. 4. (a) Surface potential \( V_s \) of stainless steel spherical probe \( r = 1.7 \) mm for different argon pressures at power \( P = 12 \) W in an unmagnetized plasma. (b) \( V_f, V_p \) and \( V_s \) of the same spherical probe for different input rf power at pressure, \( p = 30 \) Pa in an unmagnetized plasma. The errors of the measured values of \( V_f \) and \( V_p \) are within \( \pm 5\% \).

FIG. 5. Comparison of \( V_s \) for the magnetic and non-magnetic spheres at various B-field strength is depicted in Fig. 5. The simultaneous measurements of two probes have been performed once at given discharge conditions and the discharge parameters are kept constant afterwards for experiments with different probe sizes. In Fig. 5(a) the surface potential of the bronze probe has been subtracted from the magnetic ones. It is reconstructed from the \( V_s \) data for different sized stainless steel.
FIG. 4. (a) The surface potential ($V_s$) of the stainless steel spherical probe ($r = 1.25$ mm) for different rf powers at pressure, $p = 30$ Pa in the plasma for various strengths of the magnetic field (B). The dotted line represents the shifting of the maxima of $V_s$ with increasing the input rf power. (b) $V_s$ of the stainless steel spherical probe ($r = 1.25$ mm) for different argon pressures at rf power, $P = 12$ W in the plasma for various strengths of the magnetic field. (c) $V_s$ of the bronze spherical probe ($r = 1.5$ mm) for different argon pressures at rf power, $P = 12$ W in the plasma for various strengths of the magnetic field. The errors in the measured value of $V_s$ are within ±5%.

$r = 1, 1.25$ and $1.7$ mm) and bronze ($r = 1.5$ mm) probes to compare the size dependence in the presence of a magnetic field. It is clear from Fig 5(a) that the smaller size magnetic sphere (e.g., $r = 1$ mm) has a larger value of $V_s$ than non-magnetic sphere (e.g., $r = 1.5$ mm) for $B > 0.02$ T. This difference in $V_s$ increases as the magnetic field is increased. It means that equally sized magnetic and non-magnetic spherical objects or dust grains have different charges in magnetized rf discharge plasmas. Fig. 5(b) shows the effect of the magnetic field on the size dependence of $V_s$ for magnetic spheres. It is seen in Fig. 5(b) that the difference in $V_s$ between the magnetic probes of different sizes decreases with increasing magnetic field and remains almost constant at higher magnetic field. It shows that at larger magnetic fields, $B > 0.05$ T, the size dependence of the stainless steel probes is much weaker than in the unmagnetized case.

IV. DISCUSSION

The surface potential of a spherical body is determined by the electron and ion current to its surface. In a low temperature plasma, where $T_i \ll T_e$, the surface potential is mainly determined by the electron temperature. Since $v_{ihe} \gg v_{ith}$, the surface potential is always negative with respect to the plasma potential. Here, $v_{ihe}$ and $v_{ith}$ are the electron and ion thermal velocities, respectively. In an unmagnetized rf discharge plasma ($B = 0$), the surface potential of a spherical object with ra-
discharge conditions. Therefore, the condition $r > \lambda_{ge}$ can be calculated using the thin sheath theory\textsuperscript{15,16}. In an unmagnetized plasma, the variation of $V_s$ with changing the discharge parameters (see Fig. 2) is a result of the change of the plasma density ($n$) and electron temperature ($T_e$).

With the application of a magnetic field, the gyro-radius of electrons ($r_{ge} = m_e v_{the}/eB$) and of ions ($r_{gi} = m_i v_{thi}/eB$) decreases with increasing strength of the magnetic field, due to the mass differences, $r_{ge} \ll r_{gi}$. Therefore, electrons are magnetized at lower magnetic field than ions. Electrons or ions are called magnetized when $r_{ge/i} < \lambda_{ge/i}$, where $\lambda_{ge/i}$ is the collisional mean free path for the respective species. For our experimental parameter range ($p = 15$ to $50$ Pa and $P = 3.5$ to $12$ W), the plasma density and electron temperature are in the range of $2-9 \times 10^{14} \text{m}^{-3}$ and $2-4 \text{eV}$, respectively. The mean free path for electrons is $\lambda_e \sim 0.5 - 2 \text{ mm}$ and for ions $\lambda_i \approx 0.08 - 0.3 \text{ mm}$\textsuperscript{34}. The electron gyro-radius is $r_{ge} \sim 0.3 - 0.6 \text{ mm}$ for the $B = 0.01 \text{ T}$ at given discharge conditions. Therefore, the condition $r_{ge} < \lambda_e$ meets even below the magnetic field of $0.01 \text{ T}$. With increasing the magnetic field ($B > 0.01 \text{ T}$), $r_{ge}$ continuously decreases and a transition from weakly magnetized to strongly magnetized happens. Ions are assumed to be at room temperature, i.e. $T_i \approx 0.03 \text{ eV}$ corresponding to an ion gyro-radius $r_{gi}$ of $0.5 \text{ mm}$ for $B = 0.2 \text{ T}$, which indicates that ions start to become magnetized at magnetic fields ($B > 0.2 \text{ T}$). It essentially means that in the range of magnetic field ($B < 0.2 \text{ T}$), only electrons are magnetized but ions are assumed to be unmagnetized. Therefore, the ion current to the surface of spherical object in the presence of magnetic field (for $B < 0.2 \text{ T}$) is considered to be unaffected.

In the magnetized plasma, the currents $I_e$ and $I_i$ to the surface of the spherical probe are altered when the condition, $r_{ge/i} < \lambda_{ge/i}$, is satisfied, where $\lambda_{ge/i} = \sqrt{\kappa_0 k_B T_e/e^2 n_e}$ is the electron Debye length. In the present work, $\lambda_{De}$ varies between $0.3$ to $1 \text{ mm}$ for the given range of plasma parameters, i.e. the electron current is changed in the presence of a magnetic field for $B > 0.01 \text{ T}$. Even though the ions also fulfill this criteria for $B > 0.1 \text{ T}$, their dynamics remains unaffected in the sheath region of the object due to the larger mean free path.

There are two $I_e$ components in the magnetized plasma, one ($I_{e//}$) along $B$ and the other ($I_{e\perp}$) across $B$. Since the diffusion of electrons in the direction perpendicular to $B$ is always less than that in the direction of $B$, $I_{e\perp}$ is always larger than $I_{e//}$. In other word, $I_{e\perp}$ is reduced much more than $I_{e//}$ in a magnetic field. For weakly collisional low temperature plasmas, the current $I_{e\perp}$ to the surface of the object is determined by the collisional diffusion of plasma species across $B$. The cross diffusion coefficient is $D_{\perp//} = D_{e\perp}/(1 + \omega_{ce}^2 r_{\perp//}^2)$, where $D_{e\perp} = \lambda_e v_{the}/3$ is the diffusion coefficient in absence of $B$, $\omega_{ce} = eB/m_e$ is the electron cyclotron frequency and $\tau_e = \lambda_e/v_{the}$ is the collision time\textsuperscript{35,36}. In an unmagnetized plasma the energetic electrons diffuse towards the chamber wall (in radial direction) and to the probe surface. As the magnetic field is applied, the energetic electrons start to be confined due to the suppression of the diffusion of electrons across $B$ because $D_{e\perp}$ decreases with increasing $B$ for given discharge conditions (see Fig. 6). Therefore, the density of the energetic electrons should be increased with the application of a magnetic field. To verify the increase in population of energetic electrons in the presence of $B$, the electron energy distribution function (EEDF) is measured using a one dimensional planar probe ($r = \ldots$)
FIG. 6. The diffusion coefficient of electrons across the magnetic field ($D_{e\perp}$) for different argon pressure at various strengths of the magnetic field (B).

2.5 mm) in the direction of B. In such cases, EEDF is derived from the first derivative of the probe current ($I_p$) with respect to the probe bias ($V_b$)

$$F(E) = \frac{m_e^2}{2A_p e^2} \sqrt{V_p - V_b} \frac{dI_p}{dV_b}$$

(4)

where $A_p$ is area of probe and $V_p$ the space or plasma potential. The results of EEDF with magnetic field at $p = 30$ Pa and $P = 6.5$ W are shown in Fig. 7. It is found that the population of cold (or lower energy) electrons, which are reaching the probe, decreases with increasing the magnetic field. Although an opposite behaviour is seen in the case of energetic electrons. The population of energetic electrons increases at lower magnetic field ($B < 0.05$ T) and then starts to decrease towards higher magnetic fields. It means that the energetic electrons easily reach the probe surface at lower B. In other words,
the dynamics of these electrons is unaffected at low B. It is expected that the confined energetic electrons will increase the equilibrium average energy of the bulk electron population due to electron-electron interactions\textsuperscript{34}. Fig. 8 represents the variation of electron temperature ($T_e$) with magnetic field at $p = 30$ Pa and P = 3.5 and 6.5 W. The increase in $T_e$ at lower B also indicates the presence of an energetic electron population at B < 0.05 T. Experimentally, the dominating role of energetic electrons in the charging process of a spherical object or dust grain in the plasma has been confirmed\textsuperscript{39}. It is observed that the effect of the magnetic field (at low B) on the energetic electrons is negligible. Therefore, they have sufficient energy to overcome the repulsive probe potential. It essentially means that the diffusion of gyrating energetic electrons across B (i.e. $I_{e\perp}$) will not be affected significantly at low B. Thus, the net charging current, $I_e$, is observed to be higher than $I_{e0}$. Here, $I_{e0}$ is the equilibrium electron current to the spherical probe in the unmagnetized plasma (at B = 0 T). Thus, the surface potential of the spherical probe becomes more negative due to the higher charging current ($I_e$) to the probe surface at low B\textsuperscript{30}, which is clearly seen in Fig. 4. The higher charges on the dust gains or more negative surface potential in weakly magnetized plasma is also observed numerically by Tomita \textit{et al.}\textsuperscript{41}, in which they claimed a larger absorption cross section for electron capture on the dust surface in the presence of a magnetic field. As the B-field increases, the frequency of gyrating electrons increases which causes a reduction in $T_e$ due to the increase of the electron-neutral collision frequency. The reduction in $T_e$ at higher B is seen in Fig. 8. Also, no further enhancement of the energetic electron population is observed after B > 0.05 T. The low energy electrons, which have insufficient energy to overcome the repulsive potential barrier of the spherical probe, are more affected by the external magnetic field. Therefore, $I_e$ starts to decrease at higher B (B > 0.05 T) to the surface of the spherical probe. Hence, the surface potential, $V_s$, decreases or becomes less negative after the saturation value with increasing strength of B. Even though a slight decrease in the ion current with magnetic field is observed, the role of such small variation does not affect the charging processes of sphere in the magnetic field up to 0.2 T. In other experiments, such a decrease of $I_e$ to the probe surface at given potential with increasing magnetic field has also been reported by Dote \textit{et al.}\textsuperscript{42}. It has been noticed that the rate of variation of $V_s$ depends on the equilibrium plasma density, which increases with the input rf power. Thus, the quantitative and qualitative analysis explains the increase in $V_s$ at low B and decrease in $V_s$ at higher B (Fig.4).

It has been discussed that the charging currents ($I_{e\perp}$) strongly depend on the cross field diffusion, $D_{e\perp}$ in the magnetized plasma. The current $I_{e\perp} = I_{e0}/(\omega_{ce}\tau_e)$ across B decreases with increasing $\omega_{ce}\tau_e$, which is a function of B and gas pressure\textsuperscript{43}. At lower pressure ($p = 15$ Pa), $D_{e0}$ has a higher value than at higher pressure ($p = 50$ Pa). Therefore, the rate of change of $D_{e\perp}$ is higher at low pressure with increasing the strength of B, as shown in Fig. 6. Thus, $V_s$ attains its maximum value at lower B when the gas pressure is set at lower value and shifts to higher B with increasing the gas pressure (see Fig. 4(b)).
After saturation (maximum $V_s$), the current $I_e$ to the probe surface is higher at low pressure (relative to $I_{00}$) than at higher pressure at constant B. Therefore, the rate of change of $I_{e\perp}$ is higher at low pressure ($p = 15$ Pa) resulting in a higher decreasing rate of $V_s$. With increasing the gas pressure, $I_{e\perp}$ decreases at given B, which explains the lower decreasing rate of $V_s$ at higher pressure.

The difference of $V_s$ for magnetic (stainless steel) and non-magnetic (bronze) spherical objects (Fig. 5) is understood on the basis of the field line distribution around the spherical body in the magnetized plasma. Since $I_{e\perp}$ varies stronger than $I_{e\parallel}$ with magnetic field, $I_{e\perp}$ plays the dominant role to determine the surface potential or charges on the spherical object. In the case of a magnetic sphere (stainless steel), the magnetic flux density will be lower in the sheath region of the sphere (or near the sphere surface) than in the plasma region. This lower B-field density is responsible for a higher $I_{e\perp}$ which makes the surface of object more negative (higher $V_s$). In the case of the non-magnetic spherical object (bronze), the magnetic flux density in the sheath region of the object increases. Therefore, the current $I_{e\perp}$ to the probe surface is lower and makes surface less negative. Also, it is expected that there are two null points near the surface (along B) in the case of the non-magnetic sphere, which reduces the effective area along B ($A_{e\parallel}$) for the non-magnetic sphere. This reduction in $A_{e\parallel}$ is responsible for the lower value of $I_{e\parallel}$ to the probe surface at given B. Thus, the magnetic spheres have a higher $V_s$ than the non-magnetic sphere (see Fig. 5) above a certain value of the magnetic field ($B > 0.05$ T). It is also seen in Fig. 6 that the cross diffusion ($D_{e\perp}$) for different initial values ($D_{e0}$) gets nearly saturated at higher magnetic field. It indicates that $I_{e\perp}$ remains nearly the same for different sized spherical objects at higher B, which gives a smaller potential difference for different magnetic spheres (Fig. 5(b)) in the magnetized plasma. Thus, the qualitative description presented here provides a full understanding of the observed surface potential measurements for magnetic and non-magnetic spherical probes in a magnetized rf discharge plasma.

V. CONCLUSION

The surface potential of magnetic (stainless steel) and non-magnetic (bronze) spherical objects in a magnetized rf discharge plasma at various discharge conditions has been measured. A 13.56 MHz rf generator is used to produce the plasma between a transparent indium tin coated (TIO) glass electrode and a metal electrode. To achieve a magnetized plasma, a strong superconducting electromagnet ($B = 0$ to 4 T) with Helmholtz coils configuration is utilized. The aluminium vacuum chamber is placed at the centre of the magnet to provide a uniform magnetic field between the electrodes. The surface potential of different sized magnetic spherical probes ($r = 1$, 1.25 and 1.7 mm) is measured and compared with a non-magnetic spherical probe ($r = 1.5$ mm) in the plasma at various magnetic field strengths (for $B = 0$ to 0.2 T). The main findings of these experimental studies are listed below:

1. The surface potential ($V_s$) of the spherical object ($r > \lambda_{De}$) depends on its size in the unmagnetized as well as magnetized plasma background.

2. The surface potential of a spherical object either magnetic or non-magnetic increases at low magnetic field ($B < 0.05$ T), attains a maximum value and starts to decrease with further increasing the strength of the external magnetic field ($B > 0.05$ T). The rate of change of the surface potential in the magnetized plasma strongly depends on the gas pressure as well as the plasma parameters ($n$ and $T_e$).

3. The surface potential of a spherical object loses its size dependence characteristics in the plasma with the application of an external magnetic field ($B > 0.03$ T).

The increase of the surface potential of an object at lower B is due to the confinement of energetic electrons, which increases the energy or temperature of the bulk electrons. This higher value of $T_e$ enhances the electron current to the probe surface. Although the cross diffusion restricts the electron current to the probe surface, the net amount of the current to the surface increases at lower B and attains a maximum value. With increasing the B-field ($B > 0.05$ T), the population of energetic electrons or $T_e$ decreases which causes a reduction of the electron current to the probe surface because of the cross field diffusion, making the spherical object less negative. Since ions are assumed to be unmagnetized for the given range of the magnetic field, the role of the magnetic field on the ion current is considered to be negligible. Thus, the electron current determines the surface potential, determined by the balance of the electron and ion currents. The value of $V_s$ depends on the magnetic field lines density around a spherical object which affects the current to the surface of object. Therefore, the surface potential is lower (or less negative) for a non-magnetic sphere than for a magnetic sphere in the magnetized plasma.

This work highlights the role of the external magnetic field as well as the types of material of the object on the surface potential in the plasma. These findings will help to understand the dust dynamics or object charging in a magnetized plasma environment. However, in this study, the size of the spherical object has been restricted to $r > \lambda_{De}$ for direct measurements of the surface potential. In future, our focus will be on the direct or indirect measurement of charges on spherical objects or dust grains ($r < \lambda_{De}$) in a magnetized plasma to understand better the dusty plasma dynamics such as screening potential, crystallization and melting of dusty plasma crystals, instabilities associated with charge fluctuations, vortex motion of grains etc. in the presence of an external magnetic field.
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