Fusion Oriented Plasma Research in Bangladesh: Impact of Dust on Plasma

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Abstract. There are two parts of the paper: Part A is concerned with the results of the theoretical investigation on the properties and excitation of low-frequency electrostatic dust modes, e.g., the dust-acoustic (DA) and dust-lower-hybrid (DLH) waves in a streaming magnetized dusty plasmas with a back ground of neutral atoms using both the fluid and kinetic models. In this study, dust charge is considered as a dynamical variable of plasma. Dust charge fluctuation, collisional, streaming and kinetic effects on DA and DLH modes are discussed. Part B is concerned with the experimental results of the investigation on edge plasma behavior in the non-axisymmetric magnetic field region of the anchor cell of GAMMA10. The observations, which indicate the cold plasma formation in the anchor cell, are explained from the view point of enhanced outgassing from the wall due to the interaction of the drifted out ions. Experimental results on the control of the wall-plasma interaction by covering the flux tube of non-axisymmetric magnetic field region by conducting plates are discussed.

I. Introduction

Impact of dust on plasma is a fairly new field of research and is increasingly being studied these days to their applications in wide range of fields. Presence of relatively highly charged and massive dust grains in a plasma can modify or influence the collective phenomena of the plasma. The possible dust modes may explain the extremely low-frequency fluctuations, new channels for the parametric coupling of other waves, generation of wake-fields, etc., in dusty plasma. The impurities coming off from the walls of fusion device can create a dusty plasma at the edge of the discharge. These particles can enhance power loss due to radiation and dilution of fuel as well as can cool down the hot ion by charge-exchange process.

A number of new plasma modes, such as, dust-acoustic (DA), dust-ion acoustic (DIA) waves in unmagnetized dusty plasmas are discovered [1]. Magnetized dusty plasmas obviously support more additional electrostatic low-frequency waves, such as dust-lower-hybrid (DLH) wave [2]. This mode arises because of the hybrid motion of the unmagnetized dust particles and the magnetized lighter plasma particles. Recently, D'Angelo has explained theoretically the excitation of DLH mode in a laboratory and shown that this mode can be excited easily compared to the electrostatic dust-cyclotron (EDC) mode in the presence of zero order-electric field [3]. Properties of low-frequency dust modes, such as DLH mode, may depend on the collision of the plasma particles with the neutrals. In real plasma, time dependent variation of dust charge occurs when the conditions in the plasma near the dust grain are changed due to a variety of reasons, such as the wave motion. Moreover, streaming of plasma particles can occurs due to the presence of ambient electric field. Recently, we have studied the low-frequency dust-modes (viz., DLH, DA) in a collisional, streaming magnetized dusty plasma in zero-order electric field including dust charge fluctuation using fluid model [4]. The kinetic effect on these modes is also studied using Vlasov-kinetic analysis [5]. The summary of our results in a low temperature dusty plasma is given in part A.

The anchor cell of the GAMMA10 tandem mirror is only the region, where asymmetric magnetic field configuration is present. The asymmetric magnetic field component can introduce curvature,∇B, resonant drifts, etc., of the particles. Particles loss due to these drifts may introduce various limitations to the experiment, such as, may limit the density increase of the device. Moreover, the drifted out particles can collide with the wall of the device and can introduce recycling of fuel particles or dusts (impurity). The presence of fuel particles or, dusts in the anchor and plug/barrier cells can prevent the formation of high β plasma and plug potential, respectively. Therefore, it is very important to study the plasma behavior in asymmetric magnetic field region. It was investigated that due to asymmetric magnetic field effect, plasma in the outer transition region is shifted in the ion drift direction and positive drain current in ion drift side is measured [6,7]. The evidence, which indicates the cold plasma formation in the anchor cell is obtained. The results are explained from the view point of enhanced outgassing from the wall due to the interaction of the drifted out positively charged particles. Results of the plasma control experiments with covering some parts of the asymmetric magnetic field regions with large conducting plates are given in part B.

II. PART A: Properties and Excitation of Low-Frequency Dust-Modes

Fluid Theory: We have considered a homogeneous and uniform magnetized dusty plasma consisting of electrons, ions, negatively charged dust grains and neutrals. The external electric (***E***) and magnetic (***B***) fields are in the *z*-direction. The neutral gas is taken to be at rest. We consider the zero-order streaming of the electrons and ions relative to the dust grains. The dust charge is considered as negative, i.e., $Q_d = -Z_d e$, where e is the electron charge. Let us consider a low-frequency electrostatic wave propagating obliquely ($K_x^2 >> K_z^2$) to the external magnetic field with propagation vector (***K***) lying in the *xz*-plane. Due to the presence of this mode (ω, ***K***), the dust will acquire a perturbed charge, Q_{d1}. In this study, it is considered that the dust grain size (a_d) to be much smaller compared to the average Larmor radius (r_j) of the plasma particles, i.e., $r_j > a_d$,where j stands for the plasma species. In this limit the charging equation of dust grain in unmagnetized plasma can be applied to the magnetized plasma. We assume that the dust mode under consideration satisfies the following conditions:

$$\omega_{cd} << \omega << \omega_{ci} << \omega_{ce} \; ; \quad KC_d, K_z C_+ << \omega << K_z C_e ,$$

Where ω_{cj} and C_j indicate the cyclotron frequency and thermal velocity of the species j, respectively. Under these conditions, the highly charged and massive dust grains can be taken to be cold ($C_d = 0$) and unmagnetized ($\omega_{cd} = 0$). Ions are cold ($C_+ = 0$), but strongly magnetized. Electrons form a hot Boltzmann gas at temperature T_e. As $m_d >> m_+$, m_e, collision of dusts with neutrals may be neglected ($\nu_d = 0$).

In the case of high-density plasma, the dispersion relation of DLH wave is obtained:

$$\omega^2 = \omega_{DLH}^2 \left[1 + \frac{K_z^2}{K^2} \frac{\omega_{p+}^2 \omega^2}{\omega_{pd}^2 \Omega_+^2} \right] - i\beta \frac{n_{eo}\omega^2}{Kv_{+o} n_{+o}} - i\nu_+ \frac{\omega^2}{\Omega_+} - i\nu_e \frac{\Omega_e \omega_{c+}^2 \omega^2}{K_z^2 K^2 C_e^2 \lambda_{De}^2 \omega_{p+}^2}, \qquad (1)$$

where DLH frequency, $\omega_{DLH}^2 = \omega_{pd}^2 \omega_{c+}^2 / \omega_{p+}^2 = \omega_{c+}^2 \omega_{cd}^2 (Z_{do} n_{do} / n_{+o})$ and ω_{pj}, ν_j, and λ_{De} are respectively, the plasma frequency, collisional frequency, and electron Debye length of the species j. $\Omega_j = \omega - K_z v_{jo}$, is the Doppler shifted frequency and the β term is due to dust charge fluctuation.

In the case of low-density plasma, dispersion relation of DA mode is obtained:

$$\omega^2 = K^2 \omega_{DA}^2 \left[1 + \frac{K_z^2}{K^2} \frac{\omega_{p+}^2 \omega^2}{\omega_{pd}^2 \Omega_+^2} \right] - i\beta \frac{\omega^2}{Kv_{eo}} - i\nu_+ \frac{\omega_{p+}^2 K^2 \lambda_{De}^2 \omega^2}{\omega_{c+}^2 \Omega_+} - i\nu_e \frac{\Omega_e \omega^2}{K_z^2 C_e^2}, \qquad (2)$$

where DA frequency, $\omega_{DA}^2 = C_e^2 \omega_{pd}^2 / 2\omega_{pe}^2$. The natural DA and DLH modes can be obtained from the above equations when $V_{+o} = \beta = \nu_+ = \nu_e = 0$. The second term of the right hand side (RHS) of Eqs. (1) and (2) presents the dust charge fluctuation of the respective mode, which gives the damping of the mode. From the third and fourth terms of the RHS of these equations, it is seen that if either ion or electron streaming velocity exceeds the wave parallel phase velocity, then the collisions of ions or electrons with neutral gas molecules give destabilizing effect provided the effect of dust charge fluctuation is negligible.

Two-stream Instability: When $\beta = \nu_+ = \nu_e = 0$, then the two-stream instability of the DLH and DA modes will occur provided $V_{+o} > \omega / K_z$. The growth rate of the instability of these modes can be obtained from the following equation:

$$\gamma = \left[\frac{1}{2}(K_z^2 V_{+o}^2 - \omega^2) + \left(\frac{1}{4}(K_z^2 V_{+o}^2 - \omega^2) + K_z^2 V_{+o}^2 \omega_{pd}^2 \Big/ 1 + \frac{1}{K^2\lambda_{De}^2} + \frac{K_x^2 \omega_{p+}^2}{K^2 \omega_{c+}^2}\right)^{1/2}\right]^{1/2}. \quad (3)$$

Thus, the two-stream instability of DA and DLH modes arises only when the ion streaming velocity exceeds the wave parallel phase velocity.

Kinetic Theory: Kinetic instability of the DLH and DA modes in a dusty plasma in the collisionless limit, considering only ion streaming relative to the dust and dust charge fluctuation, is studied using the Vlasov-kinetic equation [5]. The Landau terms of the modes are, respectively:

$$(\beta_L)_{DLH} = \frac{2\sqrt{\pi}\omega_{c+}^2\omega^2}{K_z K_\perp^2 C_e^3}\frac{\omega^2}{\Omega_+{}^2}\frac{m_+}{m_e}\frac{n_{eo}}{n_{+o}}\left[1 + \frac{\Omega_+}{\omega}\left(\sqrt{\frac{T_e}{T_+}}\right)^3\sqrt{\frac{m_+}{m_e}}\frac{n_{+o}}{n_{eo}}\exp\left\{-\left(\frac{\Omega_+}{K_z C_+}\right)^2\right\}\right], \quad (4)$$

$$(\beta_L)_{DA} = \frac{\sqrt{\pi}\omega^2}{K_z C_e}\left[1 + \frac{\Omega_+}{\omega}\left(\sqrt{\frac{T_e}{T_+}}\right)^3\sqrt{\frac{m_+}{m_e}}\frac{n_{+o}}{n_{eo}}\exp\left\{-\left(\frac{\Omega_+}{K_z C_+}\right)^2\right\}\right]. \quad (5)$$

From these equations, it is found that the Landau damping of the DLH and DA modes is due to both electrons and ions. Instability of these modes occurs when $V_{+o} >> \omega / K_z$.

Comparison of Different Effects between the Dust Modes: The ratios of dust charge fluctuation, collisional and Landau damping effects between the DLH and DA modes can be obtained from eqs. (1), (2), (4)and (5) and are given by

$$\frac{\beta'_{DA}}{\beta'_{DLH}} = \frac{n_{+o}}{n_{eo}}\frac{V_{+o}}{V_{eo}}, \quad \frac{(\nu'_+)_{DA}}{(\nu'_+)_{DLH}} = \frac{(\nu'_e)_{DA}}{(\nu'_e)_{DLH}} = \frac{\omega_{p+}^2}{\omega_{c+}^2}K^2\lambda_{De}^2, \text{ and } \frac{(\beta_L)_{DA}}{(\beta_L)_{DLH}} = \frac{1}{2}\left(\frac{\omega_{+c}}{K_\perp C_e}\right)^{-2}\frac{n_{+o}}{n_{eo}}\frac{m_e}{m_+}. \quad (6)$$

For negatively charged dust grains, $n_{+o}/n_{eo} >> 1$. If $V_{+o}/V_{eo} \approx 1$, $K^2\lambda_{De}^2 \approx 1$, and $\omega_{+c}/K_\perp C_e \approx 10^{-2}$ then it is found from Eq. (6) that the dust charge fluctuation, collisional and Landau effects on DA mode are much greater than those of the DLH mode. Hence, the DLH mode is stable compared to the DA mode.

III. PART B: Experimental Study on Edge Plasma

Experimental Arrangement and Results: GAMMA10 is an effectively axi-symmetrized minimum-B anchored tandem mirror [8], which consists of 7 cells: one central cell, two anchor cells, two plug/barrier cells, and two end cells as shown in Fig.1. Magnetic field configuration of each cell is different and has own plasma parameter. Central, plug/barrier and end cells have axi-symmetric magnetic field configuration. In the central cell main plasma is confined and in plug/barrier cells plug and barrier potentials are produced. The open and expanding magnetic lines of forces are ended to the conducting plates in the end cells. Each of the anchor cells is situated between the central and plug/barrier cells and minimum-B magnetic field configuration exists in this cell. High β plasma is produced in the anchor cells to provide the MHD stability of the whole plasma. Each anchor cell is connected to the central and plug/barrier cells through inner and outer transition regions, respectively. Magnetic field configuration around the transition regions of each anchor cell is non-axisymmetric, where the magnetic flux tube is highly elliptic. Flux tubes of these two transition regions of each anchor cell have π/2 symmetry and hence the non-axisymmetric magnetic field effect is thought to be canceled out for the particles which pass through these two regions. Moreover, the two mirror reflection sides of the central minimum-B region have π/2 symmetry. On the other hand, shape of the flux tube at one mirror reflection side of the transition region is almost circular but that of other mirror side is highly elliptic, i.e., reflection points have π/2 asymmetry as shown in Fig.1(b).

Some parts of each elliptic flux tube region of anchor cells are covered by five pairs of conducting plates (AP). The plates are fixed few cm outside the flux tube of radius 0.18 m at the central cell mid-plane [7,8] and are at the high magnetic field regions of the anchor cells. Conducting plates are made of SUS 316 sheet with thickness 2 mm. The plates are electrically independent and can be biased, floated (grounded with high registor of about R_{AP}=1M Ω), and grounded (grounded with low registor of R_{AP}=1~100 Ω). Time dependent evolution of line density and ion temperature of the plasma in the central and anchor cells are measured by microwave interferometer and diamagnetic loop, respectively.

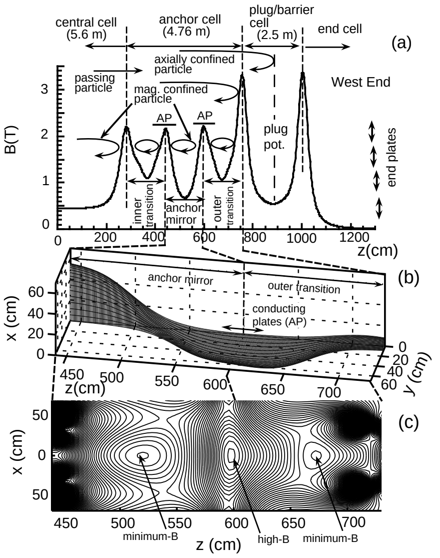

*FIG. 1. (a) Half of the axial distribution of **B** of the GAMMA10. (b) One fourth of the flux tube, and (c) Mod-B contour on xz-plane at the anchor cell.*

The time dependent line density (nl) of the plasma in the central (CC) and east anchor (EA) cells is shown in Fig.2(a), for both grounding and floating conditions of the AP. In Fig.2(b), diamagnetism of the plasma in the central and east anchor cells for both the cases of AP is given. The data for both the cases of AP indicates that in the anchor cell cold and high density plasma is formed compared to the central cell plasma. In the case of floating conducting plates, both the density and diamagnetism of central and anchor cells have a tendency to increase during axial confinement, Fig.2. On the other hand, it is observed that the density in the central cell increases up to a certain limit.

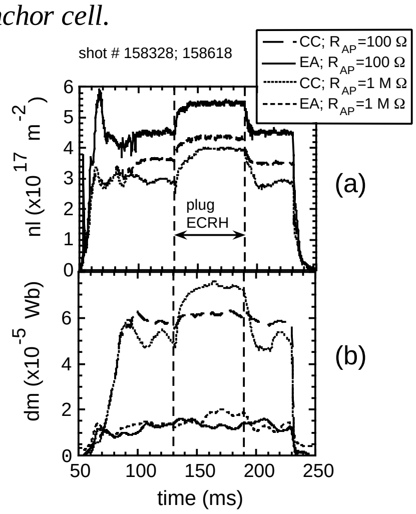

FIG. 2. (a) Line density and (b) Diamagnetism of the central and anchor cells for floated and grounded plates.

IV. Discussion and Conclusion

Theoretical Results: In high-density cold magnetized dusty plasma, the DLH mode arises due to the dynamics of negatively charged unmagnetized dust grains and the magnetized ions. If the electrons are considered as hot Boltzmann gas at temperature T_e in low-density magnetized dusty plasma, then DA mode is obtained, which propagating nearly perpendicular to the external static magnetic field. In the absence of dust charge fluctuation and collisional effects, two-stream instability of these modes occurs when the ion streaming velocity exceeds the parallel phase velocity of the respective mode. Moreover, if either ion or electron streaming velocity exceeds the wave parallel phase velocity, then the collisions of ions or electrons with neutral gas molecules give destabilizing effect on the dust modes provided the dust charge fluctuation is negligible. Dust charge fluctuation gives the damping of either of these modes. The Landau damping of these modes is due to both the electrons and ions. For small but finite K_z the condition for excitation of this modes is $v_{+o} >> \omega/K_z$. For negatively charged dust grains, $n_{+o}/n_{eo} >>1$. If $v_{+o}/v_{eo} \approx 1$, $K^2\lambda_{De}^2 \approx 1$, and $\omega_{+c}/K_\perp C_e \approx 10^{-2}$ then it is found that dust charge fluctuation, collisional and Landau effects on DA mode are much greater than those of the DLH mode. Hence, the DLH mode is stable compared to the DA mode.

Explanation of Experimental Results: Passing and magnetically confined particles are the two different characterized particles in each anchor cell, Fig.1(a). Magnetically confined particles in the transition regions will suffer $\pi/2$ non-axisymmetric resonant diffusion on each reflection. Moreover, from the calculation of magnetic field lines, it is found that the bad curvature is larger than the good curvature of a field line in an anchor cell. Therefore, the passing ions will be displaced from the flux tube by the effect of average non-axisymetric magnetic field component of an anchor cell. Due to the vast difference in Larmor radius of positively charged dusts, ions and electrons, dusts and ions will be strongly affected by the non-axisymmetric magnetic field compared to electrons. It is estimated that under the present experimental conditions, ion will shift ~80 times more than the electron in the minor axis direction by ∇B and curvature drifts in one pass through 1m long ∇B region. The cold plasma formation in the anchor cell can be explained with the wall-plasma interaction i.e., interaction of the drifted out massive positive particles (ions, dusts, etc) with the wall. In high temperature plasma, dust will be charged positively. Larmor radius of the massive dust grains is many times larger than the ions. Thus, the charged dusts in thin flux tube of anchor cell may easily collide with the wall/plates during their Larmor motion.

By the collision of the drifted out ions with grounded conducting plates, neutral particles/dusts will come off from the plates. These particles will be ionized and will trap magnetically in the mirror regions of the anchor cells. Thus the plasma density will increase and by the charge exchange process, its temperature will decrease. The fast neutrals then collide with the plates and disorption will occur again. This process will continue like a chain reaction and dusty plasma may form in this way. Moreover, during axial confinement, passing ions those bounce between the plug potentials will leave the flux tube gradually by the effect of average non-axisymmetric **B**. Due to this increase of radial loss, higher density with lower temperature plasma will be formed during plug-ECRH, Fig.2. On the other hand, floating plates will be acquired certain positive potential relative to the surrounding plasma by the collision of fast drifted out ions. Subsequently, drifted out ions with lower velocity will be reflected electrostatically by the positively charged conducting plates. Hence, the wall-plasma interaction will reduce. In this case, increase of both ion temperature and plasma density is observed during plug-ECRH, Fig.2. Drifting out of heavier particles from the transition regions may good for the MHD stability of GAMMA10. On the other hand, the recycled particles due to this drifting out may prevent the high β plasma formation. Thus, the floating conducting plates may help to improve the MHD stability of the plasma.

In conclusion, it is noticed that the theoretical investigation on DLH and DA dust modes should be useful in understanding the various properties and effects of low-frequency dust-modes in a laboratory dusty magnetoplasmas. The experimental investigation in the GAMMA10 plasma will clarify some limitations, such as, density saturation, related problems on MHD stability, and plug/barrier potential formation.

References

[1]. N.N. Rao, P.K. Shukla, and M.Y. Yu, Planet. Space Sci. **38**, 543 (1990).
[2]. M. Salimullah, Phys. Lett. A **215**, 296 (1996).
[3]. N. D'Angelo, Phys. Lett. A **292**, 195 (2001).
[4]. M. K. Islam, et al., Phys. Plasmas, under communication.
[5]. M. K. Islam, et al., Phys. Plasmas **9**, 2971 (2002).
[6]. M. K. Islam, et al., J. Phy. Soc. Japan. **69**, 2493 (2000).
[7]. Y. Nakashima, et al., J. Plasma and Fusion Res. **75**,1211 (1999).
[8]. K. Yatsu, et al., Nucl. Fusion **41**, 613 (2001).