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Dust grain in streaming ions with temperature variation

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This work presents improved numerical observations to demonstrate influence of the ion-to-electron temperature ratio on the dust grain in streaming non-Maxwellian ions for a range of ion speeds. Increase in electron-to-ion temperature ratio influences the ion-grain dynamics substantially and manifests itself as an enhancement in the wake amplitude. The interplay of streaming ion speed with temperature and their synergistic impact on the wake potential and density of the grain is discussed in detail. Physical properties like peak potential and peak position and its dependence on temperature, collision, and streaming speeds is presented. A comparison of the results obtained using 3D-6V particle-in-cell simulation with that of the linear response approach is delineated systematically. At lower temperature, peak potential and peak position exhibit monotonic increase with collision. However, at higher temperature the behavior becomes non-monotonic and initially exhibits an increase in the peak potential with collision and then a decreasing trend. For moderate streaming speeds at lower temperatures, splitting of ion focus behind grain is observed from the density contours as well as three-dimensional potential plots. Our results are reasonably consistent with that of the earlier results reported using Linear Response formalism, nevertheless, in certain regimes it endows us with richer physics.

Key words: complex plasmas, plasma wakefield, plasma polarization, streaming plasmas.
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1. Introduction

Presence of dust is ubiquitous in universe and so is its importance from the fundamental and practical application aspect. It has been one amongst the widely investigated research area due to its relevance to physical phenomena like Saturn rings [1], lunar wakes [2], Fusion devices [3], dust charging and collective effects [4] as well as wakes in laboratory plasmas, space plasmas [5] etc. Strong coupling is known to influence the low frequency collective modes in dusty plasmas [6, 7] and the nonlinear propagation of these very low-frequency waves has been presented using generalized hydrodynamic model [7]. Collisional instabilities in a dusty plasma with recombination and ion-drift effects of dust acoustic waves has also been noted [8].

Charged lunar dust has been reported to be a major concern [9] for exploration activities due to its strong adhesive property. A wake forms downstream of the Moon when it is present in the Solar window. Moon is known to spend almost a quarter of its orbit time in the magneto-sheath where the temperature is higher than that in the solar window. Influence of temperature on electrostatic nonlinear ion waves has been reported utilizing numerical schemes [10]. The temperature variation affects charging and other associated attributes significantly and makes it pertinent to advance our theoretical understanding of the Physics of dust grain. To understand the impact of temperature on dust grain, herein we model a system with single grain in the presence of streaming ions.

For a system of an isolated dust grain in stationary plasma, the electrons bombard continuously on the grain owing to its comparatively higher mobility eventually making the dust grain negatively charged. Due to the local charge imbalance, the negatively charged dust grain is shielded mostly by ions added with electrons. Now the grain is surrounded by ions symmetrically from all sides by positive charged ions. This way we have the charge of the grain shielded by the ions which in turn is shielded by the electrons.

But many a times it has been observed that the sheath region has an electric field which give ions a flow or directionality. This breaks the symmetrical ion shielding around the grain and introduces asymmetry. In the presence of the ambient electric field in the sheath region, ions flow towards the grain and accumulate behind it eventually giving rise to an ion focusing. This ion focus, in turn, attracts electrons, which attracts ions and so on. This way we have a streamlined negative charge followed by positive and negative charges. Such a juxtaposition manifests itself in the form of potential oscillations and has often been called `wake' behind the grain. This laboratory wake behind grain has a strong analogy with the lunar wake of Moon in solar wind flow. In order to understand the underlying Physics, we mimic such a system numerically and explore the effect of temperature variation coupled with varying ion streaming speeds using particle-in-cell simulation.

The wake behind grain is known to be susceptible to external electric and magnetic fields, grain size versus Debye length a / λ_{De}, collision frequency ratio, v_{in} / λ_{De}, ion streaming speeds or Mach number M as well as electron-ion temperature ratio, T_e / T_i where a is the grain radius, λ_{De} is the electron Debye length, T_e (T_i) is the electron (ion) temperature, and v_{in} denotes the ion-neutral charge exchange collisions frequency and ω_e is the electron plasma oscillation frequency. Among the collisions affecting the wake features, the most dominant is the ion-neutral charge exchange collision [11] and is considered in most of the numerical experiments. However, the aim of the present work is to explore the dependence of wake physics on electron-to-ion temperature, T_e / T_i.

It has been reported in the previous works that the wake behind grain exhibits a monotonic dependence on the T_e / T_i [12], however, the work has mostly been done keeping the distribution of ions to be Maxwellian or shifted-Maxwellian. Note that the presence of electric field and/or collision impart the ions a directionality and the distribution is no longer Maxwellian rather it has long tail along the streaming direction eventually giving rise to a non-Maxwellian distribution [11, 13-15]. Recently, in one of the works, effect of temperature on wake for non-Maxwellian streaming ions is presented in brief [13]. Here, we explore the influence on wake behind grain due to interplay of temperature and streaming speed variation.

The outline of the present work is as follows. In section 2, we first introduce the simulation scheme utilized followed by the description of methodology. In section 3, we present the systematic results regarding the impact of temperature and ion flow variation on the grain in streaming ions. Finally, we present a summary and conclusion in section 4 followed by acknowledgments in section 5.

2. Linear response approach

Our simulations have been performed with the state-of-the-art three-dimensional Cartesian mesh, oblique boundary, particles and thermals in cell COPTIC code [16]. We are exploring the dynamics at ion time scale and have safely assumed the electron to obey the Boltzmann distribution,

$$n_e = n_{e\infty} \exp\left(e\phi / k_B T_e\right), \qquad (1)$$

where Boltzmann constant is taken to be unity. The equation to delineate the ion dynamics in six-dimensional phase space in the presence of the self-consistent electric field $-\nabla\phi$, an optional external force **D** [17] is given by

$$m_i \frac{d\mathbf{v}}{dt} = e\left[-\nabla\phi\right] + \mathbf{D}. \qquad (2)$$

When the ion distribution is non-Maxwellian [11], the external force **D** is non-zero and is responsible for the ion drift while neutrals are stationary. We have performed simulations on a 32 × 32 × 96 cell grid with more than 15 million ions in the domain. To retrieve the dynamics near grain, we have performed few simulations with even higher resolutions and number of particles. Most of the simulation runs were evolved for 1000 time steps. A list of parameters employed during simulation is presented in Table 1. The normalization scheme and further simulation details could be followed from the recent work [11].

Table 1– Detailed list of the simulation parameters

Temperature ratio, T_e / T_i	10 - 100
Mach Number, M	0.1 - 1.0
Collision frequency, v_{in} / ω_e	0.002 -1.5
Electron Debye length, λ_{De}	5
Grid size,	64 × 64 × 128
Number of particles,	60 × 10^6
Total number of time steps,	1000
Grain potential, ϕ_a	0.05-0.2
Time-step, dt	0.1

3. Results

Temperature has been to known affect the grain dynamics and wake oscillations besides role in Landau damping. Here, we investigate the explicit role played by temperature on wake oscillations and its interplay with ion streaming speeds and collision frequency. At higher temperature shielding is reduced and wake effects become prominent. Wake features are best observed at a temperature ratio of 100 and weakens as one lowers the temperature. A contour plot of the wake potential for two different temperature ratios (50 and 100) is shown in Figure 1. Subplots (a)-(b) correspond to $M = 0.5$ and (c)-(d) to $M = 1$. As reported earlier [11], here also, we observe that there are no multiple wake oscillations behind grain rather a single ion focus region. Ion focusing is stronger at as one increases the electron temperature and also at higher ion flows eventually leading to higher first peak potentials. Contrary to some previous research reports [13], at very low temperature ratios i.e. $T_e / T_i = 10$, we didn't observe any ion focusing or positive potential peak downstream grain.

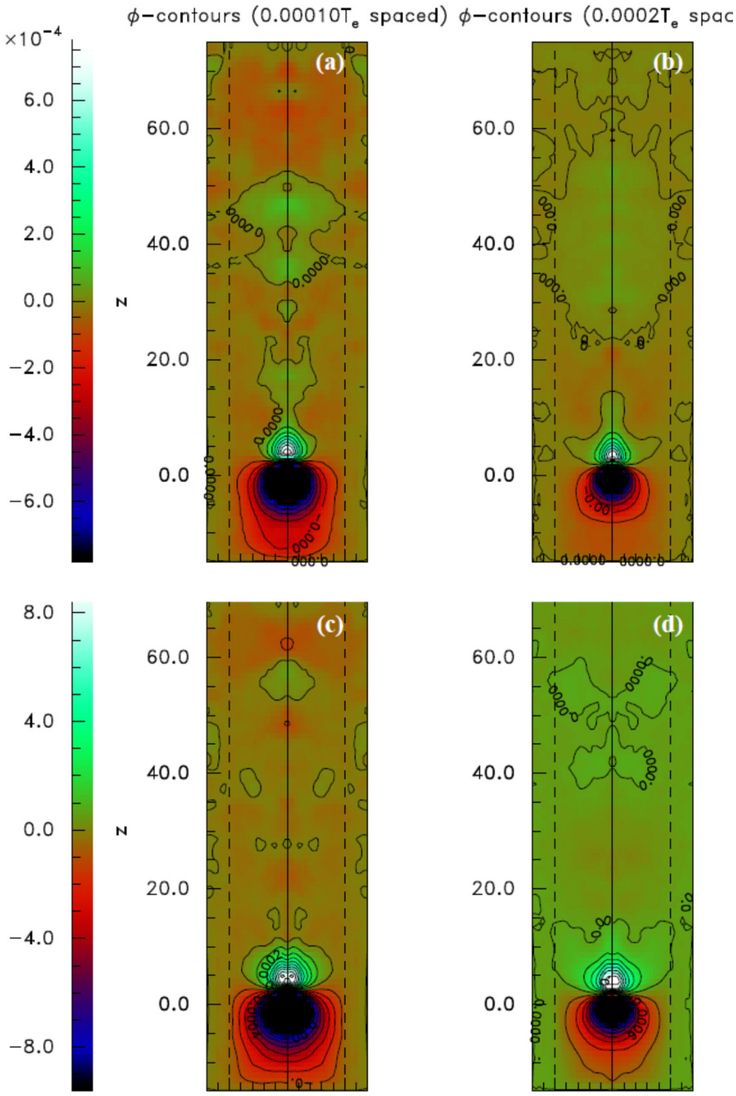

Figure 1 – Wake potential contours $e\phi / k_B T_e$, averaged over the azimuthal angle for (a) $M = 0.5$, $T_e / T_i = 50$, (b) $M = 0.5$, $T_e / T_i = 100$, (c) $M = 0.8$, $T_e / T_i = 50$, and (d) $M = 0.8$, $T_e / T_i = 100$. Here, the grain is at the origin and the normalized grain charge is $Q_d = 0.1$

A. Interplay of ion flow speed and collisionality with electron-ion temperature ratio on wakefield potential

We have seen that increase in temperature ratio increases the wake peak height. Similar effect is exhibited by increase in the ion flow speed. However, presence of collision in the system complicates the dynamics further and the change is no longer monotonic. In Figure 2, the wake first peak position (top) and peak amplitude (bottom) in normalized units as a function of Mach number is illustrated for two different temperature ratios 50 and 100. In agreement with previous research reports [11, 13] for temperature ratio 100, here also, the wake first peak potential has a bell shape curve with ion flow speed and is non-monotonic clearly exhibiting a maxima around *M = 0.5*. Exploring the wake features at lower temperatures leads us to the outcome that at lower temperature the variation in wake peak height with ion streaming speed is very small and is almost constant over the whole range. The wake amplitude decreases substantially with decrease in temperature ratio (i.e. at 50) and becomes negligible as one decreases the temperature ratio further below 10. The wake peak position is nearer to the grain at higher temperature and moves farther as we decrease the temperature. Effect of collisionality on wake peak height coupled with variation in temperature is shown in Figure 3. At higher temperature ratio (i.e. at 100), the wake peak exhibits enhancement with increase in collision frequency which further decreases at very high collisionality. However, at lower temperature ratios (i.e. at 50), the wake peak height versus collision is monotonically increasing with collisionality. Nevertheless, the wake peak amplitude at temperature ratio 50 is substantially smaller compared to that at higher temperature ratio 100. Wake peak position at temperature ratio 50 is almost constant for the whole range of collisionality. On the other hand, for temperature ratio 100, it is constant till $\nu_{in} / \omega_e = 0.6$ and exhibits an increase at higher collisionality. Note that the location of the wake peak is farther from the grain for temperature ratio 50 at lower collisonality and is closer to the grain at higher collisionality when compared with higher temperature ratio 100.

B. Impact of temperature on the ion density distribution

Wake effects are inherently related to the density and has profound effect on the density distribution. For the two different temperature ratios, the spatial profiles of the density is shown in Figure 4. The single ion focus behind grain can be traced from the density profiles. One peculiar observation we have here is for *M = 0.8* with $T_e / T_i = 50$. In this case, the ion focus is not streamlined behind the grain but is splitted in two ion bunched behind grain. In 3D potential plots also, we were able to observed splitting of the positive peak potential behind grain.

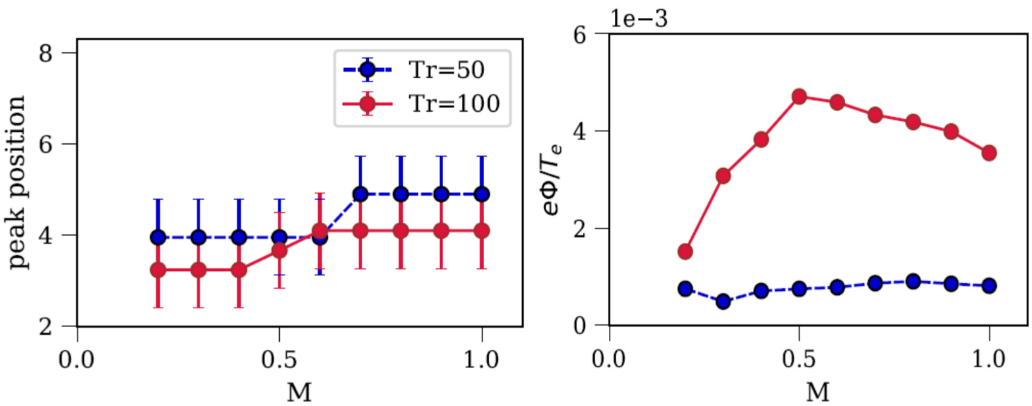

Figure 2 – Peak position (top) and peak amplitude (bottom) of the wake potential in normalized units as a function of Mach number, M, for $T_e / T_i = 100$ (solid) and $T_e / T_i = 50$ (dashed) drift-driven distribution, for the collision frequency $v = 0.1$ and $Q_d = 0.1$

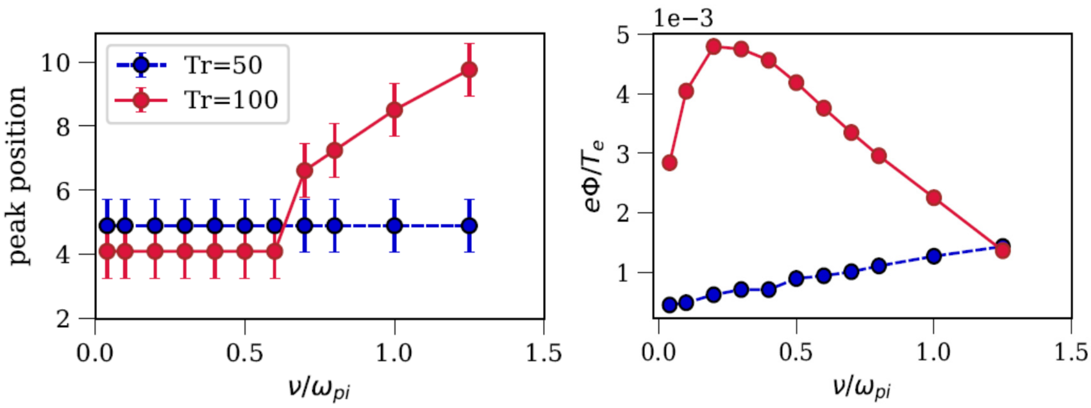

Figure 3 – Peak position (top) and peak amplitude (bottom) of the wake potential in normalized units as a function of collision frequency ν_{in} / ω_e, for T_e / T_i = 100 (solid) and T_e / T_i = 50 (dashed) drift-driven distribution, M = 0.8 and Q_d = 0.1

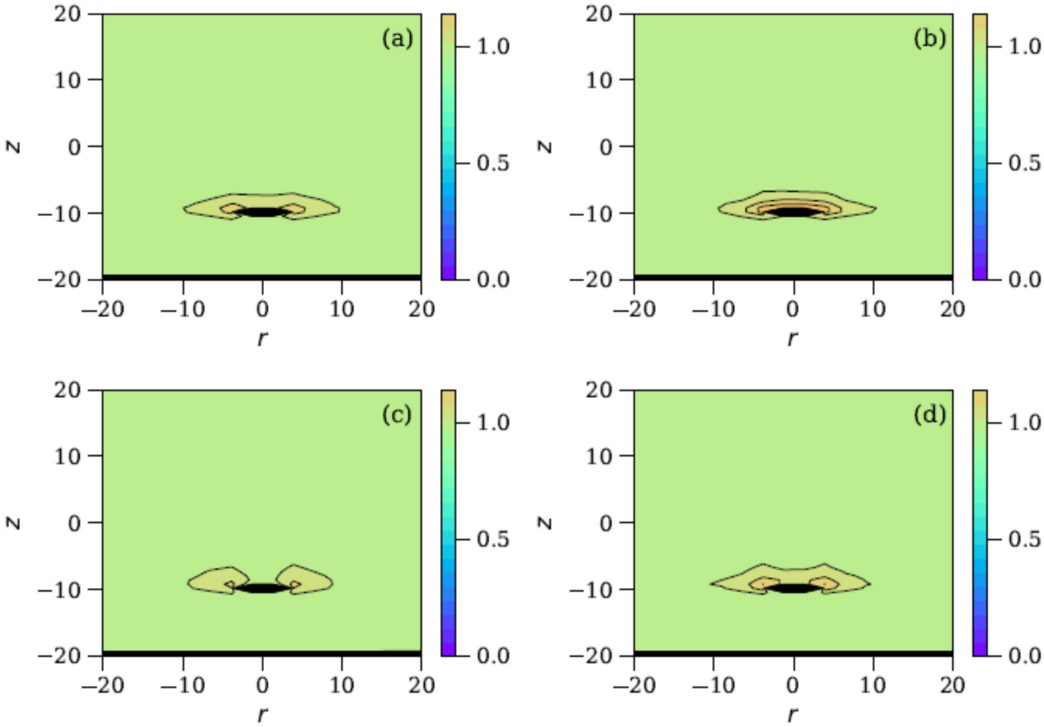

Figure 4 – Spatial profiles of the ion density (normalized to the distant unperturbed ion density), averaged over the azimuthal angle, for (a) *M = 0.5*, T_e / T_i = 50, (b) *M = 0.5*, T_e / T_i = 100, (c) *M = 0.8*, T_e / T_i = 50, and (d) *M = 0.8*, T_e / T_i = 100

4. Conclusions

The present numerical work demonstrates the influence of temperature variation on the wake feature and facilitates understanding of wake formation for grain in non-maxwellian streaming ions. We have explored the role played by electron-ion-temperature ratio on the wake formed behind grain due to ion focusing. The wake peak is observed to exhibit monotonic increase with increase in electron-to-ion temperature ratio. The variation in wake peak gets further complicated by the inclusion of varying ion flow speeds and collisionality. The density distribution presented validates the potential profile observations and puts the result on firm footing. Thorough understanding of parametric dependence of wake peak has wider implications which includes space physics, lunar wakes, laboratory experiments. Physical insights gleaned from the temperature variation effect has the potential provide an improved physical basis for thermo-phoretic force close to walls in dusty plasma experiments [19-25] eventually leading to better perspective for levitation experiments. One of the NASA research report suggests the presence of unwanted dust in space suit as well as in the lunar atmosphere [2] which could have toxic effects and calls for further research. The dust in space mission has adhesive properties which is susceptible to thermal effects. In that direction, the present work can prove to be fruitful in further exploration.

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