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Lane Dynamics in 3D Pair-Ion Plasmas: Influence of external forces

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Lane formation [1-4] serves as a prominent example of the development of non-equilibrium structures. When subjected to conditions that exceed an equilibrium state, many physical systems exhibit spontaneous pattern formation that is considerably more intricate than the typical phase transitions observed in equilibrium systems. The specific dynamics of these non-equilibrium systems, which lead to the emergence of diverse patterns, can be complex and challenging to comprehend and predict.

We investigate the dynamics of lane formation in 3D strongly correlated pair-ion plasmas (PIP) [5] under the influence of external electric and magnetic forces using extensive 3D Langevin Dynamics (LD) simulation. In our model, positively charged particles (say, type A) are pulled by external force component ($\overrightarrow{F_A}$) while the negatively charged particles (say, type B) are pulled by external force component ($\overrightarrow{F_B}$) [4]. Interestingly, when ($\overrightarrow{F_A}$)) and ($\overrightarrow{F_B}$) are parallel, the system undergoes a phase transition to Lane state parallel to applied external forces beyond a critical external field strength (*see*, **Fig. 1**). Lanes of like species of particles are formed which move collectively along the field direction; while lanes of positive and negative particles move opposite to each other. Appropriate diagnostic technique like instantaneous order parameter [1] is implemented to detect lane formation (*see,* **Fig.2**). Further, in presence of time varying fields, spontaneous formation and breaking of lanes is not observed for all values of field strengths, as previously reported in 2D cases [1, 2, 3]. However, in 3D case, such effect is observed for applied field strengths close to critical field strength value. A critical frequency ω_c of the applied field also exists above which the lane state breaks and the system transits to a disordered state. Furthermore, the study in presence of external magnetic field reveals the existence of a drift of lanes in a direction perpendicular to both electric and magnetic fields. However, the presence of magnetic field delays lane formation process. In this work, several of the above said results will be discussed in detail.

The findings presented here could have considerable implications for technology, including the assessment of the consistency of plasma surface treatments [6], the separation of particles in micro-fluidic devices [7], and various other applications.

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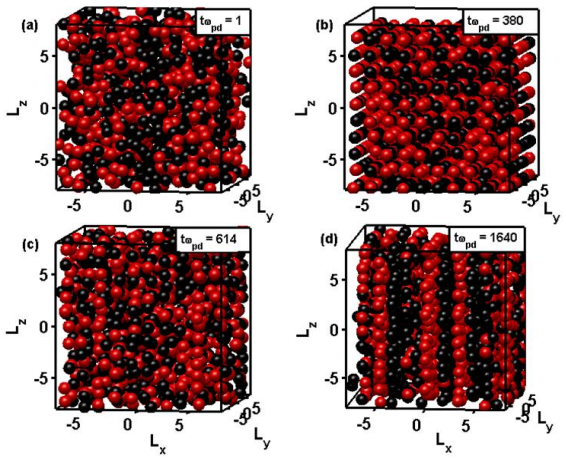

Fig.1: Typical simulation snapshots of the 3-D PIP system recorded at different time steps.

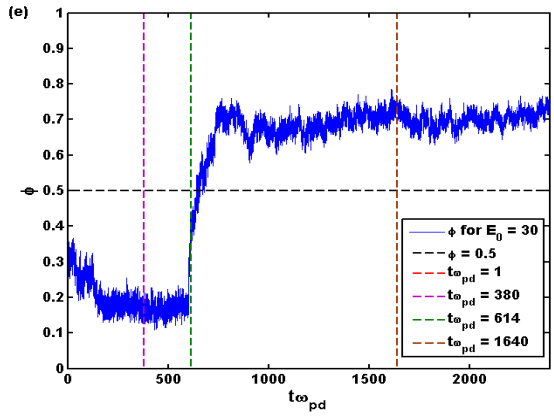

Fig.2: Time variation of order parameter plot. The corresponding times, denoted by different coloured dashed lines, when the instantaneous positions of particles are recorded is represented in **Fig.1.**

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