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Kinetic modelling of Rayleigh-Taylor instability and turbulent mixing in strongly coupled dusty plasmas

Sanat Kumar Tiwari[1], Rauoof Wani[1], Vimal Kumar[2], Mahendra Verma[2]
[1]Department of Physics Indian Institute of Technology Jammu, Jammu, India, 180019
[2]Department of Physics Indian Institute of Technology, Kanpur, India, 208016
e-mail: sanat.tiwari@iitjammu.ac.in

Rayleigh-Taylor fluid instability (RTI) is one of the usual causes of turbulent mixing in natural flows or manufactured applications involving flows. Its evolution properties are reasonably understood for hydrodynamic fluid. Though, it is an exciting domain to study the instability and driven mixing mechanism of other fluid-like systems deviating from the hydrodynamics [1]. Here we explore the RTI evolution in strongly coupled plasma; an ensemble of charges behaving collectively and their average potential energy dominating their thermal energy. Such plasmas show traits of different phases and intermediate regimes, making them close to visco-elastic fluids. Such a problem is worth exploring in the inertial confinement fusion-like scenario, where powerful lasers compress the material close to strong correlation limits before ignition. We have conducted a theoretical study using classical molecular dynamics simulation, keeping dusty plasma as a testbed [2].

We observed the evolution of instability in three broad regimes: linear growth of modes, bubble and spike formation, and nonlinear saturation of modes leading toward turbulent mixing, as shown in Fig. 1 [L]. The critical aspect of the work is how the instability is affected by the strong correlations in the medium. We found a reduction in the instability growth rate with increasing correlations, reflecting increasing solid-like properties.

The instability eventually saturates through the nonlinear mixing process leading to turbulence. Our preliminary studies suggest thermal turbulence features once the instability has grown significantly [3]. We examined the thermalization process by analyzing the energy spectrum of the system. We observe the cascading of energy occurs among the lower modes following Kolmogorov's $k^{-5/3}$ energy inertial range scale, and the higher modes find the new thermal equilibrium at a given temperature, where $E(k) \propto k^{1}$. There is a critical wave vector k_c, at which a non-equilibrium transition to the equilibrium state of modes occurs, as shown in Fig. 1 [R]. In our simulations, the gravity which drives RTI acts as a source of energy, and there is some net intrinsic viscosity in the system, which is captured inherently by MD simulations.

References
[1] Physics of Plasmas, 19, 073707, 2012.
[2] Scientific reports, 12:11557, 2022.
[3] Turbulent characteristics of strongly coupled plasma. [Under preparation]

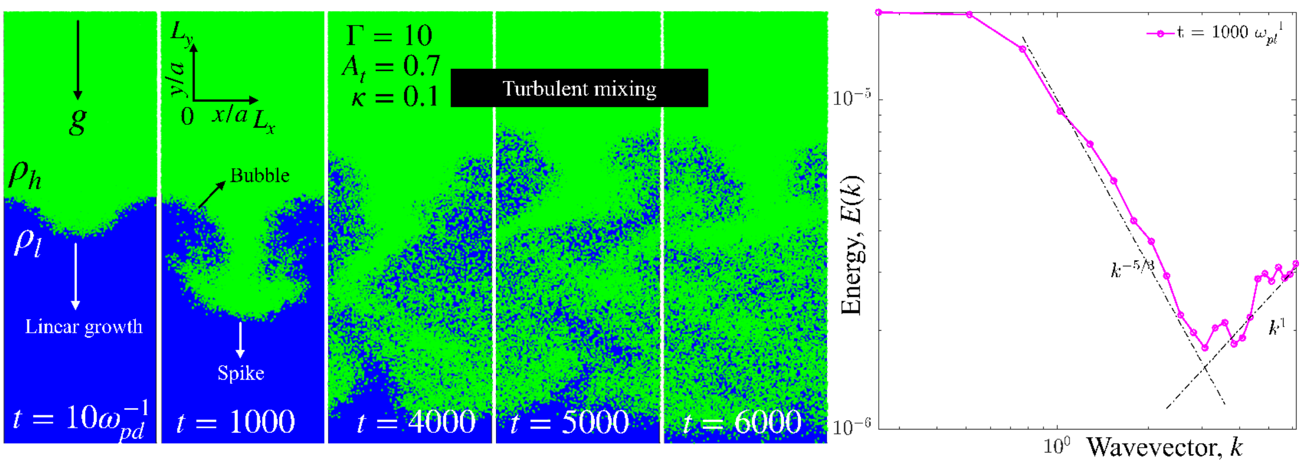

Figure 1: [L] Rayleigh-Taylor instability growth and (R) the power spectrum following +1 and -5/3 scaling law in a two-dimensional strongly coupled plasma system.