Nonlinear dynamics of complex electron plasmas

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Complex (dusty) plasmas studied in the laboratory are usually quasi-neutral, consisting in electrons and positive ions in addition to micrometric dust grains and residual neutral gas at fairly high pressures.The behaviour of non-neutral complex plasmas, where a distribution of particles with a single sign of charge is contaminated by a small population of electrically charged dust particles, has not been investigated so far. Non-neutral plasmas can be easily confined in Penning-Malmberg electro-magnetostatic traps under ultra-high vacuum conditions [1]. To investigate the dynamics of non-neutral complex plasmas, the DuEl (Dust-Electron) device, a modified Penning-Malmberg trap for the confinement of dust-contaminated electron plasmas, is currently under development at the University of Milano [2]. To support this experimental project, a two-dimensional particle-in-cell (PIC) code has been developed to simulate the transverse dynamics of such plasmas. A mass-less fluid (drift-Poisson) approximation is exploited for the electron population, while a kinetic description, including gravity, is adopted for the dynamics of the dust component. More details about the numerical code can be found in Ref. [3].

In this contribution, some preliminary simulation results are presented. We focus our attention on the occurrence of turbulence and intermittency phenomena, investigated by means of statistical methods based on the scaling analysis of probability densities and structure functions of the charge density. The simulations are performed using a 170×170 grid, $5 \cdot 10^4$ macroparticles for the electron population and $3 \cdot 10^4$ macroparticles for the dust component. The electron and dust densities are $n_e = 10^7$ cm^{-3} and $n_d = 3 \cdot 10^4$ cm^{-3} respectively, while the magnetic field is $B = 1$ T. Dust grains with a diameter of 100 nm and a surface charge number $Z = -100$ are assumed. We consider here a simulation with a triple ring initial condition. The evolution of the charge density ρ is shown in Figure 1.

One of the main tools for the study of turbulent flows is the analysis of the statistics of field increments calculated across different scale separations. This provides information about

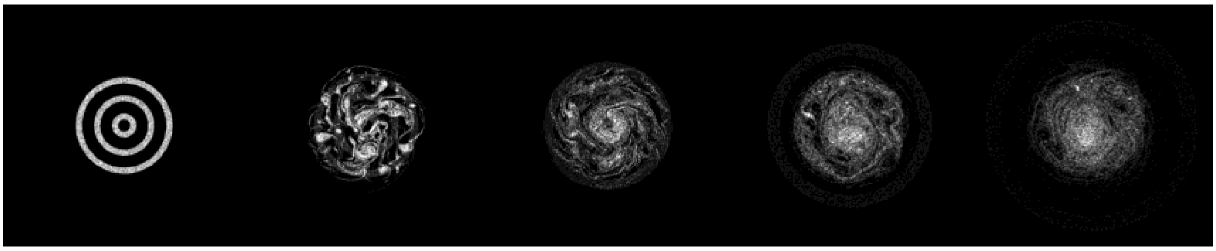

Figure 1: Evolution of the charge density, starting from an initial triple ring profile, at times 0, 16 τ_r, 32 τ_r, 48 τ_r, 64 τ_r, with $\tau_r = \pi\varepsilon_0 B/n_e e$.

intermittency phenomena and presence of coherent structures, such as vortices and filaments, and their typical spatial scales [4]. For a turbulent field $u(\boldsymbol{r},t)$ the increments across a scale separation $\boldsymbol{l}$ are defined as $\Delta u_{\boldsymbol{l}}(\boldsymbol{r},t) = u(\boldsymbol{r}+\boldsymbol{l},t) - u(\boldsymbol{r},t)$. In this work, the focus is on the properties of the charge density $\rho(x,y,t)$ in the above mentioned numerical simulations of a dust contaminated electron plasma. The spatial increments $\Delta\rho_l^{(x)}(x,y,t)$ and $\Delta\rho_l^{(y)}(x,y,t)$ in both the x and y directions are considered, namely

$$\begin{aligned}\Delta\rho_l^{(x)}(x,y,t) &= \rho(x+l,y,t) - \rho(x,y,t)\,, \\ \Delta\rho_l^{(y)}(x,y,t) &= \rho(x,y+l,t) - \rho(x,y,t)\,.\end{aligned}$$

The scaling properties of the statistics of field increments are investigated here by computing the Probability Density Functions (PDFs) and the flatness. The increments' PDFs calculated for different l values provide a first picture about the scaling behaviour of increments' statistics and the presence of intermittency. In order to compare the shapes of the PDFs at different scales, standardised increments $\Delta\rho_{l,\mathrm{st}}$, defined as

$$\Delta\rho_{l,\mathrm{st}} = \frac{\Delta\rho_l - \langle\Delta\rho_l\rangle}{\sigma_{\Delta\rho_l}}\,, \tag{1}$$

are used, where $\langle\Delta\rho_l\rangle$ and $\sigma_{\Delta\rho_l}$ are the mean value and the standard deviation of $\Delta\rho_l$ respectively.

More quantitative information about the scaling properties of field increments is given by the so-called structure functions $S_p(l)$, defined as the moments of field increments, that is, $S_p(l) = \langle\Delta\rho_l^p\rangle$, where $\langle\cdot\rangle$ denotes spatial averages. Intermittency may be quantified by the flatness $F(l)$, which is defined as the ratio of the fourth-order moment to the square of the second-order moment,

$$F(l) = \frac{S_4(l)}{[S_2(l)]^2}\,. \tag{2}$$

The flatness is 3 by definition for Gaussian PDFs, while in the presence of intermittency $F(l)$ increases as l decreases [4].

The PDFs of the charge density increments are shown in Figure 2 for three values of the separation l and at two time instants of the plasma evolution. As the time increases, the PDFs tend to

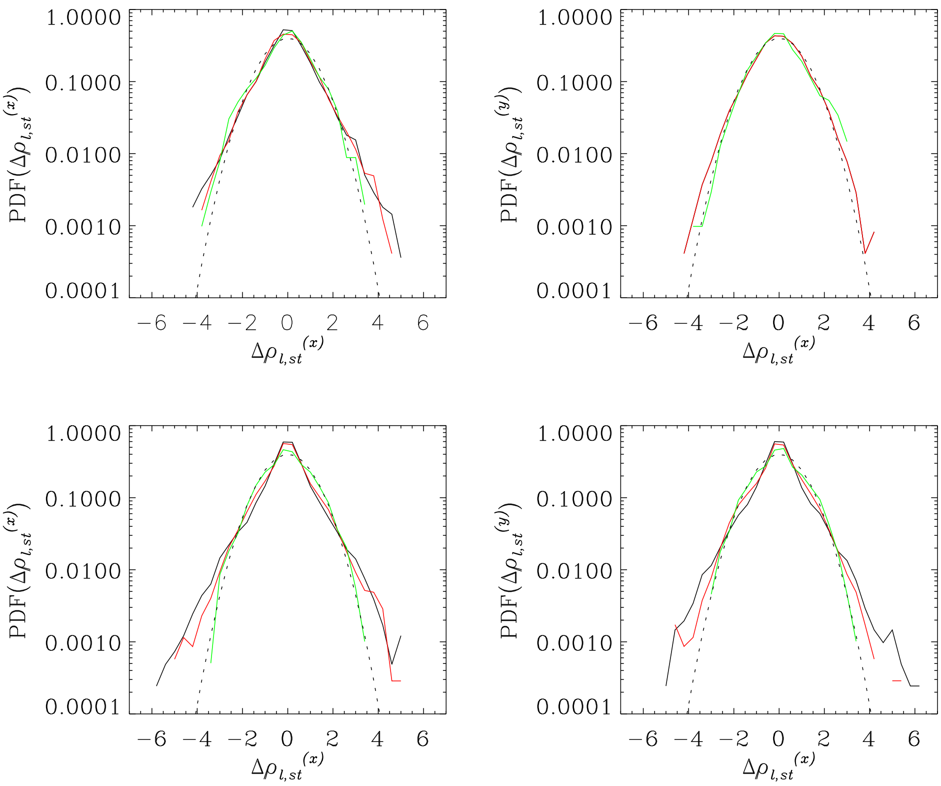

Figure 2: PDFs of the standardised density increments $\Delta\rho_{st}$ along the x (left column) and y (right column) directions for $t = 32\tau_r$ (top row) and $t = 67\tau_r$ (bottom row), and for different spatial separations l: $l = 0.006\ R_W$ (black solid curve), $l = 0.06\ R_W$ (red curve), $l = 0.29\ R_W$ (green curve), with R_W the trap radius. The Gaussian PDF with zero mean and $\sigma = 1$ is also shown for comparison (black dashed curve).

deviate more and more from the Gaussian shape at small separations, due to the appearance of tails. This deviation indicates the occurrence of intermittency in the turbulent plasma dynamics.

The occurrence of intermittency is confirmed by the flatness of the density increments along the x and y directions, which is shown in Figure 3 for different times. As the plasma evolves, $F(l)$ starts to grow going from large to small scales and this growth is observed to become stronger and stronger with time.

The occurrence of intermittency, found here in complex electron plasma simulations, was recently reported in pure electron plasma turbulence on the basis of the analysis of experiments carried out in a Penning-Malmberg trap [5]. We plan to perform numerical simulations with different initial conditions for the electrons and the dust to study the influence of the dust on the

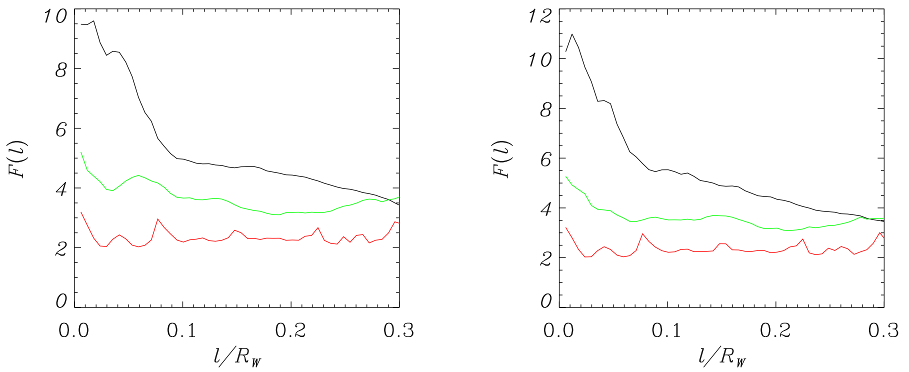

Figure 3: Flatness of the charge density increments along the x (left panel) and y (right panel) directions for different times: 0 (red curve), 32 τ_r (green curve), 67 τ_r (black curve).

formation and evolution of coherent structures and the presence of turbulence and intermittency phenomena developing in complex electron plasmas.

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