

## Particle-In-Cell investigation of magnetized non-neutral dusty plasmas

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A hot topic in the field of dusty (complex) plasma physics is the magnetization of plasma components, possibly including the dust grains [1]. Due to the extremely low charge-to-mass ( $Z/m$ ) ratio, this condition requires high magnetic fields, which is the reason why only few experiments on magnetized dusty plasmas have been performed or are under development up to now. A magnetic field may have a number of direct and indirect effects: magnetization will affect the dust charging process and hence the electrostatic interaction between grains, their diffusion and confinement time. These phenomena, in turn, will affect the dynamics of the overall plasma. A hitherto unexplored feature of complex plasmas is non-neutrality. Non-neutral plasmas and in particular plasmas made up of particles with a single sign of charge are routinely confined in Penning-Malmberg (electro-magnetostatic) traps [2] for a number of applications (ranging from atomic spectroscopy and mass spectrometry to antimatter confinement). In such devices, under usual experimental conditions one can average the particle motion over the cyclotron and axial fast motions, and the transverse evolution of the trapped sample is dominated by the onset and growth of Kelvin-Helmholtz (fluid) instabilities. The plasma transverse dynamics is hence formally isomorphic to that of a two-dimensional (2D) inviscid fluid, with the density of the plasma proportional to the fluid vorticity and the electrostatic potential to the stream function. The DuEl (Dust-Electron) device, a modified Penning-Malmberg trap under development at the University of Milano, aims at investigating a non-neutral plasma consisting of electrons with a fraction of dust grains, with particular attention to the diffusion of dust in the electron plasma and its influence on the Kelvin-Helmholtz instabilities therein [3].

As a support and extension of the experimental activity we have been developing an electrostatic two-dimensional numerical code where the transverse dynamics of such a plasma can be simulated. Three particle species can be used simultaneously, namely electrons, dust grains and also positive ions (in order to eventually take into account partially neutralized plasmas). The basis of the code is the standard particle-in-cell (PIC) technique. In our PIC code, the domain is discretized on an  $(x,y)$  Cartesian grid, with a Dirichlet condition on a circular boundary (i.e. a set potential applied on the confining electrode, which may be sectorized in azimuthal patches).

At each time step, the charge density of the particle distribution is assigned to the grid via bilinear interpolation of each charge to the four adjacent nodes and the Poisson equation is solved by means of a successive over-relaxation iterative algorithm. The particle position is advanced by a time step under the effect of the axial magnetic field  $B$  and of the transverse electric field interpolated to the particle position using the same bilinear scheme. Concerning particle advancement algorithms, the use of the  $\vec{E} \times \vec{B}$  drift approximation for electrons is computationally convenient and also desired for the physics of interest (fluid analogy). A full kinetic treatment (including gravity) is mandatory for ions and dust grains as the cyclotron radius is not negligible and it is accomplished implementing a B-field modified Velocity Verlet algorithm [4]. The extremely low ( $Z/m$ ) ratio of dust grains makes nevertheless their cyclotron motion extremely slow (with frequencies in the order of 1 – 10 Hz).

We discuss here some simulation results, focusing on the effects of dust contamination on the evolution of the electron plasma, the insurgence of the Kelvin-Helmholtz (diocotron) instability and the formation of coherent electron structures. All simulations are performed using a  $140 \times 140$  grid, 50000 macroparticles representing the electron distribution and 30000 macroparticles for the dust component. Figure 1 shows the evolution of a distribution of electrons with an initial annular density profile. The inner and outer radii are  $0.3 R_W$  and  $0.375 R_W$ , respectively, with  $R_W$  the trap radius. The density is  $n_e = 10^7 \text{ cm}^{-3}$  and the magnetic field is  $B = 1 \text{ T}$ . We assume a population of polymeric dust grains with a diameter of 100 nm and a surface charge  $Z = -100$ . The left column of Fig. 1 shows the evolution of a pure electron ring over a time corresponding to 60 plasma rotation periods. As expected from the theory [5], from these initial conditions five long-lived vortices are produced together with a highly filamented background. As seen in the middle column, where a dust density of  $n_d = 3 \cdot 10^4 \text{ cm}^{-3}$  is added to the electron plasma, the dynamics is severely altered by the high charge of the dust component and the instability is partially damped, with the most unstable mode being the  $l = 3$  diocotron mode. At the same time the dust cloud starts expanding because of the strong electric repulsion, but with a low mobility due to its large mass. Both effects increase with increasing dust density, as shown in the right column, where  $n_d = 10^5 \text{ cm}^{-3}$ . Two to three electron vortices are initially formed, followed by successive mergers to a single clump while dust expands radially.

Figure 2 shows the modification of the electron dynamics in terms of integral quantities, namely the electrostatic energy  $E = -\frac{1}{2} \iint n_e(x,y) \phi(x,y) dx dy$  (with  $\phi$  the electrostatic potential) and the second moment of density  $Z_2$ , formally equivalent to the fluid enstrophy  $\Omega$ ,  $Z_2 = \Omega = \frac{1}{2} \iint n_e^2(x,y) dx dy$ , integrated over the trap cross section, i.e. summed over the discrete grid values. While enstrophy is a weak integral and always decreases with the formation

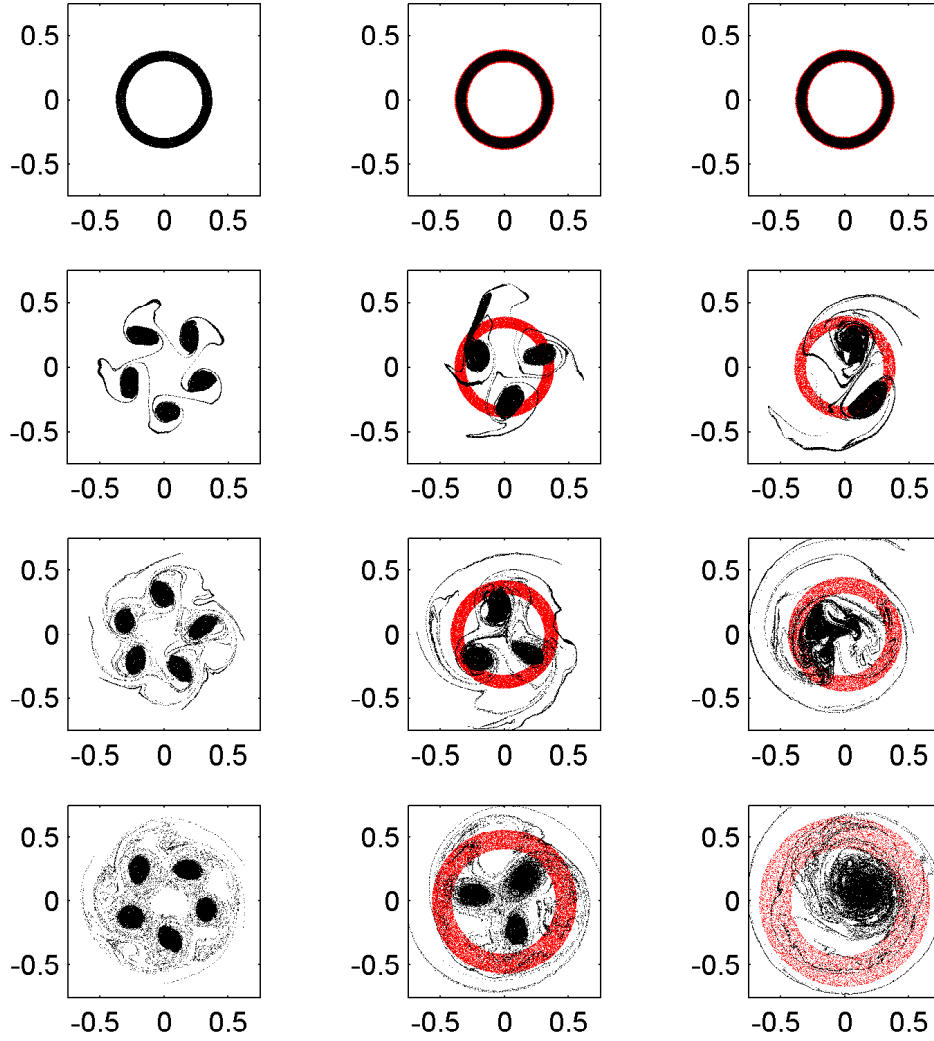


Figure 1: Evolution of an electron plasma with initial ring-like profile and increasing degree of dust contamination. Left column: pure electron plasma of density  $n_e = 10^7 \text{ cm}^{-3}$ . Middle column: charged dust of density  $n_d = 3 \cdot 10^4 \text{ cm}^{-3}$  is added. Right column: charged dust of density  $n_d = 10^5 \text{ cm}^{-3}$  is added. The time for each row is respectively  $0$ ,  $14 \cdot \tau_r$ ,  $28 \cdot \tau_r$  and  $59 \cdot \tau_r$ , with  $\tau_r = \pi \epsilon_0 B / n_e e$ . Black dots are electrons, red dots are dust grains. Spatial coordinates normalized to the trap radius.

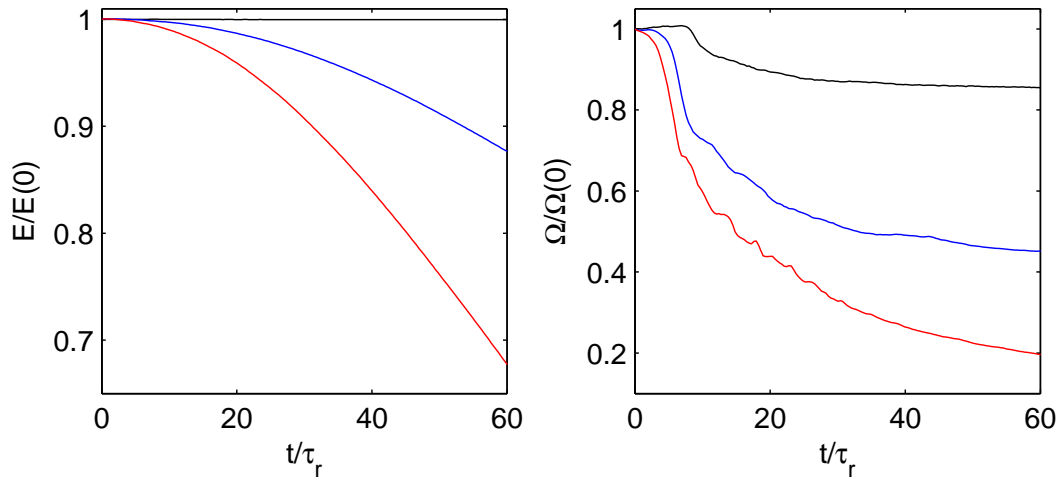


Figure 2: Time evolution of the electrostatic energy  $E$  (left) and enstrophy  $\Omega$  (right) of the electron component for the three cases of Fig. 1. Black lines correspond to the pure electron ring, blue lines to electrons with a dust density of  $3 \cdot 10^4 \text{ cm}^{-3}$  and red lines to electrons with a dust density of  $10^5 \text{ cm}^{-3}$ . All values are normalized to the initial ones.

of structures at small scales (e.g. filamentation) and the total electrostatic energy of the system is conserved, the energy associated with the electron plasma is also not conserved when dust is added and steadily drops as electrons collapse to a centered clump and dust expands. A preliminary analysis of the dynamical and statistical properties for some of the simulation results is discussed in [6].

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## References

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