Instabilities and turbulence in magnetized plasmas with a single sign of charge

M. Romé[1,2], S. Chen[3,2], G. Maero[1,2]

[1]*Dipartimento di Fisica, Università degli Studi di Milano, Via Celoria 16, 20133 Milano, Italy*
[2]*INFN Sezione di Milano, Via Celoria 16, 20133 Milano, Italy*
[3]*Institute of Fluid Physics, China Academy of Engineering Physics, Mianyang, Sichuan 621900, China*

The dynamics of a pure electron plasma has been investigated both experimentally with the Penning-Malmberg trap ELTRAP and numerically with two-dimensional (2D) particle-in-cell (PIC) simulations. A wavelet multi-resolution analysis of the experimental and numerical data highlights in particular how initial conditions and density fluctuations may influence the late evolution of the system, leading eventually to the persistence of coherent structures and to the formation of vortex crystal-like states. The experimental and numerical investigations are being extended to the study of a novel system represented by a magnetized non-neutral complex plasma, and more specifically a plasma of electrons contaminated with a fraction of charged dust particles of micrometric size. The influence of the dust on stability, fluid turbulence and equilibrium properties of the electron component has been investigated with a 2D PIC code able to treat several particle species with both fluid and kinetic descriptions. The construction of a suitably modified Penning-Malmberg trap has been recently completed in order to carry out systematic experiments on such non-ideal plasma system.

1. Electron plasmas as ideal fluid system

Magnetically confined electron plasmas evolve as essentially inviscid, incompressible two-dimensional (2D) fluids with a single sign of vorticity, allowing a quantitative study of shear flow instabilities, vortex formation and dynamics, turbulence and self-organization [1]. The dynamics of a pure electron plasma has been investigated at the Department of Physics of the University of Milano both experimentally with the Penning-Malmberg trap ELTRAP [2] and numerically with two-dimensional (2D) particle-in-cell (PIC) simulations [3]. Both experimental and numerical results show in general the development of the diocotron (Kelvin-Helmholtz) instability, vortex merging events, the emission of vorticity filaments and the development of a turbulent background.

The analysis of the experimental and numerical data is based on the use of advanced techniques like wavelets and Proper Orthogonal Decomposition and on the determination of the statistical scaling properties of the electron density fluctuations [4, 5]. In particular, these studies highlight the role played by the initial conditions and by the density fluctuations on the early dynamics of the flow, leading eventually to an evolution dominated by the formation and persistence of coherent structures [6]. In the numerical simulations fluctuations are unavoidably introduced by the random number generator used to define the initial particle distribution and may lead to quite different plasma evolutions. An example is shown in Fig. 1. Using the same simulation parameters and an initial annular distribution of the electrons with given inner and outer radii, the system evolves to a single central vortex in two runs, and to a final state with four vortices in two other runs. Similar situations are found in the experiments. For instance, the formation of the so-called vortex crystals [7], i.e. regular vortex patterns lasting for hundreds of bulk plasma rotation times, turns out to be strongly dependent on the injection conditions [8]. Even when the source characteristics are favourable for their formation, in a sequence of inject-hold-dump cycles using the same plasma trapping time and the same macroscopic injection parameters, the number of surviving strong vortices is not constant [1]. The fluctuations in this case may be due to small changes of the electron source conditions (e.g. its temperature), or small variations of the residual gas pressure.

The irreproducibility of the final state may be linked to the presence of multiple unstable diocotron modes, characterized by similar growth rates [6]. By means of a Fourier analysis of the early dynamical evolution of the flow in the numerical simulations, it is found that in this case the survival of a given number of vortices depends on the initial energy content of the different modes determined by the fluctuations of the particle distribution.

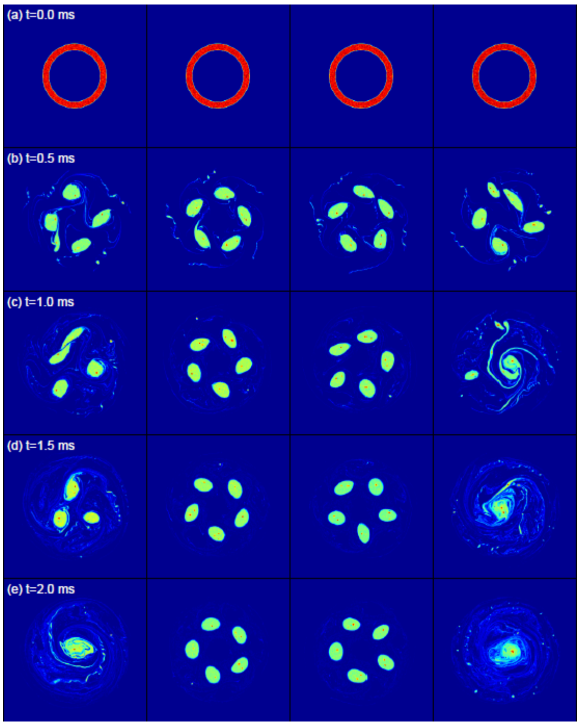

Fig. 1: Different time evolutions of an annular pure electron plasma with density 10^7 cm^{-3}, and inner and outer radii 0.36 R_w and 0.45 R_w, respectively, with R_w = 20 mm the radius of a grounded circular boundary (inscribed in the square region of each plot). The same simulation parameters ($5\cdot10^5$ macro-particles, 256x256 grid) are used in all runs. The times are indicated at the upper left corner of each frame in the first column.

2. Investigation of a non-neutral complex plasma

The experimental and theoretical investigations are being extended to the study of a novel system represented by a magnetized non-neutral complex plasma [9, 10, 11]. Complex plasmas are characterized by the presence of a fraction of micrometric or sub-micrometric particles which may collect a surface charge of the order of a few thousand electron charges. The presence of heavy contaminants has a dramatic effect on the dynamics of the overall plasma, allowing for the occurrence and study of several basic phenomena relevant to plasma physics, hydrodynamics and kinetic theory [12]. The complex plasmas studied in the experiments usually satisfy a global neutrality condition. Furthermore, regimes of partial or complete magnetization of the dust populations are investigated only in a very limited number of experiments [13]. By contrast, we consider the dynamics of a magnetized plasma of electrons contaminated with a fraction of negatively charged dust particles of micrometric size.

We simulate the two-dimensional transverse dynamics of this multi-component plasma with a 2D PIC code [3] implementing a mass-less fluid (drift-Poisson) approximation for the electrons and a kinetic description for the dust component (including gravity).

Simulations with different initial dust distributions and densities have been performed in order to investigate the influence of the dust on stability, fluid turbulence and equilibrium properties of the electron component. As a simple example, in Fig. 2 the time evolution of a uniform density pure electron plasma ring is compared with that in the presence of a uniform dust contamination. The dust grains are assumed to acquire their charge from that of the electrons, so that the electron density is depleted accordingly. The evolution of the pure electron plasma ring is dominated in this particular case by the instability of a diocotron mode with azimuthal number l = 5, leading to the formation of five long-lived vortices. When dust is added, a damping of the higher order diocotron modes and a growth of the low-order modes occur, leading to vortex merger events and the collapse to a single clump. This collapse turns out to become more rapid when the dust contamination is further increased [3].

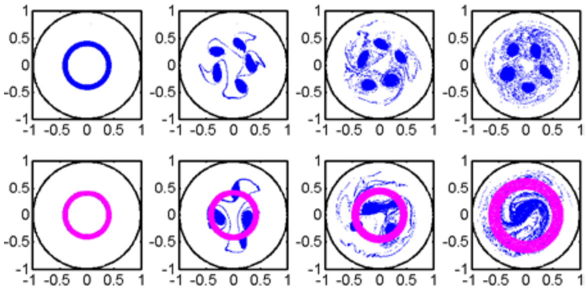

Fig. 2: Evolution of an electron plasma with initial uniform annular density profile and uniform dust contamination. All particles start at rest and the magnetic field strength is 1 T. First row: Pure electron plasma with density 10^7 cm^{-3}. Second row: contamination with dust (density $1.5\cdot10^4$ cm^{-3} and charge -100e). Blue and magenta dots correspond to electrons and dust particles, respectively (electrons and dust grains are simulated with $5\cdot10^5$ and 10^5 macro-particles, respectively; only 5% of them are plotted). A 256x256 grid is adopted. Spatial coordinates are normalized to a trap radius R_w = 20 mm. For both sequences the times are, from left to right, 0, 300 μs, 600 μs and 1.2 ms.

3. Apparatus for the confinement of a dust-contaminated electron plasma

In order to carry out systematic experimental investigations of the dynamics of a dust-contaminated electron plasma, a dedicated apparatus has been recently constructed at the Department of Physics of the University of Milano [10, 14]. The multipurpose linear magneto-static device ‘DuEl’, shown in Fig. 3, is a Penning-Malmberg trap suitably modified in order to allow for the injection of dust grains.

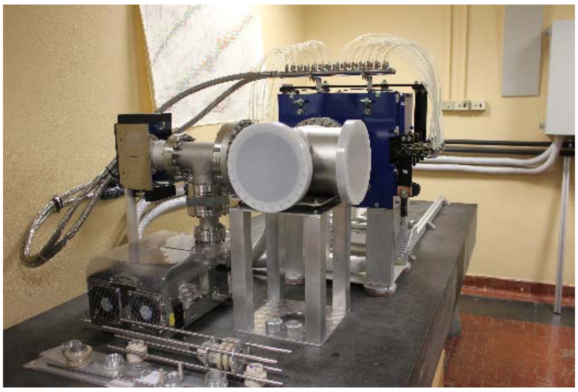

Fig. 3: The ‘DuEl’ apparatus being set up for testing in the Plasma Physics Laboratory of the Department of Physics of the University of Milano.

The device features a stack of hollow cylindrical electrodes with an inner diameter of 45 mm, separated by polyether ether ketone (PEEK) spacers. The total length of the stack is approximately 200 mm. Two of the electrodes are azimuthally segmented into four electrically insulated patches (see Fig. 4).

Fig. 4: Picture of a part of the electrode stack, showing an azimuthally split electrode, made out of four sectors with a 90 degree angular span mounted on two PEEK rings.

The electrode stack is contained within a cylindrical vacuum vessel with an inner diameter of 100 mm, evacuated to an ultra-high vacuum regime (residual gas pressure 10^{-8} mbar or lower) by means of turbo-molecular and ion pumps. The vacuum vessel is surrounded by a normal-conducting solenoid generating an axial magnetic field up to 0.9 T for the radial confinement of the electrons and for a partial magnetization of the dust contaminants. The axial confinement of the particles is provided by biasing two electrodes to a sufficiently negative potential. All other electrodes and azimuthal sectors can be set independently to static and/or time-dependent potentials in order to manipulate the axial and azimuthal dynamics of the plasma [15, 16]. The electrodes also allow for the diagnostics [17] of transverse-plane collective properties of the trapped charged particle samples, e.g. space charge [18] and fluid instabilities [19, 20].

The electron plasma is generated by a set of three thermionic spiral sources placed at one end of the electrode stack or by the application of a low power, few MHz drive on one of the inner electrodes [21]. Various features related to the continuous application of the radio-frequency excitation, like e.g. the generation of low frequency collective oscillations and the suppression of transverse instabilities, have been studied in ELTRAP [22, 23, 24]. In order to control the neutralization degree of the plasma and to systematically investigate these phenomena, the installation of a gas inlet with a pressure regulating valve is envisaged in the DuEl device.

The dust grains are injected into the system by means of a special electrode, which can be rotated by means of a drive shaft connected to an external stepper motor. The inner surface of this electrode is covered with a metallic ‘carpet’ loaded with the dust grains [25]. The rotation of the electrode allows for a steady drop (and recovery) of the dust particles through the electron plasma, where they acquire a negative charge.

The axially averaged distribution of the electrons at a given time is recorded by grounding an endcap electrode and detecting with a CCD camera the optical radiation produced by their impact on a phosphor screen held at a positive potential of a few kV. The screen is designed in such a way to be easily removed, in order to allow for an axial line of sight and an imaging of the dust grains by means of laser scattering techniques [26].

The future experimental investigations will explore physical processes in the plasma-dust system, like dust charging and sizing, and in particular the dust influence on the equilibrium, dynamics and turbulence properties of the electron plasma.

The DuEl Project has been supported by INFN National Scientific Committee V (technological researches) and by the Italian Ministry for University and Research (MIUR) “PRIN 2009” funds (Grant No. 20092YP7EY).

[1] M. Romé and F. Lepreti, Eur. Phys. J. Plus **126**, 38 (2011).

[2] M. Amoretti, G. Bettega, F. Cavaliere, M. Cavenago, F. De Luca, R. Pozzoli and M. Romé, Rev. Sci. Instrum. **74**, 3991 (2003).

[3] G. Maero, M. Romé, F. Lepreti, and M. Cavenago, Eur. Phys. J. D **68**, 277 (2014).

[4] G. Bettega, R. Pozzoli, and M. Romé, New J. Phys. **11**, 053006 (2009).

[5] F. Lepreti, M. Romé, G. Maero, B. Paroli, R. Pozzoli and V. Carbone, Phys. Rev. E **87**, 063110 (2013).

[6] S. Chen, G. Maero, and M. Romé, submitted to J. Plasma Phys. (2015).

[7] K. S. Fine, A. C. Cass, W. G. Flynn, and C. F. Driscoll, Phys. Rev. Lett. **75**, 3277 (1995).

[8] C. F. Driscoll, D. Z. Jin, D. A. Schecter, E. J. Moreau, and D. H. E. Dubin, Physica Scripta **T84**, 76 (2000).

[9] M. Romé, F. Cavaliere, M. Cavenago, M. Ikram, F. Lepreti, G. Maero, B. Paroli, and R. Pozzoli, AIP Conf. Proc. **152**1, 273 (2013).

[10] M. Maggiore, M. Cavenago, M. Comunian, F. Chirulotto, A. Galatà, M. De Lazzari, A. M. Porcellato, C. Roncolato, S. Stark, A. Caruso, A. Longhitano, F. Cavaliere, G. Maero, B. Paroli, R. Pozzoli, and M. Romé, Rev. Sci. Instrum. **85**, 02B909 (2014).

[11] E. Tassi, M. Romé, and C. Chandre, Phys. Plasmas **21**, 044504 (2014).

[12] G. E. Morfill, A. V. Ivlev, Rev. Mod. Phys. **81**, 1353 (2009).

[13] E. Thomas Jr., B. Lynch, U. Konopka, R. L. Merlino, and M. Rosenberg, Phys. Plasmas **22**, 030701 (2015).

[14] M. Romé, F. Cavaliere, M. Cavenago, S. Chen, and G. Maero, “*Effects of Dust Contamination on the Transverse Dynamics of a Magnetized Electron Plasma*”, AIP Conf. Proc. (2015), to be published.

[15] G. Bettega, F. Cavaliere, B. Paroli, R. Pozzoli, M. Romé and M. Cavenago, Phys. Plasmas **15**, 032102 (2008).

[16] G. Maero, B. Paroli, R. Pozzoli, and M. Romé, Phys. Plasmas **18**, 032101 (2011).

[17] G. Bettega, B. Paroli, R. Pozzoli, M. Romé and C. Svelto, Meas. Sci. Tech. **19**, 085703 (2008).

[18] B. Paroli, G. Bettega, G. Maero, M. Romé, M. Norgia, A. Pesatori, and C. Svelto, Rev. Sci. Instrum. **81**, 063503 (2010).

[19] G. Bettega, F. Cavaliere, B. Paroli, M. Cavenago, R. Pozzoli and M. Romé, Phys. Plasmas **14**, 102103 (2007).

[20] G. Bettega, B. Paroli, R. Pozzoli, and M. Romé, J. Appl. Phys. **105**, 053303 (2009).

[21] B. Paroli, F. De Luca, G. Maero, R. Pozzoli, and M. Romé, Plasma Sources Sci. Technol. **19**, 045013 (2010).

[22] B. Paroli, G. Maero, R. Pozzoli, and M. Romé, Phys. Plasmas **21**, 122102 (2014).

[23] M. Romé, S. Chen, G. Maero, B. Paroli, and R. Pozzoli, “*Trapped Electron Plasma Formation and Equilibrium with a Low-Power Radio-Frequency Drive*”, AIP Conf. Proc. (2015), to be published.

[24] G. Maero, S. Chen, R. Pozzoli, and M. Romé, submitted to J. Plasma Phys. (2015).

[25] W. Xu, B. Song, R. L. Merlino, and N. D’Angelo, Rev. Sci. Instrum. **63**, 5266 (1992).

[26] F. Ferri, D. Magatti, D. Pescini, M. A. C. Potenza, and M. Giglio, Phys. Rev. E **70**, 041405 (2004).