DuEl: A set-up for the study of non-neutral complex plasmas

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The last twenty years have seen an enormous increase of interest in the field of dusty or complex plasmas. This term refers to a plasma containing, in addition to electrons and ions, particles of macroscopic size, typically in the $0.01 - 10\ \mu$m range, subject to the acquisition of large numbers of elementary charges. Besides their natural occurrence in space, complex plasmas have achieved a decisive importance in technological applications, e.g. plasma deposition and etching, micro- and nanostructured materials, and nuclear fusion [1]. Depending on the application, the presence of massive particles is either desired or unwanted.

The common feature of dusty plasmas is the interplay between a wide range of scales in time and space which produces new types of collective behaviors with respect to more conventional plasmas, relating to various fundamental aspects of plasma physics, hydrodynamics, kinetics of phase transition, nonlinear physics, solid states. This has motivated a range of laboratory experiments on such plasmas, mainly produced by radio-frequency (RF) discharges in low-pressure gases, and thus in quasi-neutrality conditions, where dust grains are introduced and let to charge up by electron/ion surface deposition. Although the first experiments have been performed already twenty years ago [2], investigations on the effects of a magnetic field on complex plasmas have been less frequent and are just now gaining the spotlight [3].

On the other hand, magneto-electrostatic Penning-Malmberg traps have been successfully used for a few decades for the long-time confinement of highly-magnetized non-neutral plasmas, i.e. plasmas of particles with the same sign of charge [4], under ultra-high vacuum (UHV) conditions. Studies have been performed oriented both to basic physics problems and to a wide range of applications (among those, antimatter production). In particular, the dynamics of a trapped electron plasma is basically two-dimensional (2D) and its transverse dynamics exhibits a formal analogy with that of a 2D inviscid (eulerian) fluid [5] when the ratio between the frequency of the longitudinal bounce of the particles and that of the transverse drift is sufficiently high (a condition easily satisfied for electrons in experiments).

The present research project addresses the investigation of the dynamics of a non-neutral complex plasma, where an electron distribution is contaminated by a small fraction of electrically charged dust particles of micro- and/or submicrometric size. Specifically, the aim is the observation of the modifications in the plasma dynamics due to the presence of a dust population, with a focus on the effects of dust on stability, fluid turbulence and equilibrium properties of the electron component. The study comprises both a theoretical/numerical analysis and the design and realization of a Penning-Malmberg trap for tailored experiments. The combination of plasma magnetization, non-neutrality and dust contamination is of considerable novelty.

Preliminary simulations were performed with OOPIC Pro, a commercial Particle-In-Cell (PIC) code [6], to observe the transverse dynamics of an electron plasma in the presence of a population of massive charged dust grains. E.g., results showed that the insurgence of the Kelvin-Helmholtz instability in an annular ring of electrons with density of 10^7 cm^{-3} was slowed down by a core of dust grains, modelled as extremely massive, highly-charged negative ions, already at densities in the order of 10^5 cm^{-3}. OOPIC is nevertheless too limited for the accurate simulation of this specific physical system, due to the very large differences in time scales and the impossibility to take into account the most peculiar aspects of dust grains, namely the floating surface charge and the gravitational force. Indeed, depending on the grain size, the latter can be of the same order or dominant with respect to the Lorentz force. We are thus currently developing a polar two-dimensional PIC code with tailored capabilities to systematically investigate the transverse dynamics of the dust-electron system. In order to cover the fast (electron, $\approx$ ns for cyclotron and ms for $\vec{E}\times\vec{B}$ drift) and slow (dust, $\approx$ hundreds of ms to s) typical time scales, suitable coding strategies are used to reach sufficient computational speed. First, the use of the Fast-Fourier Transform technique to solve the Poisson equation (with choices on the boundary conditions to account for resistive wall effects and RF excitation) at each time step. Second, the implementation of a range of selectable algorithms to integrate the particles' equation of motion both in fluid $\vec{E}\times\vec{B}$ approximation and in the full kinetic treatment (B field-independent Velocity Verlet algorithm [7]). The use of the fluid approximation for electrons combined with the accuracy of the B-adapted Velocity Verlet scheme guarantees a negligible build-up of numerical errors in the computation of particle trajectories over a simulated time of seconds. Gravity is trivially implemented in the integration routine assuming a horizontal trap axis. A fixed or electron density-dependent floating charge on the dust grains can be chosen. Several options are being implemented to enlarge the observable physical phenomena, e.g. buffer-gas and interparticle Monte Carlo collisions, synchrotron cooling (whose time constant is $\approx 3.5/B^2$ s$\cdot$T^{-2} for electrons) and sympathetic cooling.

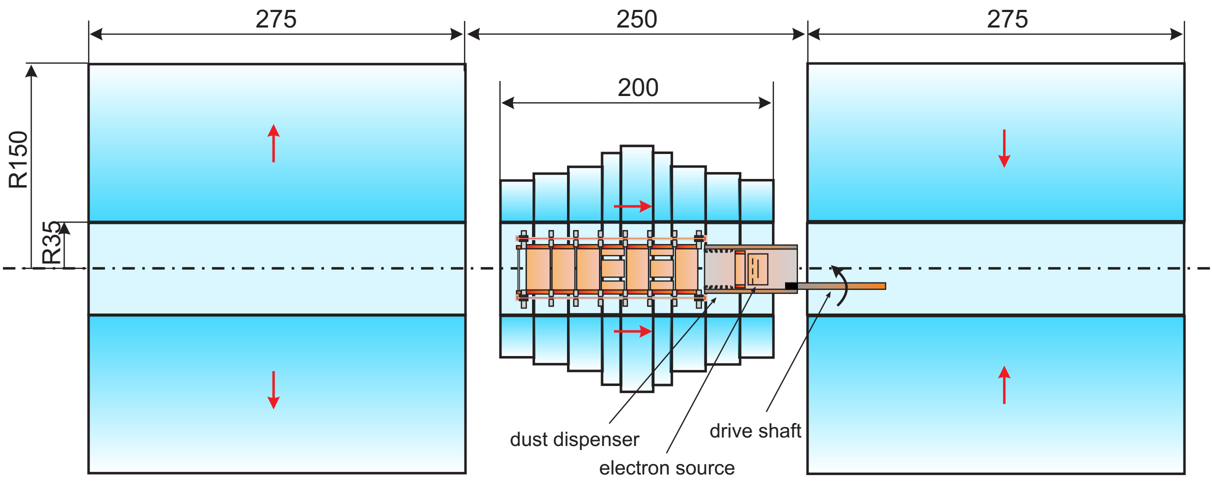

Figure 1: Sketch of the trap set-up. The magnetic ring elements are indicated in blue, with red arrows to indicate the magnetization direction. In the central region, the electrode column with a phosphor screen on the left end, the rotating dust dispenser and electron source on the right. All dimensions in millimeters.

The critical component of the set-up is represented by the magnet, as magnetic fields of few tesla would be necessary in order to effectively magnetize dust grains with extremely low charge-to-mass ratios. E.g., for a 1-μm diameter grain with density ≈ 1 g·cm^{-3} and $\approx 10^3$ unit charges at thermal velocity the cyclotron radius is in the order of some cm/T. Such fields require the use of expensive superconducting magnets. As a proof of principle, a mock-up apparatus is currently under design, whose goal is an experimental demonstration that the evolution of a stream of electrons with density in the 10^8 cm^{-3} range can be significantly influenced by the introduction of a small fraction of massive contaminants. NdFeB permanent magnets with the highest magnetization grade as well as suitable geometry and magnetization orientation will be used. A finite element simulation of the geometry seen in Fig. 1 shows that an axial magnetic field above 0.5 T can be achieved (see Fig. 2), demonstrating that this solution offers a competitive and cost-effective alternative to normal-conducting electromagnets, although at the expense of a degradation in homogeneity.

A stack of cylindrical electrodes with an inner diameter of 40 mm will be placed along the magnetic field axis within a 63-mm diameter cylindrical UHV chamber. A thermocathode at the end of the stack will provide a continuous stream of electrons (captured by raising the potential on the endcap electrodes). Induced electrostatic signals will be used for non-destructive diagnosis, while electron optical diagnostics will be available thanks to a phosphor screen at the other end of the trap. Dust imaging through laser irradiation is envisaged, too. The novel structure

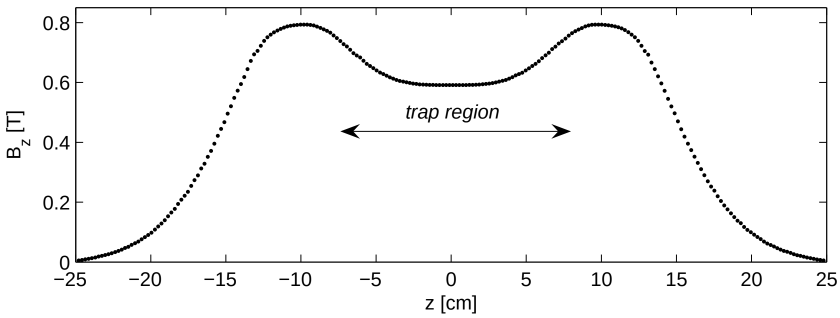

Figure 2: Axial magnetic field strength B_z along the axis of the magnet assembly. Finite element simulation considering the geometry of Fig. 1, material NdFeB with magnetization grade 52, residual magnetic induction $B_{res} \simeq 1.45$ T.

with respect to typical Penning traps will be a rotating dust dispenser. The actual design is close to that of Ref. [2]: the inner surface of a motorized cylinder is covered with a microstructured grid or metallic 'carpet' so that it can be loaded with grains of nominal diameter from 50 nm to several micrometers. The dust dispenser, placed between the electron source and the electrode stack, will be set in rotation via a drive shaft connected to an electric motor. The rotation will cause dust grains to steadily drop perpendicularly to the electron flow. The completion of both magnet structure and dust source and the test of transmission of electron-dust plasmas in the magnetic field are scheduled within the end of 2013.

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References

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

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

[3] M. Schwabe, U. Konopka, P. Bandyopadhyay and G.E. Morfill, Phys. Rev. Lett. **106**, 215004 (2011).

[4] R.C. Davidson, Physics of Nonneutral Plasmas (Addison-Wesley, Redwood City, 1990).

[5] C.F. Driscoll and K.S. Fine, Phys. Fluids B **2**, 1359 (1990).

[6] *OOPIC PRO User's Guide* , `www.txcorp.com/pdf/OOPIC_Pro/documentation/OOPIC_Pro_UsersGuide.pdf` (retrieved 2012).

[7] Q. Spreiter and M. Walter, J. Comput. Phys. **152**, 102 (1999).