Plasma Crystals of Charged Microparticles confined under Standard Temperature and Pressure (STP) conditions

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Trapping of microparticles and aerosols is of great interest for physics and chemistry. Our paper deals with microparticle trapping in multipolar linear Paul trap geometries, operating under standard temperature and pressure (STP) conditions. A 16-pole linear trap geometry has been designed and tested, with an aim to enable trapping of a larger number of particles and thus enhance the signal to noise ratio, as well as to study microparticle dynamical stability in electrodynamic fields. Different microparticle species were used, planar and volume ordered structures of the microplasmas have been observed.

1. Introduction

One of the most challenging quests for physicists has been the goal to isolate and trap trapping atomic particles, in a well-controlled environment. The advent of ion traps [1, 2] in the 1950s, influenced the future of modern physics and high technology in a very profound mode. High-precision spectroscopy and mass spectrometry measurements with unprecedented accuracy [3, 4], quantum physics tests, precise control of quantum states [5], study of non-neutral, complex and dusty plasmas [6, 7], optical frequency standards, quantum metrology and quantum information processing (QIP) [2-4] experiments, became all possible by using laser cooled atomic and molecular ions, confined in electrodynamic traps.

Microparticle trapping experiments, using an especially designed 16-pole linear trap geometry, are presented. Alumina (Al_2O_3) microparticles have been confined using three dimensional electrodynamic multipole fields. The microparticles are trapped in air, at standard temperature and pressure (STP) reference conditions, which results in an efficient ”cooling” of the particle owing to air friction. The mechanism is similar with cooling of ions in ultrahigh vacuum conditions by means of collisions with the buffer gas molecules.

Particles of micro and nanometer dimensions are found as atmospheric aerosols, interstellar dust or biological cells and bacteria. Presence of certain aerosols in conjunction with increased levels of industrial pollution is responsible for respiratory and cardiovascular diseases, as well as for lung disease, asthma and for the explosion of human allergies in town areas.

The multipolar trap geometry we report has been investigated with an aim to levitate and study microscopic particles, aerosols and other constituents or polluting agents which might exist in the atmosphere. The researches are based on previous results and experience [8 - 10]. Multipolar traps operating under ultrahigh vacuum conditions are used in laser spectroscopy for increasing the signal-to noise ratio [11, 12], a prerequisite for the achievement of quantum entanglement or for the realization of new, very accurate atomic clocks, operating in the optical range [13].

2. Experimental Setup

A linear Paul trap uses a combination of time varying and static electric potentials to create a trapping configuration which confines charged particles such as ions, electrons, positrons or charged particles. A radiofrequency (RF) voltage is used in order to generate an oscillating quadrupole potential in the *y-z* plane, which achieves radial confinement of the trapped particles. Axial confinement of positively charged ions (particles) is achieved by means of a static potential applied between two electrodes situated at the trap ends, along the trap axis (*x* plane). These electrodes are called endcap electrodes. A harmonic secular potential results within the trap if both the RF and endcap potentials are quadratic, a situation which is almost impossible to achieve for the whole trap volume. In fact, it can be assumed that the potential in the region located in the vicinity of the trap axis can be regarded as harmonic, which is a sufficiently accurate approximation.

Trapped ions or particles represent one-component plasmas (OCP), as the role of the neutralizing background charge is played by the trapping potentials. The one-component plasma is a reference model in the study of strongly coupled Coulomb systems. For quadrupole traps the second-order Doppler effect is a direct consequence of the space-charge Coulomb repulsion force between trapped ions of like electrical charges. The Coulombian forces are balanced by the ponderomotive forces which are the result of ion motion in a highly non-uniform electric field. For large ion clouds, most of the motional energy is found in the micromotion, which represents the greatest contribution to the second-order Doppler shift.

To reduce the second-order Doppler shift due to space charge repulsion of ions from the trap node line, novel multipole ion traps have been developed and investigated, where ions are weakly bound with confining fields that are effectively zero through the trap interior and grow rapidly near the trap electrode walls. Thus multipole ion trap geometries significantly reduce all ion number-dependent effects resulting through the second-order Doppler shift. Frequency standards based on multipole traps are capable of achieving higher accuracies, required by the ever increasing demands and challenges placed by applications such as satellite-based navigation (implicitly the GPS system), quantum metrology measurements and for state-of-the art technology. Multipole traps lead to a higher signal-to-noise ratio, a prerequisite for quantum logic and quantum optics experiments.

The 16-pole trap geometry is intended for studying the appearance of stable and ordered patterns for different charged microparticle species. Alumina and sillicium carbide (with dimensions ranging from 60 microns up to 200 microns) were used in order to illustrate the trapping phenomenon, but other species can be considered. Specific charge measurements over the trapped microparticle species are expected to result, as the setup can be refined. The 16-pole Paul trap we have designed exhibits a variable geometry.

An electronic supply system was designed and realized. It supplies the a.c. voltage V_{ac}, with an amplitude of 0 – 3.5 kV and a variable frequency in the 40-500 Hz range, required in order to achieve radial trapping of charged particles. The electronic supply system delivers a variable d.c voltage U_{diag} used to diagnose the charged microparticles, and another d.c. variable voltage U_{dc} is applied between the trap endcap electrodes, in order to achieve axial confinement

3. Conclusions

We have investigated a 16-pole Paul trap multipolar geometry operating in air, under STP conditions. We have been able to observe the appearance of planar and volume structures for these microplasmas. Stable and ordered microplasma structures have been obtained. From the experimental data recorded, we have obtained stronger confinement, increased stability and larger microparticle numbers under conditions of dynamical stability, compared to lower order multipole traps.

Trapped particle microplasmas have resulted (very similar to a dusty plasma, which is of great interest for astrophysics), consisting of tens up to thousands of particles. This microplasma provides a basis for the study of microparticle dynamics in electrodynamic traps and of the phenomena associated to this experiment. Such a setup would be suited in order to study and illustrate particle dynamics in electromagnetic fields, as well as the appearance of ordered structures, crystal like formations.

In Fig. 1 we present a picture which shows the stable structures we have been able to observe and photograph. All photos have been taken with a high sensitivity digital camera. We have observed filiform structures consisting of large number of microparticles far from the trap center, where the trapping potential is extremely weak.

The traps we have designed present more regions of stable trapping, located near the trap electrodes. Most of the photos we have taken prove it. We have been able to identify several regions (at least four) of stable trapping, but due to camera limitations we could only obtain focusing for a limited region of space. When looking with bare eyes and for an adequate angle, space structures could be observed in different regions within the trap volume. We can ascertain that the multipolar trap geometries we have investigated and especially the 12-pole and 16-pole linear dodecapole Paul trap, exhibit an extended region where the trapping field almost vanishes.

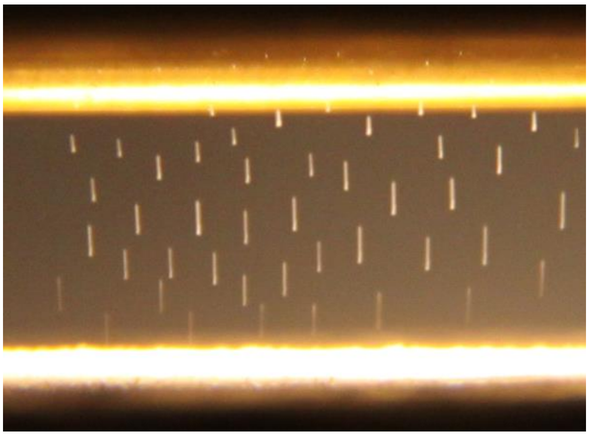

Fig. 1. Microparticle structures observed in the 16-pole Paul trap

To study the possibility and conditions of the dust structure confinement in quadrupole traps operated at atmospheric pressure, we have considered the potential forces acting upon dust particles (Fig. 2). The buffer gas influence has been taken into account by means of viscosity and random forces. The motion of dust particles is described by Brownian dynamics that takes into account the stochastic forces acting on dust particles, owing to neutral and plasma particles. The equations of motion of dust particles are described by the Langevin equations. The numerical simulations we have performed allow us to find the regions of dust particle confinement, as well as the influence of particle mass and charge on these regions, and those of the voltages and frequencies of the electrical field applied to the trap electrodes.

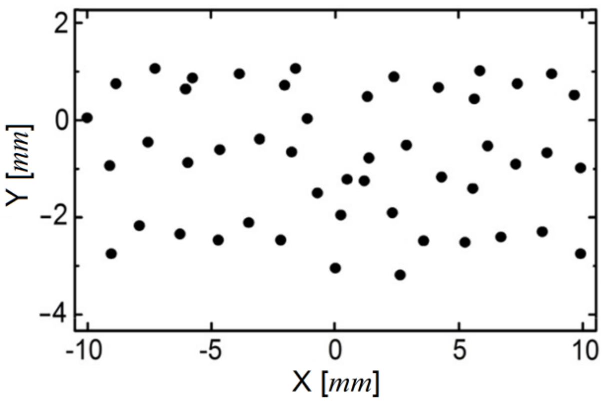

Fig. 2. Simulation with parameters: particles: r = 5-*10 μm, ρ = 0,38 10^4 kg/m3, Q = 20500 – 685000 e,* P = 1 atm, η = 17 μPas; trap: 6x1x1 cm, Uω = 2.2 – 22 kV, f = 30 – 200 Hz, Uend = 700 V; average interparticle distance l = 0.92 mm.

3. References

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