Measurement and resonant control of modulated diocotron modes in RF-excited trapped plasmas

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Radio-frequency (RF) electric fields are routinely used to create plasmas through the generation of discharges in neutral gases, where usual features include the injection of high RF power and pressures as high as $10^{-3} - 10$ mbar in order to sustain the discharge. On the contrary, Penning-Malmberg [1] traps confine non-neutral, magnetized plasmas under radically different conditions, namely in the Ultra-High Vacuum (UHV) regime and with a charged particle sample under study coming in general from an external source, like a thermo-, photo- or field-emission cathode in the case of an electron plasma. The reproducible sample injection combined with the low collision rate in UHV and the high degree of symmetry of magnetic and electric fields allows long-time confinement and precise control and manipulation of the trapped particles.

Experiments performed in recent years in the ELTRAP device [2, 3, 4] demonstrated that as an alternative to common trap sources an unconventional technique can be exploited that borrows from principles used in gas discharges (albeit in the very different context represented by Penning traps), i.e. the continuous application of a weak periodic excitation to any inner electrode of the trap when the endcaps are simultaneously set to a suitable confining potential. Experiments show in particular that a few-volt RF drive may result in significant electron heating and ionization of the residual gas when the drive frequency is of the order or larger than the typical axial bounce frequencies of few-eV electrons, eventually leading to the build-up of a confined electron plasma. A qualitative explanation on the basis of a simple one-dimensional stochastic heating model was given elsewhere [2, 5]. While often RF-generated plasmas exhibit low densities ($10^5 - 10^6$ cm^{-3}) and cover a large part of the trap cross-section, empirical tuning of the control parameters (geometry, magnetic field strength, RF parameters) results in the formation of narrow-radius columns that can reach densities of the order of 10^7 cm^{-3}, i.e. comparable to those of conventional sources. It was experimentally found that the narrow columns produced with this technique generally exhibit a radial displacement with respect to the trap axis, although they show interesting stability properties against the well-known growth of the $l = 1$ mode and can have an indefinite equilibrium at a constant offset as a result of the balance

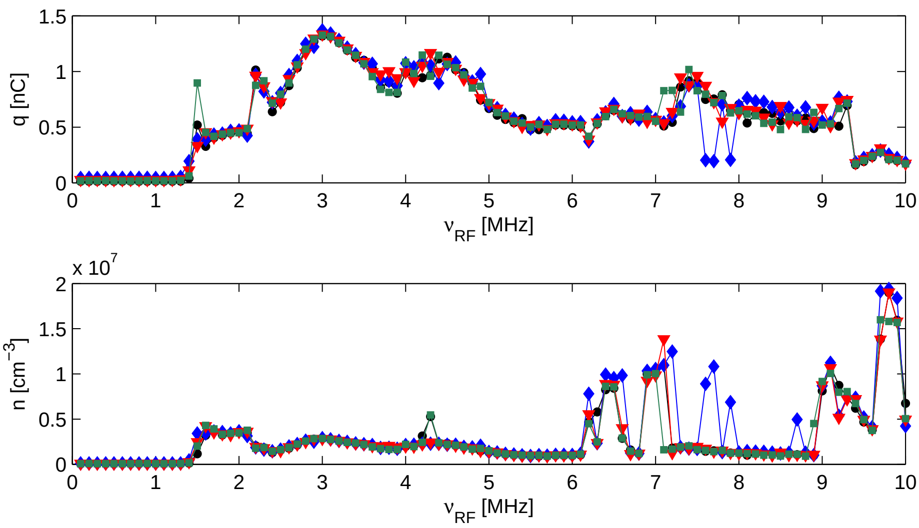

Figure 1: *Repeatability test. The four frequency scan measurements were recorded with the following set of parameters: Trapping length* 570 *mm, magnetic field* $B = 0.1$ *T, excitation amplitude* 1.5 *V. Top diagram: Total confined charge. Bottom diagram: Mean plasma core density.*

between ionization and losses in the presence of a continuous RF application.

The main disadvantage lies in the fact that the generation mechanism is extremely sensitive to experimental conditions and as a consequence the control of the properties of the resulting plasma is not straightforward. Therefore an assessment of the reproducibility of the RF-produced plasmas under constant experimental parameters was performed. In the standard experimental sequence, the frequency ν_{RF} of the drive was continuously swept at a 20 kHz/s rate in the $0.1-10$ MHz range while one of the endcap potentials was turned off every 5 s to release the plasma and record the image formed on a phosphor screen with a charge-coupled device (CCD) camera. Figure 1 shows the main results of four runs with identical experimental conditions, namely a 1.5 V excitation on the electrode adjacent to one of the endcaps in a 570 mm trapping length, endcap potentials -80 V, axial magnetic field 0.1 T. The top and bottom diagrams indicate the total confined electron charge and mean core density, respectively. Both curves are fairly well repeated over different sweep sequences. In particular, the main patterns present in the charge diagram show vertical (total charge) fluctuations within 10% while horizontal (frequency) fluctuations amount to one data point (± 50 kHz) at most. This guarantees an acceptable statistical reproducibility of the results obtained with RF-generated plasmas. The largest deviations are represented by few sharp spikes (see the range $7-8$ MHz in the picture), which correspond to phenomena like the transition from a diffuse plasma to a narrow and dense column or the modulation of the $l = 1$ diocotron mode of off-centered plasmas. In

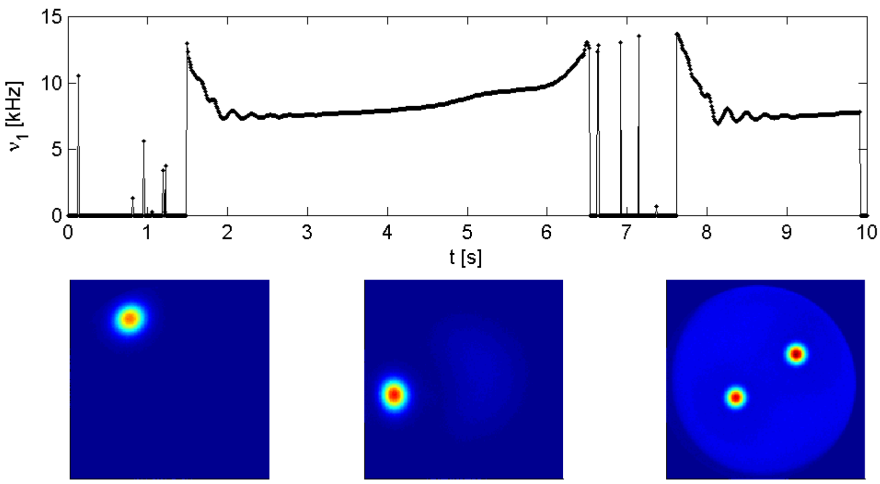

Figure 2: *Evolution of a RF-generated plasma with formation of two stable vortices. Top row: Electrostatic signal of the* $l = 1$ *diocotron mode showing the cyclic formation, evolution and disappearance of a single plasma column. Bottom row: CCD images at plasma dump. The plasma consists of a narrow column rotating at large offset; the vortex is initially background-free (left), but a diffuse background develops during the evolution (center). After the disappearance of the column, a stable double vortex may be produced (right). CCD images are cropped to the trap cross-section. All figures are normalized to the peak density of* $1.5 \cdot 10^7\ cm^{-3}$.

the latter case, the observed phenomenon is a steady modulation of both frequency and amplitude of the $l = 1$ mode, which is associated to a periodic variation of the confined charge [3] (possibly due to the damping of diocotron modes mediated by radial losses or other transport phenomena [7]) as well as to an oscillation of the radial displacement. The application of a dipole RF excitation at the modulation frequency (typically in the Hertz range) results in the amplification of the modulation amplitude. Preliminary studies have been performed showing that autoresonant excitation [8] of this slow modulation is possible, leading to new possibilities of manipulation of the plasma column (e.g., radial displacement control).

We have observed that besides diffuse plasmas and narrow columns, under particular conditions a system of two vortices can be generated. Some characteristic features of this event are summarized in Fig. 2. The plasma is created by means of a 9.9 MHz, 0.9 V sinusoidal excitation on two opposite patches of a fourfold-split electrode in a 570 mm long trap at $B = 0.15$ T. As shown by the $l = 1$ mode recorded from another sectored electrode and depicted in the top diagram of Fig. 2, a cyclic evolution takes place where a plasma column is produced, lasts few seconds ($t \simeq 1.5$ to 6.5 s in the diagram) and disappears. The whole sequence can be repeated several times. This dynamics is consistently reproduced over many experimental cycles, allowing us to record CCD images at plasma dump and reconstruct the plasma evolution by associating the image to a corresponding instant in the vortex dynamics. The bottom row of Fig. 2 displays some of such pictures. The image on the left shows the plasma about 1.5 s after the appearance of the $l = 1$ signal, i.e. right after the fast oscillations disappear: A single, narrow column at large distance from the trap axis. The center image is taken at a time corresponding to an evolution of about 4.5 s, and highlights the formation of a background opposite to the position of the dense clump. In some cases, after the disappearance of the single column, a different system is formed where two well-separated vortices can be found (rightmost image). These vortices have approximately the same charge and density and rotate around the axis at a constant separation distance that is larger than their mean radius. Once they are formed, their configuration appears to be stable within our observation times, i.e. at least up to 10 s, and thus orders of magnitude longer than typical collisional time scales. An important feature of this system is the presence of a strong background plasma with a density up to 10^6 cm^{-3}, i.e. only one order of magnitude less than the vortex peak density. Although a thorough explanation for the occurrence of this phenomenon is still missing, the experimental evidence shows that the background plays an essential role both in the formation and in the equilibrium of the system under the continuous external forcing and the ensuing balance between ionization and losses.

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