Dynamics and stability in RF-generated nonneutral plasmas

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Born and used for a long time as a tool to confine a single-species nonneutral plasma, Penning-Malmberg (PM) traps have been exploited in a wider range of applications than originally imagined [1]. Deviations from ideal conditions, like the presence of several charged-particle species and the application of radio-frequency (RF) excitations, represent a challenge both in terms of physical modelling and of accurate control and manipulation. At the same time, they have led to important results (e.g., antimatter synthesis) and offer new opportunities of physics investigations in collective systems.

A case of non-ideal conditions is the in-trap generation of a non-neutral plasma by means of low-amplitude RF fields. Our experiments performed have demonstrated that the continuous application of a RF drive on one of the PM trap inner electrodes at frequencies in the range of the axial bounce motion of electrons can initiate and sustain a discharge at pressures in the high-vacuum to ultra-high vacuum range ($10^{-7} - 10^{-9}$ mbar). More details about the features of the PM devices and the experimental procedures can be found in previous works [2, 3, 4, 5, 6]. In brief, using typical axial confinement voltages $V_C \sim -100$ V, axial magnetic fields $B = 0.05 - 0.9$ T and RF drives in the $1 - 30$ MHz range and amplitude $V_{RF} = 0.5 - 10$ V_{pp}, the few free electrons in the background gas can be heated and initiate an ionization process that leads to the accumulation of an electron plasma, with a variable fraction of positive ions up to $0.01 - 0.1$ of the total electron charge [7].

With respect to typical PM-based experiments where a single-species sample is injected in the confinement volume, here sources and sinks of electrons and ions must be taken into account in balance laws. Time variation of electron charge and density profiles, as well as the presence of transient or co-trapped positive ions leads to non-conservation of the mean square radius of the electron sample, otherwise implied by conservation of the angular momentum $P_\theta \sim \sum_j e_j r_j^2$ (e_j, r_j denoting the charge and radial position of the j-th particle) when a single plasma component is present. In turn, this should lead to potentially destructive instabilities (growth of the $l = 1$ diocotron mode and thus of the radial displacement of the electron column [8, 9]). Observation of the dynamics towards stationary states while the RF drive is continuously applied is necessary, although it is made challenging by the wide range of frequency scales covered by the process, from the axial bounce frequencies ($1 - 10$ MHz), to $\mathbf{E} \times \mathbf{B}$ trans-

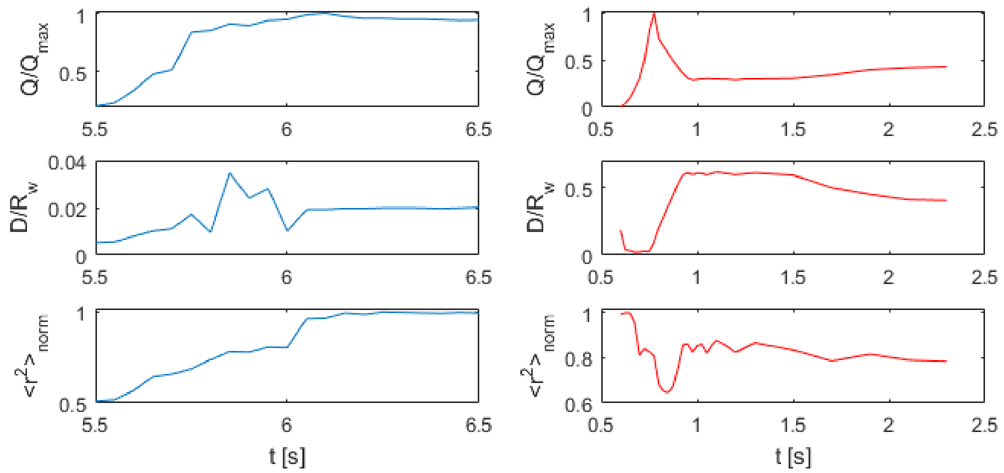

Figure 1: Evolution of the electron column under the effect of the RF generation drive. The accumulation of the total confined charge Q (upper panels) is shown together with that of the offset D (normalized to the trap radius R_w; middle panels) and of the mean square radius $\langle r^2 \rangle$ (bottom panels) for two different cases. Q and $\langle r^2 \rangle$ are normalized to the maximum value. Left column: Evolution of a centered, axisymmetric plasma. Right column: Evolution from an annular structure to a denser, small radius, large-offset column.

verse fluid scale ($10-100$ kHz), collisional frequencies ($10-100$ Hz) and finally steady-state attainment ($0.1-1$ Hz). Figure 1 summarizes the evolution of two electron plasmas obtained with different sets of confinement and excitation parameters, highlighting both expected and unexpected features in the dynamics and final states. The left column refers to a plasma obtained with a trapping length $L_p \sim 90$ cm, confining potential $V_C = -80$ V, magnetic field $B = 0.12$ T and RF drive of amplitude $V_{RF} = 5.65$ V$_{pp}$, frequency $\nu_{RF} = 7.42$ MHz, residual gas pressure $p = 0.5-1\cdot 10^{-8}$ mbar. For the right-column case parameters are $L_p \sim 100$ cm, $V_C = -100$ V, $B = 0.1$ T, quadrupolar drive with $V_{RF} = 5.0$ V$_{pp}$, $\nu_{RF} = 12.7$ MHz, $p = 1-2\cdot 10^{-8}$ mbar. A 'confine and excite - dump' cycle is performed for increasing confinement times in order to record a pseudo-evolution sequence of images by dumping the plasma onto a biased phosphor screen. In the first case, an appreciable confined charge Q is detected after ~ 5 s of continuous excitation. As the RF field is stronger in the vicinity of the electrodes, one would expect larger heating and ionization at large radius; yet the column is essentially centered (see middle panel, showing the radial offset D) during the whole evolution, and the (almost monotonic) increase in confined charge (top) is accompanied by the growth of the mean square radius (bottom) until a steady state with monotonically decreasing density profile $n(r)$ is achieved.

In the second case, the accumulation of charge is detected earlier (due to the different set of parameters, and especially the higher background pressure) with a hollow profile extending up to the trap radius. After an initial stage where the charge increases, the column evolves towards an off-axis state, with an increase of the bulk displacement D accompanied by a reduction in the total charge; the mean square radius first decreases (as the central hole in density profile is filled) and grows again (as the plasma cross section becomes smaller and moves off-axis).

A variety of such measurements on the evolution to steady-state configurations has highlighted that transitions from diffuse ($n \leq 10^{12}$ m^{-3}) to compact and denser columns ($n \sim 10^{13}$ m^{-3}) are accompanied by an intermediate stage where the core exhibits higher-order ($l = 2,3$) diocotron deformations. These produce filamentation and cat's eye structures that mix up with the background and are re-homogenized in times of some hundred milliseconds until circular-profile states are achieved, often off-axis. These off-axis states are very robust against dissipations and perturbations and their existence cannot possibly be justified on the basis of statistical models, where energy, angular momentum and particle number are conserved [10, 11]. A thorough explanation is under development. Qualitatively, experimental observations suggest that a balance can occur between the action of the RF drive and its consequences, namely simultaneous production of electrons and ions (source of instability) and loss of energetic electrons (source of instability damping), resulting in a configuration characterized by a set (Q,D). Perturbations such as electric fields in the form of bursts, frequency sweeps (e.g., '$l = 1$ autoresonant' drives) or feedback signals (commonly used to damp diocotron modes) are generally unable to produce the effect obtained in freely-evolving plasmas if the RF drive is simultaneously applied. Small-amplitude perturbations result in very minute alteration of the (Q,D) plasma configuration or in low-frequency, phase-shifted Q and D oscillations around the stability point, with a sudden jump to destructive effects if the forcing amplitude is excessively

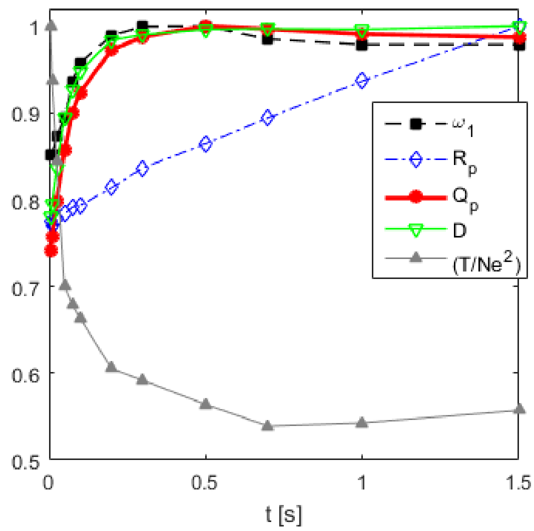

Figure 2: Evolution of parameters of interest after the RF generation drive is turned off. The frequency of the $l = 1$ mode ν_1, the plasma radius R_p, charge Q_p, offset D and temperature correction factor T/Ne^2 are normalized to the maximum value ($R_{p,max} = 0.23R_w$, $D_{max} = 0.29R_w$).

increased. These modulations, naturally occurring or induced by perturbations, can be excited autoresonantly [12].

For freely-evolving plasmas, the $l = 1$ diocotron mode frequency ω_1 reads:

$$\omega_1 = \left[\frac{enr_p^2}{2\pi\varepsilon_0 B}\right]\left[1+\frac{1-2r_p^2}{\left(1-r_p^2\right)^2}d^2\right]\left\{1+\left[1.2025\left(\frac{1}{4}-\ln r_p+\frac{T}{Ne^2}\right)-0.671\right]\frac{R_w}{L_p}\right\} \quad (1)$$

where the first bracket is the linear frequency, the second is a correction depending on the normalized offset $d = D/R_w$ and column radius $r_p = R_p/R_w$ and the third a non-zero temperature T and finite length L_p correction [13]. Figure 2 shows the evolution of the critical parameters in the formula after turning off the drive. The charge increases due to residual ionization, with a corresponding decrease in temperature. The offset grows along with the charge due to residual presence of ions and thus to ion instability, until both saturate as electrons cool off and ions escape. The mode frequency follows as a consequence. The mean radius steadily grows due to diffusion. Despite the dramatic role of the RF generation drive over the dynamics and final state attained by the electron plasma, for stable-offset, RF-excited plasmas we have observed that ω_1 still obeys Eq. 1. The latter's consistency is verified measuring charge, offset and radius of the RF-excited plasma from the optical diagnostics, and indirectly deducing T if the formula is assumed to be valid after turning off the RF drive and T is considered the same just before and after the drive is switched off. Values of ω_1 consistent with Eq. 1 within less than 3% relative error have been found in a variety of measurements for off-axis stable column. We infer that the drive does not enter directly the $l = 1$ rotation formula, while it strongly affects it by having a dominant effect on the critical ingredients entering the formula.

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