

Ion instability and off-axis equilibrium in a RF-sustained nonneutral plasma

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Penning-Malmberg traps (PMTs) are known and extensively used as unique tools for long-term charged particles storage, precise manipulation and measurement of trapped samples, creation of high-quality bunched beams. This array of opportunities also results from an ever-increasing stretching of the concept, structure and operation of electro-magnetostatic traps themselves [1]. In these terms, we have previously reported on experimental studies concerning the in-trap production of electron plasmas by background ionization due to a low-power radio-frequency (RF) excitation [2], an alternative way to the generation of electron samples to be used in studies of collective systems with interesting fluid analogues (e.g., fluid vortices and two-dimensional turbulence) [3, 4, 5, 6].

RF-generated electron plasmas (RFGEPs) are obtained through a process where the PMT is (a) set in confinement mode, with typical axial voltages $V_C \sim -100$ V on the endcap (confinement) electrodes and an axial magnetic field $B = 0.05 - 0.9$ T, and (b) a RF drive in the 1 – 30 MHz range and amplitude $V_{RF} = 0.5 - 10$ V_{pp} is applied to one of the electrodes between the endcaps. The few free electrons in the background gas, at pressures ranging from high vacuum to ultra-high vacuum ($10^{-7} - 10^{-9}$ mbar) are stochastically heated and initiate an ionization process leading to the accumulation of a $10^6 - 10^8$ cm⁻³ electron plasma, contaminated with a fraction of positive ions up to 0.01 – 0.1 of the total electron charge [7, 8]. More details about our PMTs and the experimental protocol can be found in previous papers [7, 9, 10, 11].

In our previous measurements we have observed a variety of stable states, ranging from azimuthally-symmetric, diffuse plasmas covering much of the trap cross section and to more peculiar states where a coherent vortex has a radial displacement D with respect to the longitudinal axis. This displacement induces an $\vec{E} \times \vec{B}$ rotational motion (first diocotron mode) whose control is a key issue in trapped plasmas, as its instability leads to mode growth (i.e., increase of D) and loss of particles. These RFGEPs showcase peculiar features: While the ionizing drive is active, this mode is unusually stable and resilient to typical perturbations and instability mechanisms, such as the ion-induced mode growth [12] which could be expected since ions are continuously created in the trapping volume. In some cases the mode exhibits an amplitude modulation, accompanied by a phase-shifted oscillation of the total number of electrons [13].

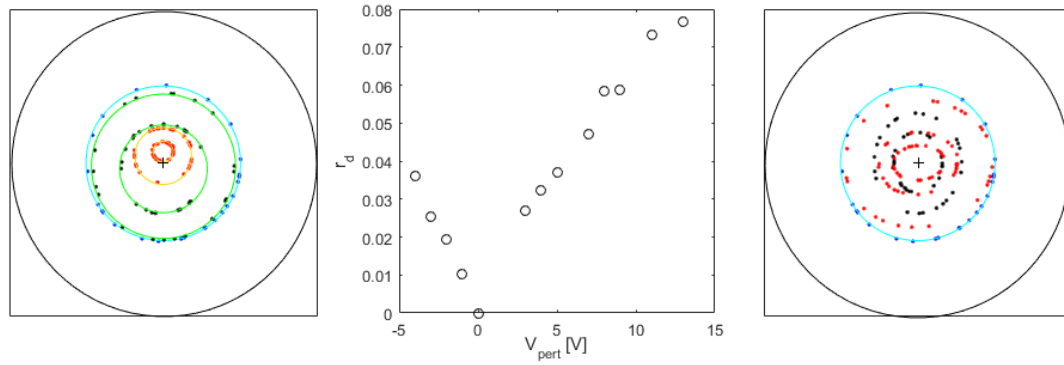


Figure 1: Effect of static multipolar fields on an RF-excited electron plasma column (vortex). Left panel: The unperturbed plasma orbit is indicated by the centers of charge of multiple plasma shots (blue dots) and their fit (cyan). Dipole perturbations of increasing positive voltages (red dots, orange lines; 9, 17 V) and negative voltages (black dots, green lines; -2, -4 V) progressively reduce the orbit size and shift the rotation axis. The black line is the trap cross section. Central panel: Normalized shift r_d of the rotation axis vs perturbation voltage. Right panel: Effect of quadrupole perturbations (same colour code). $V_{pert} = -5, -9$ V; 7, 11, 15 V.

While this stability may be advantageous, it also makes the control and manipulation of the plasma position unusually hard. Application of azimuthally-asymmetric perturbations such as resistive boundary conditions, feedback signals or voltage bursts have proved ineffective in terms of smooth control of the column radial offset. On the contrary, an interesting response has been found following a technique based on a previous investigation conducted on freely-evolving columns in Ref. [14], where a static dipole voltage was applied on an azimuthally-sectored electrode to deform the orbit while shifting the rotation from the trap axis. Expanding on this technique, we applied static dipole, quadrupole and octupole fields to 4-fold and 8-fold sectored electrodes after the RFGEP had reached a stable diocotron orbit and while maintaining the ionizing drive active. The measurements were conducted on a plasma generated by a 2.3 V, 8.5 MHz RF drive under -80 V confinement voltages and a magnetic field $B = 0.15$ T. The axially-integrated transverse density profile of the plasma was recorded multiple times by repeating the creation-manipulation-ejection cycles and acquiring the image produced by the plasma impact on a phosphor screen at the ejection. The left panel of Fig. 1 shows the unperturbed trajectory (blue) as well as the deformed orbits obtained by means of positive (orange) or negative (green) voltages on the bottom $\pi/2$ sector of a 4-fold split electrode. Voltages are comparatively high, i.e. of the same order of magnitude of both the RF drive and space charge potential. As shown in the central panel, the effect on the rotation axis displacement r_d (nor-

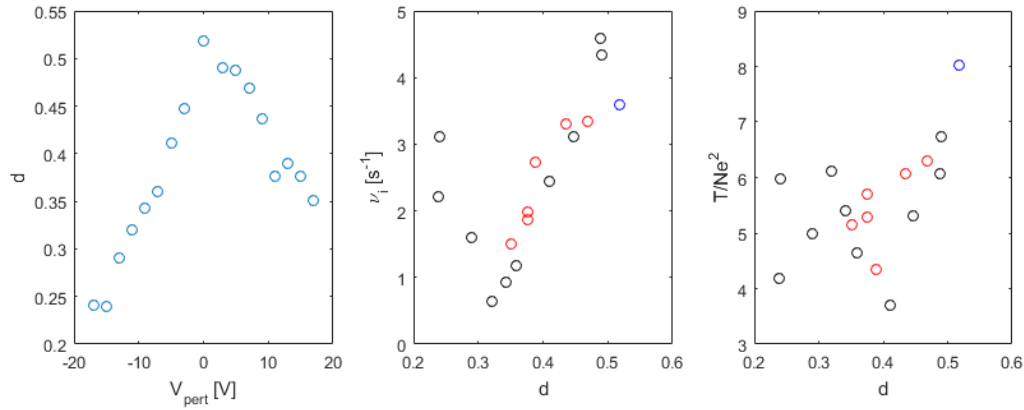


Figure 2: Effect of static octupolar fields on an RF-excited electron plasma column. Left panel: Normalized orbit amplitude d vs perturbation voltage. Central panel: Ionization rate ν_i vs d (blue: unperturbed orbit; red/black circles: positive/negative perturbation). Right panel: temperature-to-electrostatic energy ratio T/Ne^2 vs d (same colour code).

malized to the trap radius R_w) is approximately linear. In the right panel, we show the effect of a quadrupole potential obtained applying voltages to the top and bottom sectors of the split electrode, which does not shift the rotation axis but imparts an elliptic deformation to the orbit. It is notable that, as opposed to the previous findings [14], the superposition of the RF drive and the multipolar field always makes the orbits span a smaller region in the trap cross section; furthermore, the new stable state is usually characterized by a different total electron charge.

This offset manipulation technique has been used to acquire useful information on other properties of the RFGEs, i.e. temperature and ionization rate, which are necessary to attempt a description and interpretation of the off-axis steady states. The ionization rate can be inferred from the axial flow of electrons escaping the confinement region while the RF drive is active. For a steady-state vortex, i.e. at constant charge (replenishment by ionization compensates axial loss of energetic electrons) and diocotron amplitude, the ionization rate must be $\nu_i = I_{\text{esc}}/Q_e$, where I_{esc} is the escaping electron current collected by the phosphor screen and Q_e the confined plasma charge. Using a static octupole deformation, we could obtain a perfectly circular diocotron orbit centered on the trap axis and thus measure ν_i as a function of the radial displacement. The results are summarized in Fig. 2. The left panel shows the fairly linear reduction of the orbit amplitude d versus the perturbation amplitude. The central panel shows the calculated ionization rate versus the orbit amplitude. In a wide region the trend is fairly monotonic and shows larger ionization at large radii, consistent with the fact that the RF field, hence the heating, is larger when closer to the wall. The two data points at smallest d correspond to highly-perturbed plasmas with

significant distortion of the escape-current signal, and their significance is debatable.

Due to the irregular variation in the column's total charge depending on the perturbation drive V_{pert} , the dependence of the ionization rate on the offset d alone may be an insufficient information as the heating is partially shielded by the space charge. A useful information is hence the ratio between the mean kinetic energy, or temperature T of the plasma and its electrostatic energy, which gives an indication on the heating efficiency for a given space-charge shielding. We inferred the T/Ne^2 parameter by the electrostatic measurement of the $l = 1$ diocotron mode frequency ω_1 . The latter, including the nonlinear corrections related to the normalized offset $d = D/R_w$, finite radius $r_p = R_p/R_w$, and non-zero temperature T and finite length L_p reads [15]:

$$\omega_1 = \left[\frac{enr_p^2}{2\pi\epsilon_0 B} \right] \left[1 + \frac{1 - 2r_p^2}{(1 - r_p^2)^2} d^2 \right] \left\{ 1 + \left[1.2025 \left(\frac{1}{4} - \ln r_p + \frac{T}{Ne^2} \right) - 0.671 \right] \frac{R_w}{L_p} \right\} \quad (1)$$

The right panel of Fig. 2 reports T/Ne^2 versus d . The data show a considerable spread, yet an ascending trend with d can be discerned, in rough agreement with the ionization rate data. While diagnostic limitations and a relative scarcity of consistent, repeatable data demand for more measurements, these results give a qualitative support to our interpretation [8] of the off-axis stability and modulation as a balance of the ion instability driving the plasma towards the wall and the offset-dependent charge variation of the vortex, which concurs to the damping of the mode instability by replenishing the plasma charge as the column drifts radially. A more extensive discussion of the model will be the subject of a forthcoming paper.

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