Dynamical equilibrium of a radio frequency-sustained electron plasma in a Penning-Malmberg trap

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Plasma sources are generally characterized by the use of high powers to induce a discharge in gases at relatively high pressures ($10^{-3} - 10$ mbar), features that in turn guarantee the generation and sustainment of high-density plasmas [1]. We have previously demonstrated [2] a different mechanism where a lower-density, pure electron plasma is generated and confined in the ELTRAP (ELectron TRAP) device [3], in ultra-high vacuum (UHV) conditions, by means of a low-power radio frequency (RF) drive on one of the trap electrodes.

ELTRAP is a Penning-Malmberg trap [4], i.e. a device where plasmas of a single sign of charge can in principle be indefinitely confined thanks to magneto- and electrostatic fields. In particular, ELTRAP (see Fig. 1) comprises a solenoid whose highly-homogeneous axial magnetic field up to 0.2 T provides radial confinement and a stack of ten coaxial cylindrical electrodes used to create a longitudinal electrostatic well of depth up to -100 V, which guarantees the axial trapping of the electron species. Electrodes S2 and S4 are azimuthally split into two and four sectors, respectively and can be used for excitation as well as detection of azimuthally-asymmetric plasma modes. The whole device is placed in a UHV chamber with a residual gas pressure permanently kept in the $10^{-9} - 10^{-8}$ mbar range. No gas inlet at higher pressures is present. Our previous investigations showed that an electron column can be generated and confined by RF stochastic heating and impact ionization if a sinusoidal excitation of amplitude $1 - 10$ V and within a frequency range of $1 - 20$ MHz is applied on any of the inner electrodes while maintaining a negative confining potential $|V_C| \geq 80$ V on electrodes C1 and C8 [2, 5]. After few seconds of continuous RF excitation the total charge confined in the trap reaches values up to 1.5 nC due to the net balance between ionization and losses. The optical diagnostics shows that the formation of plasma is stronger in the vicinity of the inner electrodes' surface but then the plasma fills the transverse cross-section within some hundred milliseconds. For some choices of the RF and geometrical trap parameters the plasma can be compressed into a denser column of radius much smaller than that of the electrodes. With densities of $10^6 - 10^7$ cm^{-3}, this plasma is equivalent to those produced by conventional thermo- or field emission. Although compression phenomena can take place for any choice of the electrode of RF application, they are more easily obtained when the RF drive is applied on two opposite

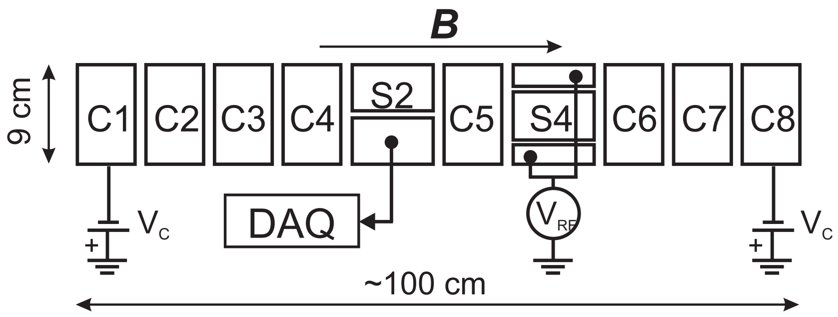

Figure 1: Sketch of the experimental set-up. A confinement potential V_C up to -100 V is applied on electrodes C1 and C8. All 'C' electrodes are 9 cm long. Electrodes S2 and S4 (of length 15 cm) are azimuthally split into two and four sectors, respectively. The excitation drive is applied on two opposite sectors of the S4 electrode. Electrostatic signals induced by plasma motions on one S2 sector are detected with a digital acquisition system.

sectors of the S4 electrode. This supports the hypothesis that compression is due to coupling between axial and transverse-plane plasma modes.

The 'squeezed' plasma column is generally not centered on the magnetic axis and therefore exhibits an $l = 1$ diocotron mode. This mode would grow exponentially leading to a complete loss of plasma on the electrodes' surface if the excitation were turned off. In particular, the application of an azimuthally-asymmetric resistive load on the circular electrode boundary is known to cause an exponential instability of the $l = 1$ mode [6]. On the contrary, while the RF excitation is maintained a dynamical equilibrium sets in and this mode is stable. Moreover, the system reacts to a perturbation with a damped oscillation around the equilibrium condition. The parameters of this experiment are as follows. The magnetic field strength is 751 G and the base pressure $4.2 \cdot 10^{-9}$ mbar. A RF drive of frequency 14 MHz and peak-to-peak amplitude 5 V_{pp} is continuously applied on two opposite patches of the S4 electrode. Resistive loads R_L between 0.5 to 9 kΩ are connected to an S2 sector to enhance the $l = 1$ instability. The $l = 1$ frequency ν_1 of the column is detected from the electrostatic signal induced on the other S2 sector.

A typical example is shown in Fig. 2, where $R_L = 1$ kΩ. A short-time Fourier transform is applied to the signal and the frequency ν_1(upper panel) and power P_1 (lower panel) of the $l = 1$ peak are extracted. Initially the system is in dynamic equilibrium and we can see a stable $l = 1$ diocotron signal of frequency $\nu_1 = 6.80$ kHz. At a time $t = 1.65$ s an electric disturbance is applied to the plasma by varying the RF amplitude from 5 to 6 V_{pp} for 0.4 s, inducing an apparent perturbation in the diocotron signal. The signal envelope is modulated by an underdamped, very low-frequency oscillation $\nu_{LF} \simeq 5$ Hz, with a characteristic damping time of several several sec-

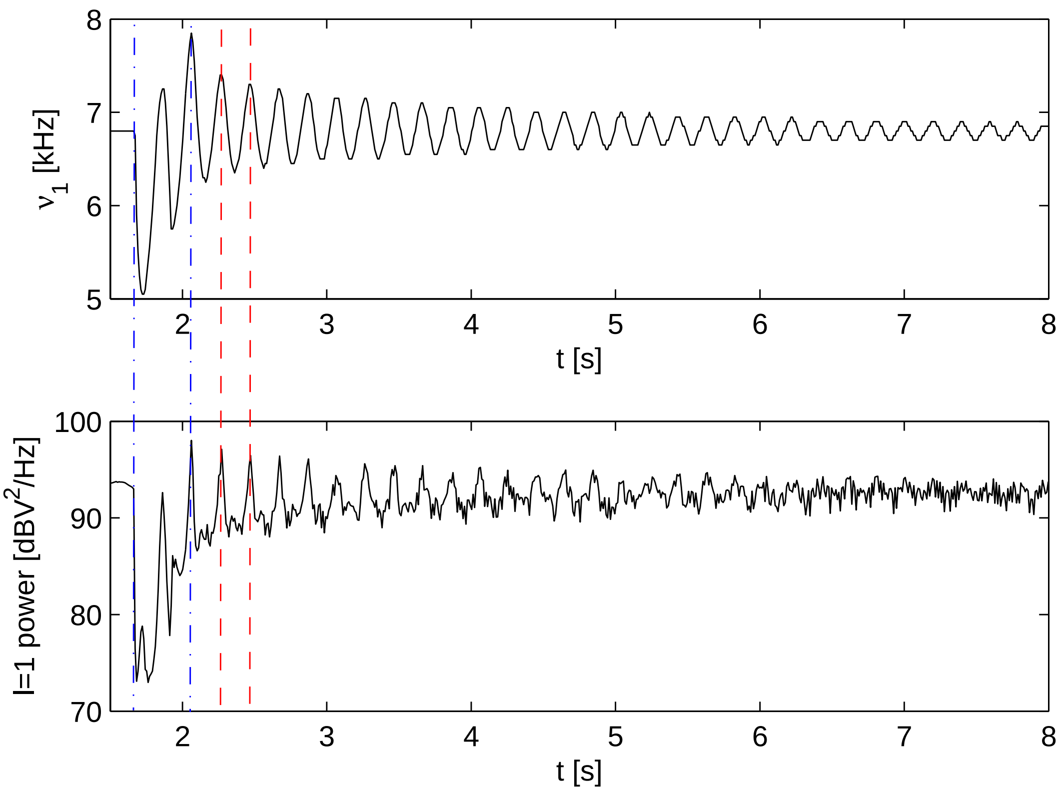

Figure 2: Electrostatic signal of the $l = 1$ diocotron mode (excerpt). A short-time Fourier transform is applied to the induced signal and the frequency ν_1(upper panel) and power (lower panel) of the $l = 1$ peak are extracted. Blue dash-dotted lines indicate the 0.4 s time span of impulsive disturbance, starting at $t = 1.65$ s. Both frequency and amplitude of the mode show a damped oscillation. Red dashed lines indicate the oscillation period over which we plot the power versus frequency in Fig. 3.

onds. Figure 2 shows that this oscillation is present both in terms of frequency and amplitude. The periodic modulations of ν_1 and P_1 maintain a constant phase over the whole time evolution, in particular peaks in frequency and amplitude are in phase. The left diagram of Fig. 3 shows this phase relation plotting P_1 versus ν_1 over a period. As the perturbation is damped the values of the curve trend change but the slope is qualitatively the same. For increasing values of R_L we observe that the modulation amplitude is reduced and faster damped. We also notice (see right panel of Fig. 3) the presence of a trend of ν_{LF} versus R_L which can be fit with the power-law function $\nu_{LF} = a \cdot R_L^{\gamma} + b$, where $a = 1.11 \cdot 10^{-3}$, $\gamma = 0.67$ and $b = 4.97$.

These phenomena can be partially interpreted with a simplified dynamical model considering the balance of the forces acting on the plasma column, treated as a rigid rod of charge. The

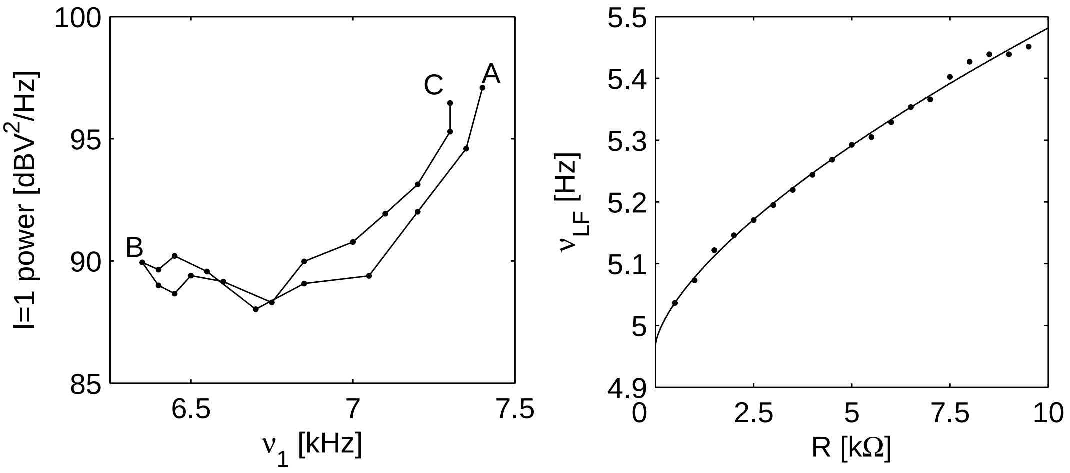

Figure 3: Left: Frequency versus power of the perturbed $l = 1$ diocotron mode (excerpt). Their phase relation over a period (see Fig. 2) is shown. A is the starting point, B the point at half period, C the final point. Right: Diocotron modulation frequency versus destabilization resistance. The perturbed $l = 1$ mode frequency ν_1 oscillates at a frequency ν_{LF}. The solid line is a power-law fit with exponent 0.67 of ν_{LF} versus the applied destabilization load R_L.

model will be thoroughly discussed in a forthcoming paper. In brief, as the electric disturbance causes a perturbation of the column from the equilibrium condition, the balance between continuous production and loss of charge is altered, resulting in a return towards the unperturbed equilibrium, in terms of the offset as well as of the quantity of confined charge. The periodic variation of these quantities is therefore reflected in the modulated diocotron signal.

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