Non-resonant radio frequency control of the m=1 diocotron instability in a Malmberg-Penning trap

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Malmberg-Penning traps [1] are routinely used for the confinement of nonneutral plasmas by the superimposition of a homogeneous, axially-directed magnetic field with a static electric field obtained applying proper potentials to a stack of coaxial cylindrical electrodes in ultra-high vacuum (UHV). In these conditions the evolution of an electron plasma column can be followed for several seconds. Averaging over the axial bounce, the system can be considered essentially two-dimensional (2D) and the transverse, $\vec{E} \times \vec{B}$-drift dominated motion is isomorphic to that of a 2D incompressible inviscid fluid. Instabilities can arise as a consequence of density perturbations called diocotron modes which have a spatial dependence of the type $\exp(im\theta)$, with $m = 1, 2, ...$ In particular, the $m = 1$ mode is a rigid off-axis rotation of the plasma with frequency

$$\omega_1 = \frac{\omega_d}{1 - D^2/R_W^2}, \tag{1}$$

with D the displacement from the center, R_W the inner radius of the trap cylinders and ω_d the diocotron frequency $\omega_d \equiv \lambda_p / 2\pi\varepsilon_o B R_W^2$. Here λ_p is the plasma line density and B the magnetic field strength. Contrary to the algebraic instability predicted by the linear theory [2], experiments have shown an exponential growth of the plasma displacement leading to a progressive loss of particles on the electrodes' surface. The instability can be triggered by several reasons, e.g. presence of ions [3], application of an oscillating dipole excitation in resonance with ω_1 on a twofold split electrode, application of a resistive load on a sector of a split electrode [4].

Several manipulation techniques have been developed to control instabilities and improve the plasma confinement, like the so-called rotating-wall technique, where the plasma is radially compressed by a rotating electric field [5]. Here we present a different mechanism based on a non-resonant, high-frequency drive on a sectored electrode. The mechanism relies on the principle of the effective force created by a rapidly oscillating potential with vanishing time average, as in Kapitza's inverted pendulum [6] or in the Paul Radio-Frequency (RF) quadrupole ion trap [7]. If the oscillation frequency is much higher than the typical frequency of the phenomenon of interest (here, ω_1) the dynamics of the system is determined by a time-independent effective potential which is proportional to the square of the periodic field's amplitude.

The experiments reported here have been performed on the Malmberg-Penning trap EL-

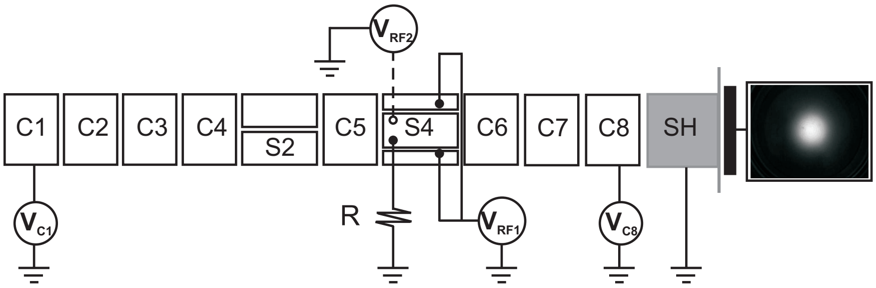

Figure 1: Sketch of the ELTRAP set-up. The electron plasma is confined by applying negative potentials on two of the ten cylindrical electrodes (C1-C8 plus S2 and S4, azimuthally two- and fourfold sectored, respectively). The additional electrode SH (in gray) is a permanently grounded shield for the phosphor screen on the extreme right.

TRAP [8], sketched in Fig. 1. Ten electrodes of 90 mm diameter are placed in a UHV chamber with a base pressure in the 10^{-9} mbar range, surrounded by a solenoid yielding an axial magnetic field up to 0.2 T. Electrodes C1 to C8 are 90 mm long while electrodes S2 and S4 are 150 mm long and are split into two and four azimuthal sectors, respectively, allowing for asymmetric excitation and detection of modes in the transverse plane. Any pair of electrodes can be chosen to confine the plasma in between by biasing to static potentials up to -100 V. The plasma is produced with a novel mechanism [9] where a sinusoidal drive V_{RF1} of few volts is applied on two opposite sectors of the S4 electrode (see Fig. 1) for some seconds to ionize the residual gas. An electron plasma column with a density of 10^6-10^7 cm^{-3} is produced. The RF drive is then turned off to let the plasma evolve freely.

In the first experiment the plasma was produced applying for 5 s a drive V_{RF1} on two opposite sectors of the S4 electrode and confined between electrodes C1 and C8 biased at -80 V. The magnetic field was 0.1 T and the pressure $3.5\cdot10^{-9}$ mbar. A resistance of 2 kΩ connected to another S4 sector induced a growth of the $m=1$ mode of initial frequency $\omega_1 \simeq 2\pi\cdot 21$ kHz. After turning off V_{RF1} a stabilizing drive V_{RF2} of amplitude of 3.5 $\mathrm{V_{pp}}$ was applied on the fourth S4 patch. After 1 s the plasma was dumped on the phosphor screen and the center of charge was computed from the image recorded by a Charge-Coupled Device (CCD) camera (see Fig. 2). Several shots were taken for each frequency value of V_{RF2}. When no drive was applied, the center of charge reached a mean displacement from the magnetic axis of ~ 26 mm. On the contrary, for a large band of frequencies between 200 and 350 kHz the displacement was reduced to values between 7 and 11 mm.

Another experiment was performed where the evolution was followed via electrostatic diagnostics and the influence of both RF frequency and amplitude were systematically investigated.

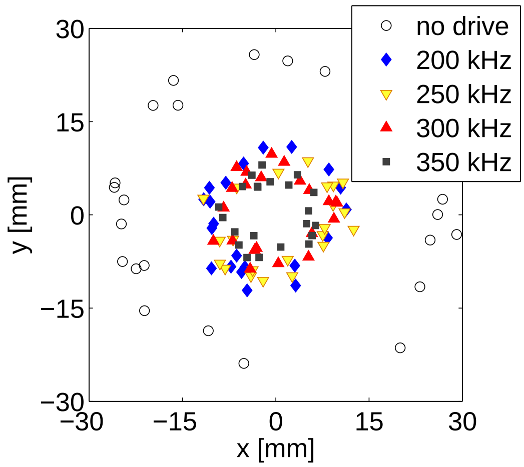

Figure 2: Center of charge of the plasma column after 1 s of stabilizing RF drive at different frequencies and constant amplitude 3.5 V_{pp}. Each point has been computed dumping the plasma on the phosphor screen and recording the image with a CCD camera.

The plasma was generated with 9 s of continuous RF ionization under slightly different conditions with respect to Fig. 1: confinement between C4 and C8 cylinders biased at -80 V, $B = 0.085$ T, pressure $3.2 \cdot 10^{-9}$ mbar. A load of 200 kΩ connected to an S2 patch induced an $m = 1$ mode of initial frequency $\omega_1 \simeq 2\pi \cdot 37.5$ kHz. The stabilizing drive was applied for 0.5 s and later turned off to observe the subsequent free evolution, followed recording the current signals induced on the other S2 sector by the rotating column. Fig. 3 shows the signal amplitude (average over 50 cycles) obtained with a drive of varying amplitude and 400 kHz frequency in the upper panel, and with different frequencies at 2 V_{pp} in the lower panel, respectively. In both subfigures, the black curve shows the free evolution without stabilizing drive. There is a rapid growth until the plasma starts to lose particles on the electrode surface. The signal amplitude continues to grow despite the losses until the bulk of the column approaches the wall, and then rapidly drops. After about 1 s there is no plasma left in the chamber.

When a stabilizing drive is applied, the mode amplitude has a rapid decrease. When the drive is turned off, the amplitude grows again, indicating that the plasma is still present and the radial drift grows again when left free to evolve. Drives below 1 V_{pp} have scarce or no effect at all, while in the range $1.5 - 2.5$ V_{pp} more than half of the sample is successfully confined. In the frequency systematic study at a constant amplitude of 2 V_{pp} we observe that for a 120 kHz drive the effect is still weak, but for higher frequencies the amplitude peak reaches 50 to 75% of the free-evolution peak, i.e. a consistent fraction of the plasma has been confined. One can notice that there is no apparent trend with the frequency: this just has to be ‘sufficiently high’ to

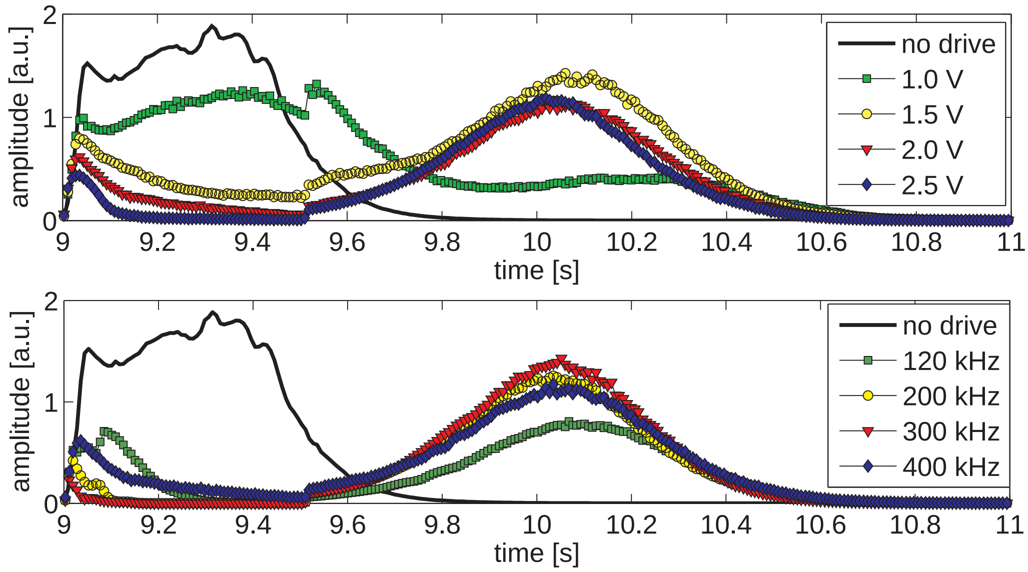

Figure 3: Electrostatic signal of the $m = 1$ diocotron mode induced on an S2 electrode sector with stabilizing RF drives of frequency 400 kHz and different amplitudes (top) or constant amplitude 2 V_{pp} and varying frequency (bottom). The record starts at $t = 9$ s, after the generation of the plasma column. The drive is applied for 0.5 s and then the plasma evolves freely.

achieve a better confinement for almost 1 s longer.

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