Decay of the Diocotron Rotation and Transport in a New Low-Density Asymmetry-Dominated Regime

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The decay of the diocotron rotation was studied in a new regime in which trap asymmetries dominate. Decay within a few diocotron periods was observed, sometimes orders of magnitude faster than predicted by the traditional ''rotational pumping'' theory. The decay does not conserve angular momentum, and is strongest for small, low-density columns. The new regime appears when ''magnetron-like'' rotation from the end confinement fields becomes dominant, and appears to be associated with errors in these fields. Transition to decay dominated by rotational pumping was observed for larger and denser columns. The asymmetry-dominated transport was also studied, and found to depend linearly on the line density (and not the density) over nearly 4 orders of magnitude.

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The $l = 1$ diocotron mode of non-neutral plasmas in Malmberg-Penning traps has been studied for more than 20 years [1–5]. The mode consists of the bulk rotation of the off axis charged plasma around the trap axis. Usually the diocotron is a long-lived mode, typically taking 10^4–10^5 rotations to damp. Several years ago, the damping was analyzed within the ''rotational pumping'' paradigm [3,4]. Rotational pumping results from the rotation of the trapped electron column around its own axis, which causes length changes when the column is shifted off axis. In the presence of collisions, these length changes irreversibly transfer electrostatic energy to thermal energy. The continuing loss of electrostatic energy results in the steady expansion of the plasma. But as these processes conserve angular momentum, this expansion must be compensated by the plasma moving towards the trap axis, thereby damping the diocotron mode.

In this work we describe a new regime of damping and transport for which most of the predictions of rotational pumping theory do not hold. This regime is characterized by very fast damping of the diocotron mode, with no conservation of angular momentum. The damping is especially strong for small, low-density columns, where the damping time can be as short as just a few rotations around the trap axis. Our experiments associate this damping with asymmetries of the end confinement fields, probably due to misalignment of the end confining cylinders with the central cylinder.

Most of the experiments presented here were performed with the photocathode Malmberg-Penning trap at U.C. Berkeley [6]. The trap consists of three cylinders of radius $R_w = 20$ mm. The two end confinement cylinders (the ''inject'' cylinder and the ''dump'' cylinder) are 80 mm long. The ''central'' cylinder where the electrons are trapped is 200 mm long. There are no sectors to drive or damp the diocotron mode. The trapped plasma electrons are diagnosed primarily by dumping the electrons onto a phosphor screen, and capturing the resultant image with a 1024×1024 CCD nitrogen-cooled camera.

The experiments described here used electron columns with initial radius R_p of 1, 2, or 4.5 mm. These radii are small compared with the wall radius R_w. Small R_p, combined with low density, is what distinguishes these experiments from previous studies of diocotron damping. The electron densities in our experiments were 1×10^6—$4 \times 10^7 \mathrm{cm}^{-3}$, and their temperature was typically 0.5 eV. For plasma potentials V_p (the potential in the center of the electron column) of less than 8 V, confinement voltages of 20 V were used; for higher plasma potentials the ratio between the plasma potential and the confinement voltages was 0.4. Unless otherwise noted, all the photocathode machine experiments described below were performed in 3 T magnetic fields.

Fast damping of the diocotron mode was observed for small and low-density electron columns. Figure 1 shows the trajectory of the center-of-mass of such a column with an initial radius of 1 mm, and an initial maximum density of 1.2×10^6 cm^{-3}. The initial displacement from the center was 2.5 mm (0.125 R_w). The decay of the diocotron mode was exponential, with a time constant of 204 ms (about four diocotron periods). Figure 1(b) shows that while the decay is very close to being purely exponential, some oscillations with the periodicity of the diocotron mode can be observed.

The damping time τ_d of the diocotron mode depends on both the density and the size of the electron columns. (We define τ_d as the time it takes for the displacement from the center to decrease to half its initial value.) Figure 2 shows the damping time τ_d for columns with $R_p = 1$, 2, and 4.5 mm. The same data points are presented as function of density (Fig. 2(a)), and plasma potential (Fig. 2(b)). For most of the data, τ_d increases linearly with density. The

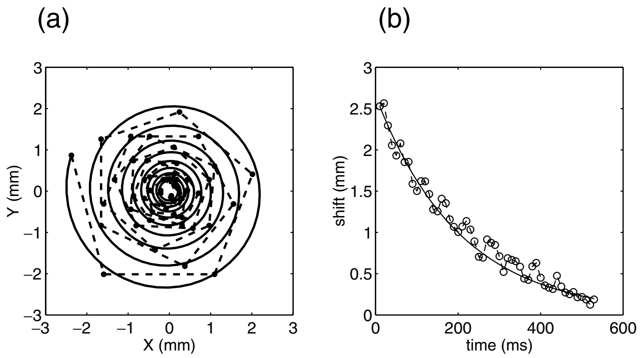

FIG. 1. (a) The trajectory of the center-of-mass of a $R_p = 1$ mm column during ten rotations. The dashed lines connect the points in time sequence, while the solid line plots the best-fit decaying exponential spiral. (b) Distance of the column center-of-mass from the trap axis vs time. The solid line is a best-fit to an exponential decay.

damping time τ_d becomes independent of density only for the higher density, 4.5 mm columns. Plasma potential better predicts τ_d than plasma density: the 1 and 2 mm columns with similar plasma potentials have similar τ_d. The dependence on size and density shown in Fig. 2 differs from that found in the previous experiments [3] that were explained by the rotational pumping theory [4]. The damping rate in the new regime decreases for larger and denser columns, while in the rotational pumping regime, it increases strongly for larger columns, and is approximately independent of the density. The data points for the 4.5 mm columns show the transition between two different regimes: for low density, with V_p well below 10 V, the damping time increases linearly with plasma potential. For denser columns, however, the damping becomes independent of plasma potential. The damping time of nearly 40 s for the higher density 4.5 mm columns is in accordance with rotational pumping theory predictions [4].

These observations suggest that, in addition to rotational pumping damping, a new damping mechanism affects small low-density columns. While rotational pumping is weak for small columns, the new regime is insensitive to the size of the column if plasma potential is fixed. The diocotron mode of the 1 and 2 mm columns damps almost exclusively by the new mechanism, which becomes linearly weaker for higher plasma potential. The damping time for low-density 4.5 mm columns is lower than the extrapolation of the data for the small columns, showing the combined effects of the two decay mechanisms. For large and dense columns the damping due to the new mechanism is small, and rotational pumping dominates the damping for the higher density 4.5 mm columns.

Fast diocotron damping rates are associated with significant loss of angular momentum. Figure 3 follows the time evolution of the line density N_l, the displacement from the axis D, the root mean square radius of the electrons with respect to the column center $\langle r^2\rangle^{1/2}$, and the total angular momentum $D^2 + \langle r^2\rangle$ for two sets of experiments.

On the left side is the evolution characterizing a dense 4.5 mm column, showing behavior typical of rotational pumping: as the displacement goes down, the column expands so that the total angular momentum remains constant (or slightly increases). The measurements for a 2 mm column are shown on the right side. While the total number of electrons (line density) is still conserved, the total angular momentum is not: the expansion is small and is

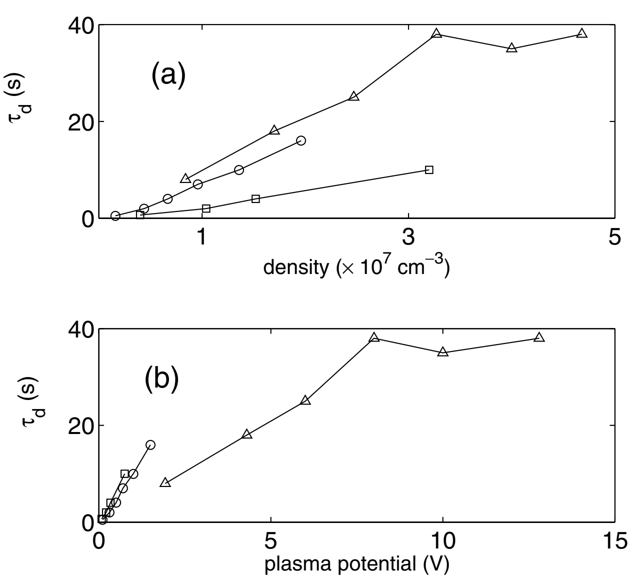

FIG. 2. Diocotron damping time for columns with initial $R_p = 1$ mm (squares), 2 mm (circles), and 4.5 mm (triangles). The same data points are presented as function of (a) density and (b) plasma potential.

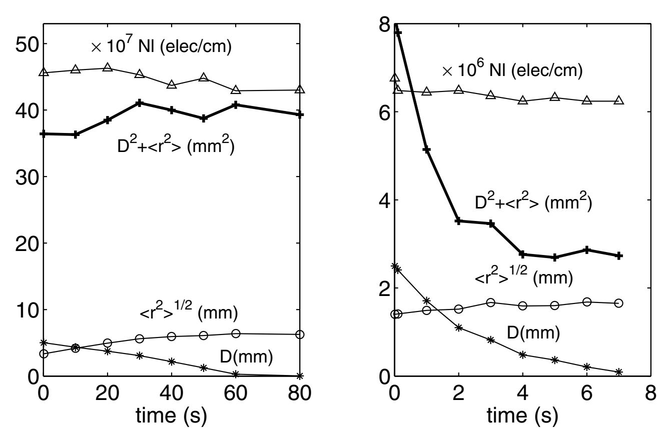

FIG. 3. Comparison of asymmetry-dominated diocotron decay (right) with a decay dominated by rotational pumping (left). Shown are the line density N_l, the displacement from the axis D, the root mean square radius of the electrons with respect to the column center $\langle r^2\rangle^{1/2}$, and the total angular momentum $L = D^2 + \langle r^2\rangle$. The new regime is characterized by nonconservation of angular momentum (thick line).

not sufficient to compensate for the decrease of displacement from the center.

Figure 4(a) shows the ratio of the final and initial angular momentum as a function of the number of rotations it took the mode to damp (the ‘‘final’’ angular momentum is for columns that reached the center). Loss of angular momentum was 50% or less for columns for which damping took at least thousands of rotations. When faster damping was observed (hundreds of rotations or less), most of the initial angular momentum was lost.

For columns which decay quickly and do not conserve angular momentum, the drift motion of the columns around the trap center is primarily caused by the radial electric fields from the confining electrodes (a ‘‘magnetron’’ effect). In contrast, for columns which decay slowly while conserving angular momentum, the drift motion around the trap center is primarily caused by the self-electric fields from the column image. Figure 4(b) demonstrates this by plotting the ratio of the observed diocotron period to that calculated for infinitely long columns having the same line density distribution as that of the actual columns. The data points are presented as a function of the same parameter that was used in Fig. 4(a) and show the same behavior: when the decay is fast and angular momentum is not conserved, end effects are important. When the decay is slow, end effects are negligible and angular momentum is conserved.

The transition between the two regimes is also accompanied by an observed shift of the position of the ‘‘center’’ around which the columns drift, and to which the columns finally settle. This shift is significant: up to 1.5 mm

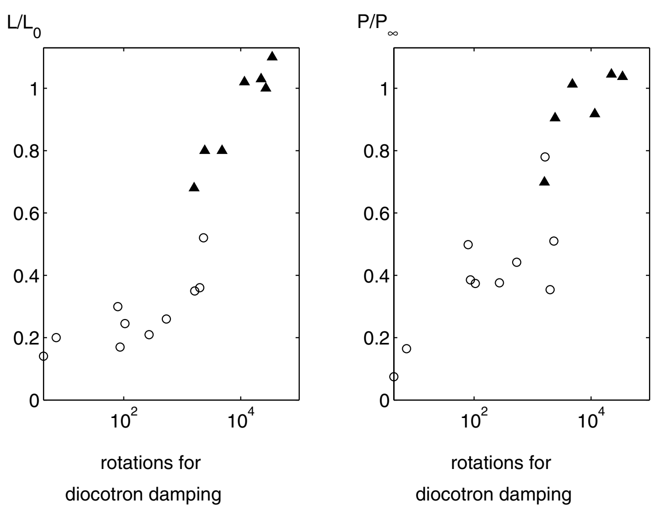

FIG. 4. (a) The angular momentum normalized by the initial angular momentum, and (b) the observed diocotron period normalized by the calculated diocotron period for an infinitely long column. Both curves are plotted against the number of rotations performed during a diocotron damping time τ_d. In both, data points for 2 mm columns are shown with circles, while data points for 4.5 mm columns are shown with triangles.

(0.075 R_w). Most of this shift coincides with the transition region, discussed above, between motion dominated by the image and motion dominated by the end fields. We found that the shift is more sensitive to changes in the end fields near the inject ring.

The shifts of the center are likely due to the misalignment of the end confining rings with respect to the central ring. ‘‘Strong’’ (large and dense) columns rotate around the center axis of the central ring because the columns primarily drift in the fields from the image charges induced on the walls of the center ring itself. On the other hand, ‘‘weak’’ (small and low-density) columns primarily drift in the end ‘‘magnetron’’ fields and, thus, are sensitive to the alignment of the end confinement rings.

The universality of the new regime was demonstrated in additional experiments performed with a conventional, spiral tungsten filament, low magnetic field machine. The size and density of the plasma in this machine were manipulated by varying the bias voltage of the filament, and initial displacements were actively introduced using available sector patches [7]. For the smaller and lower-density columns we observed shortening of the decay time (to hundreds of rotations), shifts of the center characterizing the motion of the column in the trap, and nonconservation of angular momentum. The latter, however, was less clear than in the photocathode machine because of changes in the measured total number of electrons.

With both machines we checked the effect of the magnetic field on the decay rate. We found that increasing the field increases the damping time for the smaller, lower-density columns. The results for the photocathode machine are shown in Fig. 5. For small ($R_p = 2$ mm) columns the decay time increased from 150 ms at 5 kG to 650 ms at 30 kG, in a somewhat weaker than a linear increase. On the other hand, τ_d for large ($R_p = 4.5$ mm) is independent of the magnetic field, as expected from a decay dominated by

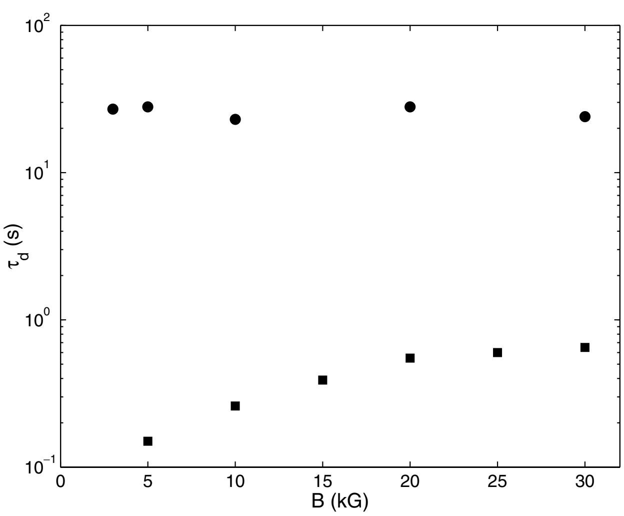

FIG. 5. τ_d vs magnetic field. Data points for 2 mm columns are given with squares, for 4.5 mm with circles.

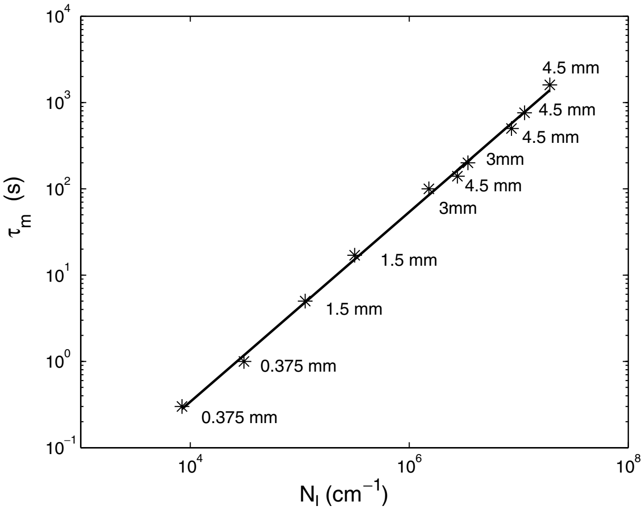

FIG. 6. Mobility time τ_m vs line density. Initial R_p is given for each data point.

rotational pumping. For both machines, the decay rate was only weakly sensitive to the steering angle of the magnetic field, even for steering angle tilts of several mrad that caused shifts of the ‘‘center’’ which were larger than that observed when using columns with different plasma potentials. (Shifts from different plasma potentials are likely associated with electric errors.) Finally, in both machines we found that increasing the background gas pressure by two to 3 orders of magnitude did not cause significant changes in the decay rate of the diocotron mode.

We have seen that transport for off axis columns depends on integral measures such as the plasma potential. For on axis columns the transport is often quantified in terms of the mobility time τ_m, the time over which the central density decreases to half its initial value. Recently, it was found that τ_m for on axis ‘‘rigid’’ columns depends linearly on density, but only same-size columns were compared [8] in that study. We also studied the transport for on axis columns for columns of different size, from tiny, $R_p = 0.375$ mm columns, up to $R_p = 4.5$ mm columns. We found that τ_m depends nearly linearly on the line density for more than 3 orders of magnitude, as shown in Fig. 6.

In summary, the new damping regime is found to differ from the known rotational pumping regime in almost every aspect. In the transition region between the rotational pumping regime and the new regime of increased damping the end confining fields start to dominate the rotation of the column in the trap, the center around which the columns rotate and finally settle shifts, and angular momentum is not conserved. All these phenomena suggest that asymmetries in the end confining fields are responsible for the increased damping. This conclusion is somewhat surprising, because asymmetries generally expand plasmas, transporting particles away from the trap center. The observed change in the angular momentum is opposite in sign to that resulting from a torque that acts as a drag on the plasma. A similar issue arises with the influence of background gas on diocotron damping. Typically, the background gas causes the plasma to expand. Nonetheless, Chao *et al.* [5] demonstrated increased diocotron damping for higher background pressure.

The mechanism by which asymmetries might cause increased damping of the diocotron mode is not yet clear and should be studied further. Length changes connected with the motion in the nonsymmetric trap might contribute to the damping. Kabantsev [9] recently suggested that edge trapped electrons might induce damping, but his suggestion is not compatible with the observed insensitivity to magnetic tilt and the decrease of the angular momentum in our experiments. We believe the effects we see are universal in the sense that all traps have some inherent asymmetries, and these asymmetries will cause damping of the diocotron mode for columns with sufficiently low plasma potential.

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