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

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Abstract. The decay of the diocotron rotation was studied in a new regime in which trap asymmetries dominate. The decay does not conserve angular momentum, and is strongest for small, low-density columns. For such columns decay of the diocotron mode within few diocotron periods was observed, orders of magnitude faster than the rotational pumping prediction. However, transition to decay dominated by rotational pumping was observed for larger and denser columns. The new regime is characterized by "magnetron-like" rotation in the trap, dominated by the end confinement fields. 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.

INTRODUCTION

The l=1 diocotron mode of non-neutral plasmas in Malmberg-Penning traps have been studied for more than 20 years [1]. Usually it has been observed to be a long-lived mode, with 10^4-10^5 rotations as a typical damping time. Several years ago, the damping was studied and understood within the "rotational damping" paradigm [2,3]. 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, and the damping time can be as short as few rotations around the trap axis. There is a solid experimental basis to associate this damping with asymmetries of the end confinement fields, probably due to misalignment of the end confining cylinders with the central cylinder.

However, the appearance of this new regime is not a characteristic of a particular machine. Rather, it is the properties of the trapped electron column that determine whether the diocotron mode is damped due to the rotational pumping mechanism or due to the new asymmetry-dominated mechanism. With the photo-cathode machine, where the new regime was first explored, we were able to retrieve a typical "rotational pumping" behavior for columns that were big and dense enough. And with a second trap, we similarly found the properties of the new regime when we studied sufficiently small and rarified plasma columns.

In this paper we report on the characteristics of the new regime and contrast them with the behavior typical of rotational pumping. Transport in this asymmetry-dominated regime is also discussed. Using different-size columns, we found that the mobility time t_m depends linearly on the line density (and not the density) over nearly 4 orders of magnitude.

While there is a solid experimental data basis for characterizing the new regime as a magnetron-like, asymmetry-dominated, low-density regime, more work needs to be done theoretically to study the mechanism by which these asymmetries cause the fast damping of the diocotron mode.

EXPERIMENTAL SYSTEM

Most of the experiments presented here were done with the photo-cathode machine of UC Berkeley[4]. The trap consists of just three cylinders, of radius R_w=20 mm. The two end confinement cylinders (the “inject” cylinder and the “dump” cylinder) are 8 cm long. The “central” cylinder where the electrons are trapped is 20 cm long. There are no sectors to drive, damp or even listen to the diocotron mode.

The photo cathode machine allows great flexibility in choosing the initial distribution of the electrons. Here this flexibility was used to control two parameters: the size of the column and its initial displacement from the trap axis. Control of the column density is obtained by changing the illumination level of the photo cathode (changing the voltage driving the halogen light source) and by changing the bias level of the photo cathode with respect to the grounded central cylinder. Either the illumination level or the photo cathode bias level can limit the density of the electron columns: the former by determining the number of available electrons emitted from the photo cathode, the latter due to space charge effects. When space charge effects dominate, the bias of the photo cathode is approximately equal to the potential at the center of the resulting electron column. We will refer to this potential as the “plasma potential” or Vp.

The experiments described here were performed with electron columns with initial radius R_p of 1, 2 or 4.5 mm. These will be referred to, according with their diameters, as 2, 4 or 9 mm columns. These radii are small compared with the wall radius R_w. The small radius, combined with low density, is what distinguishes the experiments described here from previous studies of the diocotron damping. The electron densities in our experiments were 10^6-4×10^7 cm^{-3}.

A 3T-superconducting magnet produces the axial magnetic field required for the trap. Unless noted otherwise, all the photo-cathode machine experiments described below were performed at 3T field.

The diagnostics of the trapped electrons is obtained by dumping them on a phosphor screen, and imaging the screen with a 1024×1024 CCD nitrogen-cooled camera. Almost all of the data analyzed in this work was obtained using these images.

Gradually damping the electrons and measuring the current to the phosphor screen enabled a crude measurement of the electron temperature. A typical temperature of our trapped electrons was 0.5 eV. With plasma potentials of typically less than 2 V (unless otherwise noted), confinement voltages of 20 V were enough to well-confine the electron columns.

To verify that the observations of a new damping regime are "universal" and not particular to a specific machine, we also performed experiments with a second machine. Here a spiral filament produces the electrons and the magnetic field, produced by a water-cooled coil, is limited to 1500 G. Some control on the size and density of the electron columns in this machine is possible by using different bias voltages for the filament. By such technique we observed the diocotron damping for columns with radii of 3 to 11 mm (R_w=19.05 mm), and densities of 10^6-4×10^7 cm^{-3}.

CHARACTERISTICS OF THE NEW REGIME

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 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 4 diocotron periods). Figure 1(b) shows that while the decay is very close to being an exponential one, some oscillations with the periodicity of the diocotron mode can be observed.

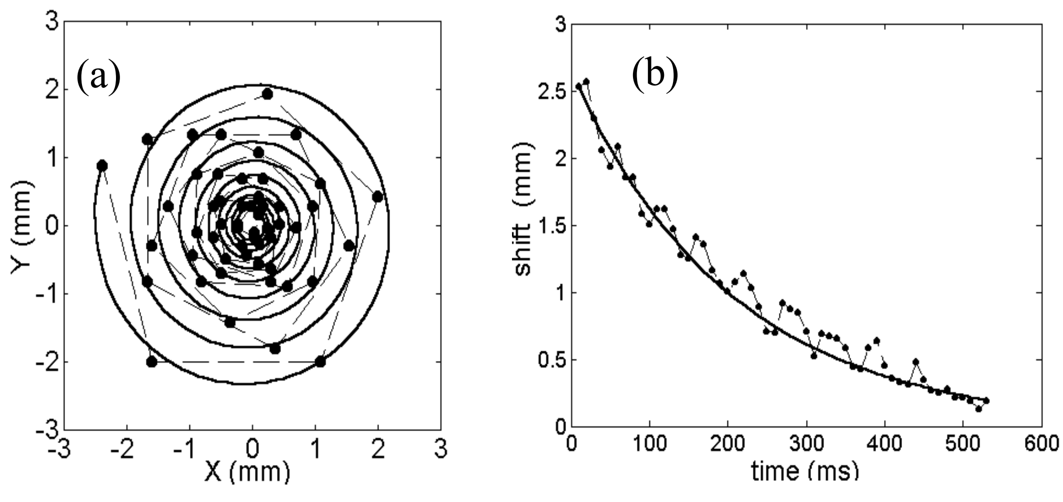

FIGURE 1. a) The trajectory of the center-of-mass of a small and low density electron column. b) The distance from the center as function of time. The solid line is a best-fit to an exponential decay.

The damping time τ_d of the diocotron mode was found to depend on both the density and the size of the electron columns. Here we shall 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 2 and 4 mm columns. . The same data is presented as function of four different parameters characterizing the columns: density (Fig. 2a), line density (Fig. 2b), diocotron period (Fig. 2c) and plasma potential (Fig. 2d). It can be seen that for both the 2 mm and the 4 mm columns, τ_d increases linearly with density, line density and plasma potential. However, density is an inadequate parameter to predict τ_d : higher density 2 mm columns can have smaller τ_d than lower density 4 mm columns. Line density (Fig. 2b) is a better predictor, but the best predictors for τ_d are the diocotron period or the plasma potential. 2 mm and the 4 mm columns having similar diocotron periods or similar plasma potentials have also very similar τ_d.

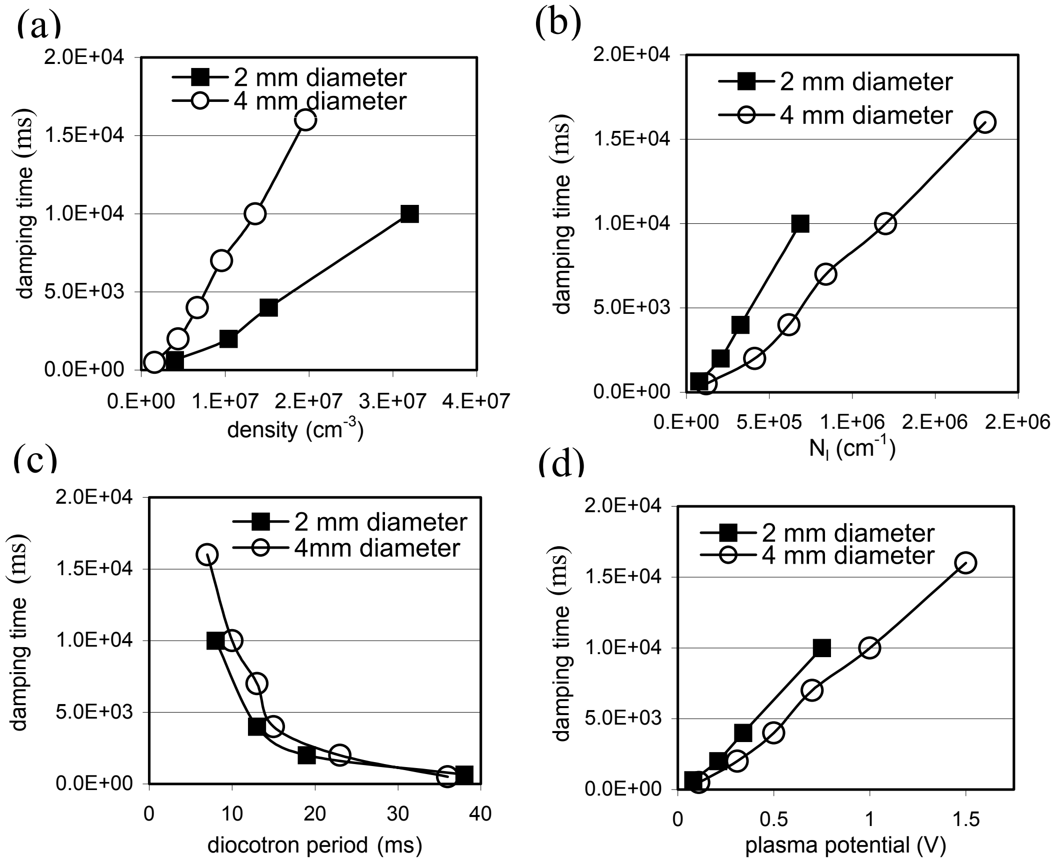

FIGURE 2. Diocotron damping time for columns with initial diameter of 2 and 4 mm. The same data is presented as function of four different parameters characterizing the columns: density, line density, diocotron period and plasma potential.

The dependence on size and density (or on plasma potential) shown in Fig. 2 is very different from the dependence that was found in previous experiments [2] that could be explained by the rotational pumping theory [3]. 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.

We found that we could obtain diocotron damping following closely the predictions of rotational pumping theory when we started with larger and denser electron columns than those of Fig. 2. Figure 3 presents the results of experiments with 9 mm columns, together with the previously discussed results for the 2 and the 4 mm columns. Since plasma potential proved to be a useful parameter for determining the damping rate for the smaller columns, we continue to use it as the parameter to characterizes the columns.

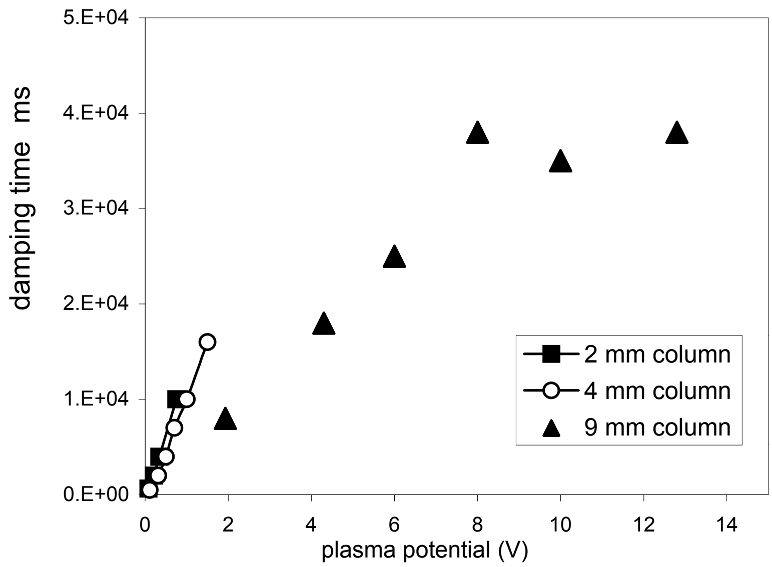

FIGURE 3. Comparison of the diocotron damping time vs. the plasma potential for columns with initial diameter of 2, 4 and 9 mm.

The data for the 9 mm columns in Fig. 3 show the transition between two different regimes: for low density 9 mm columns, with V_p well below 10 V, the damping time increases linearly with plasma potential. For the denser 9 mm columns, however, the damping becomes independent of plasma potential. The damping time of nearly 40 s for the higher density 9 mm columns is in accordance with rotational pumping theory predictions[3]. All the data in Fig. 3 were taken with confinement voltages V_c of 20 V, except for the 2 rightmost points for which a ratio of 0.4 was kept between the plasma potential and the V_c, leading to the use of V_c of 25 and 30 V, respectively (similar transition is observed for constant ratio V_p/V_c=0.4 for all the 9 mm points, but we chose to present the V_c=20 V data for lower V_p to enable comparison with data for the smaller columns).

The data suggests that the two regimes are dominated by two different and independent mechanisms for the damping of the diocotron rotation. The diocotron mode of the 2 and the 4 mm columns damp almost exclusively by a new mechanism. For large and dense columns this new mechanism becomes weak, while the larger size makes the rotational pumping mechanism strong. The damping for low-density 9 mm columns is lower than the extrapolation of the data for the small columns, showing the combined effects of the two decay mechanisms.

COMPARISON OF THE NEW REGIME AND ROTATIONAL PUMPING

There are important aspects in which the behavior of the new regime is different from that of rotational pumping. The most important one is the lack of conservation of angular momentum in the new regime. Figure 4 follows the evolution in time of the total number of electrons, the displacement from the axis D, the root mean square radius of the electrons with respect to the column center $< r^2 >^{1/2}$, and the total angular momentum $D^2 + < r^2 >$ for two sets of experiments. On the right side is the evolution characterizing a dense 9 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 even slightly increases). The data on the left side is for a 4 mm column. While the total number of electrons is still conserved, the total angular momentum is definitely not: the expansion is small and is not sufficient to compensate for the decrease of displacement from the center.

Grouping together the data for many sets of experiments, it can be seen that fast damping rate of the diocotron mode is associated with significant loss of angular momentum. Figure 5a shows the ratio of the final and initial angular momentum as 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 less than half of the initial value for columns for which damping took al least thousands of rotations. When faster damping was observed (hundreds of rotations or less), most of the initial angular momentum was lost.

For the experiments where fast, non-angular-momentum-conserving decay was observed, most of the motion of the columns around the center of the trap was caused by the radial fields near the confining electrodes (a "magnetron" effect). This is to be contrasted by the motion of columns for which slow, angular-momentum conserving decay of the diocotron mode was observed. For the latter, it is the interaction with the image charges that is responsible for the drift motion in the trap. Figure 5b demonstrates this by showing 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 are presented as function of the same parameter that was used in Figure 5a: the number of rotations it took the diocotron mode to damp. The figure looks very much like Fig 5a: when the decay is fast, end effects are important and angular momentum is not conserved. When the decay is slow, end effect are negligible and angular momentum is conserved.

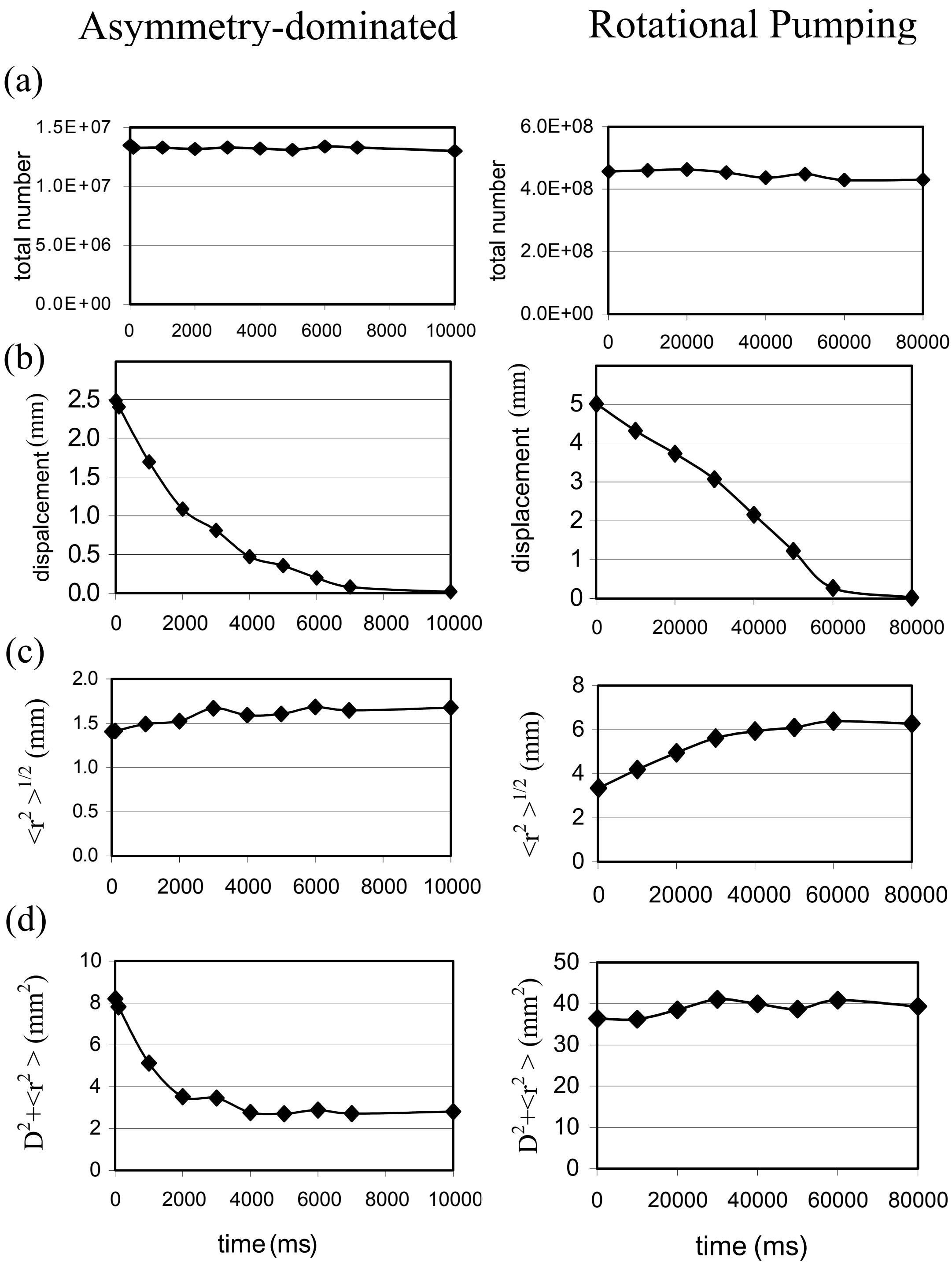

FIGURE 4. Comparison of asymmetry-dominated diocotron decay (left) with a decay dominated by rotational pumping (right). The new regime is characterized by non-conservation of angular momentum (Figure 4d, see text).

The transition between the two regimes is accompanied by one more phenomenon: observed shifts of the position of the "center" around which the columns drift, and on which they finally settle[5]. This shift is significant: up to 1.5 mm (0.075 R_w). Most of this shift coincides with the transition region shown in Fig. 5. Thus it coincides with the transition to higher significance of the end confinement fields and to non-conservation of angular momentum. It can be understood if one assumes that the end confinement rings are misaligned with the center ring. We verified that the shift is more sensitive to changed in the end fields near the "inject" ring, where presumably the misalignment is larger.

Putting all the pieces of the puzzle together, we can now characterize the new regime of fast diocotron damping. It is dominated by asymmetries in the end confinement fields that lead to non-conservation of angular momentum.

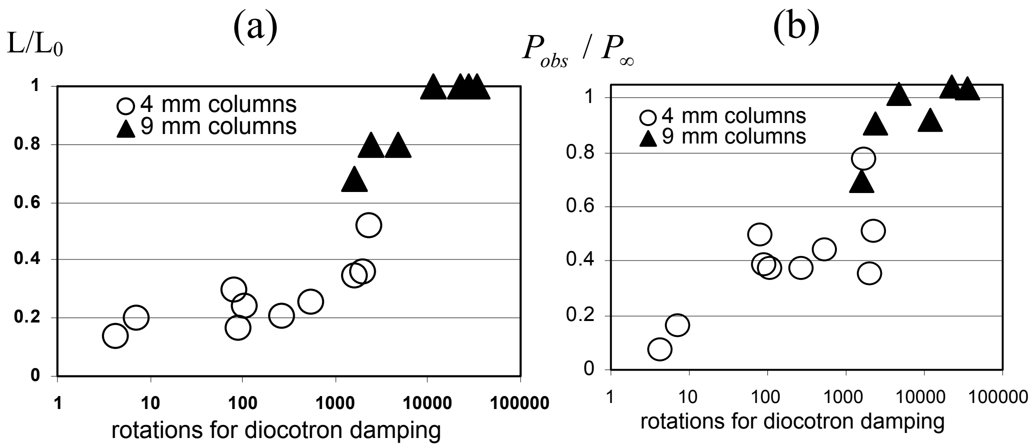

FIGURE 5. (a) level of non-conservation of angular momentum. (b) observed diocotron period relative to the period for an infinitely long column- both vs. the number of rotations for damping of the diocotron mode.

ASYMMETRY-DOMINATED TRANSPORT

The expansion rate observed for off-axis columns is much larger in our experiments than that of on-axis columns, and it increases for larger initial displacements. This holds for both the rotational pumping regime and the asymmetry regime. However, the expansion rate was more substantial in the rotational pumping regime. In that regime it was large enough to compensate for the damping of the diocotron mode in terms of the conservation of angular momentum. In the asymmetry regime this was not the case, as we have seen. For columns starting close to the axis (~0.1 R_w), there was little expansion before the columns settled on-axis, and most of the angular momentum associated with the initial displacement was lost.

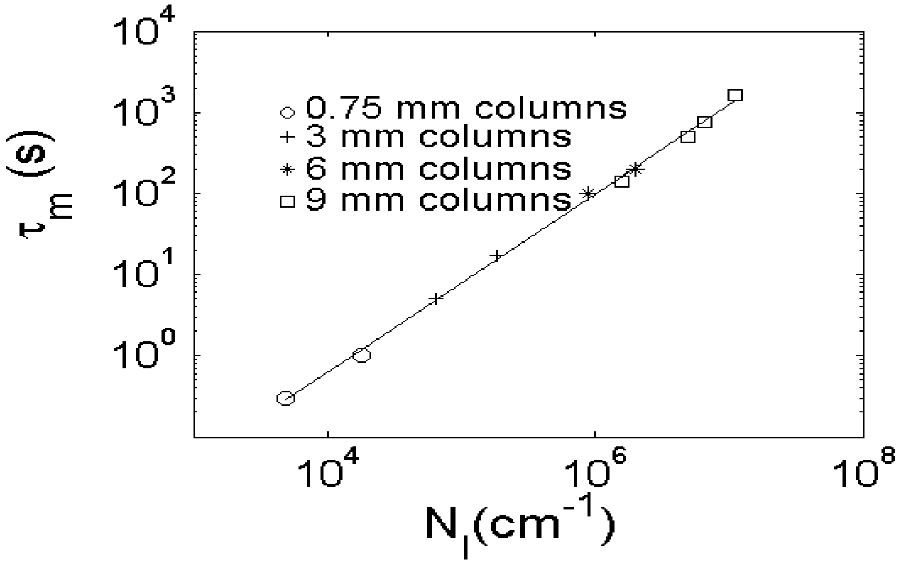

FIGURE 6. τ_m as function of line density. The solid line is a power- law best fit, with slope of 1.1.

Transport for on-axis columns was studies for columns of different size: starting with tiny, 0.75 mm diameter columns, up to the 9 mm columns that were already discussed. It was found that the mobility time τ_m depends nearly linearly on the line density, as shown in Fig. 6 (recently, it was found that τ_m for "rigid" columns depend linearly on density, but only same-size columns were compared [6] in that study).

ADDITIONAL EXPERIMENTAL CHECKS

The 'universality' of the new regime was demonstrated in additional experiments performed with a conventional, spiral filament, low magnetic field machine. Changing the size and density of the resulting plasma was done by manipulating the bias voltage of the filament, and an initial displacement was actively introduced using sector patches available in that machine. Although we could not obtain by that means extremely small columns comparable to those studied in the photo cathode machine, we were able to demonstrate that the new regime can be observed in that machine as well. For the smaller and lower-density columns we observed shortening of the decay time (to hundreds of rotations), we saw shifts of the center characterizing the motion of the column in the trap, and also non-conservation of angular momentum. The latter, however, was less clear than in the photo cathode 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, in both, that increasing the field increases the damping time for the smaller, lower-density columns. In the photo-cathode machine, the decay time increased from 150 ms at 5 kG to 650 ms at 30 kG, somewhat weaker than a linear one. For both machines, the decay rate was found to be weakly sensitive to the steering angle of the magnetic field. That was the case even for tilts of several mrad that caused shifts of the "center" which were larger than that observed when using columns with different plasma potentials (the latter are presumably associated with electric errors).

Finally, in both machines we found that increasing the background gas pressure by 2 to 3 orders of magnitude did not cause significant changes in the decay rate of the diocotron mode.

DISCUSSION

In this work we reported on the finding of a new regime of diocotron-mode decay. Starting with small electron columns displaced from the center of the trap, we studied the rate in which this displacement decays and the column reaches the center of the trap. We found that for small and rarified electron columns this decay is very fast, down to few rotation periods around the center of the trap.

The new regime was found to differ from the known "rotational pumping" regime in almost every aspect. We understand our data on the decay of the diocotron mode as the result of two different decay mechanisms, acting independently of each other. Rotational pumping depends on the length changes that occur during the rotation of the column around its own axis, and is therefore very sensitive to the size of the column. For small columns it becomes weaker. On the other hand, the new regime is insensitive to the size of the column (for fixed plasma potential). Thus it will dominate for small columns, especially if their plasma potential is low also due to low density (rotational pumping decay is independent of density in the regime studied here).

Several phenomena were observed to occur in the transition region between the "rotational pumping" regime and the new regime: increased importance of the end confining fields, shifts in the center around which the columns rotate and finally settle, and non conservation of angular momentum. All these implicate that asymmetries in the end confining fields are responsible for the new regime. The shifts of the center can be understood as being due to misalignment of the end confining rings with respect to the central ring. "Strong" (large and dense) columns rotate around the center of the central rings, because they move primarily due to the effect of the image charges induced on the walls of this ring. On the other hand, "weak" (small and low-density) columns move mainly under the influence of the end fields (magnetron-like motion) and thus are sensitive to the position of the end confinement rings. Table 1 summarizes the differences between the rotational pumping regime and the new, asymmetry-dominated, regime.

The mechanism by which asymmetries in the end fields cause increased damping of the diocotron mode should be further studied. It seems almost to defy the second law of thermodynamics: one expects non-conservation of angular momentum to increase $\sum r^2$, rather than to decrease it. Violation of the second low does not occur, however, since the displacement from the axis is coupled to a very low rotation frequency, compared with the rotation around the column axis. We think that length changes connected with the motion in the non-symmetric trap are responsible for the observed decay of the diocotron mode. This will be the topic of future work.

TABLE 1. Comparison Between Rotational Pumping and the New Asymmetry Regime

	Rotational Pumping	**New Asymmetry Regime**
Conservation of Angular Momentum	yes	no
Prime Mover in Trap	Image charges	End Confinement Fields
Reason for diocotron damping	Length changes (self-rotation)+collisions	Trap asymmetries (asymmetries in the confinement fields)
Damping rate is high for	Large columns	Small low-density columns
Dependence on column radius	Stronger than quadratic	Weak (for fixed plasma potential)
Dependence on plasma potential	Weak (for fixed radius)	linear
B dependence	Weak	$\leq 1/B$

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