Confinement of test particles in a Malmberg–Penning trap with a biased axial wire

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A non-neutral plasma trap has been constructed in which the radial electric field of a non-neutral plasma column is simulated by a biased wire stretched along the axis of the device. The confinement time of test electrons in this device is found to be comparable in magnitude and scaling with that found in pure electron plasma experiments, in spite of the fact that the test electron density is 10^2 times smaller than in a typical pure electron plasma. The confinement time is only weakly dependent on the central wire bias. These results may provide useful input to theoretical efforts to explain transport in these traps. © *1997 American Institute of Physics.* [S1070-664X(97)01405-5]

I. INTRODUCTION

Non-neutral plasmas have been studied for some time, both experimentally and theoretically.[1] Much of the recent experimental work has been performed on pure electron plasma traps similar to the one developed by Malmberg and deGrassie.[2,3] The geometry of these devices is cylindrical, and electron confinement is provided by a uniform axial magnetic field and electrostatic end potentials. Since axial confinement is assured by making the end potentials highly negative, the confinement time is determined by radial transport across magnetic-field lines. At high neutral gas pressures (above $\sim 10^{-7}$ Torr), the transport is produced by electron–neutral collisions. Experimental studies[3] in this regime agree well with theoretical predictions.[4] Below 10^{-7} Torr, the experimental confinement time is pressure independent[5] and scales roughly as $(L/B)^{-2}$, where L is the length of the plasma column and B is the axial magnetic-field strength.[6,7] It is generally believed that this ''anomalous'' transport is caused by electric- or magnetic-field asymmetries associated with construction imperfections. Experiments with applied electric[8,9] and magnetic[10] asymmetries have verified that asymmetries do indeed produce transport, but a detailed understanding of this transport has not been achieved. One difficulty in these experiments is that the plasma's response to the asymmetric voltages applied to the wall can be quite complicated, especially when standing waves are excited. The presence of such collective, often nonlinear, processes makes it difficult to know the magnitude of the asymmetric fields in the plasma.[8]

In this paper, we present results of confinement experiments on a modified non-neutral plasma trap. A primary feature of this new device is the replacement of the plasma column by a biased wire running along the axis of the trap. Low-density electrons injected into this trap have the same basic dynamical motions as electrons in a pure electron plasma: (1) axial bounce motion between the confining end potentials, and (2) azimuthal $\mathbf{E}\times\mathbf{B}$ drift motion produced by the radial electric field of the plasma, or in our case, the biased wire. Because of their low density ($<10^5$ cm^{-3}), the electrons do not contribute significantly to the radial electric field and, thus, act as test particles moving in prescribed potentials. The low density, together with increased temperature, increases the Debye length λ_D to the point where axial modes should be strongly damped. Finally, this lowering of the density should also greatly reduce the electron–electron collision frequency. In spite of these changes, we find that the test electron confinement time exhibits scalings with neutral pressure and L/B similar to those observed in pure electron plasma experiments. In addition, the *magnitude* of the confinement time is also comparable (for the same L/B) to that found in similar plasma experiments. Finally, we find there is only a weak dependence of confinement time on central wire bias and, thus, on the $\mathbf{E}\times\mathbf{B}$ rotation frequency ω_R. These results validate our approach to the study of transport and limit the physical processes that can be invoked to explain $(L/B)^{-2}$ scaling.

II. EXPERIMENTAL DEVICE

The apparatus for our experiments is shown schematically in Fig. 1(a). A gold-plated copper tube with 3.05 in. inside diameter (i.d.) is divided into eight electrically isolated parts, each 6.00 in. long. Five of these (labeled S1–S5) are further divided azimuthally into eight equal sectors to allow for future experiments with applied electric-field asymmetries. The interelectrode gaps are 0.050 in. A 0.014 in. diam inconel wire runs along the axis of the device. The wire is attached to a support on the right end of the machine and passes through a centered hole on the left end of the machine. It is then attached to a tensioning device that maintains its tautness. The wire and its supports are also electrically isolated. This electrode structure is positioned along the axis of the main vacuum chamber, which was centrifugally cast and then bored to an i.d. of 11 in. to minimize asymmetries in the material and keep them far from the trap electrodes. The use of magnetically permeable materials in the electrode structure was also avoided to minimize magnetic-field asymmetries.[7] The entire device is placed in a long solenoid that provides a uniform magnetic-field variable over the range 0–625 G. Cancellation of the earth's magnetic field and fine alignment of the electrode and solenoid axes is provided by two sets of ''bent head'' rectangular magnetic-field coils.[11] The base vacuum pressure is 3.5×10^{-10} Torr and the residual gas consists mainly of hydrogen.

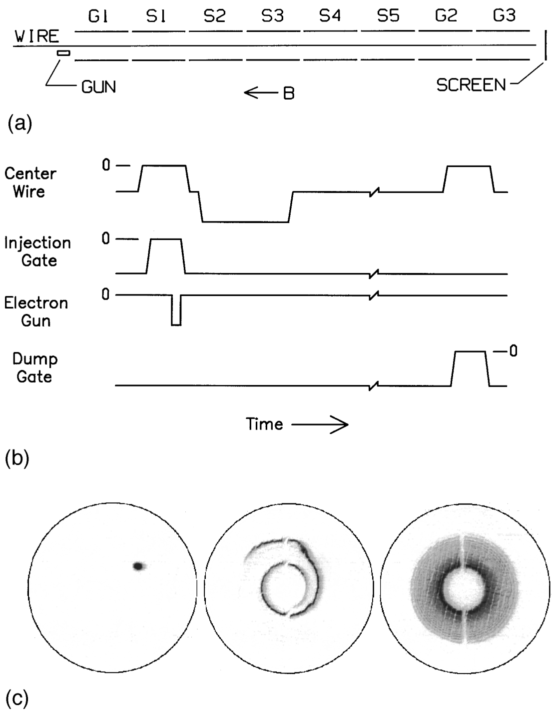

FIG. 1. Experimental device and timing sequence. (a) Schematic of experimental device. Special features include a conducting axial wire, an off-axis test electron gun, and a phosphor screen/charge collection plate diagnostic. (b) Timing diagram for one cycle of experiment. Voltages applied to the central wire, injection gate, electron gun, and dump gate are shown. (c) Phosphor screen images of the initial rapid dispersion of the injected electrons. This dispersion lowers the peak electron density to 10^5 cm^{-3} and provides a suitable starting point for test particle confinement experiments. Images are shown (from left to right) of the injected beam ($t=0$) and two later times (t = 5.9 and 110 μs).

The experimental timing sequence is shown in Fig. 1(b). Two of the electrodes (e.g., G1 and G2) are used as injection and dump gates, which are normally held at a large negative potential (typically -140 V). The remaining cylinders are grounded. The center wire is also normally at a selected bias (-140 to $+140$ V). To start a cycle the bias on the center wire is set to zero. We then ground the injection gate (typically, G1) and apply a negative pulse (1.0–12.0 V) to an off-axis electron gun cathode [cf. Fig. 1(a)]. The diode gun consists of a 0.1 in. diam oxide-coated cathode with a wire mesh anode. Two guns are available, one at a radius of 1.8 cm and the other at 2.5 cm. After the gun is pulsed, the injection gate is returned to a negative potential and the center wire is switched first to -140 V for 100 μs and then to the selected final bias level. The electrons are now trapped between G1 and G2 and are held for a variable time during which some of the electrons will be lost due to radial transport to the walls. Finally, gate G2 is grounded, allowing the remaining electrons to escape axially along magnetic-field lines and hit a positively biased phosphor-coated screen. The screen serves two diagnostic purposes: (1) as a collection plate, it provides a measurement of the total charge remaining in the machine at the dump time. (2) If the bias on the screen is increased sufficiently, the phosphor will emit light. These phosphor screen images show the spatial distribution

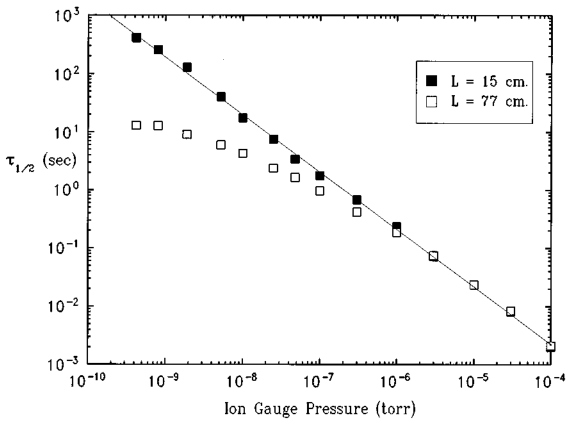

FIG. 2. Confinement time $\tau_{1/2}$ versus neutral pressure for confinement regions of two different lengths L. The solid line has slope -1.

of the electrons and, thus, along with the measurement of the total charge, allow a computation of the electron density.

The electrons from the gun initially form a small-radius off-axis column with a typical peak density of 10^7 cm^{-3}. However, the strong adverse radial shear in the $\mathbf{E}\times\mathbf{B}$ velocity produced by the high initial negative bias on the center wire quickly disperses the electrons.[12] Within 100 μs, the electrons have reached a symmetric distribution with a peak density reduced to 10^5 cm^{-3}. This process is shown in the three phosphor screen images in Fig. 1(c). Since the time for particle loss to the walls is much larger than this, we can ignore the details of this initial rearrangement and take the filled device as our initial condition. The electron density at this point is low enough that its contribution to the radial electric field is negligible for typical center wire potentials. The reduced density, together with increased axial temperature (typically >5 eV) gives a Debye length greater than 5.25 cm. This is larger than our wall radius (3.87 cm) and 22 times larger than a typical pure electron plasma (density 10^7 cm^{-3}, temperature 1 eV, Debye length 0.23 cm). Although our Debye length is still small compared to the machine length, there is no point in decreasing it further, since even vacuum potentials fall off axially with a scale length equal to the radius of the conducting wall.[13]

III. EXPERIMENTAL RESULTS

For these studies, we define a confinement time $\tau_{1/2}$, which is the time required for half of the injected electrons to be lost to the wall. This time is determined by measuring the total charge remaining in the device as a function of the hold time. This multicycle process is possible because the shot-to-shot variation in the injected number of electrons is less than 1%.

Figure 2 shows the measured dependence of $\tau_{1/2}$ on the neutral pressure for the longest and shortest confinement regions we can produce, $L=77$ and 15 cm. The neutral pressure is varied by leaking in helium gas to be consistent with the experiments of Ref. 5. The axial magnetic field and center wire bias are set at 250 G and -30 V, respectively, and the electron gun bias is -10 V.

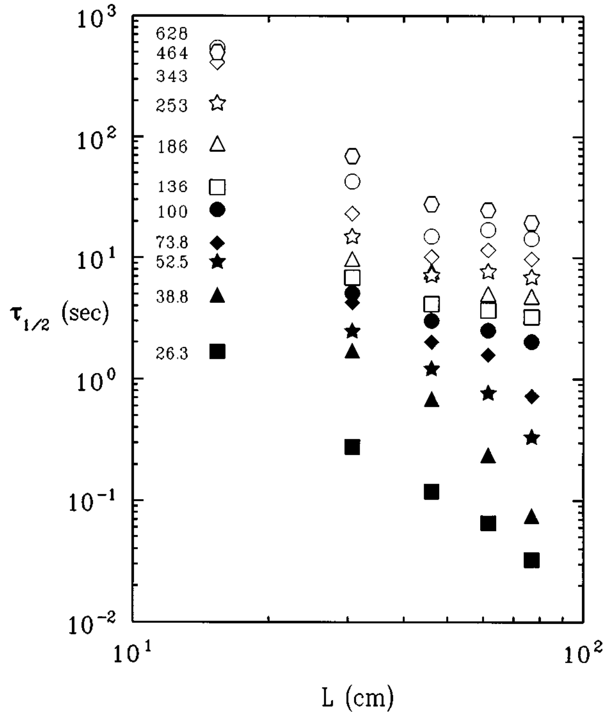

FIG. 3. Confinement time $\tau_{1/2}$ versus length of confinement region L, with axial magnetic-field strength (in gauss) as a parameter. Central wire bias is -80 V and electron gun bias is -10 V for these data.

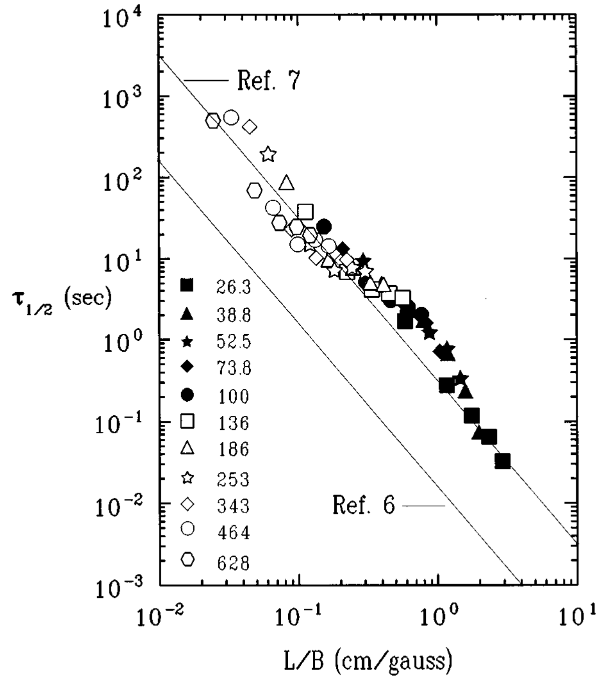

FIG. 4. Confinement times from Fig. 3 plotted versus L/B. The symbol table gives axial magnetic-field strength in gauss. The lines have slope -2 and are taken from the plasma experiments described in Refs. 6 and 7. The upper line is also a good fit to our data.

At high neutral pressures, the confinement time for both lengths varies inversely with neutral pressure, consistent with expectations for transport produced by electron–neutral collisions.[3,4] This scaling continues for the short confinement region until we reach the lowest neutral pressures. The longer trap exhibits anomalously short confinement times at gauge readings below 10^{-7} Torr and the confinement times becomes pressure independent at the lowest pressures. These test particle confinement results are consistent with those observed in previous plasma experiments.[5]

Figure 3 shows the dependence of $\tau_{1/2}$ on the length of the containment region L with magnetic-field B as a parameter. The containment length is varied by changing the placement of the confining gate potentials. The data show that confinement time increases with decreasing L and with increasing B. In Fig. 4 these same data are plotted with L/B as the abscissa. The solid lines (explained below) have slope -2. The upper line fits our data well and shows that $\tau_{1/2}$ scales roughly as $(L/B)^{-2}$ over four decades.[14]

This same $(L/B)^{-2}$ scaling has previously been observed in pure electron plasma experiments.[6,7] These experiments take as their confinement time τ_m, the time for the central density of the electron column to decrease by one-half. It is not clear how to compare τ_m with our $\tau_{1/2}$, especially since $\tau_{1/2}$ probably depends on the radius of the confining wall. However, in a similar sized plasma experiment,[6] where both quantities were measured, τ_m was typically less than $\tau_{1/2}$ by a factor between 2 and 5. In the context of the rough comparisons used in this paper, we ignore the distinction between τ_m and $\tau_{1/2}$ and, in Fig. 4, also plot the best-fit lines from two pure electron plasma experiments (Refs. 6 and 7). Note that the line from Ref. 7 also provides a good fit for our data. Even if our confinement time values are reduced by the factor mentioned above, they will still be comparable to those in the plasma experiments.

Figure 5 shows the scaling of $\tau_{1/2}$ with center wire bias ϕ_{cw}. We have varied ϕ_{cw} over its entire range, including both positive and negative values. Aside from the prominent dip in $\tau_{1/2}$ at low values of $|\phi_{cw}|$, there is only a weak dependence of $\tau_{1/2}$ on ϕ_{cw}, with $\tau_{1/2}$ decreasing by about a factor of 3 as ϕ_{cw} changes from the most negative to the most positive value.

The asymmetry between positive and negative values of ϕ_{cw} appears to be related to the initial radial distribution of electrons. For large, negative ϕ_{cw}, the radial losses occur at the outer wall since it is energetically impossible for the

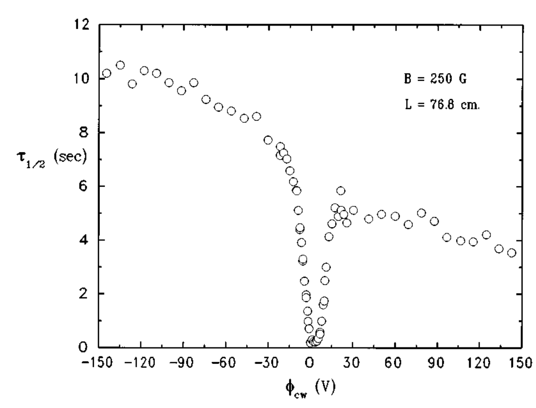

FIG. 5. Confinement time $\tau_{1/2}$ versus central wire bias. Aside from the central dip, the confinement time shows a weak dependence on wire bias.

electrons to reach the central wire. For large, positive ϕ_{cw}, the situation is reversed and the losses occur at the central wire. For the data shown, the electrons are initially closer to the center wire than to the outer wall and, thus, the transport and loss time is longer for negative ϕ_{cw}. When the electrons are injected from our second gun and are initially distributed at larger radii, the asymmetry between positive and negative values of ϕ_{cw} is reversed.

The large dip in $\tau_{1/2}$ is not understood at this time. Preliminary phosphor screen image data indicate that the dip is due to an increase in electron loss to the central wire. The speed of the loss suggests a fluid instability (e.g., the diocotron instability), however, the transition from high to low confinement is not sensitive to the test electron density, as would be expected for such instabilities.

IV. DISCUSSION

These experiments provide important additional input to attempts to explain transport in these traps. We note first that the relatively low electron density in this experiment is too low to support the axial standing waves so often observed[8] in pure electron plasmas. The damping of these waves depends exponentially on the ratio $(-a^2/\lambda_D^2)$, where a is the radius of the plasma column.[15] Since our Debye length is larger than the radius of the conducting wall, these modes should be strongly damped. It has been suggested that the length-dependent transport in these devices might have its origin in the length dependence of standing waves. Evidently, this is not the case.

The second limit involves the role of electron–electron collisions in the observed radial losses. Since the collision frequency is proportional to density, this frequency is at least 10^2 times smaller in our experiment than in the plasma experiments (even if we ignore the higher electron temperatures in our experiment). Yet, all the experiments have comparable confinement times. While it is conceivable that there are unknown factors that differ in these experiments (e.g., size of construction asymmetries), it seems unlikely that these effects would cancel so well. Our data, thus, suggests that the correct transport theory cannot depend critically on the electron–electron collision frequency, ν_{ee}. As an additional check on the density independence of the confinement time, we have varied the test particle density in our experiment by a factor of 10 using three different methods.[16] None of these gave a variation in $\tau_{1/2}$ of more than 30%.

The dependence of $\tau_{1/2}$ on the central wire bias is also of interest since this bias sets the radial electric field and affects the azimuthal rotation frequency. Aside from the large dip for low ϕ_{cw}, the dependence of $\tau_{1/2}$ on ϕ_{cw} is weak with $\tau_{1/2}$, varying only 30% as ϕ_{cw} changes by a factor of 5 (-150 to -30 V) and the corresponding ω_R at the injection radius changes from 3.45 to 0.69×10^6 rad/s. This result conflicts, for example, with the notion that the B^2 scaling of $\tau_{1/2}$ is a reflection of a more fundamental dependence on the azimuthal $\mathbf{E}\times\mathbf{B}$ rotation frequency ω_R.

It is interesting to compare our results with the basic concepts of the theory of single-particle resonant transport due to field asymmetries.[17] According to this theory, asymmetry-produced transport is dominated by particles having an axial velocity v_z that satisfies the resonance condition $\omega - m\omega_R - kv_z = 0$, where ω, m, and k are the asymmetry frequency, azimuthal mode number, and axial wave number, respectively. The diffusion coefficient for this type of transport scales in different ways, depending on the magnitude of ν_{ee} relative to the oscillation frequency ω_T of particles trapped in the trough of the asymmetry potential. As usual in nonlinear theory, ω_T is proportional to the square root of the asymmetry amplitude. For small values of ν_{ee} (banana regime), the diffusion depends linearly on ν_{ee}. For large values of ν_{ee} (plateau regime), the diffusion is independent of ν_{ee}. If the field asymmetries are large enough to produce overlapping resonances, stochastic radial transport results, which is also independent of ν_{ee}. Thus, if one follows the theory, our results would indicate that transport in these traps is either in the plateau or stochastic regime.

Although we have not attempted detailed calculations of theoretical loss rates, stochastic transport would presumably be much faster than observed and, thus, be ruled out. It also seems unlikely, however, that the field asymmetry amplitude is small enough that the plateau regime condition could still be satisfied after reducing ν_{ee} by a factor of 100. The actual value of ω_T is unknown since we do not know the amplitude or spectrum of the background field asymmetries. However, it is interesting to attempt a rough estimate of ω_T via a simple experiment. An additional, externally controlled, asymmetry is added to the experiment by applying plus and minus dc voltages to the two halves of a sectored wall ring in the confinement region. The amplitude of the voltages is increased until the plasma loss rate is twice the background rate. This typically requires about 1 V. The maximum amplitude of the Fourier modes produced by the applied asymmetry is then taken to approximate the amplitude of the background asymmetry. When this was done on the plasma experiment of Ref. 6 and the test particle experiment described here, both experiments were found to be in the banana regime rather than the plateau regime, and should, thus, exhibit transport that depends linearly on ν_{ee}.

It is also possible that something else in the experiment plays the role of a collision. It has been suggested, for example, that high-frequency noise on the confining end potentials could produce a collision-like effect on the electrons. To check this, we have run our experiment with and without large capacitive filters on the confining potentials. Although a significant reduction of noise was achieved, no change in the confinement time was observed.

In summary, we have measured the confinement time of low-density test electrons in a trap with a biased central wire. We found that the confinement time is comparable in magnitude and scaling to that obtained in pure electron plasma experiments, and that confinement time is only weakly dependent on central wire bias. These results may provide useful input to theoretical efforts to explain transport in these traps.

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[14]The abscissa of this graph can also be expressed as the ratio of the axial transit time $\tau_a = 2L/v_z$ to the azimuthal drift time $\tau_d = 2\pi rB/E(r)$. Taking the axial kinetic energy to be equal to the electron gun bias potential energy (10 eV) and the radius to be the radius of the initial injected beam, we find that $\tau_a/\tau_d = 0.78\ L/B$.

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