

# Experiments With Pure Electron Plasmas

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## Abstract

Pure electron plasmas are one of the simplest systems on which plasma wave and transport effects can be studied. Two recent experiments on this system are discussed. The loss of electrons due to anomalous transport has been measured over a six order of magnitude variation in containment time. The containment time scales approximately as [magnetic field/plasma length]<sup>2</sup>. The growth of the  $l = 1$  diocotron wave due to resistance between sections of the bounding wall has been observed. The measured growth rates agree with theory.

## 1. Introduction

In this lecture, I will report the results of two recent experiments on an unusual type of plasma — an unneutralized, magnetically confined electron gas. These pure electron plasmas, with radius much larger than their Debye length, can be made by simple methods and contained for hours [1, 2]. These plasmas display a wide range of important phenomena — some of which are unique to nonneutral plasmas and some of which are common to the physics of neutralized plasmas [3–5]. The simplicity of pure electron plasmas from both the experimental and theoretical points of view is an important advantage to the research.

We have done a number of measurements on transport of these plasmas. The experiments show that electron-neutral collisional transport is in excellent agreement with theory for high background pressures, and that this transport is negligibly small at the lowest pressures attainable [4, 6]. In experiments at pressures down to  $10^{-10}$  torr, it has been established that there is an “anomalous” loss mechanism which is independent of background pressure [2]. Here, we present data showing that this anomalous transport depends strongly on the length  $L$  of the plasma column. At base pressures, the anomalous transport is observed at all experimentally accessible lengths and magnetic field strengths: the transport rate scales approximately as  $L^2 B^{-2}$  over 6 decades. We do not yet understand the anomalous transport mechanism.

This low-noise repeatable plasma sample is also excellent for various wave experiments. Electron plasma waves and diocotron waves are readily observable [1, 4]. The diocotron modes are negative energy waves, and a resistive wall impedance can easily drive the  $l = 1$  wave unstable [7–9]. We have observed this instability and compared the measured growth rate to that calculated from a simple theoretical model. The results agree within 10%.

## 2. Pure electron plasmas

The electron plasma is contained in cylindrical geometry, with an axial magnetic field providing radial confinement, and applied potentials providing axial confinement. The containment apparatus is shown schematically in Fig. 1. The entire

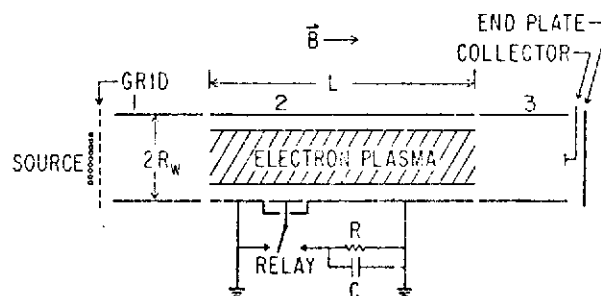


Fig. 1. The cylindrical containment geometry.

apparatus is in a uniform static axial magnetic field which is varied over the range  $42 \leq B \leq 676$  G. The electrostatic boundary is a conducting wall at radius  $R_w = 3.1$  cm; the wall consists of a series of 12 electrically isolated cylinders of various lengths (for the sake of clarity, only three are shown in Fig. 1). Any of these cylinders can be biased sufficiently negative to contain the plasma axially. A few of these wall cylinders are divided into angular sectors of 30, 60, 90, and 180 degrees which can be used to launch or detect waves having azimuthal ( $e^{i\theta}$ ) dependence; the sectors are also used to provide resistive loading on the diocotron waves.

The system is normally operated in an inject, hold, dump/measure cycle. Electrons are thermionically emitted from a directly heated spiral of tungsten wire, the center of which is biased negatively with respect to ground. During injection, all wall cylinders are grounded except for a dump gate (e.g., No. 3) biased negatively, giving a column of electrons between the filament and this gate. The injected plasma typically has a central density  $n_0 = 1.4 \times 10^7 \text{ cm}^{-3}$ , a radius  $R_p = 1.4$  cm, and average thermal energy  $T_e \approx 1$  eV. The Debye shielding length calculated from these parameters is  $\lambda_D \approx 0.2$  cm, so the plasma column is many Debye lengths across. The plasma column is rotating, since the radial electric field due to space charge gives an  $E \times B$  drift in the  $\theta$  direction. The electron plasma contains a negligible number of positive ions, since ions are not confined longitudinally.

A portion of this plasma column is trapped by gating a second cylinder (e.g., No. 1) negative. This gives a trapped plasma column with length  $6 \leq L \leq 120$  cm, depending on the choices for the injection and dump gates. Since the axial containment is energetically assured, the electrons can be lost only by radial transport across the magnetic field to the cylindrical walls. After a variable containment time  $t_0$ , the dump gate is pulsed to ground potential, allowing the remaining electrons to stream out axially along the field lines. The collection electrodes include an end plate for collecting all the remaining electrons, as well as a small movable collector for measuring the electrons remaining on the field line at a particular  $r, \theta$ .

The injection/hold/dump cycle may be repeated up to 60

times per second with nearly identical injection conditions, allowing the time evolution of the plasma to be constructed from many separate measurements with differing containment times. We typically characterize the initial plasma evolution by the time  $\tau_m$  required for the central density to decrease a factor of two.

The most important concept for discussing radial confinement is the total canonical angular momentum of the charged particles, given by

$$P_\theta = \sum_j [m_j v_{\theta j} r_j + q_j A_\theta(r_j) r_j] \quad (1)$$

Here  $v_{\theta j}$  is the  $\theta$  component of the velocity of the  $j$ th particle,  $r_j$  is the radial position of the  $j$ th particle, and  $A_\theta(r) = Br/2$  is the vector potential. If a plasma contains particles of both signs of charge in approximately equal numbers, the second term on the right sums to essentially zero; i.e., an electron and ion can cross the field together with no change in  $P_\theta$ . If only one charge species is present, the mechanical part of the angular momentum is negligible for the low electron velocities considered here, so  $P_\theta$  may be approximated by

$$P_\theta \approx (-eB/2) \sum_j r_j^2 \quad (2)$$

To the extent that  $P_\theta$  is conserved, the mean-square radius of the plasma is constant, i.e. there can be no bulk expansion [10]. Radial expansion of the plasma requires a torque from outside the plasma to change the total angular momentum of the electrons. Of course,  $P_\theta$  is conserved for electrostatic interactions between the particles, no matter how complicated and non-linear these interactions may be. Examples of effects that do not conserve  $P_\theta$  are electron-neutral collisions, finite wall resistance, radiation, and deviations from cylindrical symmetry in the construction of the device. These effects may apply torques to the plasma and allow it to expand.

### 3. Length-dependent transport

At high background pressures ( $P \geq 10^{-6}$  torr), the drag exerted by stationary neutrals on the rotating plasma is the dominant external torque causing plasma expansion and loss. At low background pressures, the plasma is observed to be lost by a mechanism which is basically independent of pressure. This "anomalous" loss can give containment times  $10^3$  times less than would be expected from electron-neutral collisions at the base pressure of  $10^{-10}$  torr.

Recent containment experiments have established that the anomalous loss times depend strongly on the length of the plasma column, as well as on the magnetic field. Figure 2 shows the dependence of the evolution time  $\tau_m$  on length, for three different magnetic field strengths, at a base pressure  $P = 5 \times 10^{-10}$  torr. A strong length dependence is observed over the entire range of accessible lengths and magnetic fields, spanning 6 decades in containment times.  $\tau_m$  scales approximately as  $L^{-2}B^2$ ; the dashed lines in Fig. 2 represent

$$\tau_m = (0.8s) (L/6 \text{ cm})^{-2} (B/42 \text{ G})^2 \quad (3)$$

Within this length scaling, there are reproducible irregularities. Different containment volumes with equal lengths can show substantially different containment times. For example, three different volumes of length 6.1 cm were measured and the containment times differ by as much as a factor of 10. In

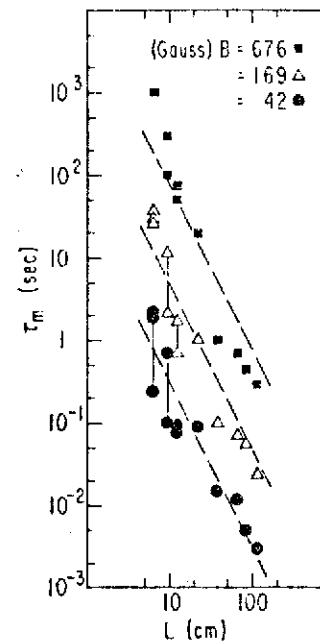


Fig. 2. Measured evolution times  $\tau_m$  for plasma columns of length  $L$ , at three different magnetic field strengths.

general, containment volumes which include sector probes have shorter containment times than do equal-length volumes without sector probes.

The most likely cause of the anomalous transport is small azimuthally asymmetric magnetostatic or electrostatic field errors coupling angular momentum into the plasma. Magnetostatic errors could arise either from irregularities in the main solenoid, or from induced magnetization of the stainless steel hangers and rails which support the containment cylinders. (The stainless steel has permeability  $\mu \leq 1.005$ .) Electrostatic errors could arise from misalignment of the gold plated copper cylinders or sectors (typically  $\pm 0.05$  mm). However, we have no direct knowledge of the magnitude or spatial distribution of the error fields.

We also do not know whether these field asymmetries would couple to the plasma through perturbations to single particle trajectories, or through collective effects such as diocotron waves. There exists an extensive body of theory treating single particle resonant transport due to field asymmetries; the main application of these theories has been ion transport in neutral plasma devices such as Tandem Mirrors [11-13]. These transport theories consider the bounce, rotation, and collision times of individual particles, and it is interesting to view our data from this perspective.

An average thermal particle bounces axially back and forth in a time  $\tau_b = 2L/v$ . Taking our plasma thermal energy to be 1 eV [14], the range of containment lengths gives  $0.3 \leq \tau_b \leq 5 \mu s$ . The particle will also  $E \times B$  drift around the plasma axis in a time  $\tau_r = 2\pi r B/E(r)$ . Taking the electric field near the axis (i.e., using the central density) gives  $0.2 \leq \tau_r \leq 3 \mu s$  for the experimental magnetic field strengths.

Consider an asymmetric field error of the form

$$\delta\phi_{n,l}(r) = \cos \frac{n\pi z}{L} \cos l\theta \quad (4)$$

A particle with axial velocity  $v$  and azimuthal rotation time  $\tau_r$  will remain resonant with the perturbation only if  $(n\pi/L)v \neq l2\pi/\tau_r = 0$ . This can be rewritten as

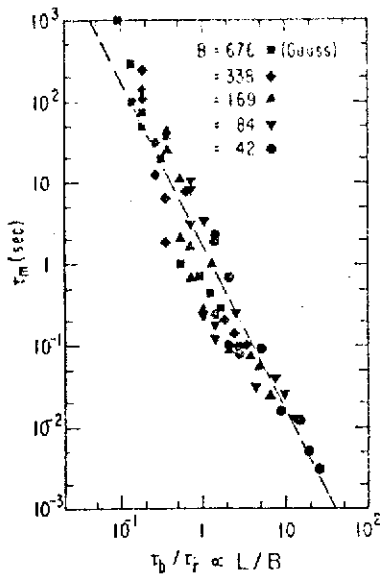


Fig. 3. Measured evolution times  $\tau_m$  vs. the ratio of axial bounce time to rotation time for a thermal particle.

$$v/\bar{v} = (l/n)(\tau_b/\tau_r) \quad (5)$$

The average bounce and rotation times, which depend on  $L$  and  $B$ , thus determine the velocity of the particles which will be resonant with a perturbation of given Fourier numbers  $n$  and  $l$ . These resonant particles may make large radial excursions, giving random diffusion with a large step size when electron-electron collisions interrupt the single particle drifts. For our plasma parameters, the  $90^\circ$  scattering time for electron-electron collisions is approximately 3 ms; of course, a scattering of less than  $90^\circ$  will generally be sufficient to disrupt a resonant drift orbit.

In Fig. 3 we plot the measured evolution time  $\tau_m$  vs.  $\tau_b/\tau_r$ , for all plasma lengths and magnetic fields studied. The experimental data scale as  $(\tau_b/\tau_r)^{-2}$  over 5 decades, with approximately 1 decade of scatter. The dashed line is

$$\tau_m = (1.5s)(\tau_b/\tau_r)^{-2} \quad (6)$$

This is the best slope = -2 fit to the data, and is the same fit as the lines shown on Fig. 2. However, when plotted this way, the transport data shows a striking continuity over the range of evolution times from  $3 \times 10^{-3}$  to  $10^3$  s.

It is highly unlikely that a single error-field Fourier component ( $n, l$ ) could give these transport results, since experimental parameters varying over the range  $0.1 \leq \tau_b/\tau_r \leq 30$  would select resonant particles over a kinetic energy range of  $1:10^5$ . This energy range would necessarily extend to such low energies that plasma fluctuations would perturb the particle trajectories, or extend to such high energies that there would be few particles with that energy. If many error components contribute to the transport, it is not apparent how they contribute in such a regular manner. The analysis of single particle resonant transport is complicated by the existence of different regimes of collision frequency vs. particle orbit frequency ("banana", "plateau", "collisional"); and by the possibility of "stochastic" transport when the number of contributing resonances becomes so large that the different resonant orbits can overlap in phase space.

From the perspective of single particle transport theory, it is therefore surprising to see such regular transport scaling over such a wide range of parameters. Further experiments and com-

parison to theory may clarify this anomalous transport mechanism, and may also contribute to understanding transport in neutral plasma devices.

#### 4. Resistive wall instability

Normally, the  $l=1$  diocotron wave is essentially neutrally stable in our plasmas, and all higher  $l$  diocotron waves are strongly damped. However, the  $l=1$  diocotron wave is a negative energy wave, and it will grow if coupled to a dissipative load. In our apparatus, resistive loads of the order of  $10^4 \Omega$  connected between sections of the bounding wall give growth rates of the order of  $100 \text{ s}^{-1}$ . Thus our experimental situation differs markedly from systems such as hollow beams, on which the fundamentally unstable diocotron modes grow rapidly to some nonlinear state [15].

The growth rate of the resistively destabilized diocotron wave can be computed from a simple model comparing the negative energy of the wave to the power dissipated in the load [7, 8]. This model treats the plasma as a cold fluid in  $E \times B$  motion, and introduces the finite length of the axisymmetric plasma column in an *ad hoc* manner.

For the case of an infinitely long plasma column and a perfectly conducting wall at  $r=R_w$  the wave perturbation potential is [9]:

$$\delta\phi(r, \theta, t) = S \frac{r}{2} \left[ \frac{\omega_E(r) - \omega}{\omega} \right] \cos(\theta - \omega t) \quad (7)$$

The wave frequency  $\omega$  is real and equal to the  $E \times B$  rotation rate at the radius of the wall:

$$\omega = \omega_E(R_w) \quad (8)$$

where

$$\omega_E(r) = \frac{e}{\epsilon_0 B r^2} \int_0^r r' dr' n(r') \quad (9)$$

Moreover, the wave frequency does not depend on the shape of the density profile  $n(r)$ ; it depends only on the density per unit length in the axial direction. The amplitude in eq. (7) has been normalized such that the radial electric field at the wall is  $S \cos(\theta - \omega t)$ .

The wave density perturbation  $\delta n(r, \theta, t)$  consistent with  $\delta\phi$  represents a displacement of the electron column from the  $r=0$  axis, combined with a revolution about that axis at the wave frequency  $\omega$ . Such a displacement is observed experimentally when the density is measured at constant phase of the received wave. This displacement of the electron column reduces the total electrostatic energy of the system. Since in ideal  $E \times B$  motion the liberated energy cannot go into the kinetic energy of the particles, the displacement can take place, i.e., the wave can grow, only if the energy can be dissipated in the wall.

The energy associated with this wave can be calculated to be  $-\pi\epsilon_0 R_w^2 S^2/4$  per unit length, for an infinitely long plasma column [8]. We assume that the wave energy for a trapped electron column of length  $L$  is given by

$$\delta W = -L(\pi\epsilon_0 R_w^2 S^2/4) \quad (10)$$

This result neglects "end effects" and depends on  $L$ , which is not measured directly. For comparison between measurements and the theory, we will take the value of  $L$  to be the length of the containment cylinder.

Now if the wall sector is connected to the external RC circuit

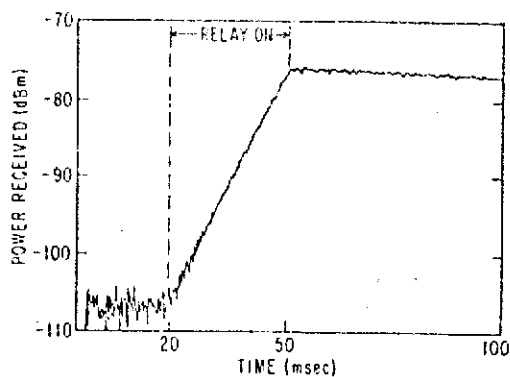


Fig. 4. Received power vs. time for  $l = 1$  diocotron wave. The wave is destabilized when a relay connects a resistive load to a wall sector.

cuit as shown in Fig. 1, the wave will drive current in the circuit by inducing surface charge on the sector probe. The power dissipated in the resistor is

$$P = \frac{1}{2} \left[ 2\epsilon_0 \omega S L_s R_w \sin\left(\frac{\Delta\theta}{2}\right) \right]^2 \left[ \frac{R}{1 + \omega^2 R^2 C^2} \right] \quad (11)$$

where  $L_s$  and  $\Delta\theta$  are the length and angular size of the sector. The wave amplitude will grow as  $\exp(\omega_i t)$ , where the growth rate is given by energy conservation as

$$\omega_i = -\frac{P}{2\delta W} = \left( \frac{4\epsilon_0}{\pi} \right) \frac{\omega^2 L_s^2 \sin^2(\Delta\theta/2)}{L} \left[ \frac{R}{1 + \omega^2 R^2 C^2} \right] \quad (12)$$

Note that the growth rate depends only on the wave frequency, on the real part of the load impedance, and on geometric factors.

The amplitude of the resistively destabilized wave is measured experimentally by taking one short duration sample of the signal during each cycle, on a separate receiver wall sector. The plot of power vs. time is constructed by changing the sample time with each cycle. Since the input impedance of the receiver amplifier is shorted except during the short sampling time, this procedure prevents that impedance from influencing the wave growth.

Figure 4 is a plot of the received power vs. time for the destabilized  $l = 1$  diocotron wave. Initially, there is a small wave present at about the same level as the amplifier noise; this wave is stable or lightly damped, since the sector probe is initially grounded. When a relay is switched to connect the sector to the RC load, the wave grows exponentially with time. The experimental growth rate is the measured slope of the plot. The wave growth continues until the sector is once again grounded, after which the wave exhibits weak damping. The jitter at high wave power ( $\pm 0.5$  dB) is due to the cycle-to-cycle variation in the wave and plasma initial conditions.

Figure 5 shows the measured growth rate of the wave as a function of the destabilizing resistance  $R$ , for two values of the capacitance  $C$ . The solid curves in the figure are the absolute predictions of eq. (12), based on the measured values of  $R$ ,  $C$ ,  $\omega$ ,  $L_s$ ,  $\Delta\theta$ , and the length of the containment cylinder.

Figure 6 shows the measured growth rate as a function of the measured wave frequency. The different wave frequencies were obtained by varying the magnetic field, and also by varying the bias voltage of the source, thereby changing the plasma density. As the frequency was changed, the resistor was adjusted as necessary to keep the real part of the load impedance constant.

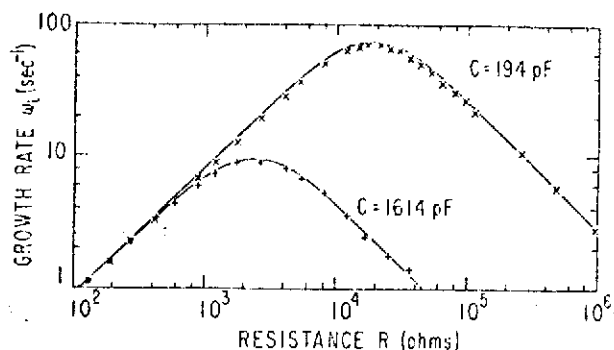


Fig. 5. Measured wave growth rate vs. the resistance in the wall circuit, for two values of the circuit capacitance. The lines are absolute predictions from theory.

The solid line is again the absolute prediction of eq. (12). Finally, the dependence of the growth rate on  $\Delta\theta$  and  $L$  has also been checked, using sectors of angular size  $\Delta\theta = 30, 60, 90, 120, 150$  and  $180$  degrees, and containment lengths  $12 < L < 120$  cm.

In general, the data agree within 10% with theory over the entire range of experimental parameter variations. We regard this agreement as satisfactory since the accuracy of these experimental measurements is approximately 10%, and since there may also be effects of this magnitude left out of the simple theoretical model.

In summary, we have shown that a resistive wall impedance destabilizes the negative energy  $l = 1$  diocotron wave in an otherwise quiet, confined electron plasma. The experimentally measured growth rates agree with the theory.

#### Acknowledgements

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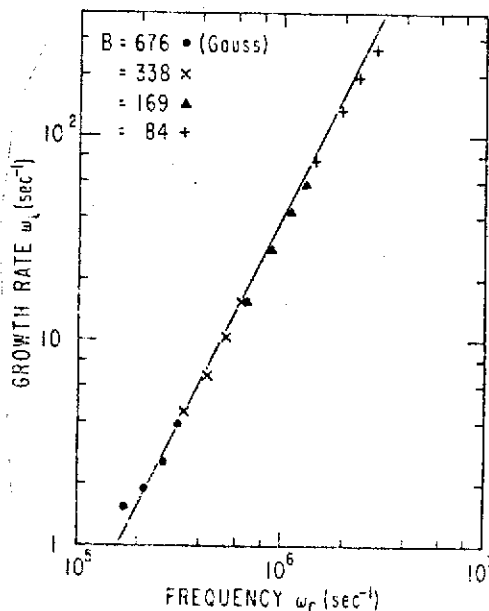


Fig. 6. Measured wave growth rate vs. measured wave frequency, with a constant real part of the load impedance. The line is the absolute prediction of theory.

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